Maritime fuels of the future

A decision support tool for shipowners

Konstantinos Kouzelis

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by

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Preface

This thesis is my final work to complete the Master's degree in Marine Technology from the Delft University of Technology. During the past eleven months, I have conducted scientific research on maritime fuels of the future. This thesis could not have been completed without the support of several people, who I would like to thank beforehand.

Firstly, I would like to express my gratitude to my supervisors Dr. ir. E.B.H.J. van Hassel and Ir. J.W. Frouws for their excellent guidance and support throughout my research. The pandemic has demanded an unprecedented amount of flexibility and creativity, both from myself and my supervisors. I am truly grateful that Edwin and Koos, as a complementary team, have managed to provide me with the same learning curve as would have been possible in person. I have genuinely enjoyed the process of brainstorming and discussing with both of you and I truly believe that our team effort has contributed to the success of this research.

Secondly, I would like to thank my parents, Dimitris and Gelly and brother, Antonios, who, although they could not always be physically close to me, have managed to support me and follow my journey as if they stood by my side. Your numerous messages and phone calls have not gone by unnoticed, and I can't emphasise enough how much I appreciate everything that all three of you have provided me. Furthermore, a very special thank you to Jasmijn, who has been an anchor and support through all ups and downs of the past months. At last, a big thank you to my housemates, Henry, Thomas and Alexander who have made the past months of working from home a true pleasure.

As a Greek, I take pride in the historical success of Greek shipowners. By setting sail for the unknown, they have managed to build empires that have laid the foundations of the present shipping industry. Although I don't know where my engineering degree will take me, I feel it's now my turn to set sail for the unknown.

Konstantinos Kouzelis
Amsterdam, March 2021

Abstract

Researchers have not reached consensus on the most appropriate maritime fuel of the future to drastically reduce the industry's greenhouse gas emissions. Although several studies have investigated potential future regulatory scenarios for the maritime industry, there is a lack of literature on how shipowners might revise their future fuel choice depending on the regulatory climate.

This study aims to develop a decision support tool which enables shipowners to select the most appropriate alternative fuel technology to comply with possible different imposed emission regulations while ensuring optimal business performance. In this context, