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Meeting IMO's climate goals for 2050: sailing on alternative fuels and its consequences

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Preface

I am delighted to present my thesis "Meeting IMO's climate goals for 2050: sailing on alternative fuels and its consequences". The thesis is the final result of the last part of my period of studying at the TU Delft, the graduation process. The graduation process and writing the thesis was carried out between August 2020 and July 2021, in order to obtain a Master's degree in Marine Technology at the University of Technology (TU) in Delft.

With the help of Dr. Ir. R. G. Hekkenberg I formulated my research questions and designed the approach for this research. After completing the research, all answers to the relevant research questions were reached. During the research period, it was always easy to ask Dr. Ir. R. G. Hekkenberg for his advice. Without his advice I would most probably not have achieved reaching the finalization of my research project.

I would like to thank Dr. Ir. R. G. Hekkenberg for his good guidance and for the time he set aside to discuss the progress of the study with me. In addition, I would like to thank Dr. A.A. Kana for his feedback after the completion of the literature study and his useful feedback and advice at the greenlight meeting. His critical eye at the greenlight meeting led to further insights that are now incorporated in the final manuscript. Further, I want to thank Dr. W.W.A. Beelaerts van Blokland for participating in my Thesis Committee.

I would also like to thank my friends, teammates and roommates for supporting me and helping me whenever I asked for assistance. I would like to thank Casper, Marloes, Spot and Bobo for all the distraction and relaxation besides graduation. Finally, but most importantly, i would like to thank my parents Wouter and Herma for being there, for their advice, for their unconditional support and all the opportunities they have given me throughout my life, that have made me who I am today.

S. de Herder
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Abstract

The global temperature is rising as a consequence of the climate change. In order to stop the further increase of the global temperature, the international community has decided to aim at reducing global greenhouse gas (GHG) emissions in the near future. To achieve this ambition, various alternatives in shipping need to be explored including sailing on alternative fuels.

This study investigates the consequences of sailing on alternative fuels. It is investigated which problems might occur when sailing on alternative fuels, which rules are mandatory when sailing on alternative fuels and as a consequence what the effects are on the cargo transport costs.

The problems occurring when sailing on alternative fuels are caused by the lower energy densities of these fuels, the rules and requirements with regard to the storage of some of these fuels and the shape of the storage tanks for some specific fuels. The shape and requirements regarding the fuel storage tanks can make it necessary to replace cargo for storage tanks, which will result in increased transports costs. Furthermore, the lower energy density of alternative fuels result in more fuel weight, or volume as compared to conventional fuels. In order to transport the same amount of cargo, an extra bunker stop, or taking less fuel and reducing the sailing speed, can be an option. Another option to compensate for the increased weight, or volume of the alternative fuels, is to reduce the cargo taken on board. All options will result in higher transports costs as compared to sailing on conventional fuels. To investigate how these extra costs are composed a main question has been formulated: "In a situation where the transport costs are minimized, how do the transport costs compare when sailing on various fuels with different energy densities than conventional fuels?".

To answer this main question, a model was developed. The model is suitable to calculate the transport costs in various situations. For this research, three vessel types on three operations, using seven fuel types have been analyzed.

The analyzed vessels were a container vessel, an oil tanker and an ore carrier. The chosen voyages are common voyages. The analyzed fuels are fuels which are able to achieve the goal of reducing the CO2 emission with 70% per transport work in 2050 as compared to 2008. Heavy fuel oil was used as benchmark. Based on the simulations used in the developed model it was found that: the costs of alternative fuels are higher than those of conventional fuels. Batteries are too heavy, too large and too expensive to be considered as an option, for the researched vessels and operations. The capital costs of fuel cells make that the use of fuels in combination with a fuel cell is currently expensive at higher speeds. High fuel storage costs make hydrogen currently not competitive with conventional fuels. The transport using an oil tanker are the lowest for hydrotreated vegetable oil, second lowest for ammonia in combination with an internal combustion engine and the highest for battery electric.

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List of Abbreviations and Acronyms

Δ	Displacement
C_2H_5OH	Ethanol
C_{day}	daily costs [$]
C_{voy}	costs of the voyage [$]
CH_3OH	Methanol
D	duration [days]
DWT	deadweight tonnage
GHGs	Greenhouse gasses
H_2	Hydrogen
HFO	Heavy Fuel Oil
HVO	Hydrotreated Vegetable Oil
IGF Code	International Code of Safety for Ships using Gases or other Low-Flashpoint Fuels
IMO	International Maritime Organization
kW	kilowatt
NCR	normal continuous rating
NH_3	Ammonia
NM	nautical mile
NO_x	Nitrogen oxides
P_d	Vessel Power
TEU	Twenty Foot Equivalent Unit
ULCC	Ultra Large Crude Carrier
V_s	Vessel speed
VLLC	Very Large Crude Carrier
W_E	equipment and outfitting weight [t]
W_M	machinery weight [t]
W_s	structural weight [t]
W_{cargo}	weight of the cargo [t]
W_{LW}	lightweight [t]

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Introduction

Like the maritime industry, the climate is always moving and changing. In the 20^{th} century alone, the global temperature on earth raised an average of 1 °Celsius while the seawater level rose with 20 centimeters (KNMI, 2019), (Rijksoverheid, 2021). Both are consequences of climate change, which can result in adverse events. Habitats can change due to warm weather which may result in the disappearance of fauna and flora. Another negative effect of global warming is that parts of the earth are becoming drier while other parts of the world become more wet, resulting in hazards as: floods, food shortages, drinking water shortage, extinction of animals, forest fires, heat waves and more unwanted effects.

Climate change can be caused by several things: the activity of the sun, the increase in greenhouse gases (GHGs), volcanic eruptions, or meteor impact. As humanity does emit heat-trapping gasses, also known as GHGs, man is at least partly responsible for global warming. The emission of GHGs results in a disturbed climate system (Warmheart Worldwide, 2021). In addition to the impact that these GHGs have on the climate, the substances can also be harmful to the human health. These are reason enough to reduce the amount of GHGs emitted.

In 2015 a climate convention was held in Paris. 196 parties came to an agreement with as main goal to reduce the rate at which the climate changes. The aim is to keep the average global temperature raise well below 2 °Celsius. To achieve this, countries aim to reduce global greenhouse gas emissions as soon as possible with the objective to live in a climate neutral world by 2050 (United Nations Climate Change, 2021). In spite of so many different countries included in the agreement, the shipping industry was not involved. The interests in this sector proved too great to reach an agreement. 2.2% of the global CO_2 emissions are caused by international shipping with a potential growth between 50 and 250% in 2050 (IMO, 2018).

In order to involve the shipping industry, the International Maritime Organization (IMO), responsible for safe, secure and efficient shipping on clean oceans organised a meeting in April 2018 to address GHG emissions from ships involved in international trade. During the meeting, the committee adopted MEPC.304(72) "Initial IMO strategy on reduction of GHG emissions from ships". The MEPC.304(72) states that the ambition is, noting the technological innovation and introduction of alternative fuels and energy sources, to achieve at least a reduction of 40% CO_2 emission by 2030 and 70% per transport work by 2050 as compared to 2008 (IMO, 2018). The total GHG emissions should be reduced by at least 50% in 2050 as compared to 2008.

Problem definition

As described above, the CO_2 emissions should be reduced by 70% per transport work by 2050 as compared to 2008 and the total GHG emissions should be reduced by 50% in 2050 as compared to 2008. Certainly achieving the goal is possible with the implementation of a fuel transition, but whether this is realistic remains the most important question.

From the first part of this research, the literature review (MT54010), it appeared that there is sufficient knowledge of how to make the shipping industry CO_2 neutral and lower the GHG emissions from shipping. Alternatively, less GHG emitting fuels are herein key. Different studies, using different approaches for comparing and selecting the most promising fuels have been analyzed ((Hansson et al., 2019), (Perčić et al., 2020), (Hansson et al., 2020), (Deniz and Zincir, 2016), (Ammar and Seddiek, 2017), (Ammar, 2019), (ben Brahim et al., 2019), (Taljegard et al., 2014), (Bergsma et al., 2019)). It was found that alternative fuels, able to reduce the GHG emission, have lower energy densities as compared to conventional fuels (the fuels used in 2008). Lower energy density results in more fuel weight, or volume as compared to conventional fuels when the same distance and speed is sailed.

More efficient fuel handling, extra stop(s) for refueling, or reduction in cargo load are options to overcome the problem of more fuel weight, or volume when sailing on alternative fuels. Unfortunately, the three described options all have negative economical consequences for the vessel and its operator. When an extra fuel stop is needed, the vessel loses time. When cargo is reduced, the vessel loses capacity and when the vessel lowers its sailing speed, the number of voyages per year decreases. These outcomes will all result in more costs per ton cargo. What the consequences are for maritime shipping and especially the consequences of costs of transport when sailing on alternative fuels is further investigated in this study.

This study gives an overview of how transport costs, when using alternative fuels, compare to each other and to conventional fuels. Different alternative fuels have been investigated together with different options to find the most cost-effective way of using alternative fuels in shipping. Different fuel types, vessel types and operations are investigated in order to find the most cost-effective solutions. Which measures are needed to make a specific alternative fuel as cost-effective as possible are investigated and which transport costs using which alternative fuel(s) are most competitive to the transport costs when using conventional fuel are further studied. In order to do so, a main question and several sub-questions have been formulated.

Main question:
In a situation where the transport costs are minimized, how do the transport costs compare when sailing on various fuels with different energy densities than conventional fuels?

Sub-questions:

- How much energy, fuel volume and fuel weight per fuel type are required for different vessels on specific routes and operations?
- Which vessels and which sailing distances should be investigated and what are the most promising fuels fulfilling all the requirements for these vessels and sailing distances?
- What is the impact of sailing on an alternative fuel with a lower energy density? Does this require more bunker stops, additional storage space for the fuel, or should sailing speed be reduced, or what are the best possible combinations?
- What are the costs in an optimized situation, including possibly extra bunker stops, decrease in speed, or a decrease in cargo space?

Structure of Study

The order of the sub-questions form the structure of the study. The sub-questions have been answered in a chronological order starting with an analysis of maritime transport. In the first chapter, the majority of commercially operating vessels have been analyzed and three major commercial vessel types have been chosen. Thereafter, it is analyzed what the common operations of these vessels are by analyzing different trade flows around the world. Next, the size and power of the vessels on the analyzed routes are presented. Lastly, three common combinations of vessels and routes, or power and range, have been selected and three reference vessels with their corresponding characteristics were selected.

After the reference vessel and operation have been selected, a study on what is needed to develop a model that investigates the economical consequences of sailing on alternative fuels was performed. In Chapter 2, first the problems of sailing on alternative fuels and potential solutions and consequences are described. This was done to analyze how the model should run from problem to consequence. Thereafter, research on what data are needed to develop a model that is able to find solutions of sailing on alternative fuels was performed. It was found that especially information on weight, volume, costs and possible relocation of storage tanks data are needed to analyze the economical consequences of sailing on alternative fuels.

In Chapter 3, the composition of costs, volume and weight is analyzed. The additional costs, additional weight and volume per fuel type and converter are described. Also, the structure of vessel costs is analyzed in this chapter. This is done, because the total vessel costs determine the transport costs. Lastly, analyses on what the economical consequences the IGF code, or special storage tanks for fuels can have on the transport costs are performed.

The information presented in Chapter 2, together with the weight, volume and costs presented in Chapter 3 form the basis for the actual model that is developed and used to investigate the differences in costs of transport. Chapter 4 describes how the model is developed and shows how it performs using examples. The model is also verified and validated in this chapter.

Chapter 5 gives an overview of the results of different scenarios calculated by the developed model. In this chapter, cargo costs are presented when using different fuels. Furthermore, it is analyzed how the differences in costs are determined and how the transport costs can be reduced.

In the last chapter sensitivity analyses have been performed to investigate the influence of assumed parameters on the calculated transport costs. It is also analyzed which potential differences in transport costs should be taken into account when values of parameters differ from the parameters used in this study.

Scope

The study is limited to specific fuels, specific vessels and specific operations as described below. The study is limited to prevent for drowning in a data overflow resulting from analyzing endless combinations of fuel types, ship types and ship operations. However, with the designed model it would be possible to analyze more different combinations for further research. The scope of the study is divided into fuels, vessels and operations.

Fuels

The fuels used in the study are combinations of different fuel types: alcohol-based fuels, biofuels and other renewable fuels. The used fuels are the fuels considered most promising to meet the IMO GHG reduction ambitions which were extracted from the literature review. The fuels consist of the most promising fuels as described in the analyzed case studies. The fuels used in the case studies are:

- Alternative marine fuels: Prospects based on multi-criteria decision analysis involving Swedish stakeholders (2019): liquid natural gas, liquid bio gas, methanol, hydrogen, hydrotreated vegetable oil & heavy fuel oil.

- Life cycle cost assessment of alternative marine fuels to reduce the carbon footprint in short-sea shipping: A case study of Croatia (2020): diesel, electricity, methanol, ethanol, natural gas, hydrogen & biodiesel.
- The Potential Role of Ammonia as Marine Fuel - Based on Energy Systems Modelling and Multi-Criteria Decision Analysis (2020): liquid natural gas, liquid bio gas, methanol, hydrogen, hydrotreated vegetable oil & ammonia.
- Environmental and economical assessment of alternative marine fuels (2016): methanol, ethanol, liquid natural gas & hydrogen.
- Eco-environmental analysis of ship emission control methods: Case study RO-RO cargovessel (2017): diesel, marine gas oil & liquid natural gas.
- An environmental and economic analysis of methanol fuel for a cellular container ship (2019): diesel & methanol.
- Pathways to climate-neutral shipping: A Danish case study (2019): biomass, liquid natural gas, hydrogen, methanol & ammonia.
- Cost-Effective Choices of Marine Fuels in a Carbon-Constrained World: Results from a Global Energy Model (2014): fuel oil, methanol, liquid natural gas & hydrogen.
- Assessment of alternative fuels for seagoing vessels using Heavy fuel oil (2019): marine gas oil, vegetable oil, biodiesel, fisher tropsch diesel, liquid natural gas & methanol.

According to the analyzed case studies, the most promising fuels are: methanol, ethanol, hydrogen, ammonia, hydrotreated vegetable oil and electricity. Heavy fuel oil is used as benchmark. The characteristics of the fuels are presented in Appendix E.

For conversion of fuel energy into propulsion energy, fuel converters are necessary. In the study, the choice has been made to only analyze common combinations of fuels and fuel converters. The common combinations are examined in Section 2.4.1 and are:

- Internal combustion engines for hydrotreated vegetable oil, methanol, ethanol, heavy fuel oil, hydrogen and ammonia.
- Fuel cells for hydrogen, ammonia, methanol and ethanol.
- Electric motors for electricity.

In this study, only emissions from tank to propeller are analyzed, which implies that it is not further investigated how alternative fuels are generated. This is excluded from the current study since the investigation of well to tank emissions is a separate study, needing many additional sub-studies.

Vessels

As reference vessels, three types of different vessels have been selected which all three have different sizes, different loads and usually sail over different distances. Characteristics of the vessels are given in the Appendix A. The vessels were chosen after analyzing worldwide seaborne trade. The goal of this study is to investigate the feasibility and economic consequences of sailing on alternative fuels. Therefore, the selected reference vessels are three widely used vessel types. The vessels are commonly used size, types and sailing the common voyages and represent a large proportion of the maritime trade market, so that results from the research have an important impact. The selection of vessels for this study are:

- 34,350 DWT Container vessel "CMA CGM Louga".
- 149,921 DWT Oil tanker "Nordic Grace".
- 400,606 DWT Ore carrier "Ore China".

However, the developed model can also be used for the analysis of less common vessel types, cargo, or sailing distances.

Operations

The operations represented in the study differ in length. A long route will be represented by the voyage from Brazil to China, or Santos to Dalian, a medium length route will be represented by the route from Arabia to Western-Europe, or Jeddah to Algeciras, and a short-sea route from the Netherlands to Russia, or Rotterdam to St. Petersburg. The operations represent common voyages for the selected vessels. The difference in length of the different voyages are shown in Figure 1.

Figure 1: Different operations within scope. Top: Rotterdam - St. Petersburg. Middle: Jeddah - Algeciras. Bottom: Santos - Dalian.

1 Maritime transport

In this section maritime transport will be investigated to make a conscious decision on what vessel(s) and route(s) will be analyzed in this study. The goal is to choose at least three representative, preferred different size and type, vessels on different shipping routes. From the literature review it was learned that vessel size and sailing distance can influence the favorable alternative fuel choice. For example, it is not likely to use batteries on long voyages due to the heavy weight, of the battery when a lot of energy is required, or the high storage costs when a large amount of electricity must be stored.

To make a well-balanced vessel choice, seaborne transport will be analyzed first. Different major shipping routes are explored and an analysis will be made of which vessels are sailing these major shipping routes. Next, there is looked into the installed power of the different vessels sailing the major shipping routes and the distance they travel. This is done to analyze what the most common range-power combinations are. From these common combinations, three different types of vessels are selected which will be used in this study. It is determined to analyze common range-power combinations in this study to cover a wide spectrum of vessels and operations used worldwide and, therewith, arrive at results that are relevant to a large group of maritime transport. So that the consequences of fuel transition for a known group with a large share of air pollution is visible. However, the developed model can also be used for the analysis of less common range-power combinations.

1.1 Seaborne transport

Today the world has more than 3000 major commercial ports. The major ocean routes are within the Atlantic, the Pacific and the Indian ocean. Sea transport is dominated by three economic geographical areas, North America, Europe and Asia (Stopford, 2008). As shown in Figure 2, the majority of commercially operating vessels, used on international waters, are bulk carriers, tankers, general cargo and container vessels.

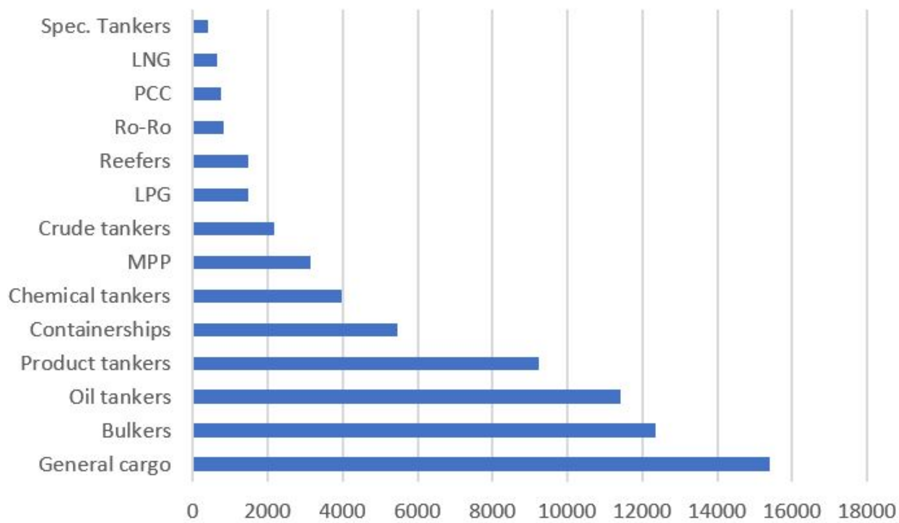


Figure 2: Number of vessels per vessel type in 2021 (Clarkson Research, 2021)

To analyze which type of vessels, general cargo vessels, bulkers and oil tankers, are represented on which transport routes different routes have been investigated, starting with general cargo liner routes, oil trade routes and lastly dry bulk routes.

1.1.1 Major liner shipping routes

The first group of sailing routes that will be investigated are the liner trade routes. With liner trade, general cargo transported by containerized liner services, which provides fast, frequent and reliable transport of almost any cargo to any foreign destination (Stopford, 2008) is meant. The liner services are generally divided into three different groups:

The East-West routes: These include prominent long-haul routes across the Pacific and Atlantic Ocean, using the biggest container-vessels (4000+ TEU) and representing almost a quarter of the maritime trade.

The North-South routes: The vessels that sail these routes are usually smaller vessels than the vessels on the East-West trade routes. North-South lines are for example routes from Europe to West Africa (Stopford, 2008). On these routes, less volume is transported than on the East-West routes.

Intraregional routes: With intraregional short-sea transport is meant. Short-sea transport plays an increasingly important part in sea-trades, because of movements between local ports. Usually small vessels make use of these short voyages but sometimes also vessels of 3000-4000 TEU. (Stopford, 2008)

In conclusion, different size container vessels are sailing different distances. The large container vessels sail the longer distances and the smaller vessels shorter voyages. In Section 1.2 the different vessels sailing the different routes will be further analyzed.

1.1.2 Oil trade routes

The next investigated trade routes are the oil trade routes. Crude oil was the world's number one export product in 2019[1] (Workman, 2019) and, therefore, plays a dominant role in maritime tradings. Different type of oil tankers are known. The size of the tanker depends on the trade route and is:

- Panamax 60,000 DWT
- Aframax 100,000 DWT
- Suezmax 150,000 DWT
- Very Large Crude Carrier (VLLC) 280,000 DWT
- Ultra Large Crude Carrier (ULCC) 300,000 DWT

Very large crude carriers and ultra large crude carriers are not able to sail the Suez Canal due to their draft requirements. Both are built and used to sail around Cape of Good Hope.

For investigating the major oil transport routes it has been investigated which countries are the big exporters of oil and which countries import this oil. The top 10 countries that exported the highest dollar value worth of crude oil are presented in Table 1 (Workman, 2019):

[1] All values used in this section represent the situation in 2019

Saudi Arabia	US $133.6 billion	13.3% of exported crude oil
Russia	$121.4 billion	12.1%
Iraq	$83.3 billion	8.3%
Canada	$68.1 billion	6.8%
United Arab Emirates	$66.1 billion	6.6%
United States	$65.3 billion	6.5%
Kuwait	$42.0 billion	4.2%
Nigeria	$41.0 billion	4.1%
Kazakhstan	$33.6 billion	3.3%
Angola	$32.2 billion	3.2%

Table 1: Top 10 oil exporting countries in 2019

As shown in Table 1, a group of middle eastern countries sold 38.2% worth of globally exported crude oil. A list of the 10 countries that imported the most crude oil is shown in Table 2. The countries that imported crude oil are mostly Asian (54.2%), European (28.2%) and North American (13.9%) countries (Workman, 2019).:

China	US$238.7 billion	22.6% of overall imported crude oil
United States	$132.4 billion	12.5%
India	$102.3 billion	9.7%
Japan	$73.1 billion	6.9%
South Korea	$70.2 billion	6.6%
Netherlands	$46.4 billion	4.4%
Germany	$40.7 billion	3.9%
Spain	$30.5 billion	2.9%
Italy	$29.6 billion	2.8%
United Kingdom	$24.5 billion	2.3%

Table 2: Top 10 oil importing countries in 2019

In Figure 3 the biggest import (in red) and export countries (in blue) of oil are indicated. Subsequently, here the major shipping routes can be evaluated

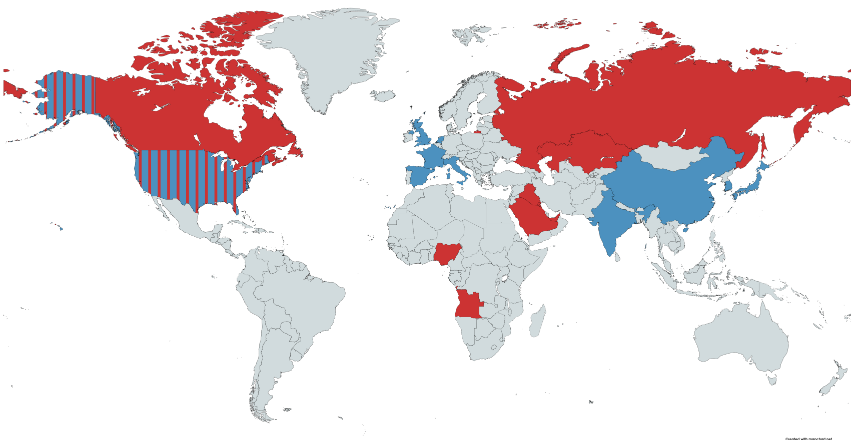


Figure 3: Biggest oil importing (blue) and exporting (red) countries (the figure is made with the help of mapchart.net)

As Russia is connected by land to Europe and Asia and has a network of oil pipelines towards Europe and Asia it doesn't depend on sea transport on large scale (Notteboom et al., 2021). Oil from Alaska and Canada is also transported by pipelines but then to the mainpart of the USA (Notteboom et al., 2021).

For evaluating the marine transport of oil, the export countries in the Persian gulf are more interesting. Figure 4 shows the major oil routes over sea.

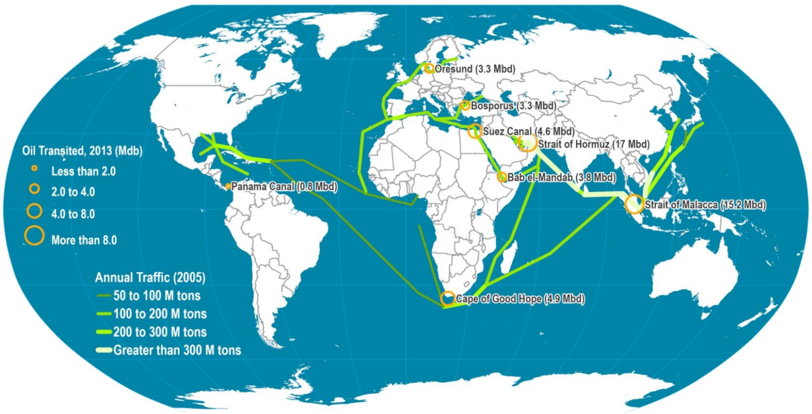


Figure 4: Major oil flow routes (Notteboom et al., 2021)

Figure 4 shows that when oil is exported from the Persian gulf to Europe the Suez Canal is used. The export of oil to China, Japan and South Korea goes through the strait of Malacca. And the export route from the Persian Gulf to North America is around the Cape of Good Hope. For shipments from the Persian gulf to Europe vessels not bigger than the Suezmax vessel can be used. Very large crude carriers and ultra large crude carriers are not able to navigate through the Suez canal due to its deep draft requirements. In the book "Maritime Economics (Stopford, 2008)" it is shown that very large crude carriers and ultra large crude carriers are used to carry long-haul cargo, so it is more likely these vessels are used on the route from the Persian golf to the USA or from the Persian gulf to Asia. Suezmax and very large crude carriers and ultra large crude carriers are also used on the route from West Africa to the USA. The Aframax vessels are used for shorter-haul trade for example within the Mediterranean to North-sea to distribute the imported oil within West-Europe and the Panamax vessels are used for trade within the Caribbean. In Section 1.2 more information about the vessels used on the different routes is given.

In conclusion, the oil transport over sea is dominated by the export of oil from the Persian gulf, using suezmax vessels to navigate through the Suez canal, towards Europe and using large oil carriers for oil transport towards East-Asia and the USA. In Section 1.2 the different vessels have been further analyzed.

1.1.3 Dry bulk cargo routes

From Figure 2 it is shown that next to oil and general cargo transport, bulk transport represents a large contribution in maritime trade. To analyze which are the major bulk trade routes, different types of bulk cargoes are analyzed. The major dry bulk cargoes are iron ore, coal ore and wheat. To analyze which routes are popular for transporting dry bulk, the biggest exporters and importers of coal, iron ore and wheat have been investigated using http://www.worldstopexports.com/ (Workman, 2019)[2]. Starting with coal, the top 5 countries that export and import coal are presented in Table 3 and Table 4.

Australia	US $44.4 billion	37.56% of total coal exports
Indonesia	$21.5 billion	18.2%
Russia	$16.0 billion	13.5%
United States	$9.8 billion	8.3%
Colombia	$5.2 billion	4.4%

Table 3: Top 5 coal exporting countries in 2019

Japan	US $23.3 billion	17.6% of total imported coal
India	$23.0 billion	17.5%
China	$18.9 billion	14.3%
South Korea	$14.1 billion	10.7%
Taiwan	$7.0 billion	5.3%

Table 4: Top 5 coal importing countries in 2019

In Figure 5 the importing (in red) and exporting (in blue) coal countries are shown to investigate what shipping routes are used. The biggest transport chain is from Australia and Indonesia to China, Japan, India, and South Korea. Transport of coal to Europe uses trade routes from the USA and Russia to Europe.

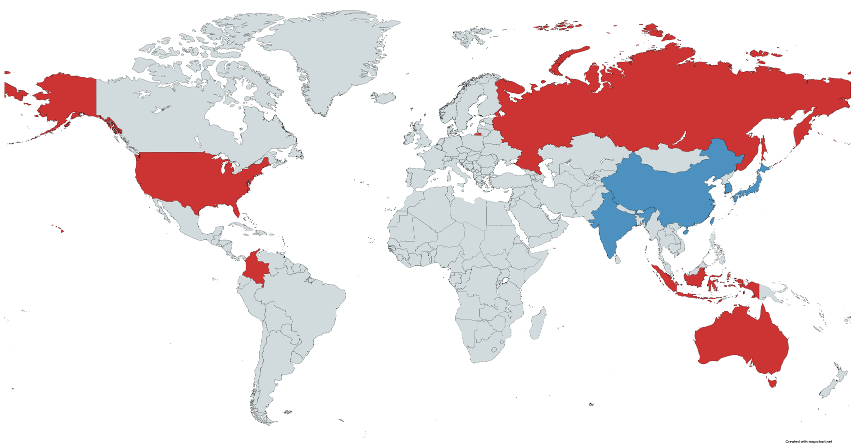


Figure 5: Biggest coal importing (blue) and exporting (red) countries (the figure is made with the help of mapchart.net)

Another major dry bulk good is wheat. The top 5 biggest wheat import and export countries are presented in Table 5 and 6

[2]All values used in this section represented the situation in 2019

Russia	US $6.4 billion	16.7% of total wheat exports
United States	$6.3 billion	16.4%
Canada	$5.4 billion	14.1%
France	$4.4 billion	11.4%
Australia	$2.5 billion	6.6%

Table 5: Top 5 wheat exporting countries in 2019

Turkey	US $2.3 billion	5.8% of total imported wheat
Egypt	$2.0 billion	5.1%
Italy	$1.9 billion	4.8%
Philippines	$1.7 billion	4.4%
Indonesia	$1.6 billion	4.2%

Table 6: Top 5 wheat importing countries in 2019

Figure 6 shows the importing and exporting wheat countries. Studying this map and the percentages wheat import and export are divided over the whole world and, therefore, it is assumed that wheat doesn't have a specific major shipping route.

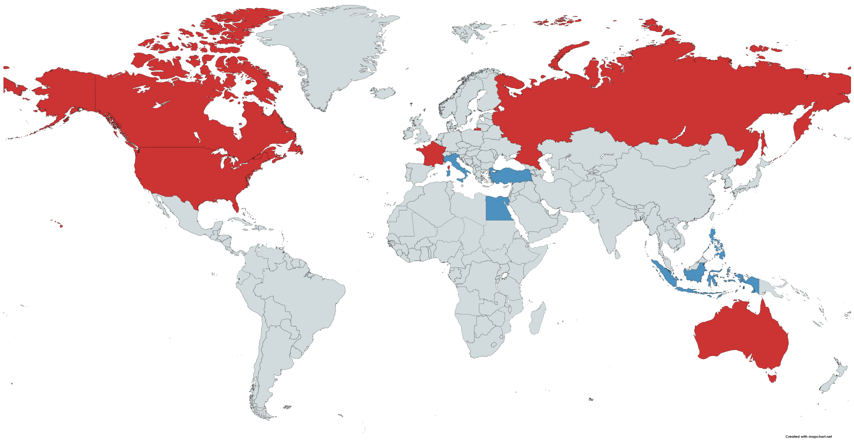


Figure 6: Biggest wheat importing (blue) and exporting (red) countries (the figure is made with help of mapchart.net)

The final investigated dry bulk cargo is iron ore. In Table 7 and Table 8 the biggest importing and exporting countries of iron ore are represented:

Australia	US $65.8 billion	53.8% of total iron ore exports
Brazil	$22.2 billion	18.1%
South Africa	$5.7 billion	4.7%
Canada	$4.9 billion	4.0%
Ukraine	$4.0 billion	3.3%

Table 7: Top 5 iron ore exporting countries in 2019

China	US $99.8 billion	69.1% of imported iron ore
Japan	$10.9 billion	7.5%
South Korea	$6.9 billion	4.8%
Germany	$3.9 billion	2.7%
Netherlands	$2.9 billion	2.0%

Table 8: Top 5 iron ore importing countries in 2019

In Figure, 7 ore importing countries are coloured blue and those exporting iron ore are shown in red. More than 80% of the iron ore is transported to China, Japan and South Korea. The big trade routes are thus all from exporting countries towards South-east Asia.

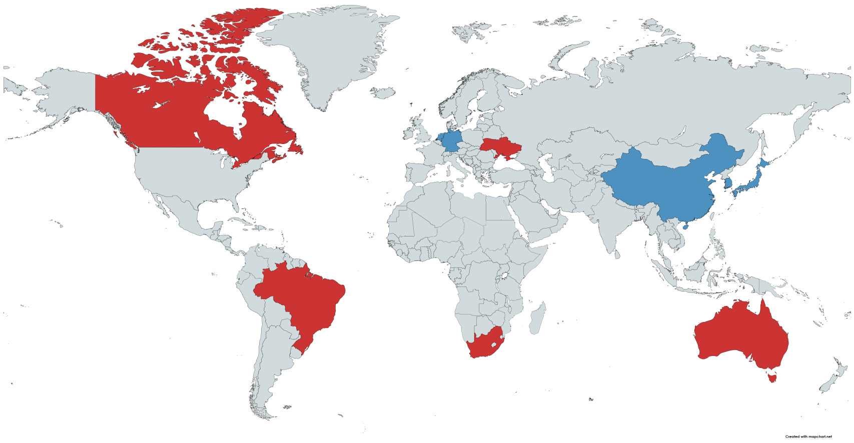


Figure 7: Biggest iron ore importing (blue) and exporting (red) countries (the figure is made with the help of mapchart.net)

Concluding that transport of iron and coal ore is dominated with sailing routes towards South-East Asia. Long routes from Brazil to South-East Asia and shorter routes from Australia to South-East Asia. There are no size limitations between the major importers and exporters of the different types of ore. Which typically power range-power combinations are used on the described routes are further analyzed in Section 1.2.

1.2 Different vessels

Now that the different routes and their limitations (for example the vessel size limitation of the Suez canal) are known, a further analysis is made on the power required for the different vessels on certain ranges.

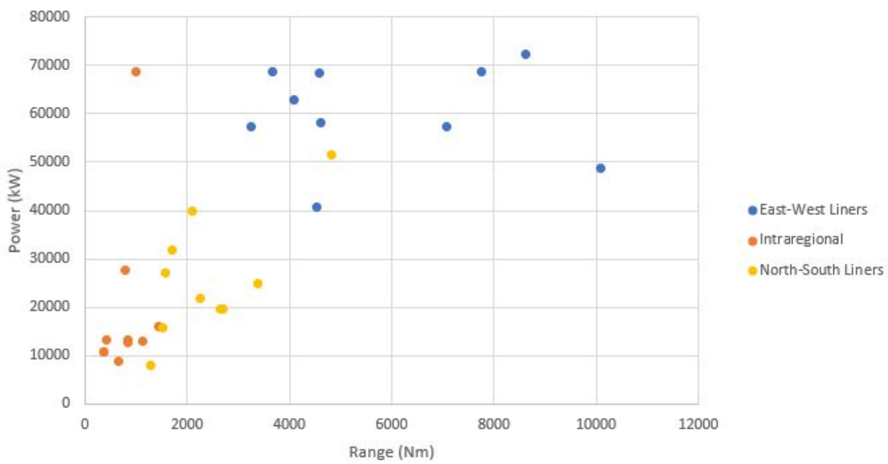
To make an overview of what power container vessels should have on different ranges, further analysis is made of which specific vessels sail the above mentioned routes. Per route, 10 container vessels have been selected and analyzed. To identify these vessels, information reported in Section 1.1.1 is used. These vessels are: 4000+ TEU for east-west lines, smaller container vessels for the north-south lines and the smallest container vessels for intraregional trade. Clarksons fleet register is used to identify these vessels and https://www.vesseltracker.com/ is used to confirm the routes of these vessels and to identify the distances between the trading countries. The sailing ranges, the capacity, speed and the power of the main engines of the different vessels can be found in Appendix A and an overview of power and range is given in the conclusion section, Section 1.3.

Next, the oil trade is analyzed. Here 10 different vessels are analyzed: 5 suezmax vessels sailing from the Persian Gulf to Europe and 5 differently sized random tankers sailing for example from West Africa to the United states. Again Clarksons world fleet register and https://www.vesseltracker.com/ are used to retrieve the needed information. The analyzed routes are based on information found in Section 1.1.2 and the results and overview are presented in Appendix A and Section 1.3.

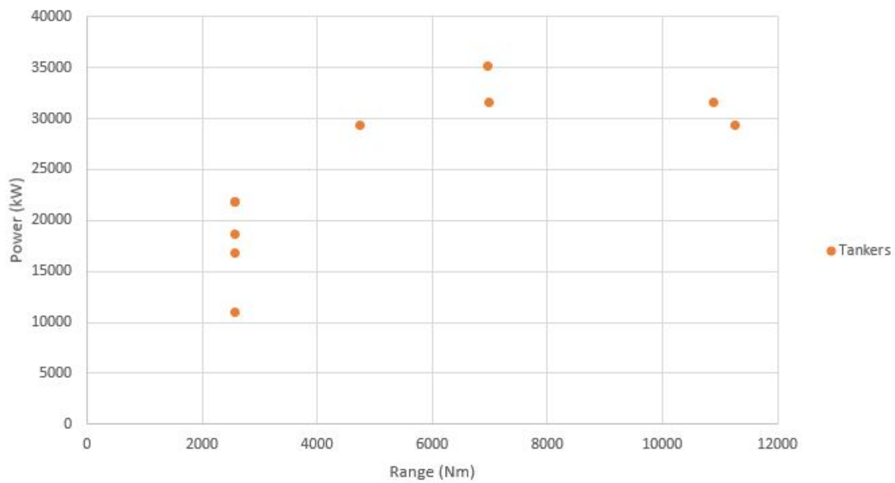
Finally, the bulkers are considered. A closer look at Section 1.1.3 shows that for the bulk cargo routes there are not certain limitations like the Suez canal. Therefore, the choice has been mode to further analyze 3 different size of bulk carriers:

1. 160,000 DWT+
2. 65,000-99,999 DWT
3. 40,000-60,999 DWT

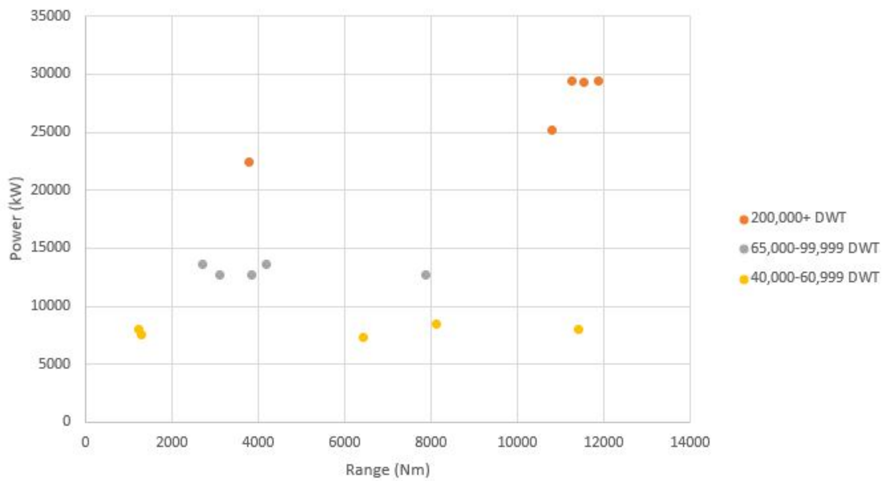
The 100,000 - 150,000 DWT size-group is mainly already analyzed while analyzing the oil tankers and is not further analyzed as bulk carrier. Using https://www.vesseltracker.com/ it was demonstrated that the 160,000+ DWT vessels are mostly used for sailing from Brazil to China, the 65,000-99,999 DWT from Oceania to China and the 40,000-60,999 DWT vessels on the remaining routes. 15 different vessels have been analyzed and the retrieved information is presented in Appendix A and in Section 1.3.



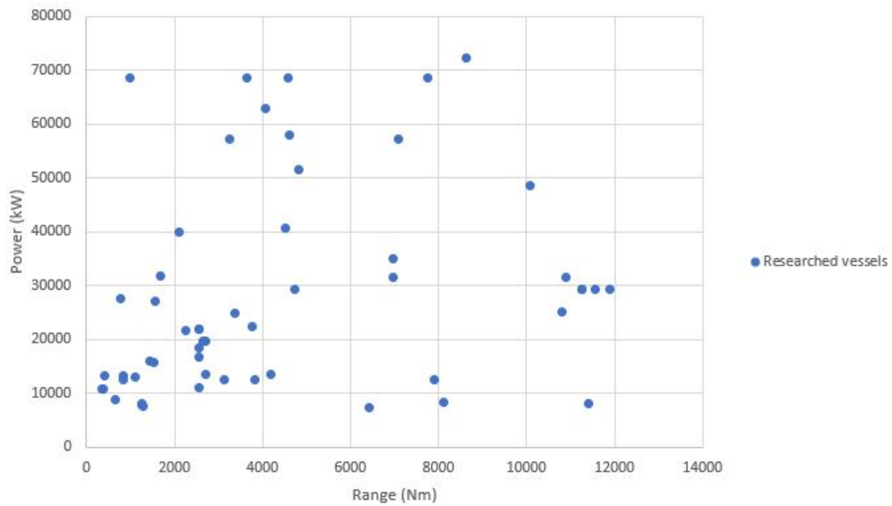
(a) Range (NM) and Power (kW) of Container vessels



(b) Range (NM) and Power (kW) of Tankers



(c) Range (NM) and Power (kW) of Bulk carriers



(d) Range (NM) and Power (kW) of Researched vessels

Figure 8: Range and Power of different vessels

1.3 Conclusion of vessels on major shipping routes

In Figure 8, the different range and power combinations of the analyzed vessels are given per vessel type. In Figure 9, all vessels are summarized and the most common power - range combinations have been analyzed to identify 3 representative vessels.

1.3.1 Vessel choice

For the vessel choice, 3 different vessels were selected, which differ in size, type and range. This selection is necessary to investigate if these properties influence the alternative fuel choice and outcomes for sailing on different fuels.

Information collected in this chapter is used to identify these different vessels. The choice has been made for common size, type and route combinations because this represents the largest share of the maritime market. In three different groups, known reference vessels have been chosen based on the analysis performed in this chapter and the results shown in Figure 8 and Appendix A. The use of existing vessels implies that different variables needed for calculations later in this study are already known.

The red circles in Figure 9 give the most common range and power combinations.

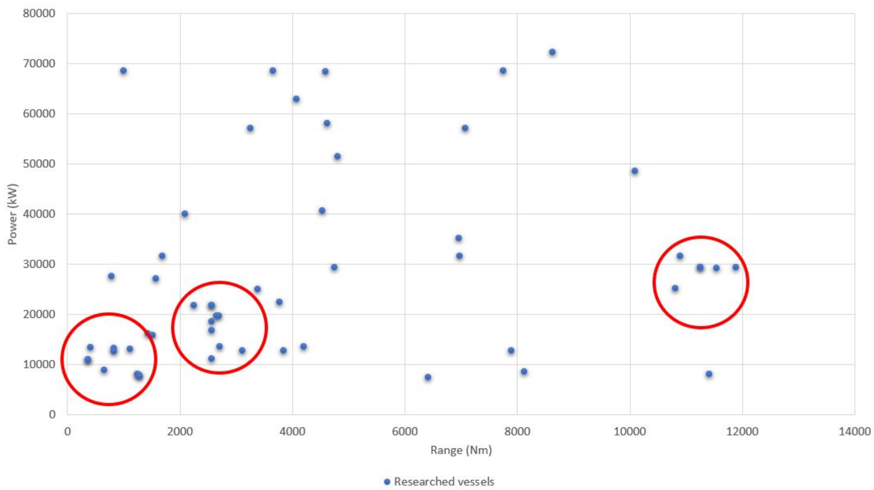


Figure 9: Most common Range (NM) and Power (kW) combinations

- **Group 1:** Power of 5000-2000 [kW] and sailing 0-2000 [NM], which is very similar to the properties of intraregional liner trades by a container vessel.
- **Group 2:** Power 10000-20000 [kW] and sailing 2000-4000 [NM], which are common characteristics by medium deadweight vessel (tankers) of 150,000 DWT.
- **Group 3:** Power 30000 [kW] and sailing long distances 10000 [NM] are the values found for the bulk (ore) carriers sailing from Brasil to China with iron ore

The three different groups are represented by the container vessel CMA CGM Louga for group 1, the medium deadweight tanker Nordic Grace for group 2 and the ore carrier Ore China for group 3. The routes are also already determined for energy calculation. However, it is possible to analyze other routes with the developed model. The CMA CGM Louga is sailing 1500 [NM] from Rotterdam (The Netherlands) to St. Petersburg (Russia), the Nordic grace 2570 [NM] from Jeddah (Saudi-Arabia) to Algeciras (Spain) and the Ore China 12000 [NM] from Santos (Brazil) to Dalian (China). Properties of the vessels are given in Appendix B and an overview of the group, representative vessel and route is given in Table 9.

Group	Vessel	Route
Container vessel	CMA CGM Louga	Rotterdam - St. Petersburg
Oil tanker	Nordic Grace	Jeddah - Algeciras
Ore carrier	Ore China	Santos - Dalian

Table 9: Vessel choice

2 Required data

In this section, it will be determined which input data are required for developing a model that analyses the economical consequences of sailing on alternative fuels. The main required data will consist of vessel data and fuel data.

The fuels that will be compared are the fuels that were considered as most favourable in the literature review, and these are: Methanol, Ethanol, Hydrogen, Ammonia, Hydrotreated Vegetable Oil and Battery electric. Heavy Fuel Oil will be included as benchmark. The vessels that will be compared differ in size and type, in order to determine what the influences are of vessel size and vessel type on the choice of a favourable fuel. The vessels that will be used in the model, as discussed in Chapter 1, are: container vessel CMA CGM Louga, tanker Nordic Grace and ore carrier Ore China.

To identify the required data from the fuels and vessel, first the problem and the model requirements will be described. The described problems and requirements will help to determine how the model should perform. After the problem and model requirements, in other words: the body of the model, are investigated the required data will be described. First, the vessel data that are required will be described in Section 2.3 and then the fuel data which are required will be described in Section 2.4. Also in the fuel data section, additional information is given on the fuel-specific regulations (IGF code), fuel specific converters and fuel specific storage tanks as this includes data to be considered while sailing on specific fuels.

2.1 Problem

As described in the introduction, the use of fuels with lower energy density can lead to different problems. As the goal of the study is to compare transport costs when sailing on alternative fuels, the problems causing an increase in transport costs while sailing on alternative fuels will be identified. The main problems that can occur and result in extra transport costs and, subsequently, in minimum required freight rate are summarized in Figure 10. The problems described include problems occurring when a vessel that used to sail fully loaded on conventional fuels has to sail on alternative fuels.

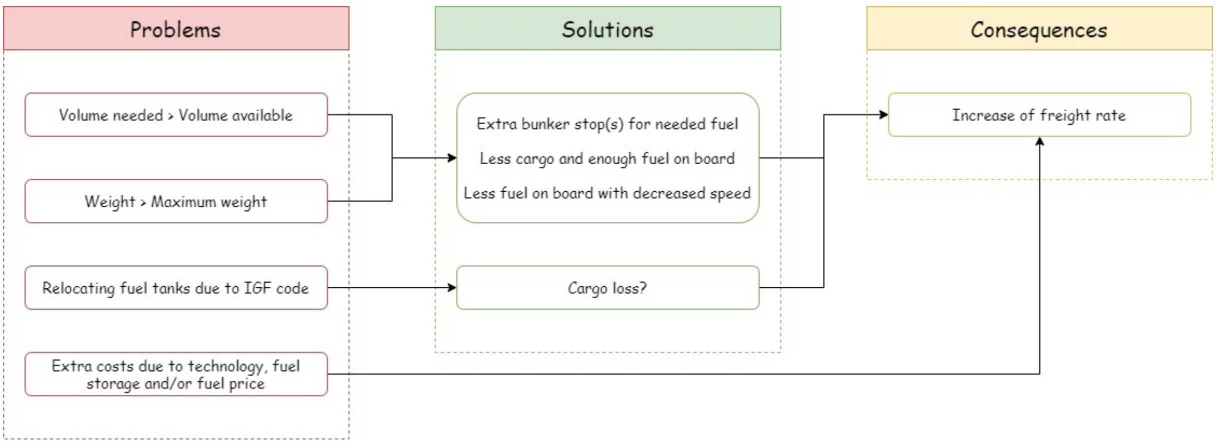


Figure 10: Problems that can occur when sailing on alternative fuels

The first problem represents the volume and the weight. If the total volume, or weight required for a certain voyage carrying a certain amount of cargo and sailing on a certain fuel exceeds the volume, or weight available on the ship, the ship will not be able to sail. Therefore, solutions to decrease the volume, or weight required must be found before the vessel can sail. As mentioned in the literature review, potential solutions can be:

1. Dividing the volume of fuel needed and making more bunker stops.
2. Replace cargo volume for fuel volume and carry less cargo.
3. Carry less fuel with and sail more efficiently by lowering the sailing speed.

All three have an influence on the transport costs. An extra bunker stop results in more voyage time, which results in less cargo transported per year. Replacing cargo volume for fuel volume results in less cargo transported per voyage and per year. Reducing the vessel speed reduces the amount of voyages per year, which also results in less cargo transported per year. If the transported cargo has to cover the transported cargo costs and less cargo per year is transported, the transport costs per tonnes cargo increases.

The next problem that can influence the transport costs is if the fuel storage tank has to be relocated as a consequence of the IGF code, as described in Section 2.4.2. This may result in the issue that less cargo can be carried, because the new fuel tank location is in place of cargo space, which in the end will result in the generation of less income.

The last issue that can influence the transport costs are the extra costs for the systems and storage space which will be necessary for the operation while sailing on a particular fuel.

From the problems identified in this section, the requirements of the model can be described. The model requirements give an overview of what the model should perform.

2.2 Model requirements

The model requirements as well as the problems described above provide insight into what data are needed for developing the model. The model that will be developed should be able to:

- Identify if the available weight or volume on the vessel is exceeded.
- Identify if the fuel tank needs to be relocated and whether this results in cargo loss.
- Calculate the transport costs in different situations
  - When an extra bunker stop is made.
  - When less cargo is taken on board.
  - When the vessels speed is reduced
  - When a combination of above mentioned events occurs
- Give the transport costs when any variable, including vessel, fuel and operation data are modified.
- Have the ability to modify any uncertain variables, for example fuel price, or mooring time.

The goal of the model is to identify the problems that occur when sailing on a certain fuel and to find solutions that result in the lowest possible transport costs. To do so, information concerning the vessel and the fuels used are required. Which data are required will be described in the following sections.

2.3 Vessel data

To identify if problems, as described in Section 2.1 occur and for calculating the transport costs, different data from the vessel in question are needed. The data required are summarized in Figure 11 and are described below.

The first box represents **energy requirements**. First, the power of the main engine and the vessel speed will be considered. If this power and speed are known and the duration of an operation is known, then the energy that is needed for the vessel on an operation can be calculated. This is necessary to find the needed volume and weight of the fuel. The energy needed can be calculated using the values for speed, range and power of the vessel.

The second box represents **tank dimensions and location**. The tank dimensions are needed to determine how much fuel storage space is available on board of the vessel and to determine if this is enough for the amount of fuel that is needed. Also, the location of the tanks is important, because this might change when sailing on alternative fuels that have to comply with the IGF code. Lastly the shape of the tanks should be considered, as some of the fuels have to be stored in cylinder-shaped storage tanks. Those tanks will require more space than conventional fuel tanks.

The third box is **amount of cargo and location.** These are required to determine what amount of cargo the vessel is able to transport and will be given in tonnes, m^3, or TEU depending on the vessel type. The location of the cargo is important to determine if the vessel loses cargo space when fuel storage tanks have to be relocated.

The fourth box is **volume and weight.** The volume and weight-dependent values such as lightweight, deadweight and displacement are important to determine whether one of them is exceeded when using alternative fuels. The calculated deadweight including the weight of fuel should not exceed the maximum deadweight of the vessel and the lightweight [t] and deadweight [t] together should not exceed the maximum displacement [t]. The options of changing the main dimensions, increase the displacement of the ship and maintain the original deadweight were not considered, but is always interesting to explore in future studies.

The last box is **costs**. The capital and running costs of the vessel are required to calculate the transport costs per tonnes cargo. The voyage costs, which in this study are limited to the fuel costs as described in Section 3.1 are included in the required fuel data.

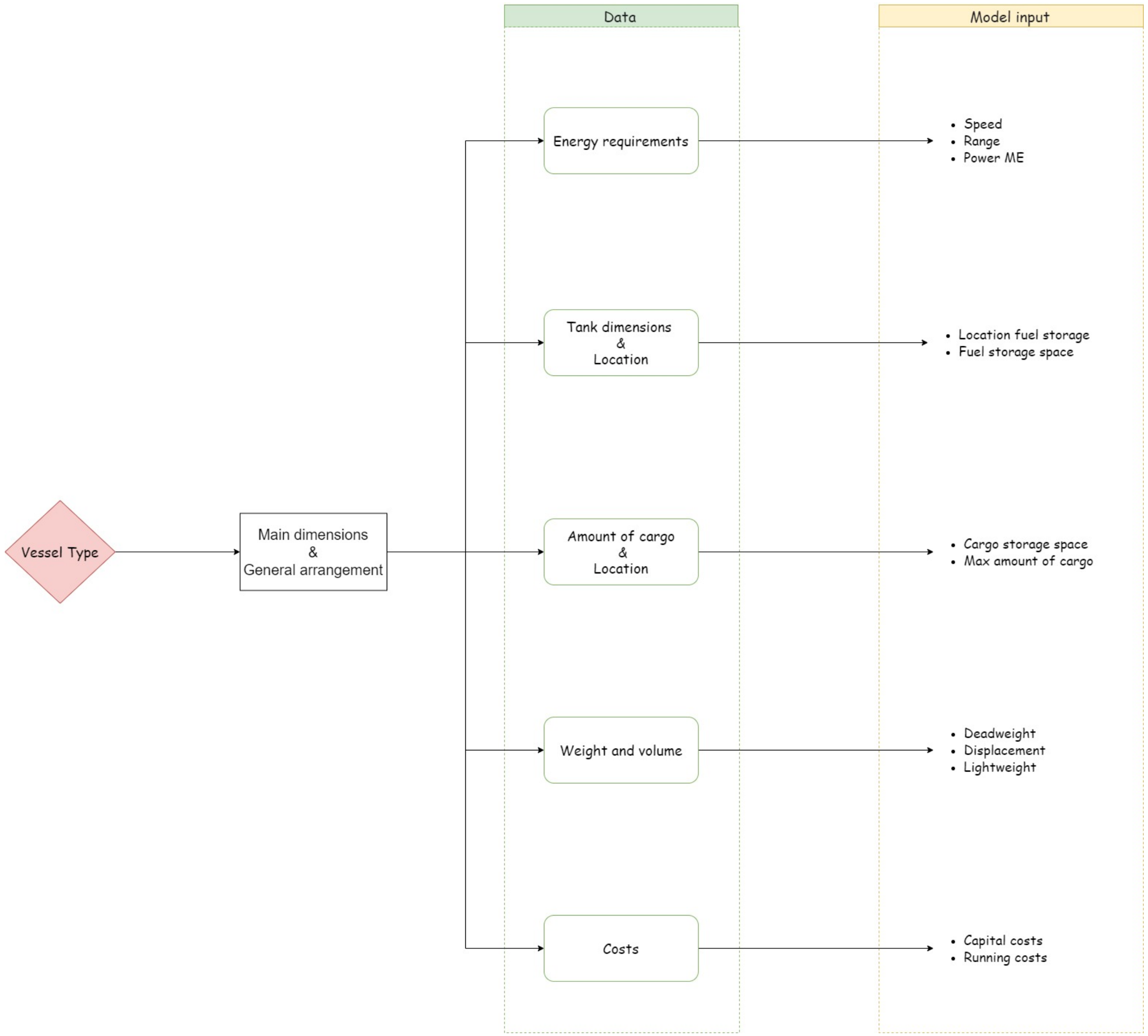


Figure 11: Required vessel data for the model

2.4 Fuel data

The input data of the fuel type, needed for evaluating the problems as presented in Figure 10, can be found in Figure 12. The fuels included in this research are Heavy fuel oil, Methanol, Hydrogen, Ammonia, Ethanol, Hydrotreated Vegetable Oil and Battery electric. For the different fuel types, additional information is required, such as whether a fuel has to comply with the IGF code, or requires special storage systems. Also decisions must be made on which type of fuel uses which converters. This information is given in Section 2.4.1, Section 2.4.2 and Section 2.4.3.

First, it is analyzed which **energy system** should be used for which fuel. The investigated energy systems are a fuel cell system, an internal combustion system, or a battery system. The options depend on the fuel type and are summarized in Table 11. Information about the energy system is needed, because the system can cause an increase in required volume, weight and costs. The increase in volume and weight may result in modifications of the vessel, or the operation, which potentially increase the costs. It is necessary to calculate these additional costs to calculate the total transport costs per ton cargo. Also the efficiency of the converter is important, because the efficiency determines the amount of fuel that is required for providing a certain amount of energy. Which fuel uses which converter is described in Section 2.4.1

The next step is to determine whether the fuel type has to comply with the **IGF code**. If a fuel has to comply with the IGF code, the location of the storage space might change. Relocating the storage tank may result in decrease of cargo which in the end increase the transport costs per tonnes cargo. Which fuels have to comply with the IGF code and what further implications will have to follow are described in Section 2.4.2

The third step is to determine if the fuel needs a **special type of storage tank**. If there is need for a special type of storage tank, there might be extra costs, additional weight, or increased volume which all three separately, or together can influence the transport costs. Which fuel uses which type of storage tank is described in Section 2.4.3

Lastly, fuel data that are important for calculating the transport costs are the **gravimetric and volumetric energy densities**, which imply if there is need for any modifications of the vessel, or operation, which in the end can result in extra costs. Also, the fuel **costs** are required for calculating the transport costs.

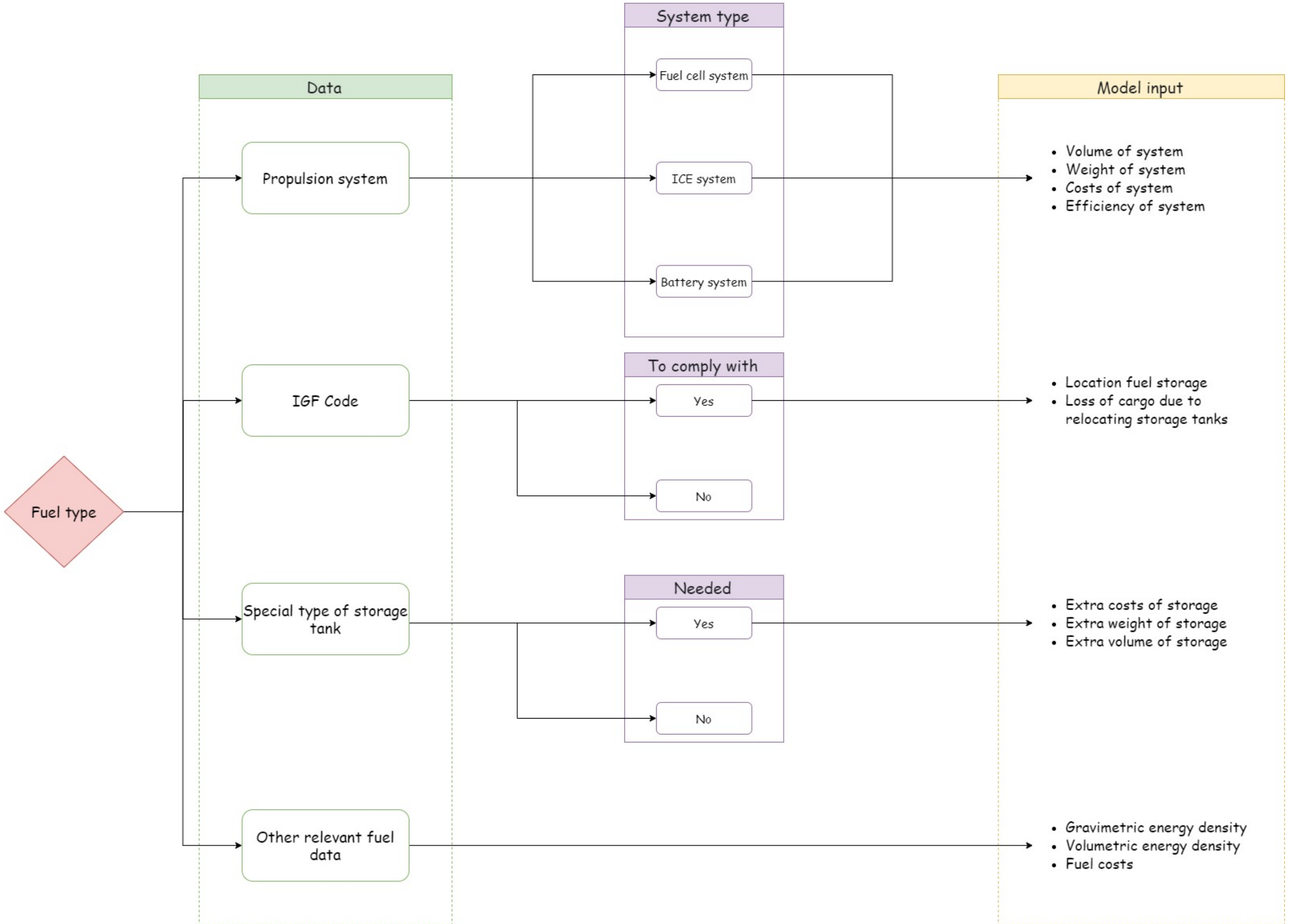


Figure 12: Model fuel type

2.4.1 Energy converters

The different types of fuel converters per fuel type are described in this section. Information on which fuel uses which converter is important for determining the weight of the fuel system, but also to determine the additional costs.

Only common combinations of fuels and fuel converters will be analyzed. For fuel cells, the common fuels include: methanol, ethanol, ammonia and hydrogen. These fuels can also be used in internal combustion engines. A disadvantage of using ammonia, methanol, or ethanol in internal combustion engines is that NO_x will be produced. However, the possibility of using the fuel in internal combustion engines will still be investigated in this study. The reason for including these is that the fuels in combination with internal combustion engines will likely have costs advantages over the use of the same fuels when used in combination with fuel cells.

Electricity is stored in a battery and an electric motor is required as converter.

Hydrotreated Vegetable Oil can be used in internal combustion engines without major modifications (DNVGL, 2019) and Heavy Fuel Oil can be used in an internal combustion engine as well. The fuel converters used per fuel type are therefore:

- Internal combustion engines for Hydrotreated vegetable oil, Methanol, Ethanol, Heavy fuel oil, Hydrogen and Ammonia.
- Fuel cells for Hydrogen, Ammonia, Methanol and Ethanol.
- Electric motors for electricity.

The fuel converters are used to convert fuel from storage to propulsion. The fuel converters are not able to convert 100% of the fuel energy into propulsion energy due to energy losses from storage tank to propulsion. Per converter it is determined what the specific efficiencies are.

Combustion engines

While burning a fuel, energy is lost due to heat loss. The thermal efficiency shows the ratio of the work output (propulsion) and the heat input (fuel). Low speed, two stroke, turbocharged diesel engines are the most commonly used marine propulsion engines exhibiting 50% efficiency (Grljušić et al., 2015) which implies that the other 50% is spilled. Wärtsilä, one of the market leaders in producing marine power plants, states that the efficiency of Wärtsilä diesel and gas engines ranges between 42-50% (Wärtsilä, 2021). From DNVGL and as shown in Figure 44 in Appendix C, the typical internal combustion engine efficiency ranges between 42-53%. The thermal efficiency of an internal combustion engine used in this study is 48%. However, a sensitivity analysis will be done to determine how much influence this assumption has on the calculated transport costs.

Fuel cell

The first successfully tested fuel cell on board of a merchant ship, the offshore supply vessel "The viking lady", was able to reach an electric efficiency of 44.5% (Mofor et al., 2015). The typical fuel cell efficiency is expected to be around 50-60% (DNVGL, 2019). The key characteristics sheet, concerning fuel cells, in Figure 45 in Appendix C of DNVGL also shows an efficiency range between 50-60%. The electric efficiency of a fuel cell is, therefore, set at an average of 55%. However, a sensitivity analysis will be done to determine how much influence this assumption has on the calculated transport costs.

(Battery) Electric motor
The electrical efficiency of a battery electric propulsor is much higher than the efficiency of fuel cells and combustion engines. According to DNVGL, this efficiency is approximately 87.5% (DNVGL, 2019). The data sheet of DNVGL shown in Figure 46 in Appendix C shows the efficiencies of different batteries and ranged between 85-95%. In the paper "Marine propulsion using battery power (Wu and Bucknall, 2016)" the efficiency for a typical battery propulsion chain are given and are 0.99 for the battery, 0.97 for the variable speed drive and 0.98 for the propulsion motor. Combining the different efficiencies results in 93% and ranges between the 85-95%. In this study an average efficiency from grid-power to propulsor of 90% is adopted.

The adopted efficiencies of the different converters are presented in Table 10. Other relevant properties of fuel converters, such as weight, or costs will be described in Chapter 3.

	Internal Combustion Engine	Fuel Cell	(Battery) Electric Motor
Efficiency	48%	55%	90%

Table 10: Efficiencies of different energy converters

2.4.2 IGF code

The IGF code has been studied, because some of the analyzed fuels need to comply with this code. The IGF code is mandatory and might cause that fuel storage tanks have to be relocated, which can influence the amount of cargo that can be carried.

The IGF code is the International Code of Safety for Ships using gases, or other low flashpoint fuels and was established in January 2017. The purpose of the code is an international standard for ships using low flashpoint fuels by providing mandatory provisions for the arrangement, installation, control and monitoring of machinery, equipment and systems. The purpose is to minimize the risk to the ship, its crew and the environment while using low flashpoint fuels (ACS, 2020). The code was initially prepared for LNG, regulations for other low-flashpoint fuels have been or will be added to the code when they are further developed (ACS, 2020). The IGF Code is addressing three main groups of fuel:

1. Gases lighter than air.
2. Gases heavier than air.
3. Low-flash point liquid fuels.

Therefore, the following fuels are considered for compliance with the IGF Code:

- Methanol.
- Ethanol.
- (liquid) Ammonia.
- (liquid) Hydrogen.

Important for this study are the IGF Code regulations on tank location, as these might influence the amount of cargo that can be carried. The other regulations, as for example for monitoring and safety systems, or piping systems that are required are excluded from this study, because they don't have influence on the problems analyzed in this study.

Tank location
The fuel tanks should be located at a minimum distance of B/5 from ship side to middle, or 11.5m and not less than 0.8m - 2m depending on V_c (gross design volume of the individual fuel tank) (ACS, 2020). The need to move a fuel tank, for complying with the IGF code, depends on the tanks current position and the design of the ship. To determine if this is necessary and if this displacement has a negative influence on the amount of cargo that can be carried, an analysis of the general arrangement of the vessel is needed.

2.4.3 Fuel storage

For the fuels that are not liquid, occupying a large volume, or vaporize under atmospheric temperature and pressure, special storage tanks for cooling, or compression are needed. These special tanks can increase the total storage weight and volume of the fuel including storage (Spiegel, Colleen, 2017). The volume and weight of the storage requirements have a significant impact on the operating range of vessels (Wärtsilla, 2020). Extra weight and volume both influence the total weight and volume used and can cause one, or more of the problems as mentioned in Section 2.1. Below it is indicated what type of storage tank is used per fuel type and why.

Ammonia
Ammonia is easy to liquefy under pressure with a liquid density of 601 g/L at 300 K (equivalent to a hydrogen volumetric density of 55 g/L). The liquefaction requires a pressure of only 10 bar at 300 K. Ammonia storage is more practical than hydrogen, because of its liquefaction temperature (-77.7 till -33.6 °C) and energy density. Lower re-liquefaction energy is needed as compared to hydrogen, or LNG (ABS, 2020). The storage tanks for ammonia are required to be made of stainless steel to tackle ammonia's corrosive properties. Ammonia can be kept pressurised, or kept in cryogenic liquid form to ambient pressure and there are strong signals that cryogenic storage will be considered safer (Wärtsilla, 2020). However, pressurized storage Type C tanks might be a more convenient marine solution, because these would eliminate the need for the installation of additional re-liquefaction equipment (ABS, 2020) and, therefore, are less heavy. This is the main reason why a compressed type C tank is preferred for ammonia storage.

Hydrogen
Hydrogen can either be stored as liquid, or as high pressured gas. For high pressure, or low temperature storage, prismatic tanks (typical cylinders) are being used. These tanks do not make efficient use of space and it will be determined whether they cause cargo loss. There are two type of tanks which can be used for the storage of hydrogen:

1. 350 bar compressed hydrogen gas tanks.
2. Cryogenic liquid hydrogen tanks.

Cryogenic liquid hydrogen tanks have a high volume-requirement, but liquid hydrogen has a lower impact on cargo capacity, due to its higher volumetric density as compared to compressed hydrogen (Raucci et al., 2015). The choice for liquid hydrogen seems more logical. Even though liquid storage needs a refrigeration unit for maintaining a cryogenic state, which adds extra costs and complexity, still the choice has been made to use liquid hydrogen in this study. It should be noted that hydrogen also needs dedicated spaces and piping through ducts to maintain the low temperatures (Raucci et al., 2015). The storage of liquid hydrogen is preferred to be located at the bottom of the ship to avoid significant increase in the vertical centre of gravity.

Methanol and ethanol
Methanol is liquid between -93 °C and 65 °Celsius and ethanol's boiling point is at 78 °Celsius making their storage less expensive and easier than hydrogen, or ammonia storage (DNVGL, 2019). The fact that the fuel is liquid at ambient temperature implies that it does not need cryogenic storage tanks, or storage under pressure. It can be stored in conventional shoreside tanks and in ballast tanks on board of the vessel and, therefore, these fuels do not require dedicated storage capacity (Greenport, 2018).

Hydrotreated vegetable oil
Hydrotreated vegetable oil can be used as drop-in fuel for conventional fuels and can use the same fuel storage spaces. It can be directly used in existing installations without major modifications (DNVGL, 2019).

Heavy fuel oil
Heavy fuel oil makes use of conventional storage spaces.

Electricity
Electricity coming from on shore will be stored in a battery. The key challenge here is the size and weight of batteries, which will be further described in Chapter 3.

2.4.4 Conclusion

Fuel	Fuel converter	Fuel storage system	IGF Code	[MJ/kg]	[MJ/L]
Heavy fuel oil	Internal combustion engine	Conventional	No	40	38.8
Methanol	Internal combustion engine Fuel cell	Conventional	Yes	19	15
Ethanol	Internal combustion engine Fuel cell	Conventional	Yes	28	21
Hydrogen	Internal combustion engine Fuel cell	Cryogenic	Yes	10	5
Ammonia	Internal combustion engine Fuel cell	Compressed	Yes	12	10
Hydrotreated vegetable oil	Internal combustion engine	Conventional	No	44.1	34.3
Battery electric	Electric motor	Batteries	No	<1	<2

Table 11: Overview of fuel converter, fuel storage, IGF code, gravimetric and volumetric energy density (including storage) per fuel type

In Table 11, an overview of fuel converters, fuel storage tanks, IGF codes and volumetric and gravimetric density of the fuels (including storage) are given. The storage tank of the fuel does influence the gravimetric and volumetric energy densities and should, therefore, be taken into account while using the fuel on board. More details on how the weights of the fuel converters, storage and fuel are determined will be described in Chapter 3 and are shown in Table 18.

3 Costs, weights and volumes

Now it has been determined which data are required for the model, parameters which help to identify the problems as described in Figure 10 need to be found. To determine if the volume needed exceeds the volume available, the volumes of the different components which may vary when sailing on different fuels need to be known. To determine if the needed weight exceeds the maximum weight, the weight of the different components should be known. To determine if the IGF code requires relocation of the new fuel tanks, the general arrangement with the old fuel tank location in the vessel is needed. Finally, to determine what the potentially extra costs are, the vessel costs need to be known.

In this Chapter it will be described how the costs of a vessel on a voyage, weight of a vessel and volume of a vessel are determined and equations for calculating differences depending on fuel choice in the purchase costs, weight and volumes are presented. First, in section 3.1 it is explained how the transport costs will be determined. The transport costs, or costs of a voyage determine the minimal required freight rate of the cargo. In Section 3.2 it is determined how the vessel's weight is distributed and what the influence of different fuel types and converters are on the lightweight and deadweight of a vessel. In Section 3.3, the values of the required volumes are determined.

3.1 Costs

The freight rate is based on negotiations between shipowners and shippers and equals a balance between amount of cargo and available ships, supply and demand. If the carrier doesn't want to make a loss on transporting freight, then it is necessary that at least the costs of the voyage are covered. The freight rate is based on negotiations which depend on market conditions. Therefore, the minimal freight rate represents the expenses, or costs of transport in this study. The total costs of transport can be divided into the costs of building the ship, running the ship, sailing the ship and cargo loading and unloading costs (Aalbers, 2000).

To determine the total costs of the voyage [$] ($C_{voy}$), the daily costs [$] (C_{day}) of a vessel are studied. These costs will then be multiplied with the duration [days] (D) of the voyage, which results in the total costs of the voyage. To determine the costs of cargo, the total costs of voyage will be divided by the weight of the cargo [t] (W_{cargo}) that the vessel can carry.

$$C_{day}[\$] \cdot D[d] = C_{voy}[\$] \tag{1}$$

$$\frac{C_{voy}[\$]}{W_{cargo}[t]} = C_{cargo}[\frac{\$}{t}] \tag{2}$$

The total costs that have to be covered depend on the various modes of chartering the vessel. An overview of different charter types is given in Table 12. In this study, the assumption is that the transport is carried out under liner charter circumstances. The reason for this assumption can be found in Chapter 1, where the choice was made to further analyze liner transport when selecting the vessels.

Cost type covered	Bare Boat	Time Charter	Voyage Charter	Liner Service	Inter Modal
Capital	X	X	X	X	X
Running		X	X	X	X
Voyage			X	X	X
Loading			(X)	X	X
Discharge				X	X
Land side					X

Table 12: Costs type covered per charter type (Aalbers, 2000)

In the following sections, the different items that determine the daily costs of a liner service charter will be described, starting with the capital costs, then the running costs, the voyage costs and finally the cargo handling costs.

3.1.1 Capital costs

In this section, the capital costs are explained. The capital costs depend on how the ship equipment and machinery are financed before the building of the ship and includes depreciation and interest. The building costs can be influenced by the type of fuel that will be used, because of the different prices for fuel storage and fuel converters.

The total value of a loan the bank is willing to offer varies between 40% and 80% (Yang and Chen, 2012). The duration of the loan and interest depends on the agreed terms between ship owner and the bank. For this study, a 20 year loan is chosen, which is as long as the usage time of the vessel. This is chosen in order to divide the capital costs over more years. The interest rate of the loan is 5% . If the interest and duration of the loan are known, the total costs for building the vessel which, because of the loan are higher than the yard price, can be calculated and divided over the voyages that the ship sails.

Capital costs		
Loan length	20	Year
Interest rate	5	%

Table 13: Overview of capital costs determiners

In this study, fixed construction costs will be used, but since the engine and supporting machinery are fuel-dependent, these costs are variable and, therefore, calculated separately. Subsequently, these additional costs will be added, or subtracted from the capital costs.

The costs of the ship and its systems are closely correlated to the weight of the respective parts (Aalbers, 2000). These costs will be estimated based on: 1) the vessel choice, 2) the fuel type, since the costs of converters and supporting machinery might differ and 3) the operation, as this might influence the expenditures as well. For example, the costs increase, or decrease when a fuel cell instead of an internal combustion engine is used. Also, a cheaper engine might be an option when the ship will sail slower for more efficient fuel use. The main determinant of capital costs analyzed in this study, is caused by the difference in the systems for propulsion and power. Also the additional costs for special fuel storage systems will be taken into account.

When components like the internal combustion engines and the systems are increased in size, often a proportional increase in weight is found (Aalbers, 2000). When an component decreases in size, for example when a less bigger engine is needed, the costs for the system will decrease. The following equation is used to calculate extra, or less costs:

$$K = c \cdot a \cdot W^b \tag{3}$$

K = costs
c = factor for complexity
a = factor for local conditions
b = factor in range 0.5-1.0
W = weight/size

The parameters used are:

System	Parameter	Am	Bm
Propulsion & Power system	P_b	4100	0.84
Systems for Prop & Power	P_b	3000	0.70

Table 14: System cost determinants (Aalbers, 2000)

For the costs of a battery, Figure 46 from DNVGL is used, where the typical costs for maritime batteries are reported.

	NMC (Nickel Manganese Cobalt Oxide)	LFP (Lithium Iron Phosphate)	LTO (Lithium Titanate Oxide)	
Battery costs	500-1000	500-1000	1000-2000	USD/kWh
Operational costs		Driven by electricity price		

Table 15: Battery costs

The capital costs for fuel cells are retrieved from the paper: "Fuel Cell Systems Applied in Expedition Cruise Ships–A Comparative Impact Analysis" (van Veldhuizen et al., 2020) and the results can be found in Appendix C. Here, the preferred combinations of fuel cell and fuel type are given. It is assumed that ethanol uses the same favourable fuel cell characteristics as methanol. Also, the costs for storage of hydrogen (liquid), methanol and ammonia can be retrieved from this paper. If more types of fuel cells are potentially usable, as for example for methanol, then the choice is made for the cheapest combination:

	Hydrogen	Methanol & Ethanol	Ammonia	
Fuel cell type	LT-PEMFC	LT-PEMFC	SOFC	
Fuel cell plant	4,213	4,939	13,167	EUR/kW
Fuel storage	10	0.09	0.54	EUR/kWh

Table 16: Fuel cell costs (van Veldhuizen et al., 2020)

The capital costs as presented in this section will serve as base case. However, the use of fuel cells is very modern and, therefore, these cells are not yet produced on a large scale. The price of fuel cells might drop towards 2050 due to manufacturing at large scale. An analyse by McKinsey shows that the price of a lithium-ion battery pack could drop from 500-600 [USD/kWh] to about 160 [USD/kWh] in 2025 due to manufacturing at large scale, lower components prices and capacity boosts (Hensley et al., 2012). As mentioned in Section 2.2 the developed model should be able to modify any uncertain variable. Later in this study it will be investigated what the impact of a drop in capital costs of a battery, or a fuel cell is on the transport costs.

3.1.2 Running costs

The operating, or running costs, exist of the different components as listed below.

Crew costs
The salaries of the vessel crew are generally difficult to determine, because the salaries of vessel crew depend on the nationality and rank of the crew members. From the paper: "evaluation of ship design alternatives (Aalbers, 2000)", the average crew costs are estimated to amount $50.000, with a roll factor of 1.5 to cover the costs for holidays. To clarify if this sum is still realistic, a further analysis of vessel crew salaries was made. Different sources reveal that the salary differs from $9.000 till $144.000 per year from cadet to captain (Chron, 2020), (Cruisejobfinder, 2020), (Seaman Memories, 2020). This makes the sum of $50.000 with a roll factor of 1.5. Thus $75.000 a year is a plausible average for the crew costs per person.

Insurance costs
The insurance costs for a vessel's hull and machinery are approximately 1% of the new building costs according to "Evaluation of ship design" (Aalbers, 2000), or 14% of the operating costs (ShipCosts, 2021). 1% of newbuilding costs is chosen as a plausible sum for the insurance costs.

Maintenance and repair
The maintenance and repair costs increase with the age of the vessel and amount to 20-30% of the total operating expenses (ShipCosts, 2021). The maintenance and repair costs are estimated to amount to approximately 0.5% of the newbuild costs of a vessel (Aalbers, 2000).

Docking and special survey
Class requires a regular inspection and drydocking of the vessel, scheduled every 3, 8 and 13 year and these costs are estimated to amount 1.1-1.3 % of the newbuilding price and depend on the age of the vessel (Aalbers, 2000). Special survey has to be performed in year 5, 10 and 15 and the costs are estimated to amount 1.4-1.8% of the newbuilding price for the additional drydockings (Aalbers, 2000).

Management costs
The management costs for the vessel represent approximately 0.5% of the newbuilding value (Aalbers, 2000).

Lube oils, paint and stores
The specific consumption of lubrication oil is between 0.5-1.0 g/kWh. The costs of lubrication oil are 1250 dollar/ton according to "Evaluation of ship design options" (Aalbers, 2000). As this source is currently more than 20 years old, an inflation calculation is used to index these costs according to its current estimate. The annual average inflation over the past 20 years was 2.2% per year (Amadeo, Kimberly and Wohlner, Roger, 2021), which implicates that 1250 dollar/ton 20 years ago is now inflated to 1932 dollar/ton.

3.1.3 Voyage costs

The voyage costs depend on the route and the speed of the vessel and are represented by harbour and canal costs, loading and unloading costs, fuel costs, commissions and claims and differences in overtime. Here the choice was made to only investigate the fuel costs, as these differ per fuel type. The other costs depend on the route and port, which will result in an incredible number of different variables.

The fuel costs differ per day. The fuel price, as found in the literature review and presented below, will be used as base case. However, history showed that fuel prices frequently fluctuate up an down and predictions are almost always incorrect. To deal with this fluctuation and for illustrating a sensitivity analysis, including a minimum fuel price case and maximum fuel price case will be presented in Chapter 5.

Heavy fuel oil
The average price of heavy fuel oil was 403.50 $/mt in December 2020 (Ship and Bunker, 2020). Since the gravimetric energy density of heavy fuel oil is known, the costs of heavy fuel oil can be calculated and amounts to 36.31 [USD/MWh]

Methanol
The production costs of biomass methanol are estimated ranging from 84-107 [USD/MWh] but can be potentially lower if capital costs for the production decrease (Svanberg et al., 2018).

Hydrogen
The reference costs for hydrogen will be the costs that are displayed in "Pathways to climate-neutral shipping: A Danish case study", (ben Brahim et al., 2019) and amount to 91.77 [USD/MWh].

Ammonia
It is difficult to estimate the fuel costs for ammonia, since at present there is no vessel sailing on ammonia. However, costs that correspond with the Japanese government's hydrogen targets are: 2050- $320 per ton ammonia and 2030 -$480 per ton ammonia (Bunro Shiozawa, 2020). Which, equals to 76.8 [USD/MWh].

Ethanol
From the paper "Study on the use of ethyl and methyl alcohol as alternative fuels in shipping" (Ellis and Tanneberger, 2015) it can be derived that the costs of ethanol per metric tonnes are higher than those of methanol. As the energy densities of ethanol are also higher than of methanol, the costs of bio-ethanol are estimated at the same level as for bio-methanol and vary between 84-107 [USD/MWh].

Hydrotreated vegatable oil
The costs of hydrotreated vegetable oil are approximately twice as high as its fossil counterparts like heavy fuel oil (Balcombe et al., 2019). The price is estimated to double that of heavy fuel oil and, therefore, amounts to 72 [USD/MWh].

Battery electric
The industrial energy price differs per country and varied between 5 and 10 pence per KWh in Europe, which equals 67-134 [USD/MWh], in 2019 (Department for business, Energy & Industrial strategy, 2020).

3.2 Weight

The weight and volume distribution of a vessel is highly dependent on the type of converter and storage that was determined in Section 2.4 and in Table 11.

3.2.1 Lightweight

The lightweight [t] (W_{LW}) of the vessel is composed of the sum of the three main components; structural weight [t] (W_s), equipment and outfitting weight [t] (W_E) and the machinery weight [t] (W_M)

$$W_{LW} = W_S + W_E + W_M \tag{4}$$

The lightweight of the vessel can be derived from the vessel data, but can change per fuel type due to the propulsion systems, or the storage tanks needed for fuel handling. To determine the influence of different fuel types, the aspects of the lightweight that change in line with the choice of fuel type are investigated separately. This extra, or less weight is thereafter added, or subtracted from the lightweight of the vessel.

The propulsion system weight is fuel-dependent and can also change when less power is installed and, therefore, it is considered as a variable that changes the lightweight of the vessel. The extra weight and volume of special storage tanks can change the lightweight as well, but as this is already included in the gravimetric and volumetric energy density of the fuel (and storage) as presented in Table 18, this is not taken into consideration for determining its contribution to the lightweight. The lightweight of the vessel in this study will be determined from the known lightweight and extra, or less potential weight of the fuel converters.

Fuel cells

The weight of the fuel cell can be calculated from the gravimetric energy density of a fuel cell plant as reported in the paper: "Fuel Cell Systems Applied in Expedition Cruise Ships–A Comparative Impact Analysis (van Veldhuizen et al., 2020)" and is presented in Table 17:

	Hydrogen	Methanol & Ethanol	Ammonia	
Fuel cell type	LT-PEMFC	LT-PEMFC	SOFC	
Gravimetric power density	408	83	119	kW/ton

Table 17: Fuel cell gravimetric power density

Internal combustion engines

When an object is larger, often a non-proportional increase in weight is found (Aalbers, 2000). As a consequence, when the size decreases, for example when a smaller motor is required because the vessel is sailing at a lower speed, the weight and, consequently, costs will decrease. The propulsion system can not function without the systems supporting it, like cooling systems, heaters, pumps, compressors. The weight of the propulsion system and supporting systems can be estimated with the formula from Watson for more recently built ships (Aalbers, 2000):

$$W_{prop} + W_{syst} = 0.27 \cdot P^{0.82} \tag{5}$$

W = Weight [t]
P = Power [kW]

Battery electric

The NMC battery is selected as storage battery in this study. The NMC battery is the battery that is mostly used in shipping as compared to the other batteries as shown in Figure 46. However, the weight of the battery is a special issue, because the battery is actually the storage system for the fuel. The additional weight for storage and system that is used can be found in Figure 46. in Appendix C and is presented in Table 18.

3.2.2 Deadweight

The deadweight is the sum of the total mass that the ship can carry and can be calculated by adding up the cargo load weight, fuel weight, ballast water weight, freshwater weight, lube oil weight, provisions weight and persons weight. The calculated deadweight should be lower than, or equal to, the maximum allowed deadweight. The maximum allowed deadweight can be calculated by subtracting the lightweight from the displacement in tonnes when sailing on the maximum draft. It is described below how every component of the deadweight will be calculated.

Cargo weight
The amount of cargo that the vessel can transport contributes to the vessel data and will be studied after selecting the vessel. If for example, the capacity is given in TEU, an maximum of 28[t] per TEU will be used. As a container weight of 28 [t] is the maximum weight, it will also be analyzed what the influence of this assumed weight is. A sensitivity study using a lower, better average container weight of 14 [t] will be performed. For bulk carriers, or tankers, a maximum cargo capacity can be displayed as volume. When this is combined with the density of the cargo, the weight can be calculated.

Fuel weight
The fuel weight is calculated from the fuel volume that is needed for a voyage and its density which equals the volumetric energy density divided by the gravimetric energy density. It should be noted that generally more fuel than required will be carried on board, since the situation that the vessel runs out of fuel before reaching the port when the route had to be changed, or the weather conditions became worse has to be taken into account. A fuel volume margin of 10% and 20% will, therefore, be used

$$\frac{[MJ/L]}{[MJ/kg]} = [kg/L] = [t/m^3] \tag{6}$$

Table 18 shows the volumetric and gravimetric energy densities (including storage). These are based on Figure 47 and 48 of Appendix D and Figure 49 of Appendix E. Fuels that don't need a special storage system will remain the same as in Figure 49 of Appendix E .

Fuel	Gravimetric energy density [MJ/kg]	Volumetric energy density [MJ/L]
Heavy Fuel Oil	40	38.8
Methanol	19	15
Ethanol	28	21
Liquid hydrogen	10	5
Ammonia	12	10
Hydrotreated Vegetable Oil	44.1	34.3
Battery electric	<1	<2

Table 18: Energy densities

Ballast water

Ballast water is carried to maintain acceptable stability conditions and to compensate for the weight loss due to consumption of water and fuel. With a full cargo hold, ballast tanks are nearly empty. There are different types of ballast conditions (Marine Insight, 2020):

1. Light ballast: when the ship is heavily loaded and does not require additional ballast. In this situation the tanks are empty.

2. Heavy ballast: during seagoing state if the ship is not fully loaded. In this situation the tanks are filled

3. Port ballast: where ballast water corrects the trim during the loading, or discharging operation.

In this study it is assumed that the cargo capacity is fully used when the vessel transports cargo and, therefore, the ballast tanks are empty in the situation when the vessel is transporting cargo.

Provision, freshwater and lube oil
The weight of the provisions, freshwater and lube oil are estimated at 425 [t] per round trip as recommended by the U.S. Maritime Administration (Perakis, 1997). This seems like a lot of weight and is dependent on installed power, ship type, or ship size and, therefore, a sensitivity analyses will be performed to analyze the impact of this assumption on the results.

Persons
The weight of persons is neglected. If there are for example 25 people on board of the bulk carrier and the estimated weight is 200 kg per person (including personal belongings), the total weight will be 5 tonnes. The total weight amounting to 5 tonnes for a vessel that is transporting containers with a maximum weight of 28 tonnes, or has 100000 tonnes deadweight can be neglected.

3.3 Volume

In this section, the volume-depending variables will be discussed. First, the cargo holds, next the machinery and lastly, the IGF code and special storage tanks will be reviewed.

3.3.1 Cargo capacity

The cargo volume that the vessel can transport can be retrieved from the vessel data. The capacity is displayed in m^3, or TEU. If displayed in TEU, the volume can be transcribed to m^3 knowing that 1 TEU has the volume of 38.5 m^3. If the particular vessel is a container vessel, the needed space for fuel will be calculated in m^3 and it will be analyzed how many containers need to be replaced, or removed from the vessel for counterbalancing the extra weight. It needs to be investigated if the amount of cargo is equal, or less than the cargo volume capacity.

3.3.2 Machinery

The space that is needed for a fuel cell, internal combustion engine and battery needs to be determined. If the machinery is larger than the available space in the engine room, the machinery needs to be relocated. Per propulsion technology it is determined if this results in a volume increase.

Internal Combustion Engines:
The machinery is designed for the vessels in order to sail on its design speed and the solution of

sailing slower for more efficient fuel use only decreases the required power. It is assumed that the lower power engines can be located in the existing engine room.

Fuel cell

The volume required for a fuel cell can be calculated using the volumetric energy densities of the fuel cell, which are known from "Fuel Cell Systems Applied in Expedition Cruise Ships–A Comparative Impact Analysis (van Veldhuizen et al., 2020)" and are presented in Table 19

	Hydrogen	Methanol & Ethanol	Ammonia	
Fuel cell type	LT-PEMFC	LT-PEMFC	SOFC	
Volumetric power density	250	90	32	kW/m^3

Table 19: Fuel cell volumetric power density

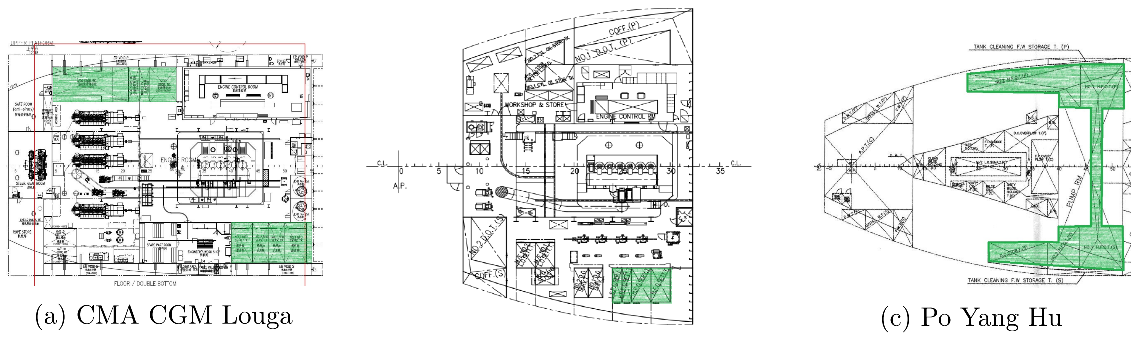
As fuel cells are easy to pile up, it is assumed that the space within the engine room is large enough for the fuel cells, auxiliary equipment and void spaces around the stacks and no volume-depending adjustments are required when using fuel cells.

Battery electric:

The volume of a battery is described in Table 18. The volume needed is high as compared to other fuels. When the battery electric propulsion is most preferred, a suitable location for the battery should be found.

3.3.3 Tank location

The tank location depends on the IGF code, but also on the type of tank that is used. In this section, solutions for fuels that have to comply with the IGF code, or use cylindrical tanks are investigated. The general arrangement of the vessel indicates whether the storage tank(s) are complying with the IGF code. The storage tank location on a container vessel, bulk carrier and oil tanker have been analyzed and are presented in Figure 13. The figure shows that the fuel tank locations are mostly against, or close to the hull. The IGF code requires that the tank location is located at a specific distance from the hull. Another problem of fuel storage tanks close to the hull is that it is not possible to locate cylindrical tanks there, because of the shape of the hull.



(a) CMA CGM Louga

(b) Union Mark

(c) Po Yang Hu

Figure 13: Fuel tank locations (in green) of Container vessel (left), Bulk carrier (middle), Oil tanker (right)

When fuel is stored in cylindrical storage tanks, or has to comply with the IGF code, the storage tank needs to be relocated. The fuels investigated are: ammonia, hydrogen, methanol and ethanol. Methanol and ethanol can be stored in the ballast tanks and do not require cylindrical tanks. Methanol is completely dilutable in water and will biodegrade rapidly. Methanol is far less hazardous than diesel or heavy fuel oil when spilled, implying that storage in ballast tanks is possible (Chatterton, 2018), (Freudendahl, 2015). It is assumed that there is enough space in the current fuel tank location combined with the ballast tanks to comply with the IGF codes for methanol and ethanol.

When Ammonia or Hydrogen are used another option is required. Ammonia and hydrogen storage requires cylindrical tanks. The maritime industry is not yet very familiar with sailing on hydrogen, or ammonia, therefore, vessels sailing on LNG fuel have been analyzed. LNG fuel is also kept in spherical storage tanks and has to comply with the IGF code.

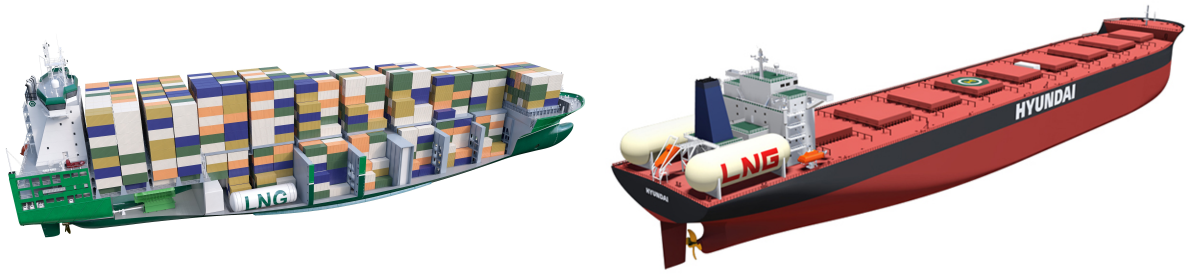


Figure 14: Fuel tank locations of cylindrical tanks on a container vessel (left) (DNV, 2015) and a tanker (right)(Vesselfinder, 2019)

Figure 14 shows that when container vessels are sailing on LNG, the fuel tanks are located below deck. This indicates that the tank is using the space where cargo could be stored before. When an oil tanker is sailing on LNG, the tanks can be placed on deck. It is assumed that for bulk carriers it is also possible to place the tanks on deck. This means that for oil tankers and bulk carriers the placement cylindrical tanks will not result in loss of cargo volume if there is enough deck space for locating the storage tanks. The volumes of the cylindrical storage tanks are included in Table 18. After the required volumes of cylindrical tanks are calculated, it should be investigated whether it is possible to locate the tank on deck for bulk carriers and oil tankers. An overview of the tank locations is given in Table 20.

	Container vessel	Bulk carrier	Oil tanker
Methanol	Ballast and old fuel tank	Ballast and old fuel tank	Ballast and old fuel tank
Ethanol	Ballast and old fuel tank	Ballast and old fuel tank	Ballast and old fuel tank
Ammonia	In cargo holds	Above deck if possible	Above deck if possible
Hydrogen	In cargo holds	Above deck if possible	Above deck if possible

Table 20: Location of fuel storage tank when a cylindrical tank is required, or the fuel has to comply with the IGF code

4 Model development

In this Chapter, the model used to determine the economical consequences of sailing on alternative fuels is described. The model has been developed based on the information which can be derived from the previous chapters. The main goal of the model is to demonstrate the financial consequences of sailing on alternative fuels, which as discussed in the introduction of this report, implies the use fuels with a lower energy density than conventional fuels. The main problem is that the cargo capacity per year decreases due to the lower energy density of the fuels. This is the result of measures that must be taken in order to sail on an alternative fuel, with a vessel that was designed for sailing on conventional fuels. The measures and their potential consequences as analyzed in this study, are as follows:

1. Less amount of cargo can be taken on board due to the need of more fuel space, or more fuel weight when using alternative fuels, as compared to conventional fuels. This will result in less cargo transported in one year.
2. The vessel lowers its sailing speed for more efficient use of the alternative fuel and as a result less fuel weight and volume needs to be carried. This will result in less voyages per year and thus less cargo can be transport in one year.
3. Bunker stops during the voyage will be made to compensate for the need for extra fuel. This will result in more voyage time and thus less cargo transported in one year.

The actual consequences of the measurements will be clear when the costs per ton cargo will be calculated. The transport costs exist of capital, operational and voyage costs. This includes the costs of possible adjustments to the vessel, or operation which are needed to actually sail on the fuel. In order to calculate the costs per ton transported cargo, a model is developed.

In this chapter, the developed model will be explained by discussing it step by step. The model exists of six different sections; the vessel section, fuel section, volume section, weight section, costs section and calculation section. The vessel and fuel section serve as data for the weight, volume and cost section, all sections together serve as input for the calculation section and an overview of the model is given in Figure 15. This chapter is divided in different sections consisting of information per section and, subsequently, examples of how the section can be applied. The outcomes of the different examples will be shown. However, the outcomes and consequences of different assumptions on the outcomes will be further assessed in Chapter 5.

The Tables used in this chapter represent tables similar to the developed model. In appendix I, screenshots of the model have been added as well.

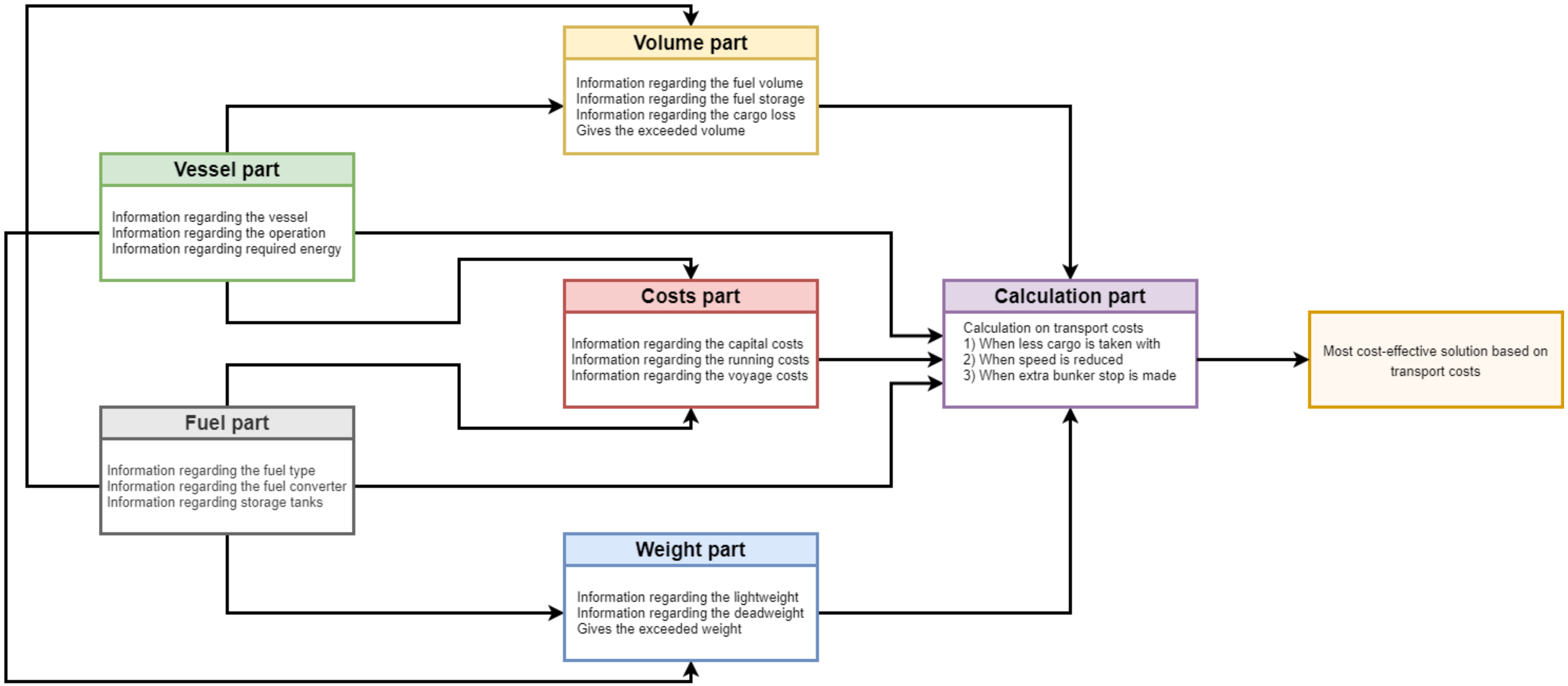


Figure 15: Overview of the developed model. The arrows indicate what information of which section is used

4.1 Vessel data

The first section of the model is the vessel data section. This section consists of three different subsections. First, information regarding the vessel, then information regarding the voyage and lastly information regarding the energy used during the voyage. The first subsection, information regarding the vessel, consists of:

- Vessel name
- Vessel type
- Built
- LOA
- Draft
- Beam
- Speed
- Bunker capacity
- Cargo capacities
- Ballast capacity
- Engine power
- Block-coefficient
- Lightweight
- Maximum deadweight
- Crew
- Max Displacement
- Admiralty constant
- Newbuild price
- Port time

Most of the data could be found in Clarksons fleet register (Clarkson Research, 2021). The red colour is used for criteria that could not be found and these are either calculated with help of available other source data, or estimated.

The first step, when using the model, is to choose a vessel in the vessel section. In a drop-down menu the following existing vessels can be chosen:

1. The +/- 150,000 DWT crude oil tanker **Nordic Grace**
2. The +/- 400,000 DWT ore carrier **Ore China**
3. The +/- 34,350 DWT container vessel **CMA CGM Louga**

The reason why these vessels are chosen is described in Section 1.3.1. The data that are shown correspond with the data of the vessel chosen in the drop-down menu. The data regarding the vessel are, when available, copied from Clarkson fleet register (Clarkson Research, 2021). However, not all required data were available in this register. Below, a description of how the irretrievable data were determined is given.

1) The bunker capacity of the Ore China and CMA CGM Louga was not found in Clarksons fleet register. For both vessels, sister vessels have been analyzed and their bunker capacity is used.

2) The block coefficient is determined using information and figures from the Hydromechanic 2 dictate MT526 (Pinkster and Bom, 2006) representing: 0.84 for tankers, 0.554 for container vessels and 0.864 for bulk carriers.

3) The block-coefficient is used to calculate the displacement of the vessel. The equation used is:

$$\nabla = c_b * T * B * L_{ord} * \rho_{seawater} \tag{7}$$

4) The displacement in tonnes is used to calculate the lightweight of the ship:

$$lightweight[t] + deadweight[t] = displacement[t] \tag{8}$$

5) The number of crew members on board the vessel is based on a survey from Deloitte concerning vessel's crew (Cambanis, 2011) and varies between 20 and 25 members.

6) The admiralty constant presents a relation between speed and power. This is used in this study to calculate the power of the main engine, when the vessel lowers it speed. The equation used is:

$$C_{adm} = \frac{\Delta^{\frac{2}{3}} * v_s^3}{P_d} \quad (9)$$

With
Δ in tonnes
V_s in m/s or knots
P_d in kW or horsepower

7) The port time depends on the port and the facilities at the port and the type of vessel. The selected port turn around time indicators can be found in "Review of Maritime Transport 2019, United Nations publication issued United Nations Conference on Trade and Development, (UNCTAD, 2019)" indicating 2.05 days for dry bulk carriers, 0.7 days for container vessels and 0.94 days for liquid bulk carriers.

8) The newbuild price of the Ore China can be found in Clarckson register. The newbuild prices of the Nordic Grace and CMA CGM Louga are determined based on newbuild costs of similar vessels. The newbuild price for the Nordic Grace, is determined at 65m USD based on an average newbuild price in 2020 (64m) (Hellenic Shipping News, 2020) and on the 2007 newbuild price (65m) (Lindstad et al., 2012). To determine the capital costs of the CMA CGM Louga the same paper (Lindstad et al., 2012) and the paper "Economies of Scale in Container Ship Costs, (Murray, 2016)" were used. The newbuild price of the CMA CGM Louga is determined at 40m USD.

In Appendix F, Table 50, the values representing the above discussed data of the CMA CGM Louga, Ore China and Nordic Grace are given.

The second subsection of the vessel section consists of information on the operation. In this subsection, the amount of cargo that the vessel transports before sailing on alternative fuels is calculated. In other words the amount of cargo that the vessel transports while sailing on design speed using heavy fuel oil. This calculation is made to analyse how much cargo the vessel can transport before using alternative fuels. This amount of cargo will be used as the vessel's cargo capacity. The data needed and calculated in this subsection are:

- Operation
- Distance
- Duration (port and sea)
- MCR
- Energy required
- Fuel margin
- Engine efficiency
- Fuel needed in [kWh], [t] and [m^3]
- Max cargo in [t] and [m^3]
- Round-trips per year
- Capacity per year [t/year]

In a drop-down menu, the voyage of the vessel can be selected and the corresponding distance will be displayed. Also, the approximate duration for the voyage when the vessel sails on its service speed is shown. The time at sea together with the engine power are used to calculate the amount of energy required for the selected voyage. It is assumed that the vessel uses 80% (Saputra et al., 2015) of his total engine power capacity (MCR) when cruising, or sailing its design speed. When the required energy is calculated, the amount of fuel required can be calculated. This is done by dividing the required energy by the efficiency of the technology used and adding a fuel margin of 10%. A fuel margin is used to avoid that the vessel will run out of fuel when it has to divert from the route. When the amount of required fuel is calculated, the required fuel weight and volume of heavy fuel oil can be calculated.

The amount of cargo in tonnes that the vessel can transport when sailing on heavy fuel oil is calculated by subtracting the non-cargo parts of the deadweight (provisions, fuel weight etc.) from the maximum deadweight. This calculated amount of cargo will be used further in the study as the cargo capacity [t] of the vessel. The cargo volume, when sailing on heavy fuel oil, is copied from the vessel data as long as this is larger then the tonnes cargo divided by the density of the cargo. Otherwise, the maximum allowable cargo volume will be lower.

The transported cargo per year can be calculated from the known amount of transported cargo and the amount of round-trips per year when sailing on heavy fuel oil. It is assumed that the vessel sails fully loaded out and empty back and that the running days per year are 360.

The cargo weight and cargo volume, when sailing on heavy fuel oil, will both be used in the weight and volume section. They help by identifying the amount of weight, or volume that will exceeded when alternative fuels are used and the cargo holds are fully loaded. A schematic overview of the calculations made in this subsection is given in Figure 16. Table 21 shows the different voyages when sailing with the Nordic grace.

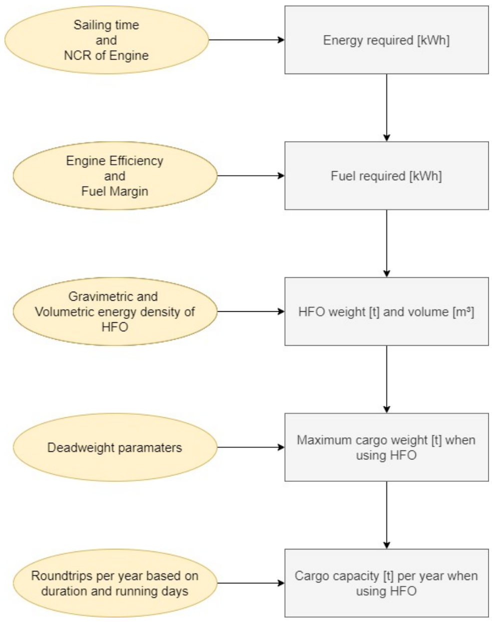


Figure 16: Schematic overview of calculations made for the second subsection of the vessel section

Operation	Santos - Dalian	
Distance	12000	[NM]
Sailing time	827.59	[h]
Port time	22.56	[h]
Duration voyage	850	[h]
NCR	14899	kW
Energy needed	1.2*10e7	[kWh]
Fuel marge	0.1	
Engine efficiency	0.48	
Fuel needed	2.8*10e7	[kWh]
Fuel needed HFO	2543	[t]
Fuel needed HFO	2622	[m^3]
Max cargo on operation	146953	[t]
Max cargo on operation	173947	[m^3]
Roundrips per year	5	
Capacity per year	7.5*10e5	[t/year]

Operation	Jeddah - Algeciras	
Distance	2570	[NM]
Sailing time	177.24	[h]
Port time	22.56	[h]
Duration voyage	200	[h]
NCR	14899	kW
Energy needed	2.6*10e6	[kWh]
Fuel marge	0.1	
Engine efficiency	0.48	
Fuel needed	6.1*10e6	[kWh]
Fuel needed HFO	545	[t]
Fuel needed HFO	562	[m^3]
Max cargo on operation	148951	[t]
Max cargo on operation	173947	[m^3]
Roundrips per year	22	
Capacity per year	3.2*10e6	[t/year]

Operation	Rotterdam - St. Petersburg	
Distance	1500	[NM]
Sailing time	103.45	[h]
Port time	22.56	[h]
Duration voyage	126	[h]
NCR	14899	kW
Energy needed	1.5*10e6	[kWh]
Fuel marge	0.1	
Engine efficiency	0.48	
Fuel needed	3.5*10e6	[kWh]
Fuel needed HFO	318	[t]
Fuel needed HFO	328	[m^3]
Max cargo on operation	149178	[t]
Max cargo on operation	173947	[m^3]
Roundrips per year	34	
Capacity per year	5.1*10e6	[t/year]

Table 21: Different voyages used within study. The specified vessel is the Nordic Grace

The final subsection of the vessel section consists of data used to determine the amount of fuel and energy needed, when sailing a certain speed using a certain fuel. The data exist of:

- Technology used
- Efficiency
- NCR
- Power
- Fuel margin
- New speed
- Power for new speed
- Duration
- Energy required
- Fuel required

The same calculations as in the second subsection are used to calculate the amount of fuel required. The data, and thus the outcomes, vary when a different fuel, different technology, or different design speed is used. The third subsection starts with selecting the technology. The technology can be selected in a drop-down menu and the corresponding efficiency as presented in Table 10 in Section 2.4.1 will be given. Subsequently, calculations will be made. The required amount of fuel is determined the same way as for heavy fuel oil and a schematic overview of the calculations can be found in Figure 16.

The new speed depends on the value that is entered when determining the minimum transport costs in the calculation section of the model. A lower sailing speed in combination with less fuel volume stored on board in order to reduce weight will result in a change of available energy. With the new speed, a new power will be calculated using equation 9, the admiralty constant. With the new power, the new normal continuous rating (NCR) corresponding with the new speed can be calculated. The new NCR equals 80% of the new power of the vessel. The new speed also determines the new duration of the voyage. The power and the duration of the voyage determine the energy that is needed for the voyage. This is only correct if there are no losses and all available fuel is used. The efficiency of the technology used and a fuel margin of 10 % need to be considered for determining how much energy is needed for a voyage. The calculated total required fuel will be used to calculate the volume and mass of the fuel for the voyage. This will be used later in the weight and volume section of the model.

Table 22 shows the difference in amount of fuel required when sailing the Nordic Grace from Santos to Dalian with a speed of 14.5 knots and 10.0 knots, respectively.

Energy		
Technology	**ICE**	
Efficiency	0.48	
NCR	14899	[kW]
Power	18624	[kW]
Fuel marge	0.10	
New speed	14.5	[kn]
Duration on sea	828	[h]
Energy needed	1.2*10e7	[kWh]
Fuel needed	2.8*10e7	[kWh]

Energy		
Technology	**ICE**	
Efficiency	0.48	
NCR for new speed	4887	[kW]
Power for new speed	6109	[kW]
Fuel marge	0.10	
New speed	10	[kn]
Duration on sea	1200	[h]
Energy needed	5.9*10e6	[kWh]
Fuel needed	1.3*10e7	[kWh]

Table 22: Energy calculation data while sailing 14.5 [kn] (left) and 10 [kn] (right) with the Nordic Grace from Santos to Dalian

4.2 Fuel data

The second section of the developed model represents the fuel data section. The fuel data section exists of information as described in Section 2.4 and is divided in three subsections. The first subsection consists of information about the fuel. In a drop down menu the fuel type and corresponding technology can be chosen. When the fuel type and machinery are selected, the corresponding values belonging to a certain fuel will appear. After selecting fuel type and the type of machinery, all data are fixed. The data corresponding with the fuel type and machinery are:

- Fuel type
- Technology used
- IGF code
- Special storage tank
- Gravimetric energy density (including special storage)
- Volumetric energy density (including special storage)
- Fuel costs from literature review
- Density

On the fuel section, information about the fuel which is needed to calculate the costs of transport is given. This also includes additional information regarding the technology used, the IGF code and special fuel storage tanks. The costs, when using a fuel cell, or battery, and gravimetric and volumetric energy density, when using a fuel cell are given and will be used to determine the costs of transport.

If a fuel cell is used, the volumetric energy density and gravimetric energy density are given. Both will be used to calculate the weight and volume of the fuel cell system. When the propulsion system is an internal combustion engine, the gravimetric energy density and volumetric energy are not given. The weight of the internal combustion engine will be calculated using equation 5. As the engine room will not be modified and the engine volume can decrease as consequence of a lower sailing speed, the volume available for the combustion engine will always be sufficient. Figure 17 shows which information of the fuel converter is distributed to which section of the model.

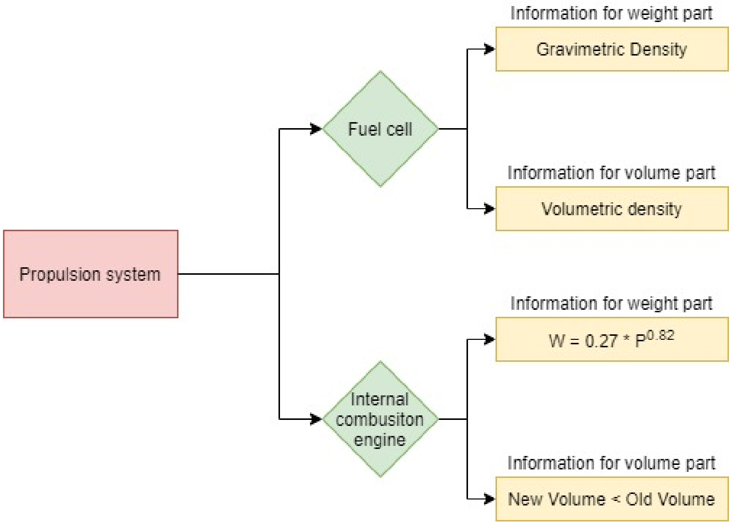


Figure 17: Schematic overview of which converter information is distributed to which section in the model

The influence of the IGF code will be visible in the volume section of the model. In the fuel data section it is only indicated whether a fuel has to comply with the IGF code.

The fuel data section does not include any calculations, but gives necessary information used in other sections of the model. Table 23 shows an example of how the data for heavy fuel oil and hydrogen (while using a fuel cell) will vary.

Fuel type	**HFO**	
Technology used	ICE	
IGF code	N/A	
Special storage tank	N/A	
Gravimetric energy density (incl. storage)	40	[MJ/kg]
Gravimetric energy density (incl. storage)	11111	[kWh/t]
Volumetric energy density (incl. storage)	38.8	[MJ/L]
Volumetric energy density (incl. storage)	10778	[kWh/m³]
Fuel costs	36	[USD/MWh]
Density (incl. storage)	0.97	[t/m³]

Propulsion system	**ICE**	
Volumetric energy density	N/A	[kW/m³]
Gravimetric energy density	TBD	[kW/t]
Costs of system	TBD	[USD/kW]

IGF code	No	
Fuel storage in cargo space?	N/A	
Loss of cargo space	N/A	

Special storage tank	No	
Extra costs of storage tank	0.00	[USD/kWh]

Fuel type	**Hydrogen FC**	
Technology used	FC	
IGF code	Yes	
Special storage tank	Yes	
Gravimetric energy density (incl. storage)	10	[MJ/kg]
Gravimetric energy density (incl. storage)	2778	[kWh/t]
Volumetric energy density (incl. storage)	5	[MJ/L]
Volumetric energy density (incl. storage)	1389	[kWh/m³]
Fuel costs	92	[USD/MWh]
Density (incl. storage)	0.50	[t/m³]

Propulsion system	FC	
Volumetric energy density	250	[kW/m³]
Gravimetric energy density	408	[kW/t]
Costs of system	5098	[USD/kW]

IGF code	Yes	
Fuel storage in cargo space?	TBD	
Loss of cargo space	TBD	

Special storage tank	Yes	
Extra costs of storage tank	12.10	[USD/kWh]

Table 23: Data shown on the fuel section after selecting heavy fuel oil (left) and Hydrogen FC (right)

4.3 Volume

The third section of the model is the volume section. In the volume section it is indicated whether the fuel capacity [m³] given in the vessel data is equal to, or higher than the fuel volume that is required. If not, the amount of excess fuel is shown. A solution for this problem will be investigated in the calculation section of the model.

Further in this section, information is given whether the fuel storage space is in the right location. In Section 3.3 is described that for some fuels the bunker storage space, now located near the hull of the vessel, needs to be relocated when cylindrical storage spaces are used, or when the fuel has to comply with the IGF code. It is not possible to fit cylindrical cryogenic or pressurized tanks against the hull, due to the hull form of the vessel.

If one of the two problems, "the fuel needs to comply with the IGF code" or "the fuel needs a special storage space" occurs, the model shows a red "NO" and the amount of fuel that needs to be replaced will be calculated. It is assumed that a vessel is designed so efficiently that it is not possible to relocate the fuel storage to empty spaces. As described in Section 3.3, cylindrical tanks will be relocated in the room for cargo when the specific vessel is a container vessel and will be placed on deck when the vessel is a tanker or bulk carrier. The calculated amount of fuel that needs to be relocated equals the amount of cargo lost when the particular vessel is a container vessel. Assuming that the volume of a container is 38 m^3 and has a maximum weight of 28 [t], the lost cargo in tonnes can be calculated. If a tanker, or bulk carrier is used it should be investigated if the amount of fuel that needs to be relocated fits on deck. If loading on deck is not possible, the fuel storage will be in place of cargo space, if the fuel is stored in place of cargo space the gross lost of cargo space is larger, because vessel crew must be able to move around the tanks for maintenance and for additional space for pumps to refuel the tanks. The amount of lost extra space depends on the length of the cylindrical tank, therefore, an extra cargo space lost of 50% is used in this study. This is based on a concept plan as shown in Figure 18 from the paper: "Economic analysis of trans-ocean LNG-fueled container ship (Adachi et al., 2014)".

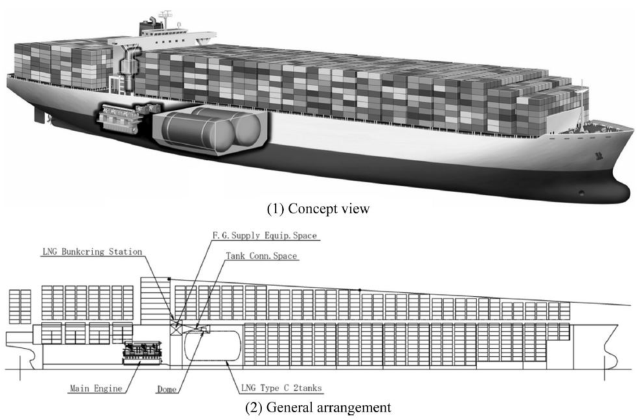


Figure 18: Concept view and general arrangement when cylindrical tanks are used (Adachi et al., 2014)

When methanol, or ethanol is selected, the special storage space part will show "Ballast". This means that methanol and ethanol can be stored in the ballast tanks. It is assumed that the relocation of these fuel tanks does not result in cargo loss as explained in Section 3.3. The relocated volumes need to be double checked for methanol and ethanol in order to analyze if it is possible to store the fuel volume in the ballast tanks.

In Table 24, the difference of when a container vessel, or when an oil tanker sails on hydrogen, a fuel that requires cylindrical storage tanks, is shown.

Tanks		
IGF code	Yes	
Special storage space	Yes	

Tanks		
IGF code	Yes	
Special storage space	Yes	

Fuel storage space		
Fuel capacity	3465	[m^3]
On right location	No	
Ballast capacity	12000	[m^3]
Cargo loss	0	[m^3]
Fuel volume needed	4357	[m^3]
Too much	0	[m^3]

Fuel storage space		
Fuel capacity	2160	[m^3]
On right location	No	
Ballast capacity	11617	[m^3]
Cargo loss	1434	[m^3]
Fuel volume needed	1434	[m^3]
Too much	0	[m^3]

Table 24: Volume data when sailing with tanker Nordic Grace (left) and container vessel CMA CGM Louga (right) from Jeddah to Algeciras with 14.5 [kn] on hydrogen

4.4 Weight

The weight section consists of two different subsections. The first subsection is the lightweight, which changes when the weight of the machinery changes. The weight of the machinery changes when the vessel sails at lower speed than its designed speed and uses a less powerful and smaller engine. The new lightweight is calculated by calculating the weight of the old machinery and subtract this weight from the known lightweight. As a result, the lightweight now only consists of the structural weight and the equipment and outfitting weight. The new propulsion and systems weight are calculated with the technology specific weight calculation formulas presented in Section 3.2 and will be added to the structural, equipment and outfitting weight to calculate the new lightweight. The new lightweight will vary when the speed and thus the required power varies. Figure 19 shows a schematic overview of the calculation.

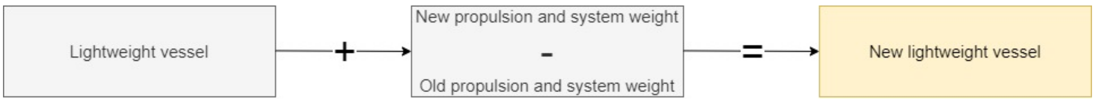


Figure 19: Schematic overview of how the new lightweight can be calculated

When the new lightweight is lower then the old lightweight then this difference in weight remains unused. This weight can be used for extra deadweight. The new maximum deadweight can be calculated by subtracting the new lightweight from the displacement. The deadweight will also be calculated by adding the fuel weight, cargo weight, ballast water weight, provision, freshwater and lube weight. The cargo weight is the calculated cargo capacity from the vessel section and represents the cargo weight on the voyage when using heavy fuel oil as described in Section 4.1. The fuel weight can be calculated from the gravimetric energy density [kWh/kg] and the energy required for the voyage [kWh]. The maximum deadweight will be subtracted from the calculated deadweight and when this is negative there will be no need for any modification of the operation, or the vessel. If the result is positive, then the vessel is too heavy and one of the problems, as described in Figure 10, occurs and additional measurements are needed. The outcomes of the measurements will be used for the calculation section of the model. Figure 20 gives a schematic overview of how the deadweight is used to calculate the "too much weight" on board of the vessel. Table 25 shows an example of a situation where the calculated weight equals the allowable weight (left) and how the model will look like when the calculated weight is higher than the allowable weight (right).

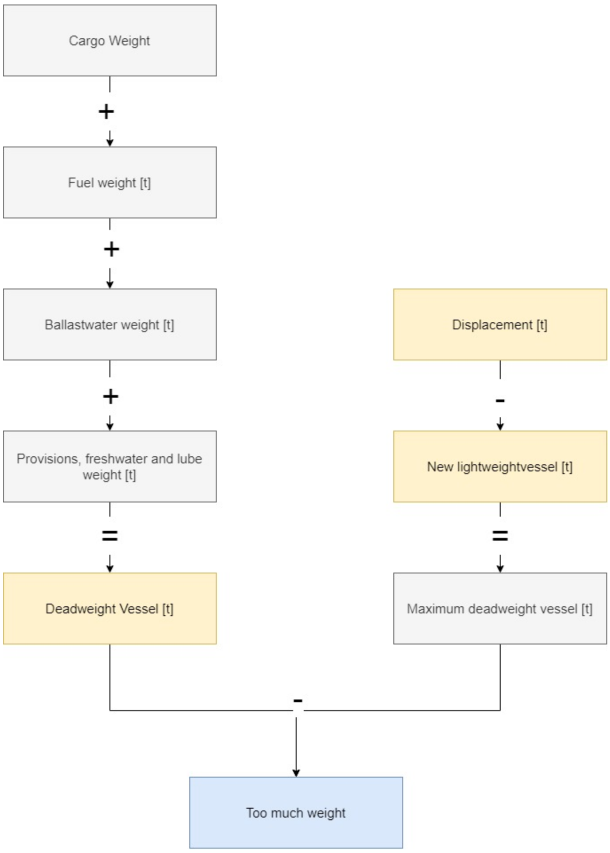


Figure 20: Schematic overview of how the excess weight can be calculated

Lightweight		
Propulsion type	ICE	
Lightweight	37170	[t]
Propulsionweight (old)	857	[t]
Lightweight - propuls	36314	[t]
Propulsionweight (new)	857	[t]
Added weight	0	
Lightweight new	36314	[t]

Lightweight		
Propulsion type	ICE	
Lightweight	37170	[t]
Propulsionweight (old)	857	[t]
Lightweight - propuls	36314	[t]
Propulsionweight (new)	857	[t]
Added weight	0	
Lightweight new	36314	[t]

Deadweight		
Displacement	187091	[t]
Max Deadweight	149921	[t]
Cargo volume	173947	[m3]
Cargo weight	148951	[t]
Fuel weight	545	[t]
Ballast water weight	0	[t]
Additional propulsion weight	0	[t]
Provision, freshwater and lube weight	425	[t]
Calculated deadweight	149921	[t]
Too much weight	0	[t]

Deadweight		
Displacement	187091	[t]
Max Deadweight	149921	[t]
Cargo volume	173947	[m3]
Cargo weight	148951	[t]
Fuel weight	1816	[t]
Ballast water weight	0	[t]
Additional propulsion weight	0	[t]
Provision, freshwater and lube weight	425	[t]
Calculated deadweight	151192	[t]
Too much weight	1271	[t]

Table 25: Weight data using HFO (left) and Ammonia ICE (right) on the Nordic Grace when sailing from Jeddah to Algeciras

4.5 Costs

The costs section is divided into three different subsections. The capital costs representing the purchase costs of the vessel and machinery and how this is financed, the running costs of the vessel and the voyage costs.

The capital costs subsection exists of:

- Building costs
- Additional costs for technology
- Additional costs for systems
- Additional costs for storage system
- Total building costs
- Financed
- Repayment term
- Interest rate
- Interest and equity costs year 1
- Interest and equity costs year 20
- Average interest and equity costs
- Total interest and equity costs
- Total costs of ship
- Annual depreciation
- Days operating
- Daily depreciation

The additional costs for the system and the propulsion for internal combustion engines are calculated using:

$$K_{propulsion} = 4100 * P_{new}^{0.84} - 4100 * P_{old}^{0.84} \quad (10)$$

$$K_{system} = 3000 * P_{new}^{0.70} - 3000 * P_{old}^{0.70} \quad (11)$$

Both equations will be 0 when the vessel is sailing its design speed and negative when the vessel is sailing on lower speed than its design speed. When the technology used consists of a fuel cell, the price per kW as described in Section 3.1.1 will be used to calculate the additional system costs. An overview of these costs together with the storage costs is given in Table 26. The battery electric technology costs are included in the fuel storage costs. The fuel storage costs for different fuels are discussed in Section 3.1.1 concerning capital costs and are presented in Table 26. When a fuel cell, or battery is used the capital costs for the internal combustion engine will be subtracted from the vessels building costs first. This is done using the following equation:

$$K_{propulsion} = 4100 * P_{old}^{0.84} \quad (12)$$

	Hydrogen	Methanol & Ethanol	Ammonia	
Fuel cell plant	5.10	5.98	15.93	[USD/kW]
Fuel storage	12.1	0.11	0.65	[USD/kWh]

	NMC (Nickel Manganese Cobalt Oxide)	LFP (Lithium Iron Phosphate)	LTO (Lithium Titanate Oxide)	
Capex	500-1000	500-1000	1000-2000	[USD/kWh]
Opex	Driven by electricity price			[USD/kWh]

Table 26: Overview of fuel cell plant, fuel storage and battery operational costs

Within the model, the capital costs vary per operation. Both the storage of the battery and fuel cell as well the costs of the fuel cell can decrease when less fuel is required. This might occur when the vessel is lowering speed and as a result less power and a less expensive power plant are needed, or when the vessel makes more fuel stops during the voyage meaning that a smaller, cheaper, storage tank can be an option. The total building costs of the vessel are the sum of the building cost that were retrieved from the literature and the additional costs for the propulsion and storage systems (which, sometimes, can be negative). How measurements influence the capital costs will be further discussed in Chapter 5.

"Financed" shows the relation between debt and equity, for financing the vessel. The repayment term is 20 years, which equals the lifetime of the vessel and machinery. This is chosen in order to spread the costs of the interest together with the cost of capital over 20 years. The interest rate includes the entire building costs, meaning that there is also interest paid over private money. This is done because private money that was used to buy the vessel could have had more value if it had been invested in stocks for example. An interest rate of 5 % is used.

The average costs of the interest are calculated by adding the costs of the interest in year 1 (maximum costs) with the costs of the interest in year 20 (minimum costs) and divided by 2. The total costs of the ship equals the total building costs + the total costs of interest and equity. When the total costs are calculated and the life span of the vessel and length of the loan are known, the annual depreciation can be calculated. Knowing the operating days (360) per year, the daily depreciation can be calculated. The top of Table 28 shows an example of how the building costs differ when the vessel is sailing on a lower speed and how the depreciation is calculated.

The second subsection of the costs section exists of the running costs. The running costs are discussed in Section 3.1 and presented in Table 27.

Running costs		
Crew costs	75000	$/year per crew member
Insurance	1	% of newbuilding costs
Maintenance & Repair	0.5	% of newbuilding costs
Docking	1.1, 1.2, 1.3	% of newbuilding costs
Special survey	1.4, 1.6, 1.8	% of newbuilding costs
Management	0.5	% of newbuilding costs
Lub. oil, Paint & Stores	0.5-1.0	g/kWh
	1931	$/ton

Table 27: Overview of running costs determinants

The yearly costs of docking and special survey costs are calculated by adding the different costs for the surveys, as presented in Table 27, and divide them over 20 years. The yearly running costs are the summation of all different outcomes except for the Lube oil, paint and store costs. These costs are calculated per day by using the values given in Table 27, the known energy required on a voyage and the duration of the voyage. The daily costs are calculated by dividing the yearly costs by running days and adding the daily lube oils, paint and store costs.

The last section are the voyage costs which exist of:

- Fuel price [USD/MWh]
- Fuel needed [MWh]
- Fuel needed [kWh]
- Total fuel costs [USD/voyage]
- Total fuel costs [USD/day]

The fuel price and fuel required are known after a fuel and operation are selected in the fuel sections and vessel sections of the model. The costs per voyage can be calculated by multiplying the fuel price with the required amount of fuel. The fuel costs represent only the costs made when the vessel is at sea, but not when the vessel is in a port. This implies that hotel costs for the accommodation are excluded from this study. The costs per voyage divided by the voyage duration in days results in the costs per day.

The total daily costs are the sum of the three separately calculated costs as mentioned above. The voyage costs are calculated by multiplying the daily costs by the days of voyage. The yearly costs are the daily costs multiplied by the running days. Figure 28 shows how the costs differ and are distributed when the Nordic Grace is sailing Jeddah to Algeciras on heavy fuel oil while sailing with a speed of 14.5 [kn] and 10 [kn]

Capital costs		
Building costs	6.5*10e7	[USD]
Additional costs for propulsion	0	[USD]
Additional costs for systems	0	[USD]
Additional costs for storage system	0	[USD]
Total building costs	6.5*10e7	[USD]
Repayment term	20	[Years]
Interest rate	5	[%]
Interest and equity costs year 1	3.3*10e6	[USD]
Interest and equity costs year 20	0	[USD]
Average interest and equity costs	1.6*10e5	[USD]
Total interest and equity costs	3.3*10e6	[USD]
Total costs of ship	6.8*10e7	[USD]
Annual depreciation	3.4*10e6	[USD/year]
Days operating per year	360	[d]
Of which in Port	41	[d]
Daily capital costs	9.5*10e3	[USD/day]

Capital costs		
Building costs	6.5*10e7	[USD]
Additional costs for propulsion	-9.6*10e6	[USD]
Additional costs for systems	-1.6*10e6	[USD]
Additional costs for storage system	0	[USD]
Total building costs	5.4*10e7	[USD]
Repayment term	20	[Years]
Interest rate	5	[%]
Interest and equity costs year 1	2.7*10e6	[USD]
Interest and equity costs year 20	0	[USD]
Average interest and equity costs	1.3*10e5	[USD]
Total interest and equity costs	2.7*10e6	[USD]
Total costs of ship	5.6*10e7	[USD]
Annual depreciation	2.8*10e6	[USD/year]
Days operating per year	360	[d]
Of which in Port	41	[d]
Daily capital costs	7.8*10e3	[USD/day]

Running costs		
Crew costs	1.7*10e6	[USD/Year]
Insurance costs	6.5*10e5	[USD/Year]
Maintenance and repair	3.3*10e5	[USD/Year]
Docking	1.2*10e4	[USD/Year]
Special survey	1.6*10e4	[USD/Year]
Management	3.3*10e5	[USD/Year]
Lube oils, paint and stores	0.75	[g/kWh]
Lube oils, paint and stores	459	[USD/day]
Yearly costs	3.0*10e6	[USD/Year]
Daily running costs	8.7*10e3	[USD/day]

Running costs		
Crew costs	1.7*10e6	[USD/Year]
Insurance costs	5.3*10e5	[USD/Year]
Maintenance and repair	2.7*10e5	[USD/Year]
Docking	9.7*10e3	[USD/Year]
Special survey	1.3*10e4	[USD/Year]
Management	2.7*10e5	[USD/Year]
Lube oils, paint and stores	0.75	[g/kWh]
Lube oils, paint and stores	459	[USD/day]
Yearly costs	2.7*10e6	[USD/Year]
Daily running costs	8.1*10e3	[USD/day]

Voyage costs		
Fuel price	36	[USD/MWh]
Fuel needed	6052	[MWh]
Total fuel costs	2.2*10e5	[USD/voyage]
Annual fuel costs	9.4*10e6	[USD/year]
Daily fuel costs	2.6*10e4	[USD/day]

Voyage costs		
Fuel price	36	[USD/MWh]
Fuel needed	2878	[MWh]
Total fuel costs	1.0*10e5	[USD/voyage]
Annual fuel costs	4.5*10e6	[USD/year]
Daily fuel costs	1.2*10e4	[USD/day]

Total daily costs	4.4*10e4	[USD/day]
Total yearly costs	1.6*10e7	[USD/year]
Total voyage costs	3.3*10e5	[USD/voyage]

Total daily costs	2.8*10e4	[USD/day]
Total yearly costs	1.0*10e7	[USD/year]
Total voyage costs	3.0*10e5	[USD/voyage]

Table 28: Costs overview of the Nordic Grace when sailing from Jeddah to Algeciras on HFO with 14.5 [kn] (left) and 10 [kn] (right)

4.6 Calculation

The calculation sections is a mathematical sections where the most cost effective solution(s) is/are calculated from the issue(s) that occur(s) within the weight or volume sections of the model. For example, what will happen if the total calculated deadweight is higher than the allowed deadweight, or when the fuel (including storage) volume is higher then the fuel storage capacity? The outcome(s) found within the volume, or weight sections will be shown in the calculation sections as presented in Table 29. Table 29 shows the overweight problem that occurrs when the Nordic Grace is sailing from Jeddah to Algeciras using methanol in combination with an internal combustion engine.

Problem		
Too much weight	602	[t]
Too much volume	0	[m^3]

Table 29: Overweight problem occuring when sailing with the Nordic Grace from Jeddah to West-Europe on Methanol ICE

When one of the two problems occurs, different solutions for solving the problem(s) will be looked at and these exist of:

Extra fuel stop(s). An extra fuel stop includes mooring time, refueling time and port time. With the extra time that is needed to refuel, the amount of round-trips per year can be calculated. The capacity per round-trip is known and together with the amount of round-trips the capacity per year can be calculated. The costs per ton cargo can be calculated by using the yearly costs of the vessel and the yearly capacity, while making extra bunker stops. An example of costs per ton cargo when sailing with the Nordic Grace from Jeddah to Algeciras when making an extra bunker stop is given in Table 30.

Bunker stop		
Mooring/Anchor time	2	[h]
Flow rate	200	[t/h]
Flow rate	267	[m^3/h]
Total time for weight	5.0	[h]
Total time for volume	2	[h]
Cost of extra bunker stop	18245	[USD]
New roundtrip duration	405	[h]
Voyages per year	21	
Capacity per year	3.2*10e6	[t/year]
Capacity loss	39877	[t/year]
Cargo costs with max cargo over a year	3.1*10e7	[USD/year]
Cargo costs with max cargo over a year	9.89	[USD/t]

Table 30: Solution of an extra bunker stop when sailing with the Nordic Grace from Jeddah to Algeciras on Methanol (ICE) with 14.5 [kn]

Reducing the amount of cargo. The excess fuel volume, or weight on board of the vessel will be compensated by reducing the weight, or volume of the cargo on board. The capacity per round-trip will decrease, which will result in less capacity per year. If the capacity per year and the yearly vessel costs are known, the costs per ton cargo can be calculated. Figure 31 shows the values representing the reducing cargo option. The calculated costs per ton cargo when sailing with the Nordic Grace from Jeddah to Algeciras on Methanol (ICE) with a reduced cargo amount are given.

Reducing cargo		
Capacity loss per voyage	602	[t/voyage]
Capacity loss per year	13016	[t/year]
New capacity per year	3.2*10e6	[t/year]
Cargo cost with max capacity	9.81	[USD/t]

Table 31: Outcome of reducing cargo when sailing with the Nordic Grace from Jeddah to Algeciras on Methanol (ICE) with 14.5 [kn]

Replacing fuel with cargo. When fuel is replaced by cargo, less energy is available on board of the vessel. This indicates that the vessel should use the amount of fuel available on board more efficiently and thus sail at a lower speed. The decrease in sailing speed results in reduced power needed as calculated with the Admiralty constant equation. How much power and which speed are required are presented in the vessel sections. If the corresponding power and speed are known, the amount of fuel required and the duration of the round-trip can be calculated. The round-trip duration and cargo capacity determine the cargo capacity per year. If the yearly vessel costs and the cargo capacity are known, the costs per ton cargo can be calculated. But in the case of reducing speed, costs are also saved. When less fuel is consumed, the expenditures on fuel decrease. But also the capital costs decrease due to the fact that a smaller engine can be used, or smaller fuel storage spaces are possible. These savings are calculated in the costs sections of the model. Figure 32 gives an overview when sailing on methanol ICE with the Nordic Grace from Jeddah to Algeciras. The speed corresponding with replacing the fuel weight by cargo for full capacity per voyage is 12 [kn] compared to 14.5 [kn].

Reducing speed		
Less fuel	3.2*10e6	[kWh]
Less Energy	1.5*10e6	[kWh]
Energy needed	2.6*10e6	[kWh]
Energy available	1.1*10e6	[kWh]
Max speed	14.5	[kn]
Duration on sea	177	[h]
Roundtrip	400	[h]
Voyages per year	22	
Capacity per year	3.2*10e6	[t/year]
Capacity loss	0	[t/year]
Cargo costs	9.77	[USD/t]
Energy corresponding with speed	2640755	[kWh]

Reducing speed		
Less	0	[kWh]
Less energy	0	[kWh]
Energy needed	1.8*10e6	[kWh]
Energy available	1.8*10e6	[kWh]
Max speed	12.0	[kn]
Duration on sea	214	[h]
Roundtrip	473	[h]
Voyages per year	18	
Capacity per year	2.7*10e6	[t/year]
Capacity loss	502350	[t/year]
Cargo costs	8.50	[USD/t]
Energy corresponding with speed	1808650	[kWh]

Table 32: Solution of reducing speed when sailing 14.5 [kn] (left) and 12.0 [kn] (right) with the Nordic Grace from Jeddah to Algeciras on Methanol (ICE)

Discussion of different options. A closer look at the different options when sailing on methanol shows a remarkable feature. In Table 32, the available energy increases when the vessel speed decreases. The explanation for this phenomenon is that the weight of the systems decrease when the speed decrease and thus the power of the engine and the size decrease.

The most cost-effective option when sailing on methanol with the Nordic Grace from Jeddah to Algeciras is the option of reducing speed. The main reason for this is that the fuel costs represent a very significant part of the daily costs when using methanol. Saving fuel by reducing speed is, therefore, the most preferred outcome. The savings on capital costs and running costs are less significant as shown in figure 21.

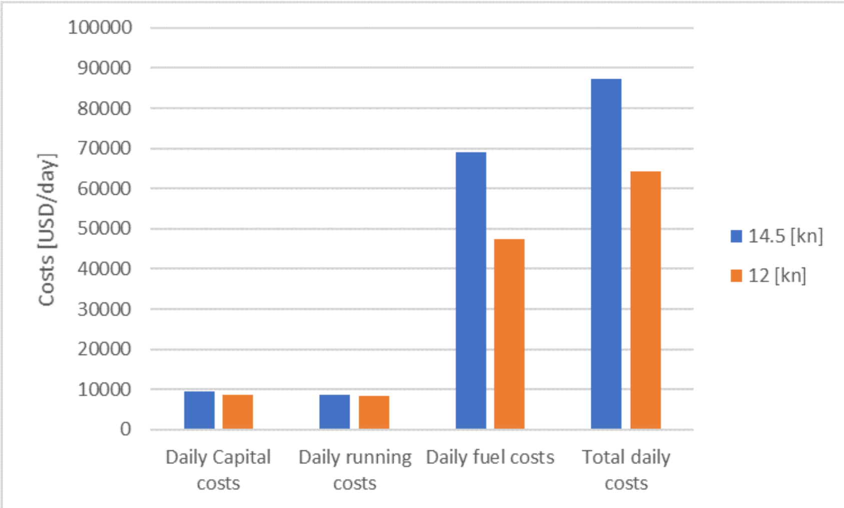


Figure 21: Overview of costs when sailing with the Nordic Grace from Jeddah to Algeciras on methanol (ICE)

4.7 Verification of the Model

In this section, the model will be tested to investigate if it works properly. This is done by entering diverse parameters which are known to lead to specific outcomes. First, the current state scenario, meaning sailing on heavy fuel oil, is tested. Within the model, none of the problems related "too much weight" or "too much volume" should occur. Next, extreme situations are considered and the expectations are illustrated. After running the extreme scenarios it will be checked whether the given values correspond with the expected outcomes. In Table 33, the scenarios and expected outcomes are described. The results in the table show whether the model has fulfilled the expectations. If the expected outcomes and the actual outcomes match then a check-mark is given in the table.

All expected outcomes, as presented in Table 33, matched the actual outcomes and the model performed as expected, and is, therefore, successfully verified. The exact results and values used for the different scenarios can be found in Appendix G.

Now that the model is developed verified and validated, different simulations and scenarios can be analyzed. In the next chapter, all fuels will be analyzed aiming to find the most cost-effective options using thoughtful ways to reduce costs. Combinations like making an extra bunker stop to reduce the size of the storage tank and thus save capital expenses of the storage tank, while reducing speed to save fuel expense will be further analyzed. Also several values used are, regretfully, not certain. For example, the flow rate that is used represents the flow rate of conventional fuels and not of ammonia, or the time in port varies per port and might be higher as estimated now. This will be further analyzed and discussed in Chapter 5

Scenario	Expectation	Result	Verified
Running on Heavy fuel oil	None of the problems ("too much weight" and "too much volume") occurs	Too much weight = 0 [t] Too much volume = 0 [t]	✓
Increase fuel storage costs [USD/kWh] to high value	A small storage tank is favourable and thus more bunker stops is most cost effective solution	0 stops = 18.66 [USD/t] 1 stop = 11.91 [USD/t] 5 stops = 7.47 [USD/t] 20 stops = 6.21 [USD/t]	✓
Increase mooring time of extra bunker stop (1 stop) to high value	The option make an extra bunker stop will increase	Mooring time 200 [h] = 17.76 [USD/t] Mooring time 250 [h] = 19.24 [USD/t] Mooring time 300 [h] = 20.72 [USD/t]	✓
Increase capital costs to high value	Influence of speed reduction and thus fuel saving reduces influence of tonnes transported increases	20 [kn] = 89.27 [USD/t] 15 [kn] = 112.47 [USD/t] 10 [kn] = 159.62 [USD/t] 5 [kn] = 303.45 [USD/t]	✓
Increase fuel costs to high value	Influence of speed reduction and thus fuel saving increases	20 [kn] = 118.81 [USD/t] 15 [kn] = 86.40 [USD/t] 10 [kn] = 56.57 [USD/t] 5 [kn] = 30.36 [USD/t]	✓
No additional costs for fuel cell	Fuel cell performance better on costs than internal combustion engine because of efficiency	Methanol ICE = 8.51 [USD/t] Methanol FC = 7.88 [USD/t]	✓
Efficiency increase of propulsion system	Costs reduces due to fuel costs	Efficiency 0.48 = 4.96 [USD/t] Efficiency 0.8 = 3.79 [USD/t]	✓
Make use of battery electric system on long distances (Santos - Dalian)	Expensive due to storage costs, heavy and big	Too much weight = 71952 [t] Too much volume = 30024 [m^3] Additional costs for storage =11302m [USD]	✓

Table 33: Verification of the Model (vessel used: Nordic Grace)

4.8 Validation of Costs

In this section, an analysis is performed if the values, which are used to indicate the daily costs of the vessel, correspond with the costs of an existing comparable vessel. Costs are variable and depend on external developments, such as fuel prices, or how the ship is financed. However, the distribution of the different aspects of daily costs help with validating the calculated daily costs which are used for this study.

The validation of costs is carried out for oil tanker Nordic Grace while sailing 14.5 knots using heavy fuel oil. Because the equations used for the other vessels and fuels are similar, the choice is made not to validate every fuel and vessel separately. In the book "Maritime Economics" an overview of how different costs (capital costs, voyage costs and running costs) relate to each other during the indicated given. The distribution of the costs according to "Maritime economics" and according to this study are presented in Figure 22.

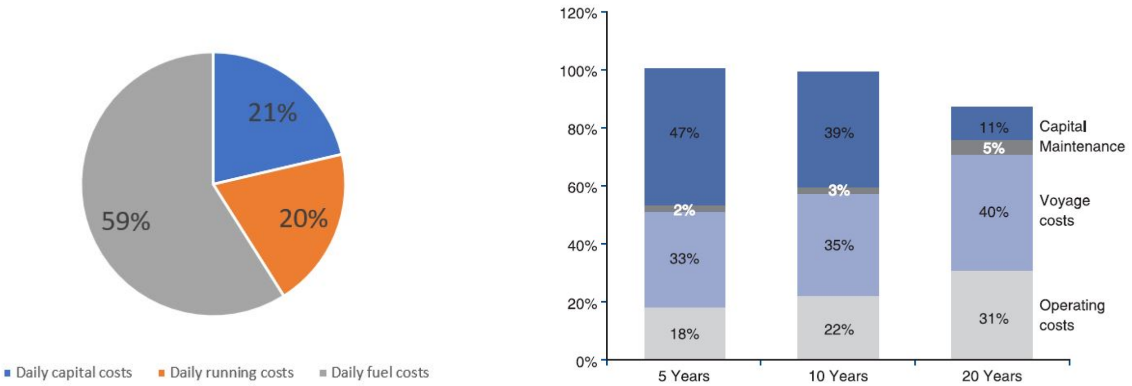


Figure 22: Costs distribution of Nordic Grace and Capesize bulk carrier (Stopford, 2008)

The left and right part of Figure 22 show that the distribution of costs is different. The capital costs used in this study are an average over 20 years and, therefore, lower than the figure shown for the first 5 years of the bulk carrier as analyzed in Maritime Economics. The amount of debt to be paid decreases every year, which results in a decrease of interest and debt over time. The capital costs differ from 11-47% in "Maritime Economics" in 15 years. If there is assumed that the the capital costs in "Maritime economics" are linear over 15 years, then the average capital costs are 29% per year. However, the capital costs decreases with an increasing decreases from 47% to 11%, indicating that the average costs will be lower than 29 % and close to the 21% average costs as used in this study.

The operating, or running costs include dry docking and inspection in for example year 3 or/and 5 or/and 10. In this study, an average is used to represent these docking costs per year, which is in contrast with the age-dependent costs as given in "Maritime Economics". Resulting in the representation of the running costs is 20 %. The running operating costs used in "Maritime Economics" are higher and vary from 18 % to 31 %. The fact that these percentages differ is also caused by the difference in percentages of the given voyage costs and the capital costs.

Analyzing the **voyage costs** shows, that the voyage costs are causing the main difference in percentages in cost distribution used in this study and in "Maritime Economics". In this study the voyage costs are higher than the voyage costs found in "Maritime Economics". The vessel used in this study is a tanker and the vessel used in "Maritime Economics" is a bulk carrier. The port time differs between these two vessel types These are 0.94 days and 2.05 days, respectively (UNCTAD, 2019). The fuel use and associated fuel costs of a bulk carrier are, therefore, less than for a tanker. Also fuel costs depend on voyage, speed and vary every day. The source used for determining the costs contribution used in "Maritime Economics" dates from 1993, implying that the crude oil price of 1993 was used. In this study, the crude oil price of 2019 is used. The historical crude oil prices and inflation adjusted price of crude oil show a difference which explains the difference in voyage costs in 1993 and 2019. The inflation-adjusted crude oil price in 1993 was 27.78 [USD/barrel] as compared to 51.44 [USD/barrel] in 2019. The outcome is that in that marine fuel was cheaper in that era indicating lower voyage costs (Macro trends, 2021).

The fact that fuel price, or voyage costs depend on voyage, speed and fuel price will implicate that the voyage costs will differ in time. More relevant is the fact that the capital costs and the running costs match the real-life situation. Different sources, like Greiner (2015) and Arnsdorf (2013) show that the daily running costs of a suezmax tanker are less then 10,000 [USD]. In this study, these costs are 10,660 [USD]. As the referred articles date from 2013 and 2015, a raise in the daily running costs, in line with the 2021 situation, seems plausible. Lastly, the distribution of the daily costs for oil tankers is analyzed using the paper: "Methodology of day-to-day ship costs assessment (Počuča, 2006)" . The daily fixed costs, representing the depreciation costs and the daily operating costs, are quite similar to the fuel costs, which is again similar to this study (54%/46%). In conclusion, the costs used in this study will be accurate enough for the purpose of this study and comparable with the real-life situation.

5 Results

In this chapter, the results of the developed model will be presented and discussed. According to the fuel type, the outcomes have been analyzed. The results consists of performed analyses using different fuel types for the vessels "Nordic Grace", "CMA CGM Louga" and "Ore China" sailing from Jeddah to Algeciras, from Rotterdam to St. Petersburg and from Santos to Dalian respectively. However, less common operation - vessel type combinations have been analyzed as well.

In this chapter, the most cost-effective measurements, when sailing on alternative fuels, are calculated. The problems that occur, as discussed in Section 2.1, are that maximum weight, or maximum volume which a vessel can carry can be exceeded, or that storage tanks have to be relocated. The "too much weight", or "too much volume" problems are the consequence of a vessel carrying its maximum cargo capacity while sailing on an alternative fuel. The maximum cargo capacity represents the cargo capacity which the vessel can transport when sailing on heavy fuel oil. The possible need for relocating fuel storage tanks is the consequence of the IGF code, or the need for using cylindrical fuel tanks.

In the model, different options will be investigated to reduce the weight, or the volume and should result in the vessel transporting cargo without being too heavy, or too full. Also the size of the fuel tank is further analyzed and it is investigated if it is possible to relocate the tank to other locations, as discussed in Section 3.3.3. When relocating the fuel storage tanks, it should be considered whether this causes a decrease in cargo capacity. The chapter is divided into different sections presenting different solutions and corresponding cargo costs. The goal is to investigate what the most cost-effective ways are to overcome the exceeded weight, exceeded volume, or tank relocation when sailing on alternative fuels. It is assumed that the vessel sails fully loaded on the way towards the importing country and returns empty.

5.1 Results of the Nordic Grace

In this section, the results of the vessel "Nordic Grace" are presented. First, the options of reducing cargo, reducing speed, or using an extra fuel stop to overcome the exceeded weight and/or exceeded volume are investigated. An extra fuel stop in this case means that the vessels make an extra stop during the voyage to compensate for the loss of fuel which was saved in order to lower the vessel weight. A flow rate for refueling of 110 - 280 [t] for marine fuel was found (Ascenz, 2019). A mooring time of 2 hours is selected which includes the time for the vessel to sail in, stop and for the barge to connect. Further, it is assumed that the tanker the Nordic-Grace can store a maximum 1000 m^3 of hydrogen and ammonia on deck to comply with the IGF code. If the tank volume exceeds 1000 m^3 the hydrogen, or ammonia fuel tank will be stored in place of cargo.

The results are shown in Table 34 and Table 35. Table 34 shows the transport costs of the different fuel types when an extra bunker stop is made, or when the amount of cargo is reduced while sailing the vessels design speed. Table 35 gives the minimum transport costs when the vessels speed is adjusted. The "too much weight" and "too much volume" columns in Table 34 indicate how much weight, or volume, is exceeded when sailing on a specific fuel. The weight and volume are not exceeded in the reduced speed scenario in Table 35, because the minimum cost is achieved at a lower speed than necessary to solve the problem of exceeded weight, or volume. "The cargo costs columns" show the transport costs in USD per tonnes of the solutions used to overcome the exceeded weight, or volume. For ammonia and hydrogen it is also investigated what the size of the fuel tanks are, in order to investigate if the tanks can be relocated on deck.

Some results, or words are highlighted, because these need extra focus, or clarification. This is done in the different subsections.

Fuel type	Too much weight [t]	Too much volume [m^3]	Location of tank	Size of storage [m^3]	Cargo costs (extra stop) [USD/t]	Cargo costs (cargo loss) [USD/t]
HFO	0	0	Correct		4.96	4.96
Methanol ICE	602	0	Ballast and fuel tank		9.89	9.81
Methanol FC	0	0	Ballast and fuel tank		10.95	10.95
Hydrogen ICE	1634	891	In place of cargo	4357	11.92	11.75
Hydrogen FC	546	337	In place of cargo	3803	12.36	12.25
Ammonia ICE	1271	0	In place of cargo	2179	8.71	8.60
Ammonia FC	340	0	In place of cargo	1901	14.29	14.19
Ethanol ICE	233	0	Ballast and fuel tank		9.44	9.38
Ethanol FC	0	0	Ballast and fuel tank		10.59	10.59
HVO	0	0	Correct		7.89	7.89
NMC Battery	14737	3707	Low in vessel		72.34	67.5

Table 34: Results of an extra bunker stop, or reducing amounts of cargo while sailing the Nordic Grace fully loaded from Jeddah to Algeciras with 14.5 [kn]

Fuel	Cargo costs [USD/t]	Speed [kn]	Location of tank	Size of tank [m^3]
HFO	4.43	9	Correct	
Methanol ICE	6.73	6	Ballast and fuel tank	
Methanol FC	6.80	6	Ballast and fuel tank	
Hydrogen ICE	7.28	6	On deck	746
Hydrogen FC	7.21	6	In place of cargo	1809
Ammonia ICE	6.16	7	On deck	508
Ammonia FC	6.99	6	In place of cargo	1901
Ethanol ICE	6.58	6	Ballast and fuel tank	
Ethanol FC	6.66	6	Ballast and fuel tank	
HVO	5.94	7	Correct	
NMC Battery	18.34	2	Low in vessel	

Table 35: Minimum cargo costs after reducing speed

5.1.1 Reducing speed, reducing cargo, or an extra stop

The results show that in all cases a reduction of speed is the most cost-effective intervention. Figure 23 and Figure 24 show the influence of speed reduction on costs when using a fuel cell and an internal combustion engine (the values used can be found in Appendix H in Table 59).

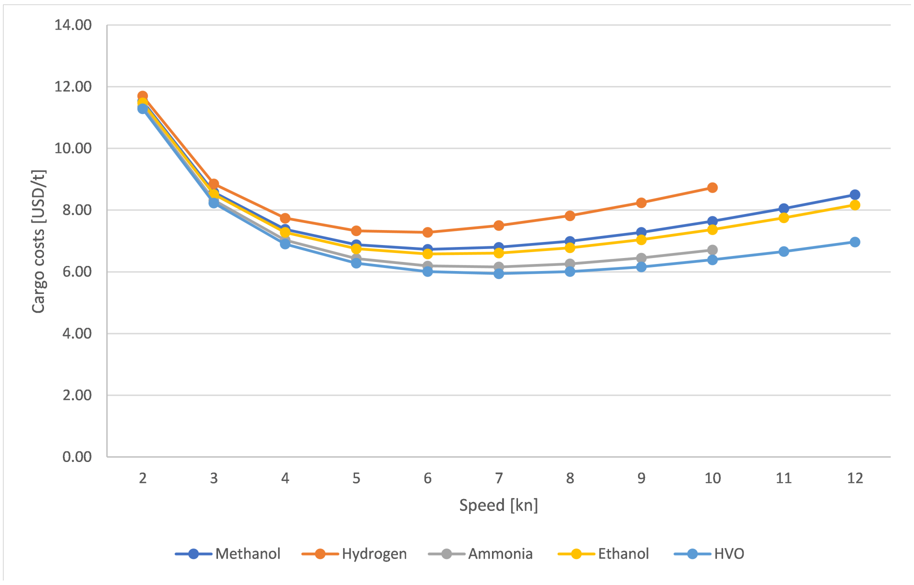


Figure 23: Influence of reducing speed [kn] on cargo costs [USD/t] while using an internal combustion engine

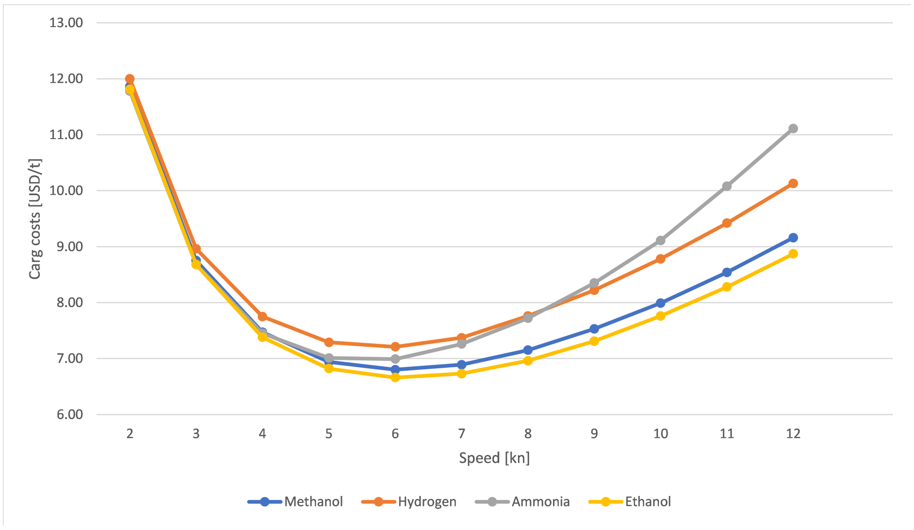


Figure 24: Influence of reducing speed [kn] on cargo costs [USD/t] while using a fuel cell

Analyzing Figure 23 and Figure 24 show that at higher speeds a fuel cell is more expensive for the same fuel used in an internal combustion engine. The reasons that causes this difference are presented in Figure 25. In Figure 25, the costs distribution of the Nordic Grace using ammonia in a fuel cell and in an internal combustion engine when sailing 10 [kn] is shown. The costs distribution shows that the fuel costs are more significant when fuels are used in an internal combustion engine at higher speed and, therefore, saving fuel and lowering speed reduces these costs significantly. The fuels used in combination with a fuel cell give more significant capital costs, reducing speed, and thus the power required, reduces the capital costs significantly. When speed is increased, power increases, leading to an increase in capital costs increase as well. The capital costs for fuel cells are currently higher than the capital costs of internal combustion engines, resulting in higher transport costs at high speeds when using a fuel cell as compared to an internal combustion engine.

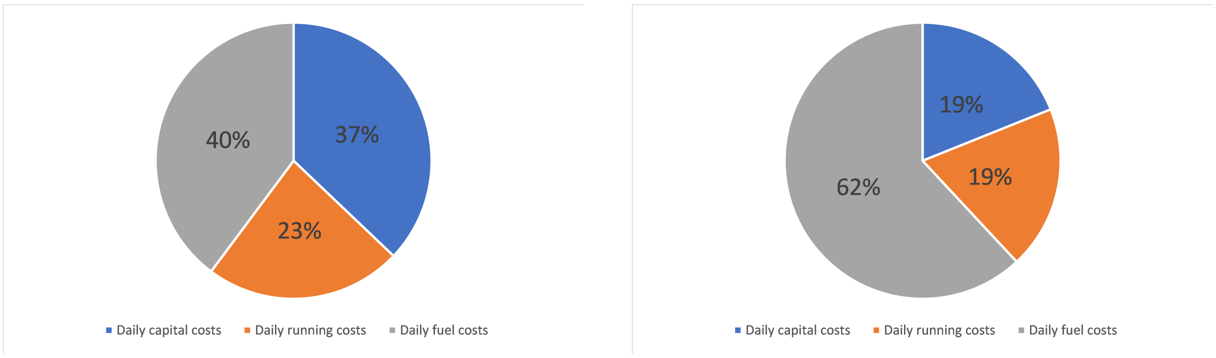


Figure 25: Costs distribution of Nordic Grace sailing on ammonia with 10 [kn] when using a fuel cell (left) and an internal combustion engine (right)

5.1.2 NMC Battery

Another aspect requiring attention is that the NMC battery is not an option for the Nordic Grace sailing from Jeddah to Algeciras, because the battery is too heavy, too big and too expensive, as shown in Table 34.

5.1.3 Location of the tank

Next, the location of the fuel tank should be carefully considered. The location of the storage tank is determined by the type of storage tank that is required and the IGF code. The exceeded volume is calculated by subtracting the size of the available fuel tank on board from the volume required. If the tank needs to be relocated, the entire volume required should be reconsidered. The volume of a cylindrical tank can be calculated with the following equation:

$$V = \pi * r^2 * L. \tag{13}$$

This indicates that when a tank of 4357 m^3 is required, as shown in Table 34, a very long, or wide tank is required. In Section 3.3.3 it was stated that fuel tanks for ammonia and hydrogen, when sailing an oil tanker, will be relocated on deck. However, even when 4 different tanks are used, the amount of 4357 m^3 volume is not likely to fit on deck because of the fuel tank size. When the transport costs, while using hydrogen, or ammonia, are compared with the transport costs, while using other fuels, it is not likely that the option of hydrogen, or ammonia at this speed will be used. Even if the vessel will sail on hydrogen, or ammonia, reducing speed, and thereby also reducing fuel volume, is a more costs-effective option as shown in Table 35. However, in the developed model, a fuel tank with volumes larger than 1000 m^3 will not be stored on deck, but located in place of cargo and will result in cargo loss and increased transport costs.

5.1.4 Difference in costs

Analyzing the minimum costs at the vessels design speed as presented in Table 34 shows that fuels used in a fuel cell are more expensive than when the same fuel is used in an internal combustion engine. The average minimum costs of fuels used in fuel cells are 12 [USD/t], while the average costs of fuels used in combination with an internal combustion engine are 8.73 [USD/t]. Even though fuel cells are more efficient and save fuel costs, the fuel cell capital costs result in a more expensive use of fuels in fuel cells. Within the minimized transport costs, presented in Table 35, differences are identifiable as well. The costs per tonnes cargo vary between 7.28-4.43 [USD/t] (excluding the expensive batteries). The fuel price influences the difference in costs, because the price of the fuel with the lowest costs is 36 [USD/MWh] while the highest fuel costs are 92 [USD/MWh] for the fuel. However, this is not the only parameter that causes the price difference. Table 36 shows the costs per tonnes cargo when all fuels have the same fuel price, while used in combination with an internal combustion engine.

Fuel	**Speed [kn]**	**Minimum cargo costs [USD/t]**
HFO	9	4.43
Methanol	8	4.43
Hydrogen	9	5.34
Ammonia	9	4.48
Ethanol	9	4.43
HVO	9	4.43

Table 36: Minimum costs when all fuels have the same costs as heavy fuel oil and used in an internal combustion engine

Analyzing the costs distribution of hydrogen shows that the 12.10 [USD/kWh] storage costs have a significant contribution in the cargo costs of hydrogen. The costs are still visible when the speed is reduced to a level where the cargo capacity and the fuel price are the same as of HFO. These storage costs can be lowered when more fuel stops are made and, subsequently, a smaller storage tank can be an option. A smaller storage tank reduces the storage costs and, in that case, hydrogen might become competitive to other alternative fuels.

5.1.5 Influence of a smaller storage tank

To investigate if alternative fuels with high fuel storage costs can be competitive with other fuels, it is analyzed how the fuel storage costs can be reduced. The fuel storage costs are presented in [USD/kWh] and are, therefore, determined by the size of the fuel storage tank. The size of the storage tank depends on the amount of fuel which the vessel requires for its voyage. This means that when the voyages become shorter, the fuel storage costs can be reduced. The reason for this is that a smaller fuel storage tank is used on board of the vessel. In order to reduce the energy required on board, the voyage is divided into parts. After each sailed part, the tank is filled up and as a result the fuel storage tank can remain small. The energy required, until a fuel stop is reached, is calculated with the following equation:

$$Energy\ required = \frac{Energy\ required\ for\ voyage}{1 + amount\ of\ stops} \tag{14}$$

The disadvantage of stopping more often is that the time needed for a voyage increases. This extra voyage time leads to the fact that less voyages can be made within a year. The result of less voyages per year is that less tonnes of cargo are transported per year, finally resulting in higher costs per tonnes cargo. The time which a bunker stop requires is calculated by Equation 15:

$$Extra\ time[h] = Amount\ of\ stops * Mooring\ time[h] + \frac{Fuel\ required[t]}{Flow\ rate[t/h]} * Amount\ of\ stops \tag{15}$$

The extra time needed for a bunker stop is added to the voyage duration, meaning that on the way towards the importing country as well as on the way back the same number of stops are made. The influence of a smaller storage tank and more fuel stops is analyzed for fuels that have known storage costs.

Hydrogen
First, hydrogen is analyzed. The influence of more bunker stops, when sailing on hydrogen in combination with an internal combustion engine, is presented in Figure 26. The minimum cargo costs [USD/t] and corresponding stops and vessel speed are presented in Table 37. In Appendix H the exact data as represented in Figure 26 can be found in Table 60.

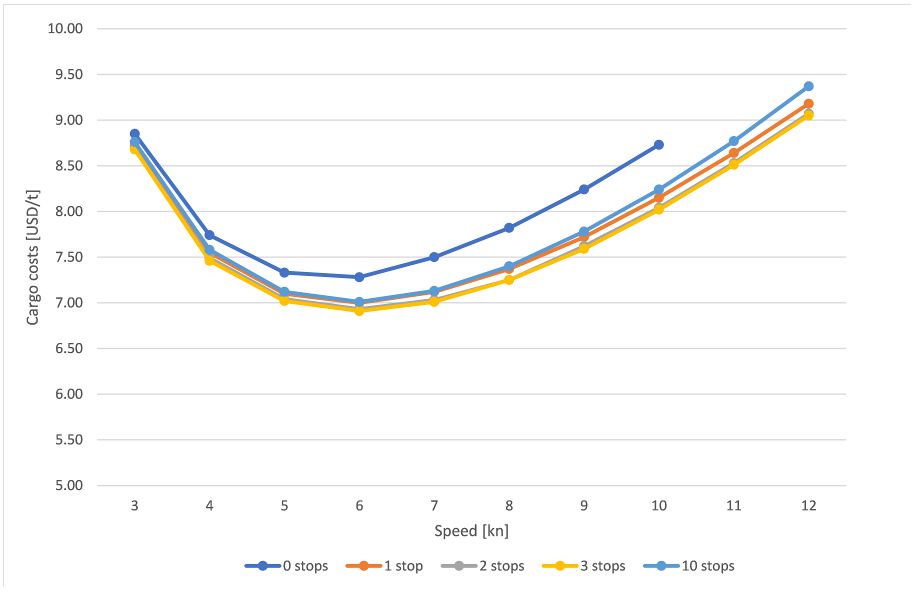


Figure 26: Influence of extra stop(s) when sailing on hydrogen in combination with internal combustion engine

Fuel	No. of stops	Size of tank at speed [m³]	Speed [kn]	Cargo costs [USD/t]	Difference with 0 stops [USD/t]
Hydrogen	0	746	6	7.28	0
Hydrogen	1	373	6	7	0.28
Hydrogen	2	249	6	6.93	0.35
Hydrogen	3	187	6	6.91	0.37
Hydrogen	10	68	6	7.01	0.27

Table 37: Minimum cargo costs when making extra stops while sailing on hydrogen using an internal combustion engine

Analyzing Figure 26 and Table 37 shows that the effect of making extra bunker stops reduces the cargo costs per tonnes significantly. When making 2, or 3 extra bunker stops, the costs per tonnes cargo reduces with 0.35-0.37 [USD/t]. However, the amount of costs reduction decrease when the number of stops increase. After a certain number of stops, the costs per tonnes cargo even increase, implying that the advantage of making extra stops is limited.

As the duration of the stops is based on assumptions and a flow rate found for conventional marine fuels, it is investigated what the influence is of the estimated additional time for the bunker stop. It is investigated what the costs are when the mooring time is 0, 2, 5 and 10 [h]. The results are presented in Figure 27 and Figure 28. The exact values per speed are given in Appendix H, in Table 61 and Table 62.

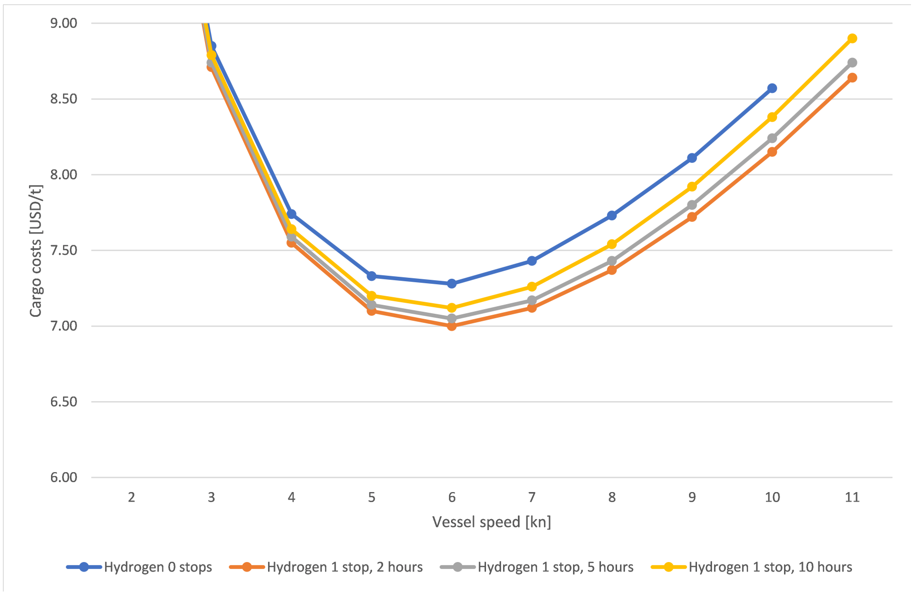


Figure 27: Influence of mooring time while making 1 extra stop when sailing on hydrogen using an internal combustion engine

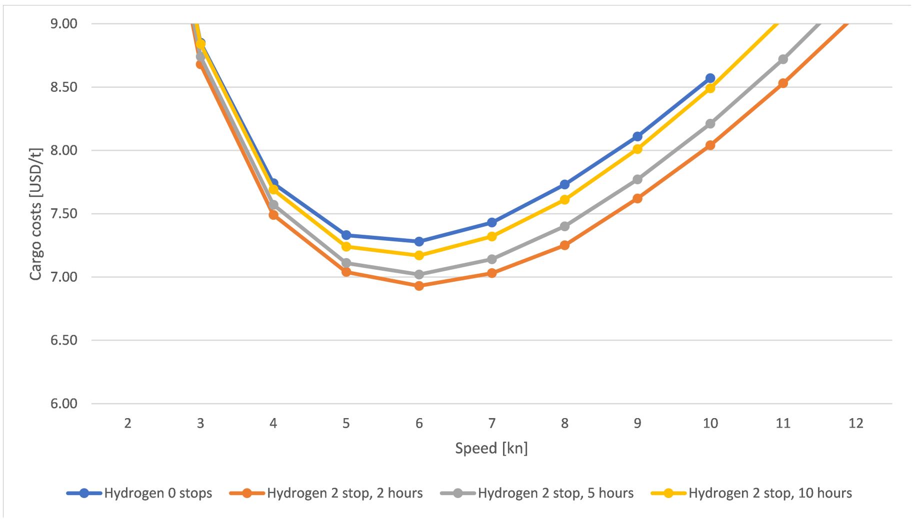


Figure 28: Influence of mooring time while making 2 extra stops when sailing on hydrogen using an internal combustion engine

Analyzing Figure 27 and Figure 28 shows two things. 1) The advantage of an extra fuel stop depends on the time of the fuel stop. This means that there must be the opportunity to refuel quickly before reducing the volume of the storage tank. 2) Even when the mooring time is 10 [h] it is still more cost-effective than zero stops and using a large fuel storage tank. However, the advantage of 2 stops as compared to 1 stop disappears. When applying the same method to lower the costs for hydrogen use in a fuel cell, the most cost-effective solution is 10.96 [USD/t] while making 1 stop sailing 10 [kn].

Other fuels with storage costs

The capital costs increase when using methanol, ethanol, or ammonia, due to storage costs as well. The costs per kWh are described in Table 38:

	Ammonia	Methanol	Ethanol	
Storage Costs	0.65	0.11	0.11	[USD/kWh]

Table 38: Costs of fuel storage

Ammonia has the second most expensive fuel storage costs. The influence of an extra stop, while using ammonia, is investigated in order to analyze if an extra stop reduces the cargo costs for ammonia as well. The differences in costs are presented in Figure 29. The exact values can be found in Appendix H in Table 63.

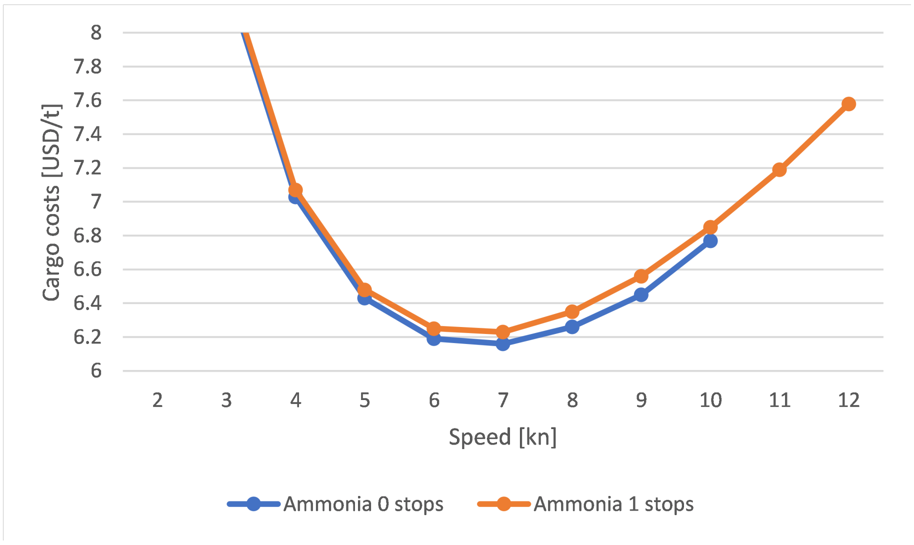


Figure 29: Influence of making 1 extra stop when sailing on ammonia using an internal combustion engine

Figure 29 shows that the cargo transport costs of ammonia increase when an extra stop is made. The influence of an extra stop on the cargo costs of ethanol and methanol are not further researched. The storage costs of ethanol and methanol are lower than for ammonia indicating that the option of making an extra stop, and use a smaller fuel tank, would not lower the transport costs on this voyage for the Nordic Grace when sailing on ethanol and methanol.

5.2 Influence of vessel size and type

The influence of vessel size, or vessel type is analyzed by determining the costs per tonnes cargo for different vessels using different fuel types. An overview is given in Table 39. The exact values corresponding to the varying vessel speed can be found in Table 64, Table 65 and Table 66 of Appendix H.

The CMA CGM Louga as well as the Ore China have, next to the measures taken to sail on hydrogen and ammonia, additional cargo loss. The storage tanks for hydrogen and ammonia for the Ore China are too large to locate on deck and are, therefore, located in the cargo space. The CMA CGM Louga is a container vessel, which implies that the storage tanks for ammonia and hydrogen have to be located in place of cargo as well. The amounts of cargo lost in these situations can be found in Table 64 and Table 65 of Appendix H. For the Nordic Grace it is assumed that the fuel storage tanks can be relocated on deck. However, it needs further research whether this is realistic. When the tanks are over 1000 m^3 they are considered too large to fit on deck and should be relocated in place of cargo. An overview, ranking from the most favourable fuel to the least favourable fuel when sailing the different vessels is given in Table 39.

	CMA CGM Louga Rotterdam - St. Petersburg				Nordic Grace Jeddah - Algeciras				Ore China Santos - Dalian			
	Fuel type	Speed [kn]	Cargo costs [USD/t]	Difference with HFO	Fuel type	Speed [kn]	Cargo costs [USD/t]	Difference with HFO	Fuel type	Speed [kn]	Cargo costs [USD/t]	Difference with HFO
1	HFO	11	6.18	0	HFO	9	4.43	0	HFO	11	13.36	0
2	HVO	8	8.22	33.01%	HVO	7	5.49	23.93%	HVO	8	18.15	35.85%
3	Ammonia ICE	8	8.5	37.54%	Ammonia ICE	7	6.16	39.05%	Ammonia ICE	7	19.70	47.46%
4	Ethanol ICE	8	9.06	46.60%	Ethanol ICE	6	6.58	48.53%	Ethanol ICE	7	20.20	51.20%
5	Ethanol FC	8	9.25	49.68%	Ammonia FC	6	6.58	48.53%	Ethanol FC	7	20.4	52.69%
6	Methanol ICE	7	9.28	50.16%	Ethanol FC	6	6.66	50.34%	Methanol FC	7	20.84	55.99%
7	Methanol FC	7	9.43	52.59%	Methanol ICE	6	6.73	51.92%	Methanol ICE	6	20.95	56.81%
8	Hydrogen ICE	7	9.60	55.34%	Methanol FC	6	6.8	53.50%	Ammonia FC	6	21.54	61.23%
9	Hydrogen FC	7	9.63	55.83%	Hydrogen FC	6	7.2	62.53%	Hydrogen FC	5	27.12	102.99%
10	Ammonia FC	7	9.62	55.66%	Hydrogen ICE	6	7.28	64.33%	Hydrogen ICE	5	28.58	113.92%
11	Battery	5	17.94	190.29%	Battery	3	18.52	318.06%	Battery	3	151.4	1033.23%

Table 39: Overview of favourable fuel types per vessel

Analyzing Table 39 shows that the ranking of the most favourable alternative fuel differs per vessel. Reducing vessel speed is for all fuels the most cost-effective solution, and this is independent of voyage, or vessel size. When the vessels are sailing their design speed and the most cost-effective solution is reducing the amount of cargo, the fuel ranking changes, as is shown in Table 40.

	CMA CGM Louga Rotterdam - St. Petersburg 20 [kn]			Nordic Grace Jeddah - Algeciras 14.5 [kn]			Ore China Santos - Dalian 14.8 [kn]		
	Fuel type	Cargo costs [USD/t]	Difference with HFO	Fuel type	Cargo costs [USD/t]	Difference with HFO	Fuel type	Cargo costs [USD/t]	Difference with HFO
1	HFO	7.59	0	HFO	4.96	0	HFO	14.15	0
2	HVO	12.31	62.19%	HVO	7.89	59.07%	HVO	22.09	56.11%
3	Ammonia ICE	13.54	78.39%	Ammonia ICE	8.58	72.98%	Ethanol ICE	26.35	86.22%
4	Ethanol ICE	14.71	93.81%	Ethanol ICE	9.38	89.11%	Methanol ICE	27.65	95.41%
5	Methanol ICE	15.43	103.29%	Methanol ICE	9.81	97.78%	Ammonia ICE	27.69	95.69%
6	Hydrogen ICE	17.37	128.85%	Ethanol FC	10.59	113.51%	Ethanol FC	30.13	112.93%
7	Ethanol FC	16.95	123.32%	Methanol FC	10.95	120.77%	Methanol FC	30.42	114.98%
8	Methanol FC	17.52	130.83%	Hydrogen ICE	11.75	136.90%	Ammonia FC	38.85	174.56%
9	Hydrogen FC	18.43	142.82%	Hydrogen FC	12.25	146.98%	Hydrogen FC	46.48	228.48%
10	Ammonia FC	20.37	168.38%	Ammonia FC	14.19	186.09%	Hydrogen ICE	47.28	234.13%
11	Battery	57.1	652.31%	Battery	67.5	1260.89%	Battery	871.18	6056.75%

Table 40: Overview of favourable fuel types per vessel sailing design speed

In minimized transport costs situation as well as in the situation that vessels sail their design speed, a different ranking of preferred fuel types appear for different vessels and operations. This implies that vessel size and operation do have an influence on the preferred alternative fuel. How the costs of the CMA CGM Louga and Ore China are distributed can be further analyzed to see what causes this specific ranking of favourable fuel types and how the costs are distributed. This investigation could possibly lead to other cost-effective options and interesting insights for sailing with these vessels.

Future considerations

When determining the transport costs of the CMA CGM Louga, it was assumed that the container vessel is fully loaded. However, when the CMA CGM Louga, or another container vessel is analyzed, it should be taken into account that container ships are almost never fully loaded. If a container vessel is not fully loaded, the excess of volume, or weight will be lower, or does not even play an important role after all. In the future, when analyzing a container vessel, it would be more logical to mention lost revenue instead of increased cargo transport costs. This means that the amount of cargo loss to compensate for the weight that is required when sailing on alternative fuels, or when the fuel tanks are placed in place of cargo should be calculated and translated to lost revenue. When the freight rate is known, the amount of lost cargo can be expressed in terms of potential loss of revenue which in case of a not fully loaded container vessel remains the same as for a fully loaded container vessel.

5.3 Influence of voyage

In Table 41, the influence of voyage is given for hydrogen in combination with an internal combustion engine, methanol in combination with a fuel cell and heavy fuel oil, when sailing the design speed with the Nordic Grace. The boxes in red imply that it is not possible to sail 14.5 [kn] when using the fuel, or that an extra stop, or reduce in cargo is not necessary. The fuel-converter combinations have been chosen to investigate what the influence of the voyage is on the effect of 1) the high capital costs of a fuel cell, 2) the high operational costs for hydrogen and 3) to investigate what the influence of the voyage is on the base case represented by heavy fuel oil. Expected is that the storage costs of hydrogen result in higher transport costs for longer voyages. This implies that making more voyages and sailing higher speed is preferred when the capital costs are high. The costs distribution using the different fuels on different voyages while varying speed are given in Figure 30, Figure 31 and Figure 32.

	Hydrogen ICE			Methanol FC			Heavy fuel oil		
	14.5 (speed)	Extra stop	Cargo loss	14.5 (speed)	Extra stop	Cargo loss	14.5 (speed)	Extra stop	Cargo loss
Rotterdam - St. Petersburg		6.56	6.43	6.57			2.98		
Jeddah - Algeciras		11.92	11.75	10.95			4.96		
Santos - Dalian		79.4	81.82		50.55	50.79	22.64		

Table 41: Influence of vessel cargo price while making an extra stop, or reducing cargo while sailing, if needed, on design speed from Jeddah - Algeciras

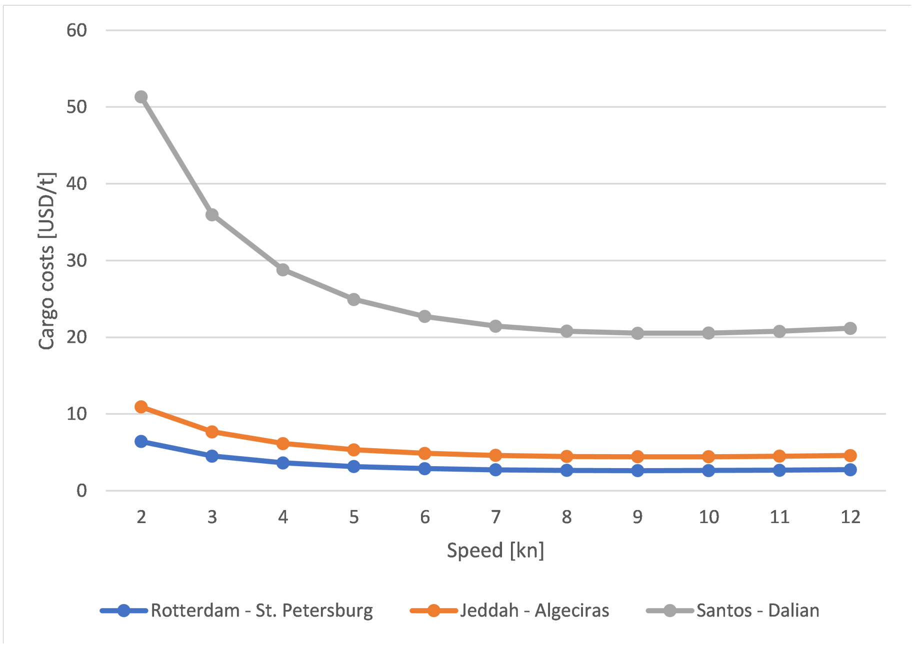


Figure 30: Influence of voyage when sailing with the Nordic Grace on heavy fuel oil

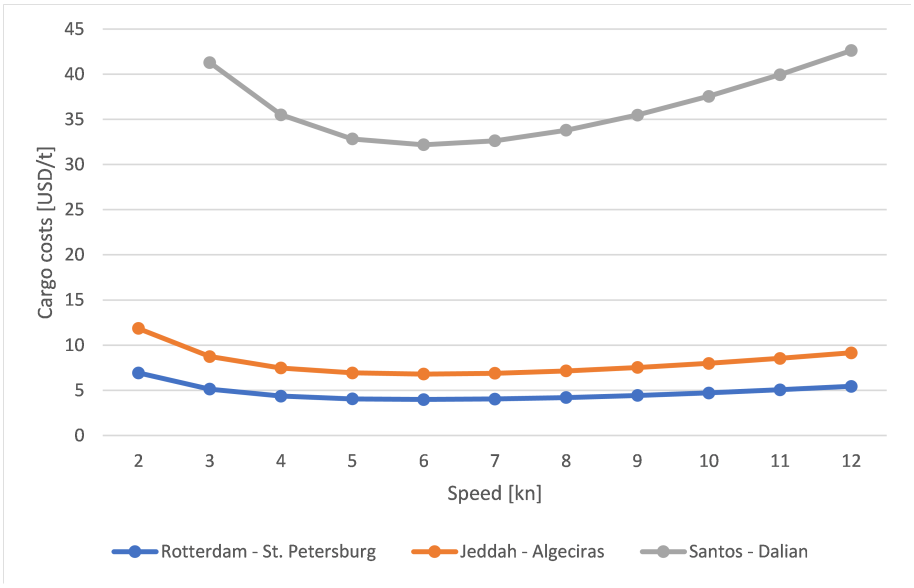


Figure 31: Influence of voyage when sailing with the Nordic Grace on methanol using a fuel cell

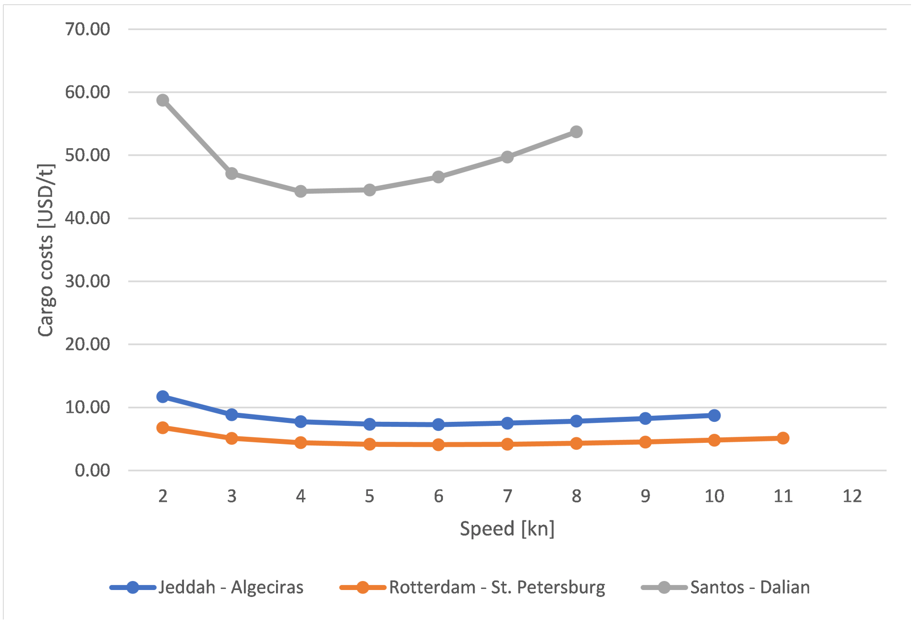


Figure 32: Influence of voyage when sailing with the Nordic Grace on hydrogen using an internal combustion engine

As shown above, it appears that shorter voyages have less influence on the transport costs per fuel type than long voyages. This might make it possible to sail at higher speed, on short voyages, and make more voyages per year for profit. In the situation where an expensive storage option is chosen, like hydrogen, the reduction of the storage tank size and lowering the speed are the most cost effective measurement. The introduction of more fuel stops on long voyages, thereby reducing the need for large storage rooms might be an interesting option as well, and can be further investigated. The exact values per speed and voyages are given in Appendix H in Table 67, Table 68 and Table 69

5.4 Fixed combustion engine, or fuel cell

In the previous results the combustion engine, or fuel cell, and their associated costs and weight are modified. The capital costs and weight of the internal combustion engine and fuel cell represent the costs and weight of a fuel cell, or combustion engine for the required power when the vessels is sailing a certain speed. In other words, when sailing slower, the required power is reduced and with it the costs, and the weight, of the combustion engine, or fuel cell. This results in lower capital costs when the vessel is sailing at lower speed which results, because of this, in lowering sailing speed was the most cost-effective solution. However, in a real-life situation when a combustion engine, or a fuel cell are installed, the capital costs remain the same. In this section, it is investigated what the most cost-effective solution is if the combustion engine, or fuel cell and its associated costs and weight remain unchanged when less power is required.

An engine power of 18,624 [kW] is used for this analysis, which represents the engine power of the Nordic Grace. The results are presented in Table 42 and a complete overview of the transport costs corresponding with different speeds can be found in Table 77 in Appendix H.

	Costs [USD/t]	Speed [kn]	Costs increase compared to HFO
HFO	4.73	11	0.00%
Methanol ICE	7.38	7	56.03%
Methanol FC	10.36	11	119.03%
Hydrogen ICE	8.00	6	69.13%
Hydrogen FC	10.78	9	127.91%
Ammonia ICE	6.75	7	42.71%
Ammonia FC	14.19	14.5	200.00%
Ethanol ICE	7.20	11	52.22%
Ethanol FC	10.10	7	113.53%
HVO	6.49	8	37.21%

Table 42: Minimized transport costs when capital costs and the weight of the engine, or the fuel cell are fixed, when sailing the Nordic Grace from Jeddah to Algeciras

Analyzing Table 42 shows that the sailing speeds, corresponding with the minimized transport costs, increases in comparison with the sailing speed corresponding to the minimum transport costs as presented in Table 35. Table 35 presents the minimized transport costs when the associated engine, or fuel cell costs were modified to the required power. The reason why the vessel requires a higher sailing speed as compared to the results as discussed in Table 35 is the fixed high capital costs of the 18,624 [kW] engine. Further analysis of Table 42 reveals that when a fuel is used in an internal combustion engine, a lower speed is more preferable for the same fuel when used in a fuel cell. When a fuel cell is used the vessels speed increase is even more significant. A fuel cell of an 18,624 [kW] is significantly more expensive than an 18,624 [kW] internal combustion engine, especially when ammonia fuel in combination with a fuel cell as shown in Table 43.

	Costs [USD]
Ammonia FC	2.97E+08
Ethanol FC	1.11E+08
Methanol FC	1.11E+08
Hydrogen FC	9.49E+07
Internal combustion engine	1.58E+07

Table 43: Costs of 18,624 kW a fuel cell (FC), or, an internal combustion engine (ICE)

In conclusion, fuels used in fuel cells have a more significant effect on capital costs. The capital costs influence the running costs as well. This will result in a less significant benefit of fuel saving as compared to the benefit of transporting more cargo over a year in order to reduce the costs per tonne cargo. In conclusion, when an 18,624 [kW] fuel cell, or internal combustion engine is installed, the calculation showed that the action of transportation of more cargo over a year is preferred over a fuel-saving measurement when an 18,624 [kW] fuel cell.

5.5 Conclusions of results

To answer the main question: "In an optimized situation, how do the transport costs when sailing on various fuels with different energy density than conventional fuels compare?", several scenarios have been analyzed. From these scenarios several conclusions can be drawn.

- Reducing speed is the most cost-effective option when sailing on alternative fuels.
- Batteries are too expensive, too heavy and too large to be cost-competitive with other alternative fuels when sailing a 150,000 DWT tanker from Jeddah to Algeciras.
- When large volumes need to be relocated, the option for relocating storage tanks on deck should be investigated. If this is not realistic, the fuel tanks should be in place of cargo. This, in the end, will influence the cargo costs.
- When the alternative fuels have the same fuel price, the difference in costs will be determined by the fuel storage tank. When vessels are sailing at higher speed the capital costs of a fuel cell will determine the difference in costs.
- A smaller storage tank and making extra stops reduces the transport costs up to a certain point, but then increases again due to the time needed for an extra fuel stop. Only a reduction in transport costs while sailing the Nordic Grace from Jeddah to Algeciras on hydrogen and making an extra stop was achieved.
- In an optimized situation, where reducing speed is most favourable, the ranking of most favourable fuel type does change when other vessel sizes, or types are used. If the vessel sails its design speed, vessel size and vessel type do influence the ranking of most favourable alternative fuels as well.
- When the capital costs are high, an increase in voyage numbers results in the reduction of the costs. For short voyages alternative fuels with high storage costs like hydrogen are more cost-effective than for long distances, making extra bunker stops on long voyages interesting when using hydrogen.

6 Sensitivity analysis

In this chapter, sensitivity analysis will be performed on estimated parameters earlier this study and on parameters of which it is uncertain how they will develop towards 2050. It is investigated what the influence of these assumed, or uncertain values, corresponding with the parameters, are on the calculated transport costs. The parameters that will be examined are:

- Fuel price
- Engine costs
- Engine efficiency
- Crew wage
- Amount of running days
- Fuel margin
- Container weight
- Provision weight

In the analysis, the effect on the transport costs when the value of an assumed, or uncertain parameter increases, or decreases is investigated and evaluated. Parameters will be adjusted towards a different, mostly a maximum and/or a minimum scenario. The values that were used for calculating the transport costs in previous chapters will be indicated as: "base case values". The base case values are the values for parameters which were considered as most likely during the study.

6.1 Fuel price

The first variable that is analyzed is the fuel price. In the previous sections, one fuel price, based on the literature review, is used. However, past experience shows that fuel price is very difficult to predict. The price of fuel is unexpected and can rise or fall at any time. Figure 33 gives an overview of the market prices of natural gas and Brent crude oil over the past 5 years.

Figure 33: Overview of price of natural gas [USD/MMBTU] (left) and brent crude oil [USD/barrel] (right) from the last 5 years (graphs from www.marketsinsider.com)

Analyzing Figure 33 shows that the prices for natural gas varied between -40% and +80% percent, and the crude oil from -60% till 70% over the previous 5 years, as compared to the baseline which represents the fuel prices in 2016. It is expected that these kind of variations will continue towards 2050 and that the fuel price, as used in this study, will differ from the fuel price in 2050. For this reason, a sensitivity study is done to show what the impact is of an increase, or decrease in fuel price on the transport costs as determined in previous sections. It is analyzed per fuel type what impact a 10%, 20%, 30%, 40% and 50% increase, or a similar decrease of the fuel price has on the transport costs. In Table 44, the effect of the percentual increases and decreases of the fuel price on the transport costs are given.

Fuel type	-50%	-40%	-30%	-20%	-10%	Base case	+10%	+20%	+30%	+40%	+50%
HFO	-23.02%	-18.06%	-13.09%	-8.58%	-4.29%	0.00%	3.84%	7.67%	11.29%	14.90%	18.28%
Methanol ICE	-26.15%	-20.06%	-14.71%	-9.36%	-4.31%	0.00%	4.46%	8.92%	13.22%	16.94%	20.51%
Methanol FC	-21.18%	-16.62%	-12.21%	-7.79%	-3.82%	0.00%	3.82%	7.65%	11.47%	14.71%	17.79%
Hydrogen ICE	-20.47%	-15.93%	-11.95%	-7.97%	-3.98%	0.00%	3.85%	7.14%	10.44%	13.74%	17.03%
Hydrogen FC	-18.45%	-14.29%	-10.54%	-7.07%	-3.47%	0.00%	3.47%	6.80%	9.71%	12.62%	15.53%
Ammonia ICE	-25.49%	-19.64%	-14.29%	-9.25%	-4.71%	0.00%	4.38%	8.28%	12.18%	16.23%	20.13%
Ammonia FC	-15.02%	-12.02%	-9.01%	-6.01%	-3.00%	0.00%	2.72%	5.15%	7.73%	10.16%	12.73%
Ethanol ICE	-25.99%	-20.21%	-14.74%	-9.57%	-4.56%	0.00%	4.26%	8.51%	12.92%	16.72%	20.36%
Ethanol FC	-20.72%	-16.37%	-12.01%	-7.66%	-3.75%	0.00%	3.75%	7.36%	11.11%	12.01%	17.72%
HVO	-25.42%	-19.70%	-14.31%	-9.26%	-4.55%	0.00%	4.55%	8.75%	15.49%	16.33%	20.20%
Battery	-1.47%	-1.20%	-0.87%	-0.60%	-0.33%	0.00%	0.27%	0.60%	0.87%	1.15%	1.47%
Average	-20.31%	-15.83%	-11.61%	-7.56%	-3.71%	0.00%	3.58%	6.98%	10.58%	13.23%	16.52%
Average without battery	-22.19%	-17.29%	-12.69%	-8.25%	-4.04%	0.00%	3.91%	7.62%	11.55%	14.44%	18.03%

Table 44: Transport costs increase, or decrease [%] per scenario (percentage added on, or subtracted from the fuel price base case) when sailing with the Nordic Grace from Jeddah to Algeciras

Analyzing Table 44 shows that when the fuel price in 2050 increases with 50% as compared to the fuel price used in this study, an average increase (excluding battery) of 18% in transport costs should be taken into account when using the developed model. When the fuel price is 50% lower than used in this study, the calculated transport costs will decrease with an average (excluding battery) of 22%.

In conclusion, the transport costs are sensitive to the influence of changing fuel price and it should be taken into account that the transport costs calculated by the developed model can differ when fuel prices differ. The differences in transport costs are given in the different figures. In Figure 34, Figure 35 and Figure 36, overviews are presented of how the transport costs develop from a fuel price decrease of 50% to the base-case (in blue) and from the base-case to a fuel price increase of 50%. The figures show how the fuel price is distributed in different scenarios and how the transport costs can vary from the transport costs as presented in this study. The specific values of transport costs are presented in Appendix H, Table 70, Table 71, Table 72 and Table 73.

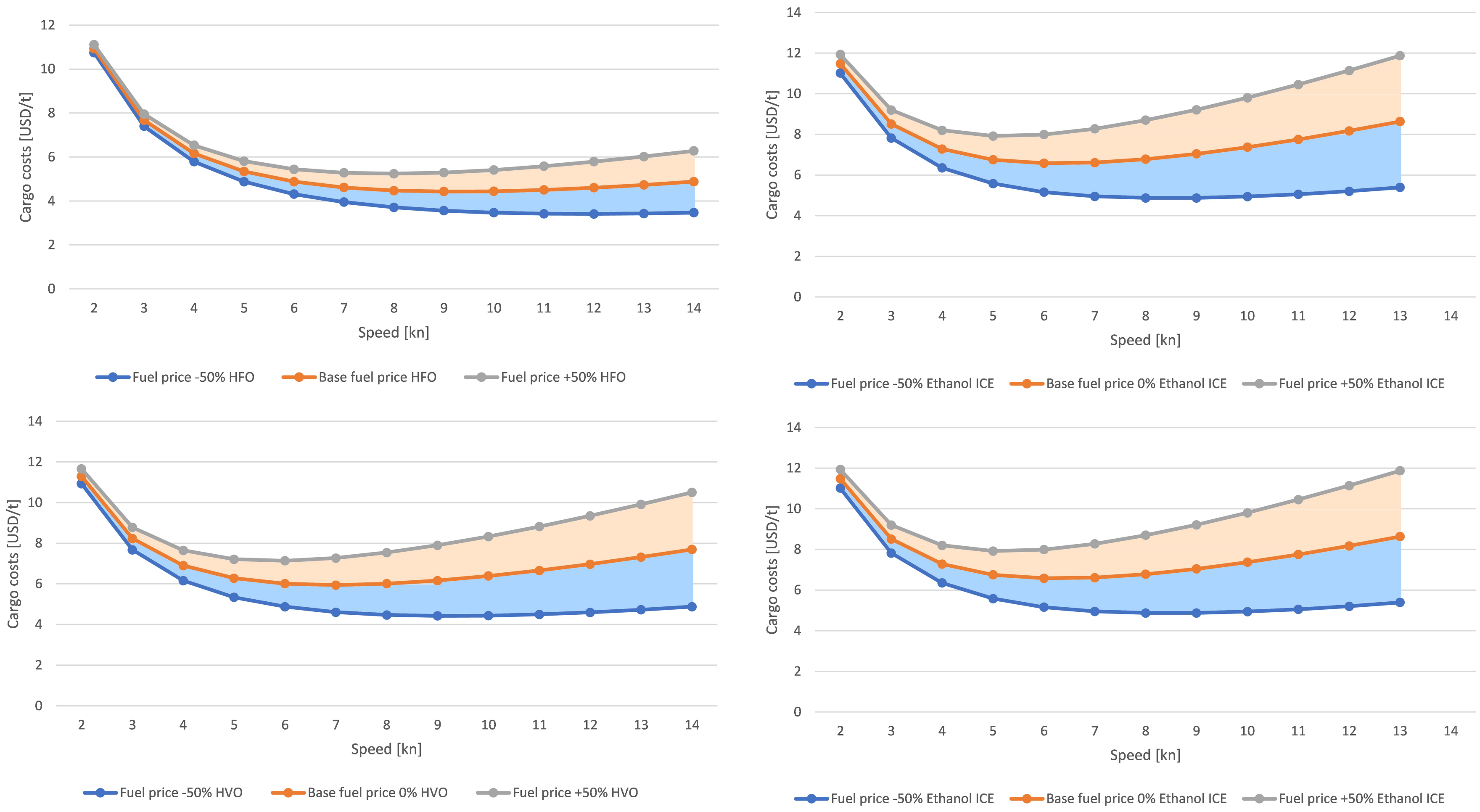


Figure 34: Fuel price distribution when using heavy fuel oil, hydrotreated vegetable oil and ethanol at speed, from base-case to +50% (orange) and from base-case to -50% (blue) when sailing with the Nordic Grace from Jeddah to Algeciras

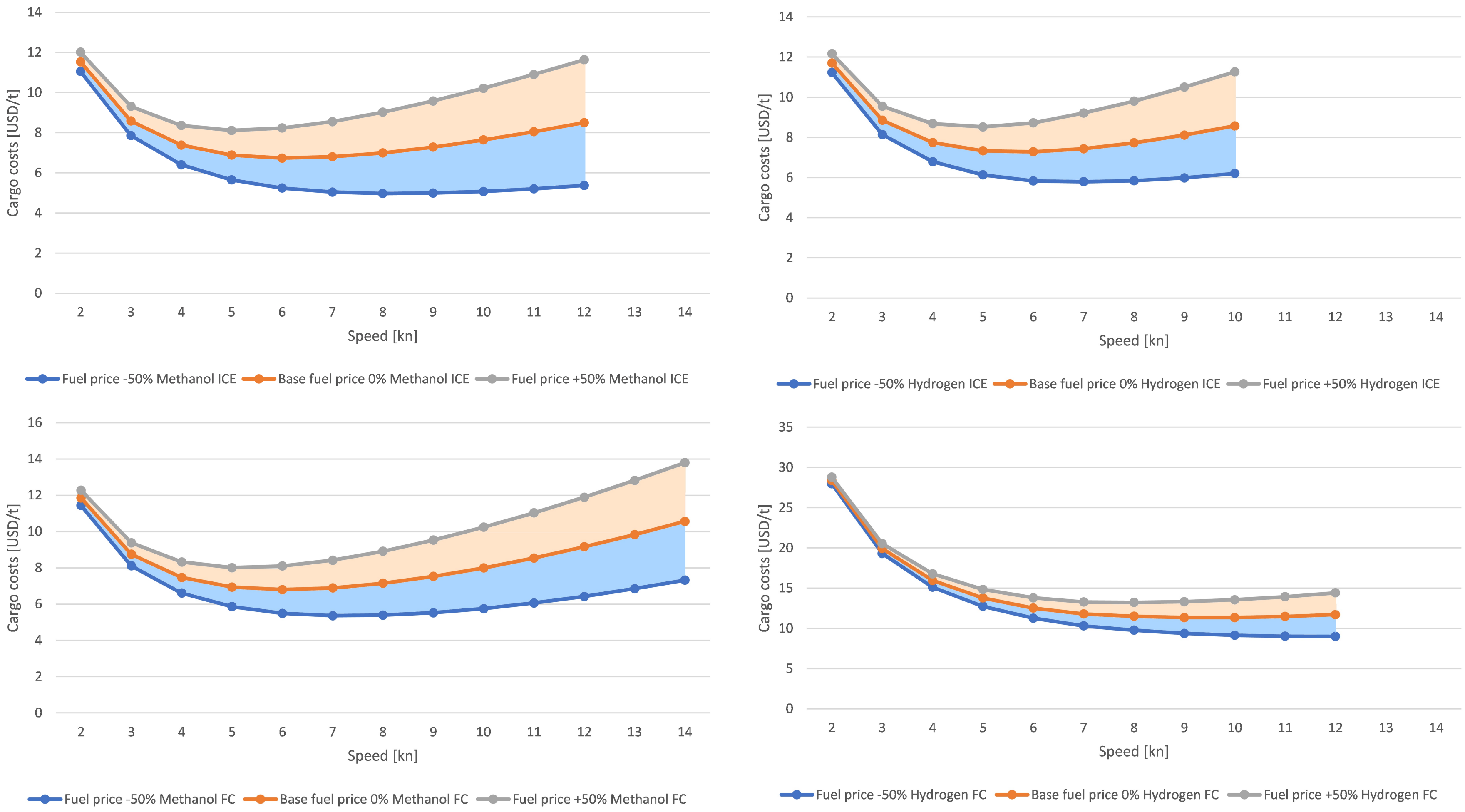


Figure 35: Fuel price distribution when using methanol and hydrogen at speed, from base-case to +50% (orange) and from base-case to -50% (blue) when sailing with the Nordic Grace from Jeddah to Algeciras

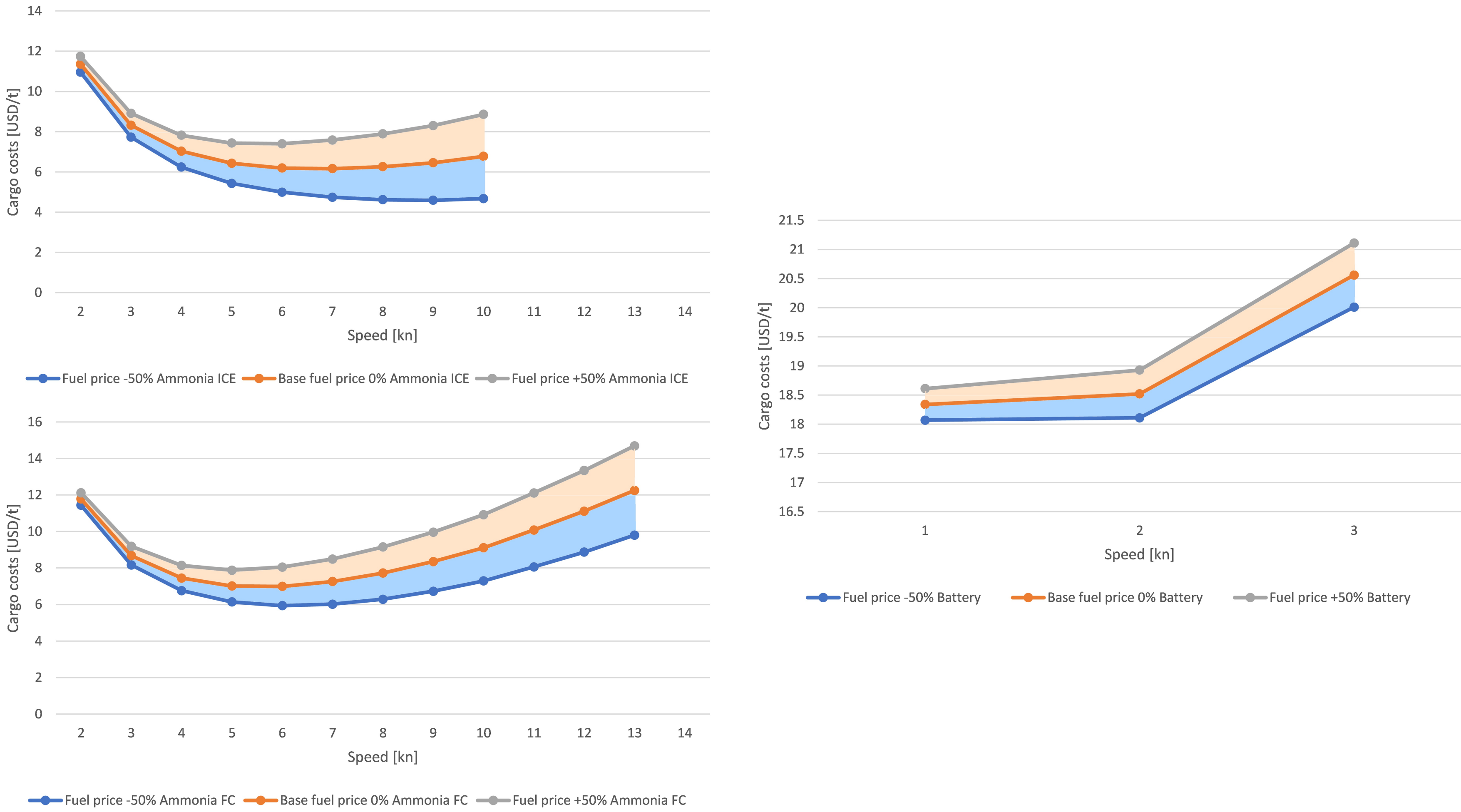


Figure 36: Fuel price distribution when using ammonia and a battery at speed, from base-case to +50% (orange) and from base-case to -50% (blue) when sailing with the Nordic Grace from Jeddah to Algeciras

6.2 Engine costs

The second sensitivity analysis involves the combustion engine and fuel cell used. First it is analyzed if fuel cells are more cost-effective, when sailing the vessels design speed, when fuel cells become less expensive. Thereafter, it is analyzed how the transport costs differ when different combustion engine, or fuel cell efficiencies are used. It will be examined what the influences are of the assumptions of 48% internal combustion engine efficiency and 55% fuel cell efficiency on transport costs.

Use of a fuel cell when sailing the vessels design speed
In Section 5.1.4 it is stated that, when the vessel is sailing at higher speed, transport costs are higher when fuels are used in combination with a fuel cell, than when the same fuel is used in an internal combustion engine. Section 5.4 shows that when the fuel cell capital costs are fixed, the minimized costs when using a fuel cell are significantly higher than when using an internal combustion engine.

The use of fuel cells is very modern and fuel cells are not produced on large scale. The price of a fuel cell might drop towards 2050 due to manufacturing at large scale. To determine what the consequence are of a drop in fuel cell capital costs, it is analyzed what the influence is of a 20%, 40%, 60% and 80% drop in fuel cell price on the transport costs, when sailing at higher speed (the vessels design speed). The results are presented in Figure 37.

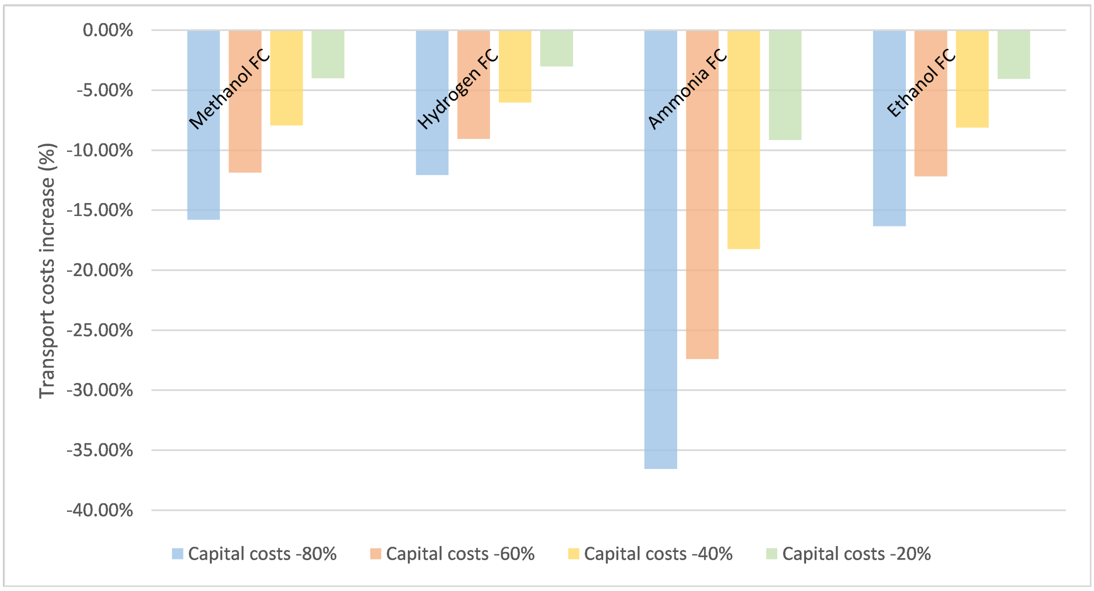


Figure 37: Transport costs decrease when the capital costs of a fuel cell or battery decrease when sailing the Nordic Grace from Jeddah to Algeciras

Figure 37 shows that a reduce in fuel cell costs can decrease the transport costs significantly when using a fuel cell, when sailing at higher speeds. It should, therefore, be taken into account that when fuel cells become cheaper, the transport costs at higher speed will be lower than presented by the developed model.

Efficiency of an internal combustion engine and a fuel cell
In this study, an internal combustion engine efficiency of 48% and a fuel cell efficiency of 55% are used. However, the efficiencies of fuel cells and internal combustion engines vary. Typically, effi-

ciencies of fuel cells vary between 50-60% and for internal combustion engines between 42-53%, according to the key characteristics of fuel cell concepts and combustion engines described by DNVGL (DNVGL, 2018). It is, therefore, analyzed what the impact of these different efficiencies are on the transport costs. For internal combustion engines, a minimum efficiency of 42% and a maximum efficiency of 53% are used. For fuel cells, a minimum of 50% and maximum of 60% efficiency are used. The results of are shown in Table 45 and Table 46.

	Fuel cell efficiency				
	50%		55% Base case	60%	
Fuel type	Minimum Costs [USD/t]	Transport costs Increase	Minimum Costs [USD/t]	Minimum Costs [USD/t]	Transport costs Increase
Methanol FC	7.06	3.82%	6.8	6.58	-3.24%
Hydrogen FC	7.52	4.30%	7.21	6.95	-3.61%
Ammonia FC	7.18	2.72%	6.99	6.82	-2.43%
Ethanol FC	6.91	3.75%	6.66	6.45	-3.15%

Table 45: Influence of different fuel cell efficiencies on the transport costs when sailing the Nordic Grace from Jeddah to Algeciras

	Fuel cell efficiency				
	42%		48% Base case	53%	
Fuel type	Minimum Costs [USD/t]	Transport costs Increase	Minimum Costs [USD/t]	Minimum Costs [USD/t]	Transport costs Increase
HFO	4.67	5.42%	4.43	4.26	-3.84%
Methanol ICE	7.16	6.39%	6.73	6.45	-4.16%
Hydrogen ICE	7.78	6.87%	7.28	6.94	-4.67%
Ammonia ICE	6.54	6.17%	6.16	5.89	-4.38%
Ethanol ICE	6.98	6.08%	6.58	6.30	-4.26%
HVO	6.32	6.40%	5.94	5.69	-4.21%

Table 46: Influence of different internal combustion engine efficiencies on the transport costs when sailing the Nordic Grace from Jeddah to Algeciras

The results show that transport costs are influenced by efficiencies used. When calculating the transport costs using a minimum and maximum efficiency, a 2.7-6.9 % increase and 2.4-4.4% decrease on minimum transport costs occurs. This implies that when a less, or more efficient propulsion system is used, the transport costs as calculated in this study will only slightly differ from the transport costs corresponding to the more, or less efficient system. This differences should be taken into account when using the developed model.

6.3 Crew wage

As described in Section 3.1.2, the salaries of the vessel crew are generally difficult to determine, because the salaries of vessel crew depend on the nationality and rank of the crew members. In this study, an average crew salary of $75.000 is used. In this section it is analyzed what the influence is of a difference of +50%, +33%, -33% and -50% on crew wage on the transport costs. The results are presented in Figure 38 and Table 74 in Appendix H.

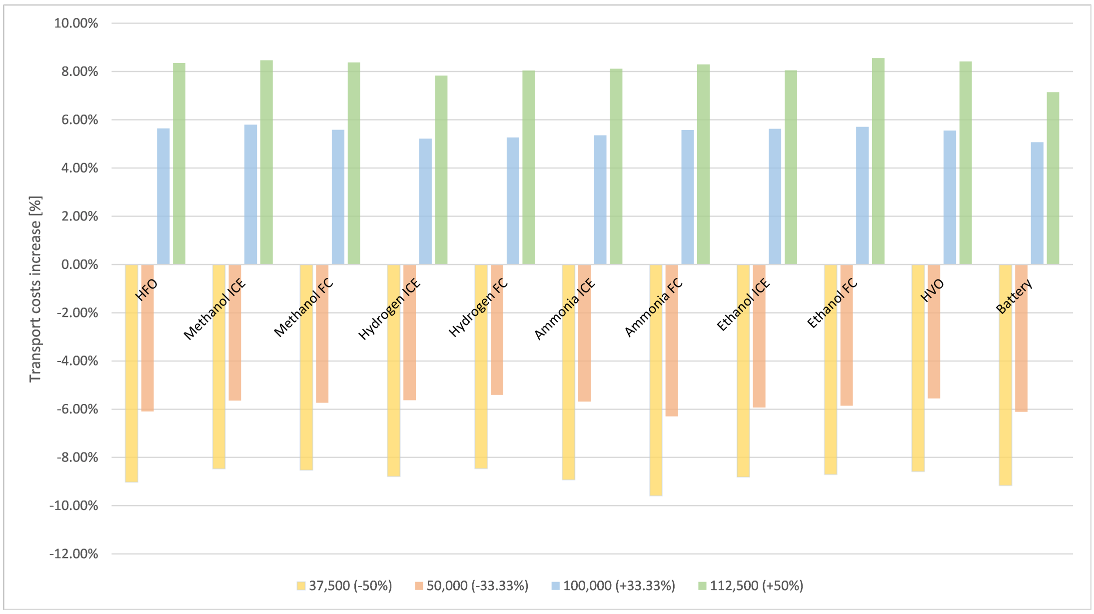


Figure 38: Influence on minimized transport costs when different crew wages are used when sailing the Nordic Grace from Jeddah to Algeciras

The minimized transport costs vary from -9% to +8% when the crew wages increase, or decrease with 50% and from +5% to -6% when the crew wages increase, or decrease with 33%. The crew wage is a relevant parameter for the transport costs. It is, therefore, necessary to keep in mind that large differences in costs between can occur when crew wages are significantly higher, or lower than 75,000 [USD].

6.4 Amount of running days

In Section 4.1 it is stated that the number of running days per year of a vessels is 360. This amount of running days is quite high, especially when an old vessel is considered. When the running days are less than used in this study, less voyages can be made, implying that the transport costs will increase. In this section it is investigated what the influence is of the number of running days by decreasing the running days from 360 to 300 days per year. The results are shown in Figure 39 and in Table 75 in Appendix H.

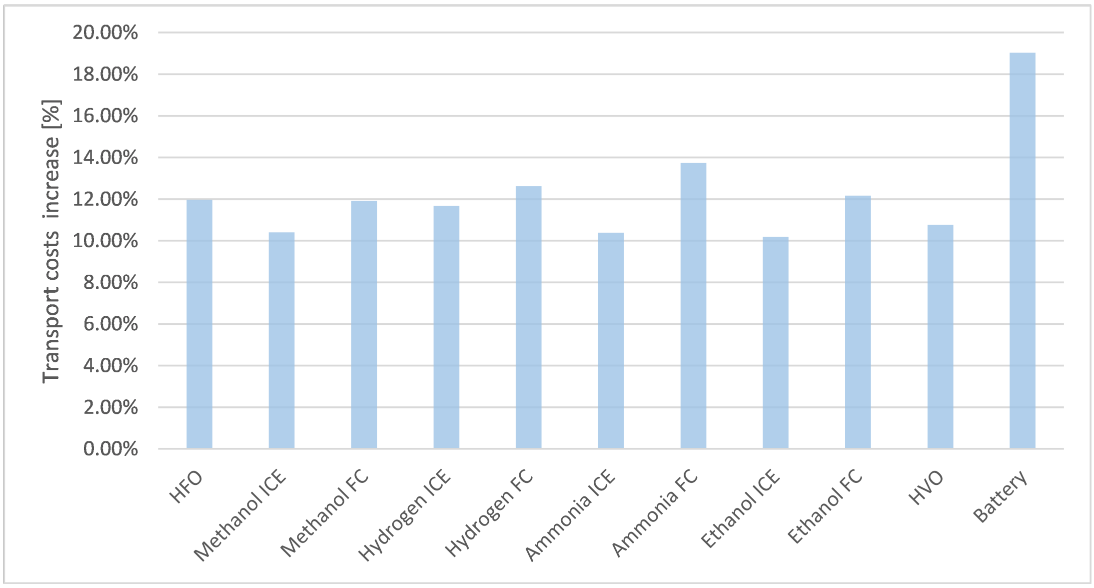


Figure 39: Influence on minimized transport costs when the vessel runs 300 days per year when sailing the Nordic Grace from Jeddah to Algeciras

Analyzing Figure 39 shows that when the running days decrease to 300 days, the minimized transport costs increases between 10-19 %, depending on the fuel type. When the model is used it should be taken into account that the amount of running days is a relevant parameter for the transport costs and the amount of running days should be determined carefully, or a transport costs increase should be taken into account.

6.5 Fuel margin

In this study, a fuel margin of 10% is assumed. To investigate the influence of this assumption it is analyzed what the minimized transport costs are when a fuel margin of 20% is used. A higher fuel margin results in less amount of weight available for cargo. It is expected that the transport costs will be higher, because less cargo can be taken with. The results when comparing a fuel margin of 20% instead of 10% are shown in Figure 40 and in Table 76 in Appendix H.

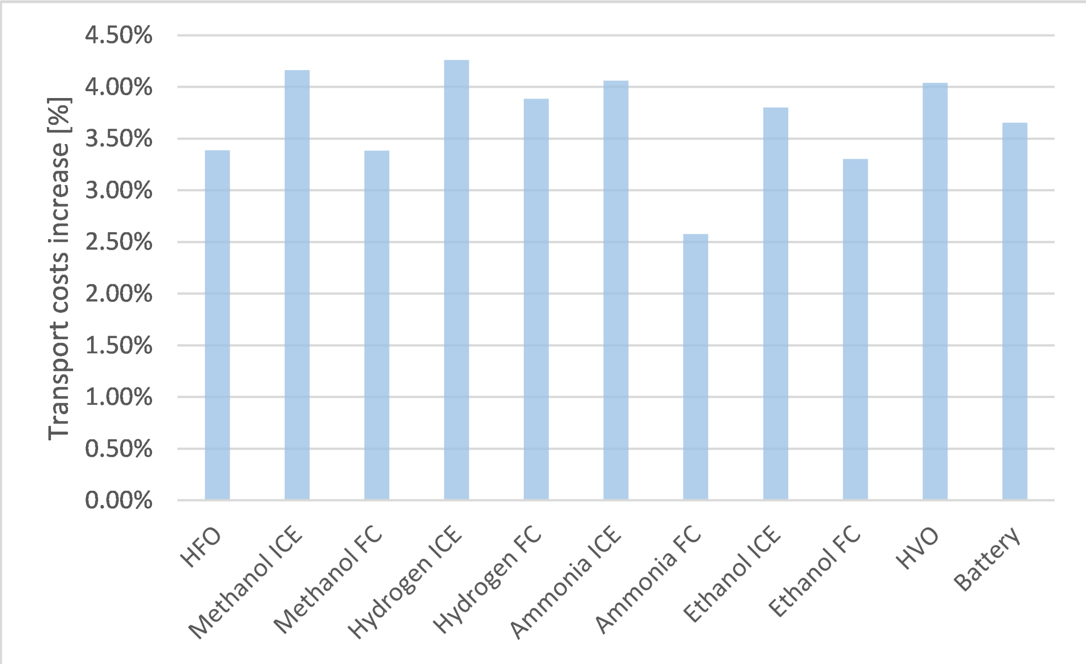


Figure 40: Influence on minimized transport costs when a fuel margin of 20% is used, when sailing the Nordic Grace from Jeddah to Algeciras

Analyzing Figure 40 shows that a fuel margin of 20% instead of 10% results in an increase of the minimized transport costs between 2.5-4.25% which seems a small difference, but should be taken into account while determining transportation costs with a fuel margin greater than 10%.

6.6 Container weight

In this study, the transport costs are given in tonnes and not TEU, implying that the weight of a TEU does not matter. However, when fuel tanks need to be placed in place of cargo, the lost (container) volume is converted to weight. In this study, a container weight of 28 [t] is used, which is the maximum weight of a container. Not all containers will be loaded with 28 [t] and, therefore, it is investigated what the minimized transport costs are when a lower container weight of 14 [t] is used. Table 47 shows the difference in transport costs when sailing from Rotterdam to St. Petersburg with the CMA CGM Louga with 14 [t] containers instead of 28 [t] containers.

	Container weight				
	28 [t]		14 [t]		
	Costs [USD/t]	Speed [kn]	Costs [USD/t]	Speed [kn]	Transport costs increase
Hydrogen ICE	9.6	7	9.57	7	-0.31%
Hydrogen FC	9.63	7	9.61	7	-0.21%
Ammonia ICE	8.5	8	8.49	8	-0.12%
Ammonia FC	9.62	7	9.61	7	-0.10%

Table 47: Influence on minimized transport costs when container weight is 14t, when sailing the CMA CGM Louga from Rotterdam to St. Petersburg

The change in container weight only influences the transport costs when using hydrogen, or ammonia, because both require special fuel storage tanks, which will be placed in place of cargo and result in cargo losses. Analyzing the transport costs increase shows that the influence of container weight is negligible. The lost volume and corresponding weight is relatively low as compared to the weight of the total cargo taken with.

6.7 Dry provision weight

The last parameter that is examined with a sensitivity analysis is the dry provision weight. In this study, a dry provision weight of 425 [t] is assumed. Provision weight varies per operation, size of the vessel and crew. It is analyzed what the influence on minimized transport costs are when instead a lower dry provision weight of 100 [t] is used. The results are given in Table 48.

	Provision weight 425t	Provision weight 100t	
	Costs [USD/t]	Costs [USD/t]	Transport costs increase
HFO	4.43	4.42	-0.23%
Methanol ICE	6.73	6.72	-0.15%
Methanol FC	6.8	6.78	-0.29%
Hydrogen ICE	7.28	7.28	0.00%
Hydrogen FC	7.21	7.19	-0.28%
Ammonia ICE	6.16	6.14	-0.32%
Ammonia FC	6.99	6.98	-0.14%
Ethanol ICE	6.58	6.56	-0.30%
Ethanol FC	6.66	6.64	-0.30%
HVO	5.94	5.93	-0.17%
Battery	18.34	18.3	-0.22%

Table 48: Influence of provision weight on minimized transport costs, when sailing the Nordic Grace from Jeddah to Algeciras

Analyzing Table 48 demonstrates that the transport costs decrease when using 100 [t] as dry provision weight is negligible. This is explained by the fact that 425-100=325 [t] of weight, left for extra cargo, is relatively low for a 150,000 DWT oil carrier and will not result in an appointive transport cost advantage.

6.8 Conclusions of sensitivity analysis

In Table 49, an overview is given of what the impact is of varying assumed, or uncertain parameters. Different colours are used to indicate which changes in parameters result in major differences and are, therefore, considered relevant. The colours used are:

- Green when minimized transport costs are not very sensitive for changes in the value of this parameter (0 - 1%)
- Yellow when minimized transport costs are sensitive for changes in the value of this parameter (1 - 5%)
- Red when minimized transport costs are very sensitive for changes in the value of this parameter (>5%)

Using different fuel prices	Minimum case (-50%)	Maximum case (+50%)
	-18.45% till -25.99%	17.03% till 20.51%

Using different fuel cell capital costs are reduced	Minimum case (-20%)	Maximum case (-80%)
	-3.02% till -9.16%	-12.08% till -36.58%

Using different internal combustion engine efficiencies	Minimum case (42%)	Maximum case (53%)
	5.24% till 6.87%	-3.84 till -4.67%

Using different fuel cell efficiencies	Minimum case (50%)	Maximum case (60%)
	2.72% till 4.30%	-2.43% till -3.61%

Using different crew wages	Minimum case (-50%)	Maximum case (50%)
	-9.59% till -8.46%	7.83% till 8.56%

Using different amount of running days	300 days
	10.18% till 13.73%

Using a different fuel margin	Fuel maring 20%
	2.58% till 4.26%

Using a different container weight	Container weight14 [t]
	-0.10% till -0.31%

Using a different provision weight	100 [t]
	0% till 0.32%

Table 49: Range of minimized transport costs increase of all fuels combined in different scenarios

Analyzing Table 49 shows that fuel price, fuel cell costs, internal combustion engine efficiency, crew wage and running days values can influence the minimized costs significantly. This may result in transport costs higher, or lower than calculated, when the used parameter values differ from the real-life situation.

7 Conclusion and Discussion

Sailing on alternative fuels is the solution in order to comply with MEPC.304(72) ambitions which were adopted by the IMO in 2018. These ambitions are to reduce the CO_2 emissions by 70% per transport work by 2050 as compared to 2008 and to reduce the greenhouse gas emission by 50% in 2050 as compared to 2008.

For this study, a model was developed. The model should be used to investigate the economical consequences of sailing on various alternative fuels. The main goal was to investigate the economical consequences using alternative fuels in international shipping. In the model various parameters can be adjusted and their influence on the cargo transport costs can be established.

The main research question was:
In a situation where the transport costs are minimized, how do the transport costs compare when sailing on various fuels with different energy densities than conventional fuels?

In order to answer this main research question, several sub-question had to be answered first.

1. How much energy, fuel volume and fuel weight per fuel type are required for different vessels on specific routes and operations?

The amount of required energy differs per vessel, voyage and fuel type. The required fuel volume and fuel weight differ per situation. The scope of the study is, therefore, limited to specific situations. The developed model, however, can be adjusted to every new situation including another specific vessel on a specific route using a specific fuel.

2. Which vessels and which sailing distances should be investigated and what are the most promising fuels fulfilling all the requirements for these vessels and sailing distances?

Three different sized and different types of representative vessels and their operations had been analyzed. The chosen vessels and operations used were:

- A 34,350 DWT container vessel sailing from the Netherlands to Russia.
- A 150,000 DWT crude oil tanker sailing from Arabia to Western-Europe.
- A 400,000 DWT ore carrier sailing from Brazil to China.

For this analysis, the combinations of three different vessel types which differ in size, type and voyage length were used in order to cover for most common and uncommon circumstances.

3. What is the impact of sailing on an alternative fuel with a lower energy density? Does this require more bunker stops, additional storage space for the fuel, or should sailing speed be reduced, or what are the best possible combinations?

The impact of sailing on alternative fuels is that in some cases the vessel becomes too heavy, or the volume of the fuel storage tank is not sufficient. The most cost-effective solution to bypass these problems is lowering the sailing speed eventually at a rate which is even lower then required for transporting maximum cargo. The financial impact of the fuel costs counter weighs the advantages of transporting more cargo. This is also the case when the overweight, or fuel density problems are already dealt with. However, for making a profit by transporting maximum cargo loads the optimized situation might change. The model showed that when the capital costs are high, the most ideal situation is to transport the maximum allowed amount of cargo at a higher speed. In the situation when the fuel storage tank costs are high, a combination of reducing speed and extra bunker stops is most preferable.

4. What are the costs in an optimized situation, including possibly extra bunker stops, decrease in speed, or a decrease in cargo space?
The transport costs in an optimized situation analyzing the 150,000 DWT oil tanker are the lowest for Hydrotreated Vegetable Oil, second lowest for ammonia in combination with an internal combustion engine and the highest for battery electric.

The fuel cell options are the least favourable at higher speed, because the capital costs of a fuel cell are high. The use of all alternative fuels are regretfully more expensive than the use of conventional heavy fuel oil. In a future situation when these prices approximate each other, a different outcome of the analysis might be expected. What will remain is the difference in storage costs.

In conclusion, the fuel costs of alternative fuels are currently higher than those of conventional fuels. Batteries are currently also too heavy, too large and too expensive to be considered. The capital costs of fuel cells make that the use of fuels in combination with a fuel cell is currently expensive at higher speeds. High fuel storage costs make hydrogen currently not competitive with conventional fuels.

Future work

The model performs as expected. It could be interesting to investigate other possible scenarios. A few examples are given below:

- In this study, the amount of exceeded weight when sailing on alternative fuels, except battery electric, was relatively low e.g. 1634 [t] as compared to deadweight of 150,000 [t] (Nordic Grace), or 464 [t] as compared to a deadweight of 34,350 [t] (CMA CGM Louga) and 11800 [t] as compared to a deadweight of 400,000 [t]. It could also be interesting to investigate situations where the amount of overweight represents a more significant percentage of the deadweight.
- In this study, reducing speed was most favourable, because the costs of fuel are relatively high as compared to other costs. Therefore, it was not a surprise that the cost saved on fuel are preferable to higher cargo capacity. When cargo becomes more profitable, cargo capacity might become more relevant and other outcomes with regard to speed when sailing on alternative fuels can be expected.
- More types of voyages and different vessels can be also analyzed. Also alternative sailing routes and port stops can be considered.
- In this study, it is assumed that the vessel returns back empty. Alternatively, a situation in which the vessel returns with another cargo load can be studied. Also hybrid situation might become an option e.g. container/general cargo, or container/bulk.

References

Aalbers, A. (2000). Evaluation of ship design alternatives. *Maritime Technology, Ship Design, Technical University Delft. 34th WEGEMT School" Developments in the Design of Propulsors and Propulsion Systems", Aula, TU Delft, June 2000, Edited by PW de Heer.*

ABS (2020). Ammonia as marine fuel. *Sustainably Whitepaper.*

ACS (2020). Acs guidelines no. 6 comparative analysis between igf code and igc code 2020. *ACS Guidelines.*

Adachi, M., Kosaka, H., Fukuda, T., Ohashi, S., and Harumi, K. (2014). Economic analysis of trans-ocean lng-fueled container ship. *Journal of Marine Science and Technology*, 19(4):470–478.

Amadeo, Kimberly and Wohlner, Roger (2021). US Inflation Rate by Year from 1929 to 2023. `https://www.thebalance.com/u-s-inflation-rate-history-by-year-and-forecast-3306093`.

Ammar, N. R. (2019). An environmental and economic analysis of methanol fuel for a cellular container ship. *Transportation Research Part D: Transport and Environment*, 69:66–76.

Ammar, N. R. and Seddiek, I. S. (2017). Eco-environmental analysis of ship emission control methods: Case study ro-ro cargo vessel. *Ocean Engineering*, 137:166–173.

Arnsdorf, I. (2013). Suezmax charter costs at 16-year low. *Bloomberg.*

Ascenz (2019). Reliable bunkering practices enhanced by new technologies. *Ascenz agile maritime digiltalization.*

Balcombe, P., Brierley, J., Lewis, C., Skatvedt, L., Speirs, J., Hawkes, A., and Staffell, I. (2019). How to decarbonise international shipping: Options for fuels, technologies and policies. *Energy conversion and management*, 182:72–88.

ben Brahim, T., Wiese, F., and Münster, M. (2019). Pathways to climate-neutral shipping: A danish case study. *Energy*, 188:116009.

Bergsma, J., 't Hart, P., Verbeek, R., and Pruyn, J. (2019). Assessment of alternative fuels for seagoing vessels using heavy fuel oil. *Netherlands Maritime Land and Ministry of Economic Affairs.*

Bunro Shiozawa (2020). The Cost of CO2-free Ammonia. `https://www.ammoniaenergy.org/articles/the-cost-of-co2-free-ammonia/`.

Cambanis, D. G. (2011). Challenge to the industry securing skilled crews in today's market place. *The Global Survey.[Online] Available: http://www2. deloitte. com/con-tent/dam Deloitte/global/08072013. pdf.(October 21st, 2014).*

Chatterton (2018). METHANOL AS FUEL: CREATING A PATHWAY TO CLEANER PORTS AND SHIPPING. `https://www.greenport.com/news101/energy-and-technology/methanol-as-fuel-creating-a-pathway-to-cleaner-ports-and-shipping`.

Chron (2020). The Average Salary of Workers on Deep Draft Vessels. `https://work.chron.com/average-salary-workers-deep-draft-vessels-7101.html`.

Clarkson Research (2021). World Fleet Register. https://www.clarksons.net/wfr/fleet.

Cruisejobfinder (2020). Maritime Salaries. https://www.cruisejobfinder.com/members/maritime/salaries/.

Deniz, C. and Zincir, B. (2016). Environmental and economical assessment of alternative marine fuels. *Journal of Cleaner Production*, 113:438–449.

Department for business, Energy & Industrial strategy (2020). Energy Prices International Comparisons. https://www.gov.uk/government/statistical-data-sets/international-industrial-energy-prices.

DNV (2015). Brodosplit builds four LNG-fuelled container ships with DNV GL class. https://www.dnv.com/news/brodosplit-builds-four-lng-fuelled-container-ships-with-dnv-gl-class-51489.

DNVGL (2018). Maritime forecast to 2050. *Energy transition outlook*, 2018.

DNVGL (2019). Comparison of alternative marine fuels. *For SEALNG, DNV GL rep*, (2019-0567).

Ellis, J. and Tanneberger, K. (2015). Study on the use of ethyl and methyl alcohol as alternative fuels in shipping. *Eur. Marit. Saf. Agency*.

Freudendahl, U. (2015). Methanol as ship fuel. handling and safety matters. In *MOT-2030 Workshop. Lund University*.

Greenport (2018). METHANOL AS FUEL: CREATING A PATHWAY TO CLEANER PORTS AND SHIPPING. https://www.greenport.com/news101/energy-and-technology/methanol-as-fuel-creating-a-pathway-to-cleaner-ports-and-shipping.

Greiner, R. (2015). Shipping under pressure. *Maritime Professional*.

Grljušić, M., Medica, V., and Radica, G. (2015). Calculation of efficiencies of a ship power plant operating with waste heat recovery through combined heat and power production. *Energies*, 8(5):4273–4299.

Hansson, J., Brynolf, S., Fridell, E., and Lehtveer, M. (2020). The potential role of ammonia as marine fuel—based on energy systems modeling and multi-criteria decision analysis. *Sustainability*, 12(8):3265.

Hansson, J., Månsson, S., Brynolf, S., and Grahn, M. (2019). Alternative marine fuels: Prospects based on multi-criteria decision analysis involving swedish stakeholders. *Biomass and Bioenergy*, 126:159–173.

Hellenic Shipping News (2020). Ship Owners Still Prefer. https://www.hellenicshippingnews.com/ship-owners-still-prefer/.

Hensley, R., Newman, J., Rogers, M., and Shahinian, M. (2012). Battery technology charges ahead. *McKinsey Quarterly*, 3:5–50.

IMO (2018). Resolution mepc. 304 (72). *Initial IMO Strategy on Reduction of GHG Emissions from Ships*.

KNMI (2019). Zeespiegelstijging. https://www.knmi.nl/kennis-en-datacentrum/uitleg/zeespiegelstijging.

Lindstad, H., Asbjørnslett, B. E., and Strømman, A. H. (2012). The importance of economies of scale for reductions in greenhouse gas emissions from shipping. *Energy policy*, 46:386–398.

Macro trends (2021). Crude Oil Prices - 70 Year Historical Chart. https://www.macrotrends.net/1369/crude-oil-price-history-chart.

Marine Insight (2020). A Guide To Ballast Tanks On Ships. https://www.marineinsight.com/naval-architecture/a-guide-to-ballast-tanks-on-ships/.

Mofor, L., Nuttall, P., and Newell, A. (2015). Renewable energy options for shipping. *Technology Brief.*

Murray, W. (2016). Economies of scale in container ship costs. In *North America's Premier International Shipping Conference.*

Notteboom, T., Pallis, A., and Rodrigue, J.-P. (2021). *Port Economics, Management and Policy.* Routledge. Forthcoming.

of Energy, U. D. (2015). Fuel cell. *Fuel Cell Technologies Office.*

Perakis, A. (1997). Models for estimating dimensional and capacity characteristics of oceangoing vessels for use in port planning. In *University of Michigan, Department of Naval Architecture and Marine Engineering, International Association of maritime Economists, London Conference.*

Perčić, M., Vladimir, N., and Fan, A. (2020). Life-cycle cost assessment of alternative marine fuels to reduce the carbon footprint in short-sea shipping: A case study of croatia. *Applied Energy*, 279:115848.

Pinkster, J. and Bom, C. J. (2006). *Hydromechanica 2 Geometrie en Stabiliteit.* TU Delft.

Počuča, M. (2006). Methodology of day-to-day ship costs assessment. *Promet-Traffic&Transportation*, 18(5):337–345.

Raucci, C., Calleya, J., Suarez De La Fuente, S., and Pawling, R. (2015). Hydrogen on board ship: A first analysis of key parameters and implications. University of Strathclyde.

Rijksoverheid (2021). Klimaatverandering en gevolgen. https://www.rijksoverheid.nl/onderwerpen/klimaatverandering.

Saputra, H., Muvariz, M. F., Satoto, S. W., and Koto, J. (2015). Estimation of exhaust ship emission from marine traffic in the straits of singapore and batam waterways using automatic identification system (ais) data. *Jurnal Teknologi*, 77(23).

Seaman Memories (2020). Seaman's Salary Per Month on International Ships. https://www.seamanmemories.com/seamans-salary-per-month-on-international-ships/.

Ship and Bunker (2020). Global bunker prices. https://shipandbunker.com/prices/av/global/av-g20-global-20-ports-average.

ShipCosts (2021). Vessel operating costs. https://shipcosts.com/vessel-operating-costs.html.

Spiegel, Colleen (2017). Alternative Liquid Fuel Types for Fuel Cells. https://www.fuelcellstore.com/blog-section/alternative-liquid-fuel-types-fuel-cells.

Stopford, M. (2008). *Maritime economics 3e.* Routledge.

Svanberg, M., Ellis, J., Lundgren, J., and Landälv, I. (2018). Renewable methanol as a fuel for the shipping industry. *Renewable and Sustainable Energy Reviews*, 94:1217–1228.

Taljegard, M., Brynolf, S., Grahn, M., Andersson, K., and Johnson, H. (2014). Cost-effective choices of marine fuels in a carbon-constrained world: results from a global energy model. *Environmental science & technology*, 48(21):12986–12993.

UNCTAD (2019). *Review of Maritime Transport 2019.* United Nations.

United Nations Climate Change (2021). The Paris Agreement. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

van Veldhuizen, B., Hekkenberg, R., and Codiglia, L. (2020). Fuel cell systems applied in expedition cruise ships–a comparative impact analysis. *Delft University of Technology.*

Vesselfinder (2019). Hyundai Heavy Industries localizing tech for LNG fuel tanks. https://www.vesselfinder.com/news/16516-Hyundai-Heavy-Industries-localizing-tech-for-LNG-fuel-tanks.

Warmheart Worldwide (2021). Climate Change Primer. https://warmheartworldwide.org/climate-change/?gclid=CjwKCAiA_9r_BRBZEiwAHZ_v17Hf6QJ2vWw5te04JpfKwg17lvBsqZmVA4Dp0uegjDM1LCPQEbBXJRoCn0EQAvD_BwE.

Workman (2019). World's Top Exports. http://www.worldstopexports.com/.

Wu, P. and Bucknall, R. (2016). Marine propulsion using battery power. Shipping in Changing Climates Conference 2016.

Wärtsilla (2020). What does an ammonia-ready vessel look like? https://www.wartsila.com/insights/article/what-does-an-ammonia-ready-vessel-look-like.

Wärtsilä (2021). Improving efficiency. https://www.wartsila.com/sustainability/innovating-for-sustainable-societies/improving-efficiency.

Yang, Z. and Chen, J. (2012). Elements of ship finance. *Department of management, Dalian Maritime University.*

A Different vessels and operations

East-West Liners (+4000 TEU)

	Vessel	Departure	Arrival	Distance (Nm)	Service speed (kn)	Engine Power (kW)	Capacity (TEU)	Remarks
1	CMA CGM Leo	Colombo, LK (10.02.2021)	New York, US (03.03.2021)	8629.9	24.7	72240	11400	Suez canal
2	Ever Urban	San Antonio, CL (20.01.2021)	Hong Kong, CN (14.02.2021)	10092.13	24.5	48635	5652	Pacific
3	Maersk Columbus	New York, US (06.02.2021)	Algeciras, ES (14.02.2021)	3254.81	25.6	57200	6188	Atlantic
4	Dalian Express	Colombo, LK (21.01.2021)	Halifax, CA (11.02.2021)	7746.01	25.0	68640	7506	Suez canal
5	MSC Lucy	Le Havre, FR (21.02.2021)	King Abdullah Port, KSA (02.03.2021)	3655.79	25.0	68666	8089	Suez canal
6	OOCL Genoa	Shanghai, CN (02.02.2021)	Prince Rupert, CA (17.02.2021)	4585.85	22.8	68520	8888	Pacific
7	Cap San Augustin	Algeciras, ES (27.01.2021)	Santos, BRA (09.02.2021)	4536.07	21.0	40670	9669	Atlantic
8	CSCL Summer	Shanghai, CN (22.01.2021)	Prince Rupert, CA (01.02.2021)	4619.39	21.0	58100	10036	Pacific
9	Al Bahia	Hamburg, DE (06.02.2021)	New York, US (23.02.2021)	4076.4	25.0	62920	6500	Atlantic
10	RDO Concord	Manzanillo, MX (05.02.2021)	Busan, KR (24.02.2021	7074.87	27.1	57199	6966	Pacific

Intraregional

	Vessel	Departure	Arrival	Distance (Nm)	Service speed (kn)	Engine Power (kW)	Capacity (TEU)	Remarks
1	MSC Yokohoma	Gioia Tauro, IT (27.01.2021)	Mersin, TR (29.01.2021)	1001.65	24	68640	7849	Mediterranean and R
2	MSC Eloise	Puerto Bolivar, EC (28.02.2021)	Balboa, PAN (03.03.2021)	788.05	20	27600	2440	Golfo de Panama Are
3	CMA CGM Louga	Rotterdam, NL (14.02.2021)	St. Petersburg, RU (17.02.2021)	1429.94	20	16080	2487	Baltic Sea Area
4	Zhong Gu Shang Hai	Shanghai, CN (25.02.2021)	Tianjin, CN (02.03.2021)	658.73	15	8900	2500	Yellow Sea Area
5	Cape Monterey	Port Klang, MY (17.02.2021)	Chittagong, BD (26.02.2021)	1117.54	19	13000	2190	Strait of Malacca
6	Ever Charm	Shekou, CN (02.03.2021)	Kaohsiung, TW (04.03.2021)	374.4	15	10919	1800	South China Sea Area
7	Diane E	Lisbon, PT (22.02.2021)	Las Palmas, ES (24.02.2021)	833.5	19	13280	1604	North Atlantic Ocean
8	Cape Fawley	Laem Chabang, TH (27.02.2021)	Singapore, SG (04.03.2021)	826.49	19.8	12640	1440	Strait of Singapore
9	MSC Panaya	Port Harcourt, NI (28.02.2021)	Lome, TG (04.03.2021)	410.18	19	13320	1730	Gulf of Guinea
10	MSC Belle	Varna, BG (27.02.2021)	Istanbul, TR (01.03.2021)	361.11	19	10880	1116	Black sea

North-South

	Vessel	Departure	Arrival	Distance (Nm)	Service speed (kn)	Engine Power (kW)	Capacity (TEU)	Remarks
1	MSC Bhavya	Las Palmas, ES (14.02.2021)	Cape Town, ZA (03.03.2021)	4810.17	25.5	51480	5043	Africa-Europe
2	MSC Carmen	Dakar, SN (17.01.2021)	Barcelona, ES (22.01.2021)	2097.22	24	39970	4870	Africa-Europe
3	Maersk Cape Coast	Tanger-Med, MA (15.02.2021)	Dakar, SN (22.02.2021)	1568.87	24.1	27060	4500	Marocco/Spain-Africa
4	Niledutch Breda	Kribi, CM (24.01.2021)	Antwerp, BE (04.02.2021)	2654.04	20	19620	3510	Africa-Europe
5	HSL Portsmouth	Monrovia, LI (13.02.2021)	Tanger-Med, MA (25.02.2021)	2250.98	21.9	21770	2478	Marocco/Spain-Africa
6	Polar Mexico	San Antonio, CL (18.02.2021)	Balboa, PA (26.02.2021)	2701.49	18	19620	3868	South America
7	Nordic Macau	Valencia, ES (14.02.2021)	Cotonou, BJ (25.02.2021)	3377.12	20.85	25040	3400	Africa-Europe
8	Hansa Europe	Dakar, SN (19.02.2021)	Tanger-Med, MA (26.02.2021)	1691.72	22.7	31710	3635	Marocco/Spain-Africa
9	CMA CGM Herodote	Algecrias, ES (27.02.2021)	Dakar, SN (05.03.2021)	1520.32	19.42	15820	1691	Marocco/Spain-Africa
10	Adilia 1	Rotterdam, NL (26.02.2021)	Tanger-Med, MA (03.03.2021)	1271.92	18	7902	956	Africa-Europe

Tankers

	Vessel	Departure	Arrival	Distance (Nm)	Service speed (kn)	Engine Power (kW)	Capacity (DWT)	Remarks
1	Nordic Grace	Jeddah, SA	Genova, IT	2570	15	18624	149921	Route based on expor
2	Monte Serantes	Jeddah, SA	Genova, IT	2570	12	21840	149994	Route based on expor

3	Navion Stavanger	Jeddah, SA	Genova, IT	2570	15.2	16860	148729	Route based on expoı
4	Norest Spirit	Jeddah, SA	Genova, IT	2570	13	21840	148167	Route based on expoı
5	Polar endeavour	Jeddah, SA	Genova, IT	2570	16	11060	141740	Route based on expoı
6	Sara	Lagos, NI	Rotterdam, NL	4744	24.5	29340	323183	Route based on expoı
7	Anahi	Lagos, NI	Corpus Christi, US	6958	16	35130	299999	Route based on expoı
8	Texas	Dubai, AE	Qingdao, CN	6979	16.1	31640	299999	Route based on expoı
9	Cosmo Ace	Dubai, AE	Corpus Christi, US	10895	15.9	31640	320054	Route based on expoı
10	Red Nova	Luanda, AO	Qingdao, CN	11260	16	29340	319778	Route based on expoı

Bulk Carriers

	Vessel	**Departure**	**Arrival**	**Distance (Nm)**	**Service speed (kn)**	**Engine Power (kW)**	**Capacity (DWT)**	**Remarks**
1	Sea Qingdao	Tubarao, BR (21.12.2020)	Zhongjia, CN (31.01.2021)	11549.35	14.8	29260	403880	200,000+ DWT, ore ca
2	Ore China	Itaqui, BR (25.04.2020)	Dachu Shan Island, CN (13.06.2020)	11881.04	14.8	29400	400606	200,000+ DWT, ore ca
3	Berge Everest	Tabarao, BR (08.08.2020)	Dalian, CN (27.09.2020)	11260.06	14.8	29400	388133	200,000+ DWT, ore ca
4	CSB Briljant	Itaqui, BR (17.12.2020)	Zhangjiang, CN (01.02.2021)	10813.31	15	25200	315228	200,000+ DWT, ore ca
5	Bao An	Port Hedland, AU (04.01.2021)	Caofeidian, CN (23.01.2021)	3770.9	15.1	22432	229117	200,000+ DWT, ore ca
6	Am Liberia	Port Hedland, AU (30.08.2020)	Zhuhai, CN (10.09.2020)	2716.15	16.9	13560	98730	65,000-99,999 DWT
7	Amami	Richards Bay, ZA (29.06.2020)	Tianjin, CN (11.08.2020)	7891.44	14.5	12700	98681	65,000-99,999 DWT
8	Kk Pirapo	Yantai, CN (10.10.2020)	Gladstone, AU (27.10.2020)	4197.11	16.1	13560	98704	65,000-99,999 DWT
9	Anglo Marimar	Port Hedland, AU (17.02.2021)	Ningbo, CN (03.03.2021)	3117.65	14.5	12700	98681	65,000-99,999 DWT
10	Star Sirius	Port Hedland, AU (25.05.2020)	Huanghua, CN (13.06.2020)	3841.42	15	12700	98681	65,000-99,999 DWT
11	African Lion	Richards Bay, ZA (09.10.2020)	New Orleans, US (08.11.2020)	8122.61	16	8470	66721	40,000-60,999 DWT
12	Lowlands Mimosa	Itagui, BR (15.11.2020)	Brownsville, US (04.12.2020)	6419	13.8	7360	63697	40,000-60,999 DWT
13	Spar Nova	Terneuzen, NL (26.02.2020)	Narvik, NO (03.03.2021)	1245.09		8050	63800	40,000-60,999 DWT
14	Bao Lucky	Santos, BR (10.06.2020)	Huanghua, CN (24.07.2020)	11420.14		8050	63800	40,000-60,999 DWT
15	Cmb Van Dijck	Callao, PE (26.01.2021)	Buenaventure, CO (31.01.2021)	1280		7560	63590	40,000-60,999 DWT

B Reference vessels

CMA CGM Louga 2,487 TEU Fully Cellular Container Built 2018 (In Service)

Standard Details

IMO Number 9745550, Owners are CMA CGM, Built at Jinhai Manufacturing delivered in Jul 2018, Malta Flagged, DNV Classed, Ice Strengthened 1A Class, P&I insurance with Gard P&I, Length Overall of 194.99 m., Length Between Perpendiculars of 184.90 m., Draught of 11.50 m., Beam of 32.20 m., Gross Tonnage of 29,316, Design SDARI 2500 TEU by SDARI, MAN B. & W. Engine, Speed of 20.03 kts, Heavy Fuel Oil (IFO 380), Horsepower of 21,863, Power Type: Diesel 2-Stroke, BWTS (Fitted), Scrubber (Installed), Eco – Electronic Engine Modern.

Company Details

Owner: CMA CGM SA, 4 Quai d'Arenc, B.P. 2409, Marseille, France, 13235, Telephone Number: +33 48 891 9000, Fax Number: +33 48 891 9095, E-mail Address: media@cma-cgm.com, URL: http://www.cma-cgm.com.
Technical Manager: CMA Ships, 4, Quai d'Arenc, Marseille, France, 13002, Telephone Number: +33 (0) 048 891 8484, E-mail Address: ho.int-fleet@cma-cgm.com, URL: http://www.cma-cgm.com.
Operator: CMA CGM SA, 4 Quai d'Arenc, B.P. 2409, Marseille, France, 13235, Telephone Number: +33 48 891 9000, Fax Number: +33 48 891 9095, E-mail Address: media@cma-cgm.com, URL: http://www.cma-cgm.com.
P&I insurance with: Assuranceforeningen Gard (Gard P&I), Kittelsbuktveien 31, Arendal, Norway, 4836, Telephone Number: +47 (0) 37 01 9100, Fax Number: +47 37 02 48 10, URL: http://www.gard.no.
Registered Owner: Baltic 261 S.N.C.

Eco Details

Power Type: Diesel 2-Stroke. BWTS (Fitted). Scrubber (Installed). Eco – Electronic Engine Modern.

ENVIRONMENTAL EQUIPMENT 1 x Exhaust Scrubber - SOx - Wartsila Moss Hybrid. 1 x BWTS - Ballast Water Treatment System - Wartsila Water AQ-500-UV at 500cu.m/hr.

Specialist Details

Teu Capacities of 2,487 Total, 1,870 Homogeneous and 1,420 Reefer, Ship is able to transit the neo-Panamax locks of the Panama Canal based on current official dimension restrictions, and is also able to transit the old locks, Dwt to Teu ratio of 13.81. Total Teu Capacity of 2,487.

Additional Information

IDENTIFICATION: Launch Name was CMA CGM Louga. Feeder Containership <3,000 TEU, Call Sign 9HA4747, IMO Number 9745550, Hull Number J0261. DIMENSIONS/TONNAGES: Tonnage of 12,379 International Net and 33,807 Dwt (long). ENGINE DETAILS: Engine Description 2 S.A. 6-cyl., Engine Model 6G60ME-C9.2, 1 FP Propellor. SAFETY AND OTHER DETAILS: Last known special survey in July 2018. CARGO HANDLING: 710 Reefer Plugs.

Equipment Details

MAIN ENGINE 1 x Diesel - MAN B. & W. 6G60ME-C9.2 - 2-stroke 6-cyl. 600mm x2790mm bore/stroke 16,080mkW total at 97rpm.

AUXILIARY 4 x Aux. Diesel Gen. - HHI-EMD (HiMSEN) 8H25/33 - 4-stroke 8-cyl. 250mm x 330mm bore/stroke 9,600mkW total at 900rpm driving 3 x AC generator(s) at 9,120ekW total, (11,400kVA total) at 60Hz.

PROPULSOR 1 x FP Propeller (Aft Centre) (mechanical), Wartsila CME.

POS, PROPULSOR 2 x Pos, Tunnel Thruster (Aft & Fwd) (electric), Kawasaki AC.

OTHER ENGINE EQUIPMENT 1 x Screw Shaft. 1 x Steering Gear.

ENVIRONMENTAL EQUIPMENT 1 x Exhaust Scrubber - SOx - Wartsila Moss Hybrid. 1 x BWTS - Ballast Water Treatment System - Wartsila Water AQ-500-UV at 500cu.m/hr.

BOILER EQUIPMENT 1 x Boiler, Composite - Kangrim.

EMERGENCY 1 x Emergency Diesel Gen. - MAN Energy Solutions D2866LXE20 - 4-stroke 6-cyl. 128mm x 155mm bore/stroke 182mkW total at 1,800rpm driving 1 x AC generator(s) at 60Hz.

Owner History

(1) - Owned by CMA CGM (France) since 20 May 2014

Sister Vessels

Status	Name	Type	Size	Unit	Dwt	Flag	Built	Builder	Owner Group
In Service	CMA CGM Neva	Container	2,487	TEU	34,350	Malta	2018	Jinhai Manufacturing	CMA CGM
In Service	CMA CGM Pregolia	Container	2,487	TEU	37,000	Malta	2018	Jinhai Manufacturing	CMA CGM

Peer Group Analysis

There are 73 vessels that are similar to the CMA CGM Louga based on type, size and age. NB. This peer group is based on Fully Cellular Container vessels with an age of between 0.2 Years and 5.2 Years and a size of 2256 to 2708 TEU.

Peer Group Analysis Table:

	Low	High	Avg.	CMA CGM Louga	% Diff. to Avg.
TEU	2256	2708	2458	**2487**	1.2
DWT	22380	41154	35468	**34350**	-3.3
Age	0.2	5.2	2.5	**2.7**	6.3
LOA	179.90	197.40	185.96	**194.99**	4.6
Draft	9.00	11.70	10.85	**11.50**	5.7
Breadth	30.00	35.20	32.19	**32.20**	0.0
Speed	14.0	20.0	17.4	**20.0**	13.1
Consumption	38.9	49.0	45.3		
% Idle Days (during last 12 months)	0.0	66.0	5.9		
% Active Days (during last 12 months)	34.0	100.0	96.5	**100.0**	3.5

Further Comparisons to Peer Group

Builder Country/Region	No.	%
China P.R.	68	93.2
South Korea	5	6.8
Total	73	100
The **CMA CGM Louga** was built in **China P.R.**.		

Builders	No.	%
Jiangsu New YZJ	11	15.1
Zhejiang Yangfan	11	15.1
Xiamen Shipbuilding	8	11.0
Huangpu Wenchong	8	11.0
Shanghai Shipyard	6	8.2
Others	29	39.7
Total	73	100
The **CMA CGM Louga** was built at **Jinhai Manufacturing**.		

Engine Designers	No.	%
MAN B. & W. 6G60ME-C9.2	20	27.4
MAN B. & W. 7S60ME-C10.5	11	15.1
WinGD 6RT-flex48T-D	10	13.7
MAN B. & W. 6G60ME-C9.5	9	12.3
MAN B. & W. 6S50MC-C8.2	8	11.0
Others	15	20.5
Total	73	100
The **CMA CGM Louga** main engine is a **MAN B. & W. 6G60ME-C9.2**.		

Classes	No.	%
China Classification Society	22	30.1
DNV	19	26.0
Lloyd's Register	9	12.3
Nippon Kaiji Kyokai	9	12.3
Unknown	6	8.2
Others	8	11.0

Classes	No.	%
Total	73	100
The **CMA CGM Louga** is classed with **DNV**.		

Flags	No.	%
Peoples' Republic of China	28	38.4
Hong Kong	14	19.2
Liberia	10	13.7
Singapore	6	8.2
Malta	6	8.2
Others	9	12.3
Total	73	100
The **CMA CGM Louga** is registered in **Malta**.		

Group Owner	No.	%
Zhonggu Logistics	12	16.4
Quanzhou Ansheng	10	13.7
SITC	9	12.3
Seatrade Groningen	5	6.8
KMTC	5	6.8
Others	32	43.8
Total	73	100
The **CMA CGM Louga** is owned by **CMA CGM**.		

SOx Scrubber	No.	%
Not Fitted	51	69.9
Fitted	22	30.1
Total	73	100
The **CMA CGM Louga** is **Fitted** with a SOx Scrubber.		

'Eco' Vessels	No.	%
Eco – Electronic Engine Modern	65	89.0
Non - Eco	8	11.0
Total	73	100
The **CMA CGM Louga** is **Eco – Electronic Engine Modern**.		

Alternative Fuels	No.	%
Conventional Fuels Only	73	100
Total	73	100
The **CMA CGM Louga** can be fuelled by **Conventional Fuels Only**.		

Peer Group Timecharters

Date	Name	Built	DC	Charterer	Dwt	Size	Unit	TC Period	TC Rate	Delivery	Delivery Place
19/04/2021	Nordpacific	2018		CMA-CGM		2506	TEU	3 Months	$14000	09/05/2021	
19/04/2021	Nordmarsh	2018		CMA-CGM		2506	TEU	36-39 Months	$23850	19/04/2021	
01/04/2021	California Trader	2017		Sea Consortium		2708	TEU	12 Months	$31000	22/05/2021	
17/03/2021	Carolina Trader	2017		FESCO		2708	TEU	18-21 Months	$28000	05/04/2021	
09/12/2020	Nordamelia	2017		CMA-CGM		2506	TEU	6-9 Months	$12250	21/12/2020	

Nordic Grace (Ex:Seagrace) 149,921 DWT Tanker Built 2002 (In Service)

Standard Details

IMO Number 9230892, Owners are Nordic American, Built at Hyundai Samho HI delivered in Mar 2002, Double Hull, Cayman Islands Flagged, DNV Classed, P&I insurance with Gard P&I, Length Overall of 274.19 m., Length Between Perpendiculars of 264.00 m., Draught of 15.85 m., Beam of 50.00 m., 121.87 Tonnes per Centimetre Immersion, Gross Tonnage of 84,598, MAN B. & W. Engine, Speed of 14.50 kts at 64.00 tonnes per day, Intermediate Fuel Oil - Very Low Sulphur (VLS IFO), Horsepower of 25,320, Bunker Capacity of 3,850.70 VLS IFO, Power Type: Diesel 2-Stroke.

Company Details

Owner: Nordic American Tankers Limited (NAT), Leif Weldingsvei 20, P.O.B. 56, Sandefjord, Norway, N-3201, Telephone Number: +47 (0) 334 273 00, Fax Number: +47 (0) 334 273 01, E-mail Address: ir@nat.bm, URL: http://www.nat.bm.
Technical Manager: Hellespont Ship Management GmbH & Co. KG, Beim Strohhause 27, Hamburg, Germany, Telephone Number: +49 (0) 40 879 7980, E-mail Address: info@hsm.hellespont.com, URL: http://www.hellespont.com.
Operator: Nordic American Tankers Limited (NAT), Leif Weldingsvei 20, P.O.B. 56, Sandefjord, Norway, N-3201, Telephone Number: +47 (0) 334 273 00, Fax Number: +47 (0) 334 273 01, E-mail Address: ir@nat.bm, URL: http://www.nat.bm.
P&I insurance with: Assuranceforeningen Gard (Gard P&I), Kittelsbuktveien 31, Arendal, Norway, 4836, Telephone Number: +47 (0) 37 01 9100, Fax Number: +47 37 02 48 10, URL: http://www.gard.no.
Registered Owner: NAT Bermuda Holdings Ltd.

Eco Details

Power Type: Diesel 2-Stroke.

ENERGY SAVING TECHNOLOGIES (EST) 1 x Propeller Duct - Becker.

Specialist Details

Cargo Capacities of 173,947 cu.m. and 1,094,000 Barrels, Segregated Ballast Tanks, 12 Tanks, 3 Pumps with a total Capacity of 12,000 cu.m., Heating Coils, Maximum heating capacity of 66 degrees celsius, Ship is able to transit the neo-Panamax locks of the Panama Canal based on current official dimension restrictions, but is not able to transit the old locks.

Additional Information

IDENTIFICATION: Exname is Seagrace. Launch Name was Seagrace. Suezmax Tanker, Call Sign ZGDM8, IMO Number 9230892, Hull Number S127. DIMENSIONS/TONNAGES: Moulded Depth of 23.10 m., Lightship air draft of 43.29 m., Keel to mast air draft of 50.95 m., Tonnage of 80,534 Suez Canal Net, 46,548 International Net, 24,882 Light Displacement and 147,553 Dwt (long). ENGINE DETAILS: Engine Description 2 S.A. 6-cyl., Engine Model 6S70MC-C7.1, 1 FP Propellor. CARGO HANDLING: 3 Cargo Separations, 12 Wing Tanks with a capacity of 173,947 cu.m., all of which are fitted with heating coils, 3 Cargo Manifolds, Stern Discharge, Closed Loading System, Cargo connections have diameters of 24 inches, Manifold height above deck of 1.91 m., Distance from bow to centre manifold is 135.80 m., 3 Centrifugal Pump(s) in 1 Pumproom(s), Maximum operating capacity of cargo pumps is 12,000 t/hr, Cast Steel cargo lines, Crude Oil Washing. SAFETY AND OTHER DETAILS: Last known special survey in April 2017, Ballast Capacity of 58,766 tonnes, Satellite Communications, Marpol Certificate, Solas Certificate, High Level Alarms, Automatic Ullaging, Stripping System, Inert Gas System, OPA 90 Design, OPA 90 Approved, Vapour Return Ashore, Centre Line Bulkhead.

Equipment Details

MAIN ENGINE 1 x Diesel - MAN B. & W. 6S70MC-C7.1 - 2-stroke 6-cyl. 700mm x2800mm bore/stroke 18,623mkW total at 91rpm.

AUXILIARY 3 x Aux. Diesel Gen. - MAN Energy Solutions 5L28/32H - 4-stroke 5-cyl. 280mm x 320mm bore/stroke 3,150mkW total at 720rpm driving 3 x ac generator(s) at 2,850ekW total, (3,562.50kVA total) at 60Hz.

PROPULSOR 1 x FP Propeller (Aft Centre) (mechanical), HHI-EMD (HiMSEN), 91rpm.

OTHER ENGINE EQUIPMENT 1 x Screw Shaft. 1 x Steering Gear.

LIFTING EQUIPMENT 2 x Crane SWL 20 tons.

MISCELLANEOUS EQUIPMENT Coating - Hull, Antifouling - Jotun SeaQuantum - Apr 2012 application date.

ENERGY SAVING TECHNOLOGIES (EST) 1 x Propeller Duct - Becker Becker Mewis Duct® - 2013 installation year.

BOILER EQUIPMENT 2 x Boiler, Oil/Gas fired - Aalborg - . 1 x Boiler, Composite - Kangrim.

EMERGENCY 1 x Emergency Diesel Gen. - Cummins Inc4-stroke driving 1 x ac generator(s) at 60Hz.

Sale & Purchase History

Reported newbuild price of 44.5 $m contracted on 28 April 2000. Reported sold to Clients of NATS on 6 May 2009 for US$ 57m.

Fixture History

Reported voyage charter by IOC from RAS TANURA to CHENNAI with a CRUDE cargo of 130,000t at 60 on 17 March 2021. Reported voyage charter by AVIN from BASRAH OIL TERMINAL to GREECE with a CRUDE cargo of 135,000t on 8 February 2021. Reported voyage charter by HMEL from AG to MUNDRA with a CRUDE cargo of 130,000t on 26 November 2020. Reported voyage charter by BPCL from CEYHAN TERMINAL to KOCHI with a CRUDE cargo of 130,000t at 1,500,000 USD on 9 November 2020. Reported voyage charter by UML from CEYHAN TERMINAL to MED with a CRUDE cargo of 135,000t at 45 on 28 October 2020. Reported voyage charter from BASRAH OIL TERMINAL to MED with a CRUDE cargo of 140,000t on 15 September 2020. Reported voyage charter by IOC from BASRAH OIL TERMINAL to CHENNAI with a CRUDE cargo of 138,000t at 160 on 19 March 2020. Reported voyage charter by BPCL from CEYHAN TERMINAL to MUMBAI with a CRUDE cargo of 130,000t at 2,125,000 USD on 27 February 2020. Reported voyage charter from BASRAH OIL TERMINAL to GREECE with a CRUDE cargo of 135,000t at 105 on 15 January 2020. Reported voyage charter by IOC from KOLE to PARADIP with a CRUDE cargo of 130,000t at 3,825,000 USD on 4 November 2019.

Owner History

(1) - Owned by Nordic American (Norway) since 14 Jul 2009

Peer Group Analysis

There are 92 vessels that are similar to the Nordic Grace based on type, size and age. NB. This peer group is based on Tanker vessels with an age of between 16.5 Years and 21.4 Years and a size of 160636 to 178201 cu.m..

Peer Group Analysis Table:

	Low	High	Avg.	Nordic Grace	% Diff. to Avg.
cu.m.	160636	178201	167321	**173947**	3.8
DWT	141740	165293	156416	**149921**	-4.3
Age	16.5	21.4	18.8	**19.0**	1.1
LOA	269.19	281.20	273.83	**274.19**	0.1
Draft	15.75	17.52	16.79	**15.85**	-5.9
Breadth	45.60	50.04	47.96	**50.00**	4.1
Speed	10.5	17.0	15.0	**14.5**	-3.4
Consumption	35.0	82.0	63.5	**64.0**	0.8
% Idle Days (during last 12 months)	0.0	100.0	9.4		
% Active Days (during last 12 months)	0.0	100.0	81.5	**54.5**	-49.5

Further Comparisons to Peer Group

Builder Country/Region	No.	%
South Korea	69	75.0
Japan	16	17.4
United States	4	4.3
China P.R.	2	2.2

Builder Country/Region	No.	%
Croatia	1	1.1
Total	92	100
The **Nordic Grace** was built in **South Korea**.		

Builders	No.	%
Hyundai HI (Ulsan)	28	30.4
Daewoo (DSME)	19	20.7
Samsung HI	13	14.1
Hyundai Samho HI	9	9.8
NKK (Tsu)	8	8.7
Others	15	16.3
Total	92	100
The **Nordic Grace** was built at **Hyundai Samho HI**.		

Engine Designers	No.	%
MAN B. & W. 6S70MC-C7.1	27	29.3
MAN B. & W. 6S70MC6.1	26	28.3
MAN B. & W. 6S70MC6	15	16.3
Sulzer 6RTA72	6	6.5
MAN B. & W. 6S70MC-C7	5	5.4
Others	13	14.1
Total	92	100
The **Nordic Grace** main engine is a **MAN B. & W. 6S70MC-C7.1**.		

Classes	No.	%
American Bureau of Shipping	25	27.2
DNV	24	26.1
Unknown	12	13.0
Lloyd's Register	9	9.8
Bureau Veritas	9	9.8
Others	13	14.1
Total	92	100
The **Nordic Grace** is classed with **DNV**.		

Flags	No.	%
Liberia	20	21.7
Marshall Islands	10	10.9
Panama	8	8.7
Iran	8	8.7
Greece	7	7.6
Others	39	42.4
Total	92	100
The **Nordic Grace** is registered in **Cayman Islands**.		

Group Owner	No.	%
Unknown	12	13.0
Nordic American	8	8.7
Nat Iranian Tanker	5	5.4
New Shipping	4	4.3
ConocoPhillips	4	4.3
Others	59	64.1
Total	92	100
The **Nordic Grace** is owned by **Nordic American**.		

SOx Scrubber	No.	%
Not Fitted	87	94.6
Fitted	3	3.3
Pending	2	2.2
Total	92	100
The **Nordic Grace** is **Not Fitted** with a SOx Scrubber.		

'Eco' Vessels	No.	%
Non - Eco	91	98.9
Eco – Electronic Engine	1	1.1
Total	92	100
The **Nordic Grace** is **Non - Eco**.		

Alternative Fuels	No.	%
Conventional Fuels Only	92	100
Total	92	100
The **Nordic Grace** can be fuelled by **Conventional Fuels Only**.		

Peer Group Timecharters

Date	Name	Built	DC	Charterer	Dwt	Size	Unit	TC Period	TC Rate	Delivery	Delivery Place
24/11/2020	MONTE TOLEDO	2004	D	VITOL	150,611	150611	Dwt	30-90 Days	$17,500	25/11/2020	SPORE
05/08/2020	ZENO	2003	D	ST SHIPPING	151,848	151848	Dwt	3-6 Mths	$17,500	06/08/2020	THAIGULF
30/03/2020	OLYMPIC FUTURE	2004	D	BP	149,500	149500	Dwt	1 Yr	RNR	13/04/2020	MEG
12/03/2020	NELL JACOB	2003	D	TRAFIGURA	159,999	159999	Dwt	5-9 Mths	$28,000	15/03/2020	UKCONT

Peer Group Sales

Name	Dwt	Built	Builder	Sold	Currency	Price	En Bloc	Buyers	Sellers

Name	Dwt	Built	Builder	Sold	Currency	Price	En Bloc	Buyers	Sellers
A Melody*	149,995	2001	Sasebo HI	15/04/2021	USD	30.00		Undisclosed interests	NGM Energy
A Symphony*	149,995	2001	Sasebo HI	15/04/2021			#	Undisclosed interests	NGM Energy
Supreme	164,551	2002	Hyundai HI (Ulsan)	07/04/2021	USD	15.90		Bangladeshi interests	UML Switzerland
Nell Jacob	159,999	2003	Samsung HI	24/02/2021				Undisclosed interests	Ernst Jacob
Lady Ava	160,383	2001	Daewoo (DSME)	24/02/2021	USD	13.40		Greek interests	Pentacontinent

Nordic Grace (Ex:Seagrace) 149,921 DWT Tanker Built 2002 (In Service)

Standard Details

IMO Number 9230892, Owners are Nordic American, Built at Hyundai Samho HI delivered in Mar 2002, Double Hull, Cayman Islands Flagged, DNV Classed, P&I insurance with Gard P&I, Length Overall of 274.19 m., Length Between Perpendiculars of 264.00 m., Draught of 15.85 m., Beam of 50.00 m., 121.87 Tonnes per Centimetre Immersion, Gross Tonnage of 84,598, MAN B. & W. Engine, Speed of 14.50 kts at 64.00 tonnes per day, Intermediate Fuel Oil - Very Low Sulphur (VLS IFO), Horsepower of 25,320, Bunker Capacity of 3,850.70 VLS IFO, Power Type: Diesel 2-Stroke.

Company Details

Owner: Nordic American Tankers Limited (NAT), Leif Weldingsvei 20, P.O.B. 56, Sandefjord, Norway, N-3201, Telephone Number: +47 (0) 334 273 00, Fax Number: +47 (0) 334 273 01, E-mail Address: ir@nat.bm, URL: http://www.nat.bm.
Technical Manager: Hellespont Ship Management GmbH & Co. KG, Beim Strohhause 27, Hamburg, Germany, Telephone Number: +49 (0) 40 879 7980, E-mail Address: info@hsm.hellespont.com, URL: http://www.hellespont.com.
Operator: Nordic American Tankers Limited (NAT), Leif Weldingsvei 20, P.O.B. 56, Sandefjord, Norway, N-3201, Telephone Number: +47 (0) 334 273 00, Fax Number: +47 (0) 334 273 01, E-mail Address: ir@nat.bm, URL: http://www.nat.bm.
P&I insurance with: Assuranceforeningen Gard (Gard P&I), Kittelsbuktveien 31, Arendal, Norway, 4836, Telephone Number: +47 (0) 37 01 9100, Fax Number: +47 37 02 48 10, URL: http://www.gard.no.
Registered Owner: NAT Bermuda Holdings Ltd.

Eco Details

Power Type: Diesel 2-Stroke.

ENERGY SAVING TECHNOLOGIES (EST) 1 x Propeller Duct - Becker.

Specialist Details

Cargo Capacities of 173,947 cu.m. and 1,094,000 Barrels, Segregated Ballast Tanks, 12 Tanks, 3 Pumps with a total Capacity of 12,000 cu.m., Heating Coils, Maximum heating capacity of 66 degrees celsius, Ship is able to transit the neo-Panamax locks of the Panama Canal based on current official dimension restrictions, but is not able to transit the old locks.

Additional Information

IDENTIFICATION: Exname is Seagrace. Launch Name was Seagrace. Suezmax Tanker, Call Sign ZGDM8, IMO Number 9230892, Hull Number S127. DIMENSIONS/TONNAGES: Moulded Depth of 23.10 m., Lightship air draft of 43.29 m., Keel to mast air draft of 50.95 m., Tonnage of 80,534 Suez Canal Net, 46,548 International Net, 24,882 Light Displacement and 147,553 Dwt (long). ENGINE DETAILS: Engine Description 2 S.A. 6-cyl., Engine Model 6S70MC-C7.1, 1 FP Propellor. CARGO HANDLING: 3 Cargo Separations, 12 Wing Tanks with a capacity of 173,947 cu.m., all of which are fitted with heating coils, 3 Cargo Manifolds, Stern Discharge, Closed Loading System, Cargo connections have diameters of 24 inches, Manifold height above deck of 1.91 m., Distance from bow to centre manifold is 135.80 m., 3 Centrifugal Pump(s) in 1 Pumproom(s), Maximum operating capacity of cargo pumps is 12,000 t/hr, Cast Steel cargo lines, Crude Oil Washing. SAFETY AND OTHER DETAILS: Last known special survey in April 2017, Ballast Capacity of 58,766 tonnes, Satellite Communications, Marpol Certificate, Solas Certificate, High Level Alarms, Automatic Ullaging, Stripping System, Inert Gas System, OPA 90 Design, OPA 90 Approved, Vapour Return Ashore, Centre Line Bulkhead.

Equipment Details

MAIN ENGINE 1 x Diesel - MAN B. & W. 6S70MC-C7.1 - 2-stroke 6-cyl. 700mm x2800mm bore/stroke 18,623mkW total at 91rpm.

AUXILIARY 3 x Aux. Diesel Gen. - MAN Energy Solutions 5L28/32H - 4-stroke 5-cyl. 280mm x 320mm bore/stroke 3,150mkW total at 720rpm driving 3 x ac generator(s) at 2,850ekW total, (3,562.50kVA total) at 60Hz.

PROPULSOR 1 x FP Propeller (Aft Centre) (mechanical), HHI-EMD (HiMSEN), 91rpm.

OTHER ENGINE EQUIPMENT 1 x Screw Shaft. 1 x Steering Gear.

LIFTING EQUIPMENT 2 x Crane SWL 20 tons.

MISCELLANEOUS EQUIPMENT Coating - Hull, Antifouling - Jotun SeaQuantum - Apr 2012 application date.

ENERGY SAVING TECHNOLOGIES (EST) 1 x Propeller Duct - Becker Becker Mewis Duct® - 2013 installation year.

BOILER EQUIPMENT 2 x Boiler, Oil/Gas fired - Aalborg - . 1 x Boiler, Composite - Kangrim.

EMERGENCY 1 x Emergency Diesel Gen. - Cummins Inc4-stroke driving 1 x ac generator(s) at 60Hz.

Sale & Purchase History

Reported newbuild price of 44.5 $m contracted on 28 April 2000. Reported sold to Clients of NATS on 6 May 2009 for US$ 57m.

Fixture History

Reported voyage charter by IOC from RAS TANURA to CHENNAI with a CRUDE cargo of 130,000t at 60 on 17 March 2021. Reported voyage charter by AVIN from BASRAH OIL TERMINAL to GREECE with a CRUDE cargo of 135,000t on 8 February 2021. Reported voyage charter by HMEL from AG to MUNDRA with a CRUDE cargo of 130,000t on 26 November 2020. Reported voyage charter by BPCL from CEYHAN TERMINAL to KOCHI with a CRUDE cargo of 130,000t at 1,500,000 USD on 9 November 2020. Reported voyage charter by UML from CEYHAN TERMINAL to MED with a CRUDE cargo of 135,000t at 45 on 28 October 2020. Reported voyage charter from BASRAH OIL TERMINAL to MED with a CRUDE cargo of 140,000t on 15 September 2020. Reported voyage charter by IOC from BASRAH OIL TERMINAL to CHENNAI with a CRUDE cargo of 138,000t at 160 on 19 March 2020. Reported voyage charter by BPCL from CEYHAN TERMINAL to MUMBAI with a CRUDE cargo of 130,000t at 2,125,000 USD on 27 February 2020. Reported voyage charter from BASRAH OIL TERMINAL to GREECE with a CRUDE cargo of 135,000t at 105 on 15 January 2020. Reported voyage charter by IOC from KOLE to PARADIP with a CRUDE cargo of 130,000t at 3,825,000 USD on 4 November 2019.

Owner History

(1) - Owned by Nordic American (Norway) since 14 Jul 2009

Peer Group Analysis

There are 92 vessels that are similar to the Nordic Grace based on type, size and age. NB. This peer group is based on Tanker vessels with an age of between 16.5 Years and 21.4 Years and a size of 160636 to 178201 cu.m..

Peer Group Analysis Table:

	Low	High	Avg.	Nordic Grace	% Diff. to Avg.
cu.m.	160636	178201	167321	**173947**	3.8
DWT	141740	165293	156416	**149921**	-4.3
Age	16.5	21.4	18.8	**19.0**	1.1
LOA	269.19	281.20	273.83	**274.19**	0.1
Draft	15.75	17.52	16.79	**15.85**	-5.9
Breadth	45.60	50.04	47.96	**50.00**	4.1
Speed	10.5	17.0	15.0	**14.5**	-3.4
Consumption	35.0	82.0	63.5	**64.0**	0.8
% Idle Days (during last 12 months)	0.0	100.0	9.4		
% Active Days (during last 12 months)	0.0	100.0	81.5	**54.5**	-49.5

Further Comparisons to Peer Group

Builder Country/Region	No.	%
South Korea	69	75.0
Japan	16	17.4

Builder Country/Region	No.	%
United States	4	4.3
China P.R.	2	2.2
Croatia	1	1.1
Total	92	100
The **Nordic Grace** was built in **South Korea**.		

Builders	No.	%
Hyundai HI (Ulsan)	28	30.4
Daewoo (DSME)	19	20.7
Samsung HI	13	14.1
Hyundai Samho HI	9	9.8
NKK (Tsu)	8	8.7
Others	15	16.3
Total	92	100
The **Nordic Grace** was built at **Hyundai Samho HI**.		

Engine Designers	No.	%
MAN B. & W. 6S70MC-C7.1	27	29.3
MAN B. & W. 6S70MC6.1	26	28.3
MAN B. & W. 6S70MC6	15	16.3
Sulzer 6RTA72	6	6.5
MAN B. & W. 6S70MC-C7	5	5.4
Others	13	14.1
Total	92	100
The **Nordic Grace** main engine is a **MAN B. & W. 6S70MC-C7.1**.		

Classes	No.	%
American Bureau of Shipping	25	27.2
DNV	24	26.1
Unknown	12	13.0
Lloyd's Register	9	9.8
Bureau Veritas	9	9.8
Others	13	14.1
Total	92	100
The **Nordic Grace** is classed with **DNV**.		

Flags	No.	%
Liberia	20	21.7
Marshall Islands	10	10.9
Panama	8	8.7
Iran	8	8.7
Greece	7	7.6
Others	39	42.4
Total	92	100
The **Nordic Grace** is registered in **Cayman Islands**.		

Group Owner	No.	%
Unknown	12	13.0
Nordic American	8	8.7
Nat Iranian Tanker	5	5.4
New Shipping	4	4.3
ConocoPhillips	4	4.3
Others	59	64.1
Total	92	100
The **Nordic Grace** is owned by **Nordic American**.		

SOx Scrubber	No.	%
Not Fitted	87	94.6
Fitted	3	3.3
Pending	2	2.2
Total	92	100
The **Nordic Grace** is **Not Fitted** with a SOx Scrubber.		

'Eco' Vessels	No.	%
Non - Eco	91	98.9
Eco – Electronic Engine	1	1.1
Total	92	100
The **Nordic Grace** is **Non - Eco**.		

Alternative Fuels	No.	%
Conventional Fuels Only	92	100
Total	92	100
The **Nordic Grace** can be fuelled by **Conventional Fuels Only**.		

Peer Group Timecharters

Date	Name	Built	DC	Charterer	Dwt	Size	Unit	TC Period	TC Rate	Delivery	Delivery Place
24/11/2020	MONTE TOLEDO	2004	D	VITOL	150,611	150611	Dwt	30-90 Days	$17,500	25/11/2020	SPORE
05/08/2020	ZENO	2003	D	ST SHIPPING	151,848	151848	Dwt	3-6 Mths	$17,500	06/08/2020	THAIGULF
30/03/2020	OLYMPIC FUTURE	2004	D	BP	149,500	149500	Dwt	1 Yr	RNR	13/04/2020	MEG
12/03/2020	NELL JACOB	2003	D	TRAFIGURA	159,999	159999	Dwt	5-9 Mths	$28,000	15/03/2020	UKCONT

Peer Group Sales

Name	Dwt	Built	Builder	Sold	Currency	Price	En Bloc	Buyers	Sellers
A Melody*	149,995	2001	Sasebo HI	15/04/2021	USD	30.00		Undisclosed interests	NGM Energy
A Symphony*	149,995	2001	Sasebo HI	15/04/2021			#	Undisclosed interests	NGM Energy
Supreme	164,551	2002	Hyundai HI (Ulsan)	07/04/2021	USD	15.90		Bangladeshi interests	UML Switzerland
Nell Jacob	159,999	2003	Samsung HI	24/02/2021				Undisclosed interests	Ernst Jacob
Lady Ava	160,383	2001	Daewoo (DSME)	24/02/2021	USD	13.40		Greek interests	Pentacontinent

Ore China (Ex:Vale China) 400,606 DWT Ore Carrier Built 2011 (In Service)

Standard Details

IMO Number 9522972, Owners are VLOC Holding, Built at Jiangsu Rongsheng delivered in Nov 2011, Hong Kong Flagged, DNV Classed, P&I insurance with Skuld, Leased by ICBC Leasing, Length Overall of 359.94 m., Length Between Perpendiculars of 353.00 m., Draught of 23.00 m., Beam of 64.99 m., Gross Tonnage of 201,384, Design SDARI Valemax by SDARI, Wartsila 2-stroke Engine, Speed of 14.80 kts, Heavy Fuel Oil (IFO 380), Horsepower of 39,972, Power Type: Diesel 2-Stroke, BWTS (Pending), Scrubber (Installed), Eco – Electronic Engine.

Company Details

Owner: VLOC Maritime Holdings Limited, C/O ICBC Leasing, 10/F, Bank of Beijing Building,, Beijing, China P.R., Telephone Number: +86 (0) 106 610 5888, URL: http://www.icbcleasing.com. VLOC Maritime Holdings Limited is a group company of Industrial and Commercial Bank of China (ICBC). VLOC Maritime Holdings Limited is a joint venture between ICBC Leasing (70%) and China Merchants Shpg (30%).
Group Company: Industrial and Commercial Bank of China (ICBC), No.55 FuXingMenNei Street, Beijing, China P.R., 100140.
Technical Manager: Bernhard Schulte Shipmanagement (India) Private Ltd., 401 Olympia Hiranandani Gardens, Powai, Mumbai, India, 400076, Telephone Number: +91 22 4001 7300, Fax Number: +91 22 4001 7333, E-mail Address: in-sdc1-man@bs-shipmanagement.com, URL: http://www.bs-shipmanagement.com.
Operator: Hong Kong Ming Wah Shipping Co Ltd, 31/F, China Merchants Tower, Shun Tak Centre, Hong Kong, Hong Kong, Telephone Number: +(852) 2517 2128, Fax Number: +(852) 2547 3482, URL: http://www.cmenergyshipping.com.
Financial Lessor: Industrial and Commercial Bank of China Financial Leasing Co Ltd (ICBC), 10/F, Bank of Beijing Building, 17(C) Jinrong Street, Beijing, China P.R., 100033, Telephone Number: +86 (0) 106 610 5888, Fax Number: +86 (0) 106 610 5999, E-mail Address: webmaster@icbcleasing.com, URL: http://www.icbcleasing.com.
P&I insurance with: Assuranceforeningen Skuld, Radhusgaten 27, Oslo, Norway, 0158, Telephone Number: +47 (0) 22 00 2200, Fax Number: +47 22 42 42 22, E-mail Address: osl@skuld.com, URL: http://www.skuld.com.
Registered Owner: Ore China HK Limited.

Eco Details

Power Type: Diesel 2-Stroke. BWTS (Pending). Scrubber (Installed). Eco – Electronic Engine.

ENVIRONMENTAL EQUIPMENT 1 x Exhaust Scrubber - SOx - Alfa Laval PureSOx - 2020 installation year. 2 x BWTS - Ballast Water Treatment System - Sunrui BC-3500 at 3500cu.m/hr - 2021 installation year.

Specialist Details

Grain Capacity of 224,427 cu.m., 7 Holds, 7 Hatches, Ship is too large to transit the neo-Panamax locks of the Panama Canal based on current official dimension restrictions.

Additional Information

IDENTIFICATION: Exname is Vale China. Launch Name was Vale China. Capesize Bulker, Call Sign VRPH2, IMO Number 9522972, Hull Number H1105. DIMENSIONS/TONNAGES: Moulded Depth of 30.40 m., Tonnage of 68,974 International Net and 394,279 Dwt (long). ENGINE DETAILS: Engine Description 2 S.A. 7-cyl., Engine Model 7RT-flex82T-A, 1 FP Propellor. SAFETY AND OTHER DETAILS: Last known special survey in October 2016, Ballast Capacity of 190,826 tonnes.

Equipment Details

MAIN ENGINE 1 x Diesel - Wartsila 2-stroke 7RT-flex82T-A - 2-stroke 7-cyl. 820mm x3375mm bore/stroke 29,400mkW total at 76rpm.

AUXILIARY 3 x Aux. Diesel Gen. - Wartsila 4-stroke 8L20 - 4-stroke 8-cyl. 200mm x 280mm bore/stroke 4,560mkW total at 1,000rpm driving 3 x AC generator(s) at 4,398ekW total, (5,498kVA total) at 50Hz.

PROPULSOR 1 x FP Propeller (Aft Centre) (mechanical), Dalian Marine, 76rpm, Ø1m.

OTHER ENGINE EQUIPMENT 1 x Screw Shaft.

ENVIRONMENTAL EQUIPMENT 1 x Exhaust Scrubber - SOx - Alfa Laval PureSOx - 2020 installation year. 2 x BWTS - Ballast Water Treatment System - Sunrui BC-3500 at 3500cu.m/hr - 2021 installation year.

BOILER EQUIPMENT 1 x Boiler, Composite - Zhangjiagang Greens LYF3.5/3.3-0.7 at 9 bar.

EMERGENCY 1 x Emergency Diesel Gen. - Scania DC12 - 4-stroke 6-cyl. 127mm x 154mm bore/stroke 445mkW total at 1,800rpm driving 1 x AC generator(s) at 50Hz.

Sale & Purchase History

Reported newbuild price of 140 $m contracted on 31 July 2008. Reported sold to Clients of ICBC Financial on 8 December 2015 as part of a enbloc sale.

Owner History

(1) - Owned by VLOC Holding (China P.R.) since 31 May 2016

Sister Vessels

Status	Name	Type	Size	Unit	Dwt	Flag	Built	Builder	Owner Group
Idle	Ore Dongjiakou	Ore	400,606	DWT	400,606	Hong Kong	2012	Jiangsu Rongsheng	ICBC
In Service	Ore Hebei	Ore	400,535	DWT	400,535	Hong Kong	2012	Jiangsu Rongsheng	ICBC
In Service	Ore Shandong	Ore	400,000	DWT	400,000	Hong Kong	2012	Jiangsu Rongsheng	ICBC
In Service	Pacific Mariner	Ore	400,032	DWT	400,032	Hong Kong	2015	Jiangsu Rongsheng	China Merchants
In Service	Pacific Merchants	Ore	400,101	DWT	400,101	Hong Kong	2014	Jiangsu Rongsheng	China Merchants
Idle	Pacific Warrior	Ore	400,398	DWT	400,398	Hong Kong	2012	Jiangsu Rongsheng	China Merchants
In Service	Pacific Winner	Ore	400,065	DWT	400,065	Hong Kong	2014	Jiangsu Rongsheng	China Merchants
In Service	Yuan Jian Hai	Ore	399,995	DWT	399,995	Singapore	2013	Jiangsu Rongsheng	China COSCO Shipping
In Service	Yuan Shi Hai	Ore	400,000	DWT	400,000	Singapore	2013	Jiangsu Rongsheng	China COSCO Shipping
In Service	Yuan Zhen Hai	Ore	399,997	DWT	399,997	Singapore	2013	Jiangsu Rongsheng	China COSCO Shipping

Peer Group Analysis

There are 25 vessels that are similar to the Ore China based on type, size and age. NB. This peer group is based on Ore Carrier vessels with an age of between 7.3 Years and 10.0 Years and a size of 224427 to 243730 Grain cu.m..

Peer Group Analysis Table:

	Low	High	Avg.	Ore China	% Diff. to Avg.
Grain cu.m.	224427	243730	229831	**224427**	-2.4
DWT	399995	403919	401739	**400606**	-0.3
Age	7.3	10.0	8.5	**9.3**	8.9
LOA	359.87	362.00	360.82	**359.94**	-0.2
Draft	22.00	23.00	22.72	**23.00**	1.2
Breadth	64.99	65.00	65.00	**64.99**	0.0
Speed	14.8	16.4	15.0	**14.8**	-1.4
Consumption					
% Idle Days (during last 12 months)	0.0	18.1	4.2		
% Active Days (during last 12 months)	81.9	100.0	95.4	**100.0**	4.6

Further Comparisons to Peer Group

Builder Country/Region	No.	%
China P.R.	14	56.0
South Korea	11	44.0
Total	25	100
The **Ore China** was built in **China P.R.**.		

Builders	No.	%
Jiangsu Rongsheng	11	44.0
Daewoo (DSME)	7	28.0
STX SB (Jinhae)	4	16.0
STX Dalian	3	12.0
Total	25	100

Builders	No.	%
The **Ore China** was built at **Jiangsu Rongsheng**.		

Engine Designers	No.	%
MAN B. & W. 7S80ME-C8.2	14	56.0
Wartsila 2-stroke 7RT-flex82T-A	11	44.0
Total	25	100
The **Ore China** main engine is a **Wartsila 2-stroke 7RT-flex82T-A**.		

Classes	No.	%
DNV	16	64.0
China Classification Society	5	20.0
American Bureau of Shipping	2	8.0
Lloyd's Register	2	8.0
Total	25	100
The **Ore China** is classed with **DNV**.		

Flags	No.	%
Hong Kong	11	44.0
Marshall Islands	11	44.0
Singapore	3	12.0
Total	25	100
The **Ore China** is registered in **Hong Kong**.		

Group Owner	No.	%
Pan Ocean	7	28.0
ICBC	6	24.0
Oman Shipping Co	4	16.0
BoCom	4	16.0
China COSCO Shipping	3	12.0
Others	1	4.0
Total	25	100
The **Ore China** is owned by **ICBC**.		

SOx Scrubber	No.	%
Fitted	24	96.0
Pending	1	4.0
Total	25	100
The **Ore China** is **Fitted** with a SOx Scrubber.		

'Eco' Vessels	No.	%
Eco – Electronic Engine	25	100
Total	25	100
The **Ore China** is **Eco – Electronic Engine**.		

Alternative Fuels	No.	%
Conventional Fuels Only	25	100
Total	25	100
The **Ore China** can be fuelled by **Conventional Fuels Only**.		

C Information of different fuel converters

Fuel cell system *bunker fuel*	 *fuel cell*	*Fuel cell plant* **volumetric power density** kW/m^3	*Fuel storage (inc. efficiency)* **volumetric energy density** kWh/m^3	*Fuel cell plant* **gravimetric power density** kW/ton	*Fuel storage (inc. efficiency)* **gravimetric energy density** kWh/ton	*for 15 years* **FC plant** €/kW	*inc. efficiency* **Fuel storage** €/kWh	*inc. efficiency* **Fuel cost** €/MWhe
LH2	LT-PEMFC	250	604	408	1250	€ 4,213	€ 10.00	€ 898
LH2	HT-PEMFC	99	543	74	1125	€ 6,256	€ 11.11	€ 998
LH2	MCFC	11	604	16	1250	€ 9,532	€ 10.00	€ 898
LH2	SOFC	32	604	119	1250	€ 13,043	€ 10.00	€ 898
LNG	LT-PEMFC	90	1254	272	2931	€ 5,393	€ 3.61	€ 51
LNG	HT-PEMFC	58	1098	74	2565	€ 7,681	€ 4.12	€ 58
LNG	MCFC	11	1411	16	3298	€ 10,735	€ 3.21	€ 45
LNG	SOFC	32	1882	119	4397	€ 14,658	€ 2.41	€ 34
MeOH	LT-PEMFC	41	1575	83	1755	€ 4,929	€ 0.09	€ 159
MeOH	HT-PEMFC	31	1400	74	1560	€ 7,000	€ 0.10	€ 179
MeOH	MCFC	8	1575	16	1755	€ 10,643	€ 0.09	€ 159
MeOH	SOFC	18	1925	119	2145	€ 14,534	€ 0.07	€ 130
NH3	LT-PEMFC	102	1130	155	1620	€ 4,466	€ 0.73	€ 365
NH3	HT-PEMFC	53	1004	74	1440	€ 6,628	€ 0.82	€ 410
NH3	MCFC	10	1256	16	1800	€ 10,087	€ 0.65	€ 328
NH3	SOFC	32	1507	119	2160	€ 13,167	€ 0.54	€ 274
MGO	DG	67	3985	79	3320	€ 425	€ 0.05	€ 121

Figure 41: Performance of different fuel cells and different fuels (van Veldhuizen et al., 2020)

Fuel cell system							
LH_2	LT-PEMFC	LNG	LT-PEMFC	$MeOH$	LT-PEMFC	NH_3	LT-PEMFC
LH_2	HT-PEMFC	LNG	HT-PEMFC	$MeOH$	HT-PEMFC	NH_3	HT-PEMFC
LH_2	MCFC	LNG	MCFC	$MeOH$	MCFC	NH_3	MCFC
LH_2	SOFC	LNG	SOFC	$MeOH$	SOFC	NH_3	SOFC

Figure 42: Preferred fuel cell systems (van Veldhuizen et al., 2020)

Comparison of Fuel Cell Technologies

Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Electrical Efficiency (LHV)	Applications	Advantages	Challenges
Polymer Electrolyte Membrane (PEM)	Perfluoro sulfonic acid	<120°C	<1 kW - 100 kW	60% direct H_2;[i] 40% reformed fuel[ii]	• Backup power • Portable power • Distributed generation • Transportation • Specialty vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up and load following	• Expensive catalysts • Sensitive to fuel impurities
Alkaline (AFC)	Aqueous potassium hydroxide soaked in a porous matrix, or alkaline polymer membrane	<100°C	1 - 100 kW	60%[iii]	• Military • Space • Backup power • Transportation	• Wider range of stable materials allows lower cost components • Low temperature • Quick start-up	• Sensitive to CO_2 in fuel and air • Electrolyte management (aqueous) • Electrolyte conductivity (polymer)
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a porous matrix or imbibed in a polymer membrane	150 - 200°C	5 - 400 kW, 100 kW module (liquid PAFC); <10 kW (polymer membrane)	40%[iv]	• Distributed generation	• Suitable for CHP • Increased tolerance to fuel impurities	• Expensive catalysts • Long start-up time • Sulfur sensitivity
Molten Carbonate (MCFC)	Molten lithium, sodium, and/or potassium carbonates, soaked in a porous matrix	600 - 700°C	300 kW - 3 MW, 300 kW module	50%[v]	• Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Suitable for CHP • Hybrid/gas turbine cycle	• High temperature corrosion and breakdown of cell components • Long start-up time • Low power density
Solid Oxide (SOFC)	Yttria stabilized zirconia	500 - 1000°C	1 kW - 2 MW	60%[vi]	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Solid electrolyte • Suitable for CHP • Hybrid/gas turbine cycle	• High temperature corrosion and breakdown of cell components • Long start-up time • Limited number of shutdowns

i NREL Composite Data Product 8, "Fuel Cell System Efficiency," http://www.nrel.gov/hydrogen/docs/cdp/cdp_8.jpg
ii Panasonic Headquarters News Release, "Launch of New 'Ene-Farm' Home Fuel Cell Product More Affordable and Easier to Install," http://panasonic.co.jp/corp/news/official.data/data.dir/2013/01/en130117-5/en130117-5.html
iii G. Mulder et al., "Market-ready stationary 6 kW generator with alkaline fuel cells," ECS Transactions 12 (2008) 743-758
iv Doosan PureCell® Model 400 System Specifications, http://www.doosanfuelcell.com/en/solutions/system.do
v FuelCell Energy DFC300 Product Specifications, http://www.fuelcellenergy.com/assets/DFC300-product-specifications1.pdf
vi Ceramic Fuel Cells Gennex Product Specifications, http://www.cfcl.com.au/Assets/Files/Gennex_Brochure_%28EN%29_Apr-2010.pdf

Figure 43: Comparison of different Fuel Cell Technologies (of Energy, 2015)

Category		Pure gas four-stroke (Low pressure)	Dual-fuel four-stroke (Low pressure)	Dual-fuel two-stroke (Low pressure)	Dual-fuel two-stroke (High pressure)
TECHNICAL CHARACTERISTICS	Typical application	Short-sea		Deep-sea	
	Power range (megawatts)	0.5-10 MW Medium to high speed	1-18 MW Medium speed	5-65 MW Slow speed	2.5-90 MW Slow speed
	Combustion cycle/fuel injection	Otto cycle (pre-mixed)			Diesel (diffusing)
	Gas supply pressure	4-6 bar		<16 bar	>300 bar
	Thermal efficiency	42%-49%	40%-45%	48%-51%	50%-53%
	Issues	Methane slip, knocking, backup fuel	Methane slip, knocking	Methane slip, knocking, pre-ignition	Possible gas leakage at high pressure
LNG EMISSIONS REDUCTION POTENTIAL	GHG	5%-15%	0%-10%	15%-18%	20%-24%
	NOx	85%-90%	75%-90%		25%-30% Require EGR/ SCR
	SOx	>98%			92%-97%
	PM	>99%	95%-98%		N/A
Additional investment needs (ship)		15%-20%			
Other OPEX (ex. fuel)		~0%			
CONVERTER FUEL FLEXIBILITY	Fossil	LNG			
			MGO/HFO		
	Non-fossil	Liquefied biogas (LBG)			
		Synthetic methane (electrofuel)			
			Biodiesel		
			Synthetic diesel (electrofuel)		
CURRENT UPTAKE	LNG ships in operation	29	88	25	
	LNG ships on order	8	53	30	

Key assumptions for estimating emission reduction: All emissions are tank-to-propeller only. Reduction potential is compared with using MGO. GHG (25 Global-Warming Potential), SOx (compared to 0.5 S m/m), PM (per mass).

Note that:

- The engine efficiency is based on a engine load of 25%-100%.
- In addition to the indicated fuel flexibility, technically feasible retrofit options are under development (or exist) to enable other alternative fuels such as ammonia, methanol and hydrogen. There are also options for mixing in alternative fuels, including hydrogen.
- The information is mainly from a comprehensive review of LNG literature (DNV GL, 2019c), though other sources are also considered. Current uptake of LNG is based on data collected from the AFI portal.

Key: EGC, exhaust gas recirculation; SCR, selective catalytic reduction

Figure 44: Key characteristics for engine concepts (DNVGL, 2018)

		PEMFC	HT-PEMFC	SOFC
TECHNICAL CHARACTERISTICS	Typical application	Short-sea / Auxiliary		
	Power/size	<400 kW	<30 kW	>100 kW
	Stack lifetime	Moderate	Unknown	Moderate
	Electrical efficiency	50%–60%		~60%
	Operation temperature	50–90°C	140–200°C	500–1 000°C
	Tolerance for load variations	High	Medium	Low
	Sensitivity of fuel impurities	High	Low	Low
	Maturity	High	Low	Moderate
	Energy density	High	High	Moderate
Air emissions reduction potential on hydrogen (GHG, SOx, NOx, PM)		100%		
Relative cost (among fuel cells)		Low	Moderate	High
FUEL FLEXIBILITY	Fossil	H_2 only	H_2/LNG/MGO/methanol	
	Non-fossil	H_2 only	H_2/LBG/biodiesel/biofuels	
CURRENT UPTAKE	Hydrogen ships on order	Four new ferries are planned to be delivered by 2021		

Note that the emission-reduction potential will change if the fuel cell is run on other fuel.
Key: GHG, greenhouse gas; H2, hydrogen; kW, kilowatts; LBG, liquefied biogas; LNG, liquefied natural gas; MGO, marine gas oil; NOx, nitrogen oxides; PM, particulate matter; SOx, sulphur oxides
Source: Information extracted mainly from DNV GL (2017c), but other sources are also considered.

Figure 45: Key characteristics for fuel cell concepts (DNVGL, 2018)

		NMC (Nickel Manganese Cobalt Oxide)	LFP (Lithium Iron Phosphate)	LTO (Lithium Titanate Oxide)
TECHNICAL CHARACTERISTICS	Typical application	Short-sea (all-electric) to deep-sea (hybrid)		
	Specific power	450-660 W/kg	1 000 W/kg	3 000-5 100 W/kg
	Specific energy density (Gravimetric)	150-220 Wh/kg	90-120 Wh/kg	50-80 Wh/kg
	Specific energy density (Volumetric)	350-580 Wh/L	300-350 Wh/L	110-140 Wh/L
	Thermal stability	Medium	Medium	High
	Flammability	High	Medium	Medium
	Toxicity	High	High	High
	Efficiency	85%-95%		
	Issues	Key properties equilibrium may be difficult to ensure for a stable lifespan	Relatively low specific energy; lower voltage; lower power capabili-ties	Relatively low specific energy; high initial cost
Potential reduction in emissions to air (GHG, SOx, NOx, PM)		100%		
Typical CAPEX		500-1 000 USD/kWh		1 000-2 000 USD/kWh
OPEX		Driven by electricity price		
Fuel flexibility		Feasible for most fuels with hybrid configuration		
CURRENT UPTAKE	Battery ships in operation	93	21	1
	Battery ships on order	79	9	7

Note that:
- The emission reduction assumes 100% battery power, charged from shore.
- The current uptake of ships with batteries is based on Maritime Battery Forum's ship register. There are other cell chemistries that can be used, and the total number of ships with batteries is larger.

Key: CAPEX, capital expense; GHG, greenhouse gas; kg, kilogram; kWh, kilowatt hours; L, litre; NOx, nitrogen oxides; OPEX, operational expense; PM, particulate matter; SOx, sulphur oxides; W, watts; Wh, watt hours

Source: The information is extracted mainly from DNV GL (2019d), but other sources are also considered.

Figure 46: Key characteristics of the three principal lithium-ion battery chemistry's in maritime batteries (DNVGL, 2018)

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D Information of energy densities including storage

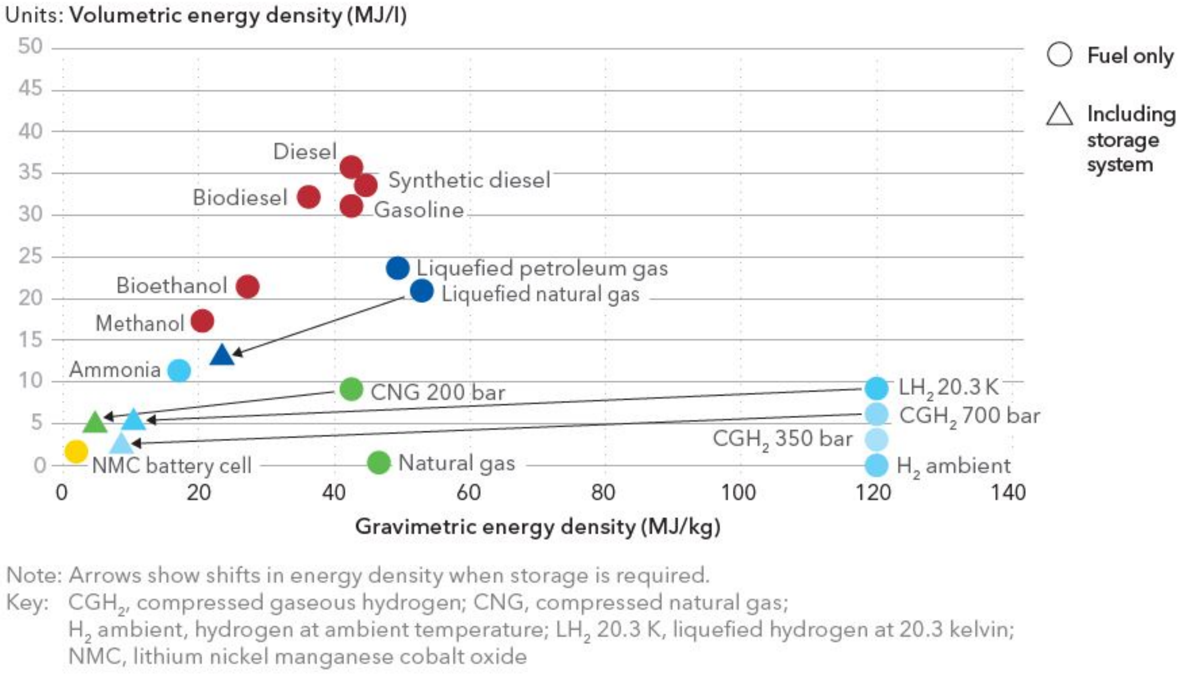

Figure 47: Comparison of gravimetric and volumetric storage density for fuels (DNVGL, 2018)

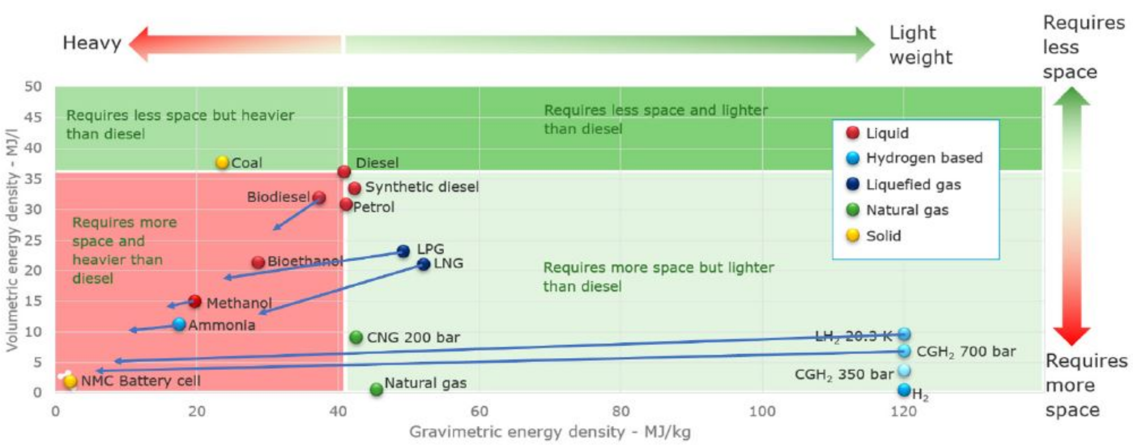

Figure 48: Energy densities for different energy carriers. The arrows represent the impact on density when taking into account the storage systems for the different types of fuel (indicative values only) (DNVGL, 2019)

E Information from literature review

	Heavy Fuel Oil	Marine Gas Oil	Liquid Bio Gas	Methanol	Hydrogen	Ammonia	Ethanol	Hydrotreated Vegetable Oil	Electricity	Average	
Gravimetric energy density	40.0	43.0	53.0	20.0	142.0	22.5	29.7	44.1	<5	44	[MJ/kg]
Volumetric energy density	38.8	34.5	22.0	16.0	10.0	13.6	23.3	34.3	<10	23	[MJ/L]
Emissions	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes		Favorable
Energy costs	36	38	122 (LBG)	84-107 (Bio)	92	6.94-9.27	84-107 (Bio)	72	67-134	84	[USD/MWh]
Capital costs	--	--	+/-	+/-	+	+	+/-	--	+/-		
Maintenance costs	--	--	+/-	+/-	+	+	+/-	--	+/-		
Safety (IGF code)	No	No	Yes	Yes	Unknown	Unknown	Yes	No	No		

Figure 49: Overview of how different aspects compare for the different analysed fuel types from literature review MT54010

F Vessel data

Vessel	Nordic Grace	
Type	Tanker	
Built	2002	
LOA	274.19	[m]
Draft	15.85	[m]
Beam	50	[m]
Speed	14.5	[kn]
Bunker capacity	3850.7	[m^3]
Cargo capacities	173947	[m^3]
Cargo capacities	1094000	[Barrels]
Cargo density	0.8757	[t/m^3]
Ballast capacity	12000	[m^3]
Engine power	18624	[kW]
Cb	0.84	
Lightweight	37170	[t]
Maximum deadweight	149921	[t]
Crew	22	
Max Displacement	182528	[m^3]
Max Displacement	187091	[t]
Admiralty constant	535.47	
Newbuild price	65000000	
Port time	22.56	[h]

Vessel	CMA CGM Louga	
Type	Container Vessel	
Built	2018	
LOA	194.99	[m]
Draft	11.5	[m]
Beam	32.2	[m]
Speed	20	[kn]
Bunker capacity	2400	[m^3]
Cargo capacities		[m^3]
Cargo capacities	2487	[TEU]
Cargo density		[t/m^3]
Ballast capacity	11617	[m^3]
Engine power	16080	[kW]
Cb	0.554	
Lightweight	6651	[t]
Maximum deadweight	34350	[t]
Crew	20	
Max Displacement	40001	[m^3]
Max Displacement	41001	[t]
Admiralty constant	591.57	
Newbuild price	40000000	
Port time	16.8	[h]

Vessel	Ore China	
Type	Ore carrier	
Built	2011	
LOA	359.94	[m]
Draft	23	[m]
Beam	64.99	[m]
Speed	14.8	[kn]
Bunker capacity	8616	[m^3]
Cargo capacities	224427	[m^3]
Cargo capacities	224427	[m^3 Ore]
Cargo density		[t/m^3]
Ballast capacity	190826	[m^3]
Engine power	29400	[kW]
Cb	0.864	
Lightweight	75871	[t]
Maximum deadweight	400606	[t]
Crew	25	
Max Displacement	464856	[m^3]
Max Displacement	476477	[t]
Admiralty constant	672.67	
Newbuild price	140000000	
Port time	49.2	[h]

Table 50: Different vessels used in the study

G Verification of model

Fuel type	**HFO**	
Propulsion system	ICE	
IGF code	N/A	
Special storage tank	N/A	
Gravimetric energy density (incl. storage)	40	[MJ/kg]
Gravimetric energy density (incl. storage)	11111	[kWh/t]
Volumetric energy density (incl. storage)	38.8	[MJ/L]
Volumetric energy density (incl. storage)	10778	[kWh/m^3]
Fuel costs	36	[USD/MWh]
Density (incl. storage)	0.97	[t/m^3]

Problem		
Too much weight	0	[t]
Too much volume	0	[m^3]

Table 51: Running on heavy fuel oil

Extra costs of storage	100	USD/kWh

Amount of stops	0	
Cargo costs	18.66	[USD/t]

Amount of stops	1	
Cargo costs	11.91	[USD/t]

Amount of stops	5	
Cargo costs	7.47	[USD/t]

Amount of stops	20	
Cargo costs	6.21	[USD/t]

Table 52: Increase of fuel storage to extreme value

Mooring/Anchor time	200	[h]
Cargo costs	17.76	[USD/t]

Mooring/Anchor time	250	[h]
Cargo costs	19.24	[USD/t]

Mooring/Anchor time	300	[h]
Cargo costs	20.72	[USD/t]

Table 53: Increase mooring time of extra stop

Daily capital costs	1000000	[USD/day]

Speed	20.0	knots
Cargo costs	89.57	[USD/t]

Speed	10.0	knots
Cargo costs	159.62	[USD/t]

Speed	15.0	knots
Cargo costs	112.47	[USD/t]

Speed	5.0	knots
Cargo costs	303.45	[USD/t]

Table 54: Increase capital costs

Fuel price	1000	[USD/MWh]

Design speed	20.0	knots
Cargo costs	118.81	[USD/t]

Design speed	10.0	knots
Cargo costs	56.57	[USD/t]

Design speed	15.0	knots
Cargo costs	86.40	[USD/t]

Design speed	5.0	knots
Cargo costs	30.36	[USD/t]

Table 55: Increase fuel costs

Fuel type	Methanol ICE

Additional costs for propulsion	0	[USD]
Additional costs for systems	0	[USD]
Cargo costs	8.51	[USD/t]

Fuel type	Methanol FC	
Cargo costs	7.88	[USD/t]

Table 56: No additional costs for fuel cells

Engine type	ICE
Efficiency	0.48

Engine type	ICE
Efficiency	0.80

Cargo costs	4.96	[USD/t]

Cargo costs	3.79	[USD/t]

Table 57: Efficiency increase

Too much weight	71952	[t]
Too much Volume	30024	[m^3]
Additional costs for storage system	11302841379	[USD]

Table 58: Battery on long distance

H Results

Fuel type	1	2	3	4	5	6	7	8	9	10	11	12	13	14	14.5 (speed)	Extra stop	Cargo loss
HFO	21.09 [USD/t]	10.93	7.68	6.16	5.34	4.88	4.61	4.47	4.43	4.44	4.50	4.60	4.73	4.88	4.96	4.96	4.96
Methanol ICE	21.38	11.53	8.58	7.38	6.88	6.73	6.80	6.99	7.28	7.64	8.05	8.50				9.89	9.81
Methanol FC	22.19	11.86	8.75	7.47	6.94	6.80	6.89	7.15	7.53	7.99	8.54	9.16	9.83	10.56	10.95		
Hydrogen ICE	21.47	11.70	8.85	7.74	7.33	7.28	7.43	7.73	8.11	8.57						11.92	11.75
Hydrogen FC	22.26	12.00	8.96	7.75	7.29	7.21	7.37	7.76	8.22	8.78	9.42	10.13				12.36	12.25
Ammonia ICE	21.3	11.35	8.32	7.03	6.43	6.19	6.16	6.26	6.45	6.77						8.71	8.6
Ammonia FC	22.13	11.78	8.68	7.45	7.01	6.99	7.26	7.72	8.35	9.11	10.08	11.11	12.25			14.29	14.19
Ethanol ICE	21.36	11.48	8.51	7.28	6.75	6.58	6.61	6.78	7.04	7.37	7.75	8.17	8.63			9.44	9.38
Ethanol FC	22.16	11.81	8.68	7.38	6.82	6.66	6.73	6.96	7.31	7.76	8.28	8.87	9.52	10.22	10.59		
HVO	21.27	11.29	8.23	6.9	6.28	6.01	5.94	6.01	6.16	6.39	6.66	6.97	7.32	7.69	7.89	7.89	7.89
NMC Battery	25.41	18.34	18.52	20.56												72.34	67.5

Table 59: Transport costs for the Nordic Grace sailing from Jeddah to Algeciras on different speeds and fuels

Fuel	Too much weight (14.5 knots) [t]	Size of tank at 6 [kn] [m³]	No. of stops	1	2	3	4	5	6	7	8	9	10	11	12	13	14	14.5 (speed)
Hydrogen	1634	746	0	21.47 [USD/t]	11.70	8.85	7.74	7.33	7.28	7.43	7.73	8.11	8.57					
Hydrogen	545	373	1	21.44	11.62	8.71	7.55	7.1	7	7.12	7.37	7.72	8.15	8.64	9.18			
Hydrogen	182	249	2	21.44	11.6	8.68	7.49	7.04	6.93	7.03	8	7.62	8.04	8.53	9.07	9.66		
Hydrogen	0	187	3	21.44	11.6	8.68	7.46	7.02	6.91	7.01	7.25	7.59	8.02	8.51	9.05	9.65	10.29	10.63
Hydrogen	0	68	10	21.54	11.69	8.76	7.58	7.12	7.01	7.13	7.4	7.78	8.24	8.77	9.37	10.02	10.37	11.11

Table 60: Results extra stop while using hydrogen in an internal combustion engine

Fuel	**Too much weight (14.5 knots)**	**Size of tank 6[kn]**	**Mooring time [h]**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**14.5 (speed)**
Hydrogen	545	373	2	21.44 [USD/t]	11.62	8.71	7.55	7.1	7	7.12	7.37	7.72	8.15	8.64	9.18			
Hydrogen	545	373	5	21.46	11.64	8.74	7.59	7.14	7.05	7.17	7.43	7.8	8.24	8.74	9.29			
Hydrogen	545	373	10	21.5	11.69	8.79	7.64	7.2	7.12	7.26	7.54	7.92	8.38	8.9	9.48			

Table 61: Results 1 extra stop with different mooring times using hydrogen in an internal combustion engine

Fuel	Too much weight (14.5 knots)	Size of tank 6[kn]	Mooring time [h]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	14.5 (speed)
Hydrogen	182	249	2	21.44 [USD/t]	11.6	8.68	7.49	7.04	6.93	7.03	7.25	7.62	8.04	8.53	9.07	9.66		
Hydrogen	182	249	5	21.49	11.65	8.74	7.57	7.11	7.02	7.14	7.4	7.77	8.21	8.72	9.29	9.91		
Hydrogen	182	249	10	21.57	11.74	8.84	7.69	7.24	7.17	7.32	7.61	8.01	8.49	9.05	9.66	10.33		

Table 62: Results 2 extra stop with different mooring times while using hydrogen in an internal combustion engine

Fuel	Too much weight 14.5 [kn]	Size of storage tank at 7 [kn]	No. of stops	1	2	3	4	5	6	7	8	9	10	11	12	13
Ammonia	1271	508		21.3 [USD/t]	11.35	8.32	7.03	6.43	6.19	6.16	6.26	6.45	6.77	7		
Ammonia	363	508		21.34	11.39	8.36	7.07	6.48	6.25	6.23	6.35	6.56	6.85	7.19	7.58	8.01

Table 63: Results of 1 extra stop while using Ammonia

Fuel type	Too much weight (14.5 [kn]) [t]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20 (speed)	20 (stop)	20 (cargo)
HFO	0	34.93 [USD/t]	17.97	12.47	9.84	8.36	7.64	6.89	6.54	6.33	6.22	6.18	6.21	6.28	6.39	6.53	6.7	6.89	7.11	7.34	7.59		
Methanol ICE	220	35.25	18.62	13.45	11.16	10.03	9.49	9.28	9.3	9.46	9.74	10.09	10.52	10.99	11.52	12.08	12.67	13.3	13.95			15.59	15.43
Methanol FC	0	37.18	19.51	13.97	11.49	10.26	9.65	9.43	9.45	9.65	9.98	10.43	10.96	11.57	12.24	12.98	13.78	14.64	15.55	16.51	17.52		
Hydrogen ICE	597	35.28	18.7	13.57	11.33	10.24	9.75	9.6	9.67	9.9	10.24	10.68	11.19	11.75	12.38	13.05	13.77					17.54	17.37
Hydrogen FC	0	37.22	19.57	14.07	11.62	10.4	9.83	9.63	9.68	9.91	10.28	10.76	11.33	11.98	12.7	13.5	14.36	15.82	16.72	17.32	18.43		
Ammonia ICE	464	35.15	18.43	13.16	10.78	9.54	8.9	8.59	8.50	8.56	8.73	8.99	9.31	9.68	10.10	10.56	11.06					13.67	13.54
Ammonia FC	0	37.12	19.4	13.86	11.41	10.23	9.72	9.62	9.81	10.21	10.79	11.52	12.38	13.36	14.47	15.68	17.00	18.43	19.97	21.61	23.37		
Ethanol ICE	85	35.22	18.56	13.37	11.05	9.89	9.31	9.08	9.06	9.2	9.44	9.76	10.15	10.59	11.08	11.61	12.17	12.76	13.37	14.01	14.71		
Ethanol FC	0	37.16	19.46	13.9	11.4	10.13	9.5	9.25	9.25	9.42	9.72	10.14	10.64	11.22	11.87	12.58	13.34	14.17	15.04	15.97	16.95		
HVO	0	35.12	18.37	13.07	10.65	9.38	8.69	8.35	8.22	8.24	8.36	8.57	8.83	9.15	9.51	9.91	10.34	10.8	11.28	11.78	12.31		
NMC Battery	4938	38.69	22.54	18.55	17.62	17.94	18.92	20.28	21.91													57.1	58.4

Table 64: Overview of results of the CMA CGM Louga sailing from Rotterdam to St. Petersburg

Fuel type	Too much weight (14.5 [kn]) [t]	Size of tank [m³]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	14.8 (speed)	14.8 (stop)	14.8 (cargo)
HFO	0				26.17 [USD/t]	20.68	17.62	15.79	14.66	13.97	13.57	13.39	13.36	13.46	13.64	13.9	14.15		
Methanol ICE	4347				28.72	24.1	21.91	20.95	20.71	20.91	21.41	22.14	23.02					27.72	27.65
Methanol FC	2402				29.05	24.23	21.96	21.01	20.84	21.19	21.91	22.9	24.11	25.51				30.48	30.42
Hydrogen ICE	11800	5387 m³			32.31	28.9	27.94	28.21	29.21	30.66								47.5	47.28
Hydrogen FC	8624	4701 m³			32.14	28.35	27.12	27.2	28.06	29.44	31.18							46.66	46.48
Ammonia ICE	9178	6895 m³			28.11	23.28	20.89	19.72	19.26	19.25								24.87	24.77
Ammonia FC	6510	3385 m³			28.94	24.27	22.25	21.64	21.91	22.8	24.15							38.98	38.85
Ethanol ICE	1686				28.51	23.81	21.55	20.52	20.2	20.33	20.76	21.41	22.22	23.15				26.4	26.35
Ethanol FC	79				28.87	23.98	21.65	20.64	20.4	20.68	21.33	22.26	23.41	24.74	26.24	27.87		29.32	29.28
HVO	0				27.71	22.74	20.2	18.9	18.3	18.15	18.29	18.66	19.18	19.82	20.57	21.39	22.09		
NMC Battery	111362				151.4													914.58	871.18

Table 65: Overview of results of the Ore China sailing from Santos to Dalian

Fuel type	Too much weight (14.5 [kn]) [t]	Size of tank on deck [m³]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	14.5 (speed)	Extra stop	Cargo loss
HFO	0		21.09 [USD/t]	10.93	7.68	6.16	5.34	4.88	4.61	4.47	4.43	4.44	4.50	4.60	4.73	4.88	4.96	4.96	4.96
Methanol ICE	602		21.38	11.53	8.58	7.38	6.88	6.73	6.80	6.99	7.28	7.64	8.05	8.50				9.81	9.89
Methanol FC	0		22.19	11.86	8.75	7.47	6.94	6.80	6.89	7.15	7.53	7.99	8.54	9.16	9.83	10.56	10.95		
Hydrogen ICE	1634	1119	21.47	11.70	8.85	7.74	7.33	7.28	7.43	7.73	8.11	8.57						11.92	11.75
Hydrogen FC	546	977	22.26	12.00	8.96	7.75	7.29	7.21	7.37	7.76	8.22	8.78	9.42	10.13				12.36	12.25
Ammonia ICE	1271	560	21.3	11.35	8.32	7.03	6.43	6.19	6.16	6.26	6.45	6.77						8.71	8.6
Ammonia FC	340	488	22.13	11.78	8.68	7.45	7.01	6.99	7.26	7.72	8.35	9.11	10.08	11.11	12.25			14.29	14.19
Ethanol ICE	233		21.36	11.48	8.51	7.28	6.75	6.58	6.61	6.78	7.04	7.37	7.75	8.17	8.63			9.44	9.38
Ethanol FC	0		22.16	11.81	8.68	7.38	6.82	6.66	6.73	6.96	7.31	7.76	8.28	8.87	9.52	10.22	10.59		
HVO	0		21.27	11.29	8.23	6.9	6.28	6.01	5.94	6.01	6.16	6.39	6.66	6.97	7.32	7.69	7.89	7.89	7.89
NMC Battery	14737		25.41	18.34	18.52	20.56												72.34	67.5

Table 66: Overview of results of the Nordic Grace sailing from Jeddah to Algeciras

Route	Fuel	Technology	Too much weight 14.5 [kn]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	14.5 (speed)	Extra stop	Cargo loss
Rotterdam - St. Petersburg	Hydrogen	ICE	954	12.52 [USD/t]	6.8	5.1	4.42	4.15	4.09	4.16	4.31	4.52	4.82	5.12					6.56	6.43
Jeddah - Algeciras	Hydrogen	ICE	1634	21.47	11.70	8.85	7.74	7.33	7.28	7.50	7.82	8.24	8.73						11.92	11.75
Santos - Dalian	Hydrogen	ICE	7629	103.2	58.74	47.09	44.27	44.51	46.54	49.72	53.71								79.4	81.82

Table 67: Results of sailing different routes with the Nordic Grace using Hydrogen ICE

Route	Fuel	Technology	Too much weight 14.5 [kn]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	14.5 (speed)	Extra stop	Cargo loss
Rotterdam - St. Petersburg	Methanol	FC	0	12.96 [USD/t]	6.94	5.13	4.37	4.06	3.98	4.04	4.2	4.43	4.72	5.06	5.44	5.86	6.33	6.57		
Jeddah - Algeciras	Methanol	FC	0	22.19	11.86	8.75	7.47	6.94	6.80	6.89	7.15	7.53	7.99	8.54	9.16	9.83	10.56	10.95		
Santos - Dalian	Methanol	FC	1497			41.29	35.5	32.83	32.19	32.62	33.79	35.47	37.55	39.95	42.62				50.55	50.79

Table 68: Results of sailing different routes with the Nordic Grace using methanol FC

	Fuel	Technology	Too much weight [t]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	14.5 (speed)	Extra stop	Cargo loss
Rotterdam - St. Petersburg	HFO	ICE	0	12.33 [USD/t]	6.42	4.52	3.64	3.16	2.89	2.73	2.66	2.63	2.64	2.68	2.75	2.83	2.93	2.98	2.98	2.98
Jeddah - Algeciras	HFO	ICE	0	21.09	10.93	7.68	6.16	5.34	4.88	4.61	4.47	4.43	4.44	4.50	4.60	4.73	4.88	4.96	4.96	4.96
Santos - Dalian	HFO	ICE	0	99.51	51.33	35.96	28.8	24.93	22.72	21.46	20.79	20.53	20.55	20.78	21.17	21.69	22.3	22.64	22.64	22.64

Table 69: Results of sailing different routes with the Nordic Grace using methanol HFO

	-50%		-40%		-30%		-20%		-10%		Base case		10%		20%		30%		40%		50%	
HFO	3.41 [USD/t]	12 [kn]	3.63	11 [kn]	3.85	11 [kn]	4.05	10 [kn]	4.24	10 [kn]	4.43	9 [kn]	4.60	9 [kn]	4.77	9 [kn]	4.93	8 [kn]	5.09	8 [kn]	5.24	8 [kn]
Price growth	-23.02%		-18.06%		-13.09%		-8.58%		-4.29%		0.00%		3.84%		7.67%		11.29%		14.90%		18.28%	

	-50%		-40%		-30%		-20%		-10%		Base case		10%		20%		30%		40%		50%	
Methanol ICE	4.97	8 [kn]	5.38	8 [kn]	5.74	7 [kn]	6.10	7 [kn]	6.44	6 [kn]	6.73	6 [kn]	7.03	6 [kn]	7.33	6[kn]	7.62	5 [kn]	7.87	5 [kn]	8.11	5 [kn]
Price growth	-26.15%		-20.06%		-14.71%		-9.36%		-4.31%		0.00%		4.46%		8.92%		13.22%		16.94%		20.51%	

	-50%		-40%		-30%		-20%		-10%		Base case		10%		20%		30%		40%		50%	
Methanol FC	5.36	7 [kn]	5.67	7 [kn]	5.97	7 [kn]	6.27	6 [kn]	6.54	6 [kn]	6.80	6 [kn]	7.06	6 [kn]	7.32	6 [kn]	7.58	6 [kn]	7.80	5 [kn]	8.01	5 [kn]
Price growth	-21.18%		-16.62%		-12.21%		-7.79%		-3.82%		0.00%		3.82%		7.65%		11.47%		14.71%		17.79%	

	-50%		-40%		-30%		-20%		-10%		Base case		10%		20%		30%		40%		50%	
Hydrogen ICE	5.79	7 [kn]	6.12	6 [kn]	6.41	6 [kn]	6.70	6 [kn]	6.99	6 [kn]	7.28	6 [kn]	7.56	6 [kn]	7.80	5 [kn]	8.04	5 [kn]	8.28	5 [kn]	8.52	5 [kn]
Price growth	-20.47%		-15.93%		-11.95%		-7.97%		-3.98%		0.00%		3.85%		7.14%		10.44%		13.74%		17.03%	

	-50%		-40%		-30%		-20%		-10%		Base case		10%		20%		30%		40%		50%	
Hydrogen FC	5.88	7 [kn]	6.18	7 [kn]	6.45	6 [kn]	6.70	6 [kn]	6.96	6 [kn]	7.21	6 [kn]	7.46	6 [kn]	7.70	5 [kn]	7.91	5 [kn]	8.12	5 [kn]	8.33	5 [kn]
Price growth	-18.45%		-14.29%		-10.54%		-7.07%		-3.47%		0.00%		3.47%		6.80%		9.71%		12.62%		15.53%	

Table 70: Transport costs increase per fuel price scenario when sailing with the Nordic Grace from Jeddah to Algeciras

	-50%		-40%		-30%		-20%		-10%		Base case		10%		20%		30%		40%		50%	
Ammonia ICE	4.59	9 [kn]	4.95	8 [kn]	5.28	8 [kn]	5.59	7 [kn]	5.87	7 [kn]	6.16	7 [kn]	6.43	6 [kn]	6.67	6 [kn]	6.91	6 [kn]	7.16	6 [kn]	7.4	6 [kn]
Price growth	-25.49%		-19.64%		-14.29%		-9.25%		-4.71%		0.00%		4.38%		8.28%		12.18%		16.23%		20.13%	

	-50%		-40%		-30%		-20%		-10%		Base case		10%		20%		30%		40%		50%	
Ammonia FC	5.94	6 [kn]	6.15	6 [kn]	6.36	6 [kn]	6.57	6 [kn]	6.78	6 [kn]	6.99	6 [kn]	7.18	5 [kn]	7.35	5 [kn]	7.53	5 [kn]	7.7	5 [kn]	7.88	5 [kn]
Price growth	-15.02%		-12.02%		-9.01%		-6.01%		-3.00%		0.00%		2.72%		5.15%		7.73%		10.16%		12.73%	

	-50%		-40%		-30%		-20%		-10%		Base case		10%		20%		30%		40%		50%	
Ethanol ICE	4.87	9 [kn]	5.25	8 [kn]	5.61	7 [kn]	5.95	7 [kn]	6.28	7 [kn]	6.58	6 [kn]	6.86	6 [kn]	7.14	6 [kn]	7.43	6 [kn]	7.68	5 [kn]	7.92	5 [kn]
Price growth	-25.99%		-20.21%		-14.74%		-9.57%		-4.56%		0.00%		4.26%		8.51%		12.92%		16.72%		20.36%	

	-50%		-40%		-30%		-20%		-10%		Base case		10%		20%		30%		40%		50%	
Ethanol FC	5.28	7 [kn]	5.57	7 [kn]	5.86	7 [kn]	6.15	7 [kn]	6.41	6 [kn]	6.66	6 [kn]	6.91	6 [kn]	7.15	6 [kn]	7.40	6 [kn]	7.46	6 [kn]	7.84	5 [kn]
Price growth	-20.72%		-16.37%		-12.01%		-7.66%		-3.75%		0.00%		3.75%		7.36%		11.11%		12.01%		17.72%	

	-50%		-40%		-30%		-20%		-10%		Base case		10%		20%		30%		40%		50%	
HVO	4.43	9 [kn]	4.77	9 [kn]	5.09	8 [kn]	5.39	8 [kn]	5.67	7 [kn]	5.94	7 [kn]	6.21	7 [kn]	6.46	6 [kn]	6.86	6 [kn]	6.91	6 [kn]	7.14	6 [kn]
Price growth	-25.42%		-19.70%		-14.31%		-9.26%		-4.55%		0.00%		4.55%		8.75%		15.49%		16.33%		20.20%	

	-50%		-40%		-30%		-20%		-10%		Base case		10%		20%		30%		40%		50%	
NMC Battery	18.07	2 [kn]	18.12	2 [kn]	18.18	2 [kn]	18.23	2 [kn]	18.28	2 [kn]	18.34	2 [kn]	18.39	2 [kn]	18.45	2 [kn]	18.5	2 [kn]	18.55	2 [kn]	18.61	2 [kn]
Price growth	-1.47%		-1.20%		-0.87%		-0.60%		-0.33%		0.00%		0.27%		0.60%		0.87%		1.15%		1.47%	

Table 71: Transport costs increase per fuel price scenario when sailing with the Nordic Grace from Jeddah to Algeciras

	Too much weight (14.5 knots)	Too much Volume (14.5 knots)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	14.5 (speed)
Fuel price -50% HFO	0	0	21 [USD/t]	10.75	7.4	5.79	4.88	4.31	3.95	3.71	3.56	3.47	3.42	3.41	3.43	3.47	3.5
Base fuel price HFO	0	0	21.09	10.93	7.68	6.16	5.34	4.88	4.61	4.47	4.43	4.44	4.50	4.60	4.73	4.88	4.96
Fuel price +50% HFO	0	0	21.18	11.11	7.95	6.53	5.81	5.44	5.28	5.24	5.29	5.41	5.58	5.79	6.02	6.28	6.42

	Too much weight (14.5 knots)	Too much Volume (14.5 knots)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	14.5 (speed)
Fuel price -50% Methanol ICE	602	0	21.15	11.05	7.86	6.4	5.65	5.24	5.04	4.97	4.99	5.07	5.2	5.37			
Base fuel price 0% Methanol ICE	602	0	21.38	11.53	8.58	7.38	6.88	6.73	6.80	6.99	7.28	7.64	8.05	8.50			
Fuel price +50% Methanol ICE	602	0	21.62	12.01	9.31	8.36	8.11	8.23	8.55	9.02	9.58	10.21	10.9	11.63			

	Too much weight (14.5 knots)	Too much Volume (14.5 knots)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	14.5 (speed)
Fuel price -50% Methanol FC	0	0	21.98	11.44	8.11	6.61	5.86	5.49	5.36	5.39	5.52	5.75	6.06	6.42	6.85	7.32	7.58
Base fuel price 0% Methanol FC	0	0	22.19	11.86	8.75	7.47	6.94	6.80	6.89	7.15	7.53	7.99	8.54	9.16	9.83	10.56	10.95
Fuel price +50% Methanol FC	0	0	22.39	12.28	9.38	8.32	8.01	8.1	8.42	8.91	9.53	10.24	11.03	11.89	12.82	13.8	14.32

	Too much weight (14.5 knots)	Volume on deck at cost-effective option	1	2	3	4	5	6	7	8	9	10	11	12	13	14	14.5 (speed)
Fuel price -50% Hydrogen ICE	1634	1015	21.24	11.23	8.14	6.79	6.13	5.83	5.79	5.84	5.98	6.2					
Base fuel price 0% Hydrogen ICE	1634	746	21.47	11.70	8.85	7.74	7.33	7.28	7.43	7.73	8.11	8.57					
Fuel price +50% Hydrogen ICE	1634	518	21.7	12.17	9.55	8.68	8.52	8.72	9.21	9.8	10.5	11.26					

	Too much weight (14.5 knots)	Volume on deck at cost-effective option	1	2	3	4	5	6	7	8	9	10	11	12	13	14	14.5 (speed)
Fuel price -50% Hydrogen FC	546	2188	22.06	11.6	8.35	6.92	6.24	5.95	5.88	6.03	6.26	6.57	6.96	7.42			
Base fuel price 0% Hydrogen FC	546	1809	22.26	12.00	8.96	7.75	7.29	7.21	7.37	7.76	8.22	8.78	9.42	10.13			
Fuel price +50% Hydrogen FC	546	1158	22.46	12.41	9.58	8.58	8.33	8.47	8.85	9.49	10.18	10.98	11.87	12.84			

Table 72: Overview of results when fuel price is adjusted when sailing with the Nordic Grace from Jeddah to Algeciras

	Too much weight (14.5 knots)	Volume on deck at cost-effective option	1	2	3	4	5	6	7	8	9	10	11	12	13	14	14.5 (speed)	Extra stop	Cargo loss
Fuel price -50% Ammonia ICE	1271	839	21.11	10.96	7.73	6.24	5.43	4.99	4.74	4.62	4.59	4.67						5.46	5.39
Base fuel price 0% Ammonia ICE	1271	508	21.3	11.354	8.32	7.03	6.43	6.19	6.16	6.26	6.45	6.77						8.71	8.6
Fuel price +50% Ammonia ICE	1271		21.49	11.74	8.91	7.82	7.43	7.4	7.58	7.89	8.3	8.86						11.96	11.81

	Too much weight (14.5 knots)	Volume on deck at cost-effective option	1	2	3	4	5	6	7	8	9	10	11	12	13	14	14.5 (speed)	Extra stop	Cargo loss
Fuel price -50% Ammonia FC	340	1901	21.96	11.44	8.17	6.76	6.14	5.94	6.02	6.29	6.73	7.29	8.06	8.87	9.8			11.49	11.41
Base fuel price 0% Ammonia FC	340	1901	22.13	11.78	8.68	7.45	7.01	6.99	7.26	7.72	8.35	9.11	10.08	11.11	12.25			14.29	14.19
Fuel price +50% Ammonia FC	340	1901	22.3	12.12	9.19	8.14	7.88	8.05	8.49	9.15	9.96	10.92	12.11	13.34	14.69			17.09	16.97

	Too much weight (14.5 knots)	Too much Volume (14.5 knots)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	14.5 (speed)	Extra stop	Cargo loss
Fuel price -50% Ethanol ICE	233		21.13	11.02	7.82	6.35	5.58	5.16	4.95	4.87	4.87	4.94	5.05	5.2	5.39			5.75	5.72
Base fuel price 0% Ethanol ICE	233		21.36	11.48	8.51	7.28	6.75	6.58	6.61	6.78	7.04	7.37	7.75	8.17	8.63			9.44	9.38
Fuel price +50% Ethanol ICE	233		21.59	11.93	9.2	8.2	7.92	7.99	8.27	8.7	9.21	9.8	10.45	11.14	11.87			13.12	13.02

	Too much weight (14.5 knots)	Too much Volume (14.5 knots)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	14.5 (speed)	Extra stop	Cargo loss
Fuel price -50% Ethanol FC	0	0	21.97	11.42	8.08	6.57	5.8	5.43	5.28	5.29	5.42	5.64	5.93	6.28	6.69	7.15	7.4		
Base fuel price 0% Ethanol FC	0	0	22.16	11.81	8.68	7.38	6.82	6.66	6.73	6.96	7.31	7.76	8.28	8.87	9.52	10.22	10.59		
Fuel price +50% Ethanol FC	0	0	22.36	12.21	9.28	8.19	7.84	7.89	8.18	8.64	9.21	9.88	10.64	11.46	12.35	13.29	13.78		

	Too much weight (14.5 knots)	Too much Volume (14.5 knots)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	14.5 (speed)	Extra stop	Cargo loss
Fuel price -50% HVO	0		21.09	10.93	7.68	6.16	5.34	4.88	4.61	4.47	4.43	4.44	4.5	4.6	4.73	4.88	4.96		
Base fuel price 0% HVO	0		21.27	11.29	8.23	6.9	6.28	6.01	5.94	6.01	6.16	6.39	6.66	6.97	7.32	7.69	7.89		
Fuel price +50% HVO	0		21.45	11.66	8.78	7.65	7.21	7.14	7.27	7.54	7.9	8.33	8.82	9.35	9.91	10.5	10.81		

	Too much weight (14.5 knots)	Too much Volume (14.5 knots)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	14.5 (speed)	Extra stop	Cargo loss
Fuel price -50% Battery			25.27	18.07	18.11	20.01												69.76	65.09
Base fuel price 0% Battery			25.41	18.34	18.52	20.56												72.34	67.5
Fuel price +50% Battery			25.54	18.61	18.93	21.11												74.92	69.9

Table 73: Overview of results when fuel price is adjusted when sailing with the Nordic Grace from Jeddah to Algeciras

	37,500 (-50%)			50,000 (-33.33%)			75,000		100,000 (+33.33%)			112,500 (+50%)		
	Costs [USD/t]	Speed [kn]	Transport costs increase	Costs [USD/t]	Speed [kn]	Transport costs increase	Costs [USD/t]	Speed	Costs [USD/t]	Speed [kn]	Transport costs increase	Costs [USD/t]	Speed [kn]	Transport costs increase
HFO	4.03	9	-9.03%	4.16	9	-6.09%	4.43	9	4.68	10	5.64%	4.8	10	8.35%
Methanol ICE	6.16	6	-8.47%	6.35	6	-5.65%	6.73	6	7.12	6	5.79%	7.3	7	8.47%
Methanol FC	6.22	6	-8.53%	6.41	6	-5.74%	6.8	6	7.18	6	5.59%	7.37	6	8.38%
Hydrogen ICE	6.64	5	-8.79%	6.87	5	-5.63%	7.28	6	7.66	6	5.22%	7.85	6	7.83%
Hydrogen FC	6.6	5	-8.46%	6.82	6	-5.41%	7.21	6	7.59	6	5.27%	7.79	6	8.04%
Ammonia ICE	5.61	6	-8.93%	5.81	6	-5.68%	6.16	7	6.49	7	5.36%	6.66	7	8.12%
Ammonia FC	6.32	5	-9.59%	6.55	6	-6.29%	6.99	6	7.38	6	5.58%	7.57	6	8.30%
Ethanol ICE	6	6	-8.81%	6.19	6	-5.93%	6.58	6	6.95	7	5.62%	7.11	7	8.05%
Ethanol FC	6.08	6	-8.71%	6.27	6	-5.86%	6.66	6	7.04	6	5.71%	7.23	7	8.56%
HVO	5.43	6	-8.59%	5.61	7	-5.56%	5.94	7	6.27	7	5.56%	6.44	7	8.42%
Battery	16.66	2	-9.16%	17.22	2	-6.11%	18.34	2	19.27	3	5.07%	19.65	3	7.14%

Table 74: Influence on minimized transport costs when crew wages are varied, when sailing the Nordic Grace from Jeddah to Algeciras

	360 days		300 days		Percentage
HFO	4.43	9 [kn]	4.96	11 [kn]	11.96%
Methanol ICE	6.73	6 [kn]	7.43	7 [kn]	10.40%
Methanol FC	6.8	6 [kn]	7.61	6 [kn]	11.91%
Hydrogen ICE	7.28	6 [kn]	8.13	6 [kn]	11.68%
Hydrogen FC	7.21	6 [kn]	8.12	6 [kn]	12.62%
Ammonia ICE	6.16	7 [kn]	6.8	7 [kn]	10.39%
Ammonia FC	6.99	6 [kn]	7.95	6 [kn]	13.73%
Ethanol ICE	6.58	6 [kn]	7.25	7 [kn]	10.18%
Ethanol FC	6.66	6 [kn]	7.47	6 [kn]	12.16%
HVO	5.94	7 [kn]	6.58	8 [kn]	10.77%
Battery	18.34	2 [kn]	21.83	2 [kn]	19.03%

Table 75: Influence of amount of running days on minimized transport costs when sailing the Nordic Grace from Jeddah to Algeciras

	Fuel margin				
	10.00%		20.00%		
	Costs [USD/t]	Speed [kn]	Costs [USD/t]	Speed [kn]	Transport costs increase
HFO	4.43	9 [kn]	4.58	9 [kn]	3.39%
Methanol ICE	6.73	6 [kn]	7.01	6 [kn]	4.16%
Methanol FC	6.8	6 [kn]	7.03	6 [kn]	3.38%
Hydrogen ICE	7.28	6 [kn]	7.59	5 [kn]	4.26%
Hydrogen FC	7.21	6 [kn]	7.49	6 [kn]	3.88%
Ammonia ICE	6.16	7 [kn]	6.41	6 [kn]	4.06%
Ammonia FC	6.99	6 [kn]	7.17	5 [kn]	2.58%
Ethanol ICE	6.58	6 [kn]	6.83	6 [kn]	3.80%
Ethanol FC	6.66	6 [kn]	6.88	6 [kn]	3.30%
HVO	5.94	7 [kn]	6.18	7 [kn]	4.04%
Battery	18.34	2 [kn]	19.01	2 [kn]	3.65%

Table 76: Influence of fuel margin on minimized transport costs, when sailing the Nordic Grace from Jeddah to Algeciras

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	14.5 (speed)	Extra stop	Cargo loss
HFO	25.74 [USD/t]	13.26	9.23	7.31	6.24	5.6	5.2	4.95	4.81	4.74	4.73	4.76	4.82	4.91	4.96		
Methanol ICE	26.03	13.86	10.13	8.53	7.78	7.46	7.38	7.47	7.67	7.95	8.28	8.66				9.89	9.81
Methanol FC	54.87	28.31	19.74	15.68	13.43	12.08	11.25	10.76	10.48	10.36	10.36	10.45	10.61	10.82	10.95		
Hydrogen ICE	26.12	14.03	10.4	8.88	8.22	8	8.09									11.79	11.75
Hydrogen FC	50.15	26.04	18.34	14.76	12.82	11.72	11.09	10.87	10.78	10.83	11	11.26				12.36	12.25
Ammonia ICE	25.95	13.68	9.87	8.17	7.33	6.91	6.75									8.71	8.6
Ammonia FC	109.27	55.63	37.98	29.34	24.31	21.08	18.89	17.34	16.23	15.42	14.99	14.6				14.29	14.19
Ethanol ICE	26.01	13.81	10.06	8.43	7.65	7.3	7.2	7.26	7.43	7.67	7.98	8.33				9.44	9.38
Ethanol FC	54.85	28.26	19.67	15.59	13.31	11.94	11.09	10.57	10.27	10.13	10.1	10.16	10.29	10.48	10.59		
HVO	25.92	13.62	9.78	8.05	7.18	6.73	6.53	6.49	6.55	6.69	6.89	7.13	7.41	7.72	7.89		

Table 77: Transport costs when capital costs and weight of engine, or fuel cell is fixed, when sailing the Nordic Grace from Jeddah to Algeciras

I Model

In this section screenshots of the developed model are shown.

Vessel part

Vessel	Nordic Grace	
Type	Tanker	
Built	2002	
LOA	274.19	[m]
Draft	15.85	[m]
Beam	50	[m]
Speed	14.5	[kn]
Bunker capacity	3850.7	[m3]
Cargo capacities	173947	[m3]
Cargo capacities	1094000	[Barrels]
Cargo density	0.8757	[t/m3]
Ballast capacity	12000	[m3]
Engine power	18624	[kW]
Cb	0.84	
Lightweight	37170	[t]
Maximum deadweight	149921	[t]
Crew	22	
Max Displacement	182528	[m3]
Max Displacement	187091	[t]
Admiralty constant	535	
Newbuild price	65000000	[USD]
Port time	22.56	[h]

Operation	Arabia - West-Europe	
Distance	2570	[NM]
Sailing time	177.24	[h]
Port time	22.56	[h]
Duration voyage	200	[h]
NCR	14899	kW
Energy needed	2640755	[kWh]
Fuel margin	0.1	
Engine efficiency	0.48	
Fuel needed	6051730	[kWh]
Fuel needed HFO	545	[t]
Fuel needed HFO	562	[m³]
Max cargo on operation	148951	[t]
Max cargo on operation	173947	[m³]
Roundrips per year	22	
Capacity per year	3220547	[t/year]

Energy		
Engine type	FC	
Efficiency	0.55	
NCR	14899	[kW]
Power	18624	[kW]
Fuel marge	0.10	
New speed	14.5	[kn]
Power for new speed	18624	[kW]
NCR for new speed	14899	kW
Duration on sea	177	[h]
Energy needed	2640755	[kWh]
Fuel needed	5281510	[kWh]

Fuel part

Fuel type	Methanol FC	
Propulsion system	FC	
IGF code	Ballast	
Special storage tank	Ballast	
Gravimetric energy density (incl. storage)	19	[MJ/kg]
Gravimetric energy density (incl. storage)	5278	[kWh/t]
Volumetric energy density (incl. storage)	15	[MJ/L]
Volumetric energy density (incl. storage)	4167	[kWh/m³]
Fuel costs	95	[USD/MWh]
Density (incl. storage)	0.79	[t/m³]

Propulsion system	FC	
Volumetric energy density	90	[kW/m³]
Gravimetric energy density	83	[kW/t]
Costs of system	5976	[USD/kW]

IGF code	Ballast	
Fuel storage in cargo space?	TBD	
Loss of cargo space	TBD	

Special storage tank	Ballast	
Extra costs of storage	0.11	[USD/kWh]

Volume part

Tanks	
IGF code	Ballast
Special storage space	Ballast

Fuel storage space		
Fuel capacity	3465.63	[m³]
On right location	Ballast	
Ballast capacity	12000	
Cargo loss	0	[m³]
Fuel volume needed	1268	[m³]
Too much	0	[m³]
Cargo capacity	173947	[m³]
Cargo with	170094	[m³]

Weight part

Lightweight		
Propulsion type	FC	
Lightweight	37170	[t]
Propulsionweight (old)	857	[t]
Lightweight - propuls	36314	[t]
Propulsionweight (new)	224	[t]
Added weight	-632	
Lightweight new	36538	[t]

Deadweight		
Displacement	187091	[t]
Max Deadweight	150553	[t]
Deadweight	149921	[t]
Cargo volume	173947	[m^3]
Cargo weight	148951	[t]
Fuel weight	1001	[t]
Ballast water weight	0	[t]
Provision, freshwater and lube weight	425	[t]
Calculated deadweight	150377	[t]
Too much weight	-176	[t]

Costs part

Capital costs		
Building costs	65000000	[USD]
Additional costs for propulsion	95461037	[USD]
Additional costs for systems	0	[USD]
Additional costs for storage system	580966	[USD]
Total building costs	161042003	[USD]
Financed	60/40	[debt/equity]
Repayment term	20	[Years]
Interest rate	5	[%]
Interest and equity costs year 1	8052100.136	[USD]
Interest and equity costs year 20	0	[USD]
Average interest and equity costs	402605.0068	[USD]
Total interest and equity costs	8052100	[USD]
Total costs of ship	169094103	[USD]
Annual depreciation	8454705	[USD/year]
Days operating per year	360	[d]
Of which in Port	41	[d]
Daily capital costs	23485	[USD/day]

Running costs		
Crew costs	1650000	[USD/Year]
Insurance costs	1610420	[USD/Year]
Maintenance and repair	805210	[USD/Year]
Docking	28988	[USD/Year]
Special survey	38650	[USD/Year]
Management	805210	[USD/Year]
Lube oils, paint and stores	0.75	[g/kWh]
Lube oils, paint and stores	459	[USD/day]
Yearly costs	4938478	[USD/Year]
Daily running costs	14177	[USD/day]

Running costs		
Crew costs	1650000	[USD/Year]
Insurance costs	1610420	[USD/Year]
Maintenance and repair	805210	[USD/Year]
Docking	28988	[USD/Year]
Special survey	38650	[USD/Year]
Management	805210	[USD/Year]
Lube oils, paint and stores	0.75	[g/kWh]
Lube oils, paint and stores	459	[USD/day]
Yearly costs	4938478	[USD/Year]
Daily running costs	14177	[USD/day]

Voyage costs		
Fuel price	95	[USD/MWh]
Fuel needed	5282	[MWh]
Total fuel costs	501743	[USD/voyage]
Annual fuel costs	21696862	[USD/year]
Daily fuel costs	60269	USD/day

Total daily costs	97932	[USD/day]
Total yearly costs	35255427	[USD/year]
Total voyage costs	723232	[USD/voyage]

Calculation part

Daily voyage costs	97932	[USD/d]
Hourly voyage costs	4080	[USD/h]
Maximum capacity per year	3220547	[t/year]
Yearly costs	35255427	[USD/year]
Cargo costs	10.95	[USD/t]

Problem		
Too much weight	0	[t]
Too much volume	0	[m³]
Fuel density	0.789473684	[t/m³]
Volume * fuel density	0	[t]
Cargo density	0.876	
Volume * Cargo density	0.000	
Problem	Weight	
Cargo loss due to IGF	0	[m³]
Fuel volume needed	1268	[m³]

Bunker stop		
Mooring/Anchor time	2	[h]
Flow rate	200	[t/h]
Flow rate	267	[m³/h]
Total time for weight	2.0	[h]
Total time for volume	2	[h]
Cost of extra bunker stop	8161	[USD]
New roundtrip duration	402	[h]
Voyages per year	22	
Capacity per year	3204509	[t/year]
Capacity loss	16038	[t/year]
Cargo costs with max cargo over a year	35255427	[USD/year]
Cargo costs with max cargo over a year	11.00	[USD/t]

Reducing cargo		
Capacity loss per voyage	0	[t/voyage]
Capacity loss per year	0	[t/year]
New capacity per year	3220547	[t/year]
Cargo cost with max capacity	10.95	[USD/t]

Reducing speed because of less fuel		
Fuel loss	0	[kWh]
Energy loss	0	[kWh]
Energy needed	2640755	[kWh]
Energy available	2640755	[kWh]
Max speed	14.5	knots
Duration on sea	177	hours
Roundtrip	400	[h]
Voyages per year	21.621	
Capacity per year	3220547	[t/year]
Capacity loss	0	[t/year]
Cargo costs	10.95	[USD/t]
Energy corresponding with speed	2640755	kWh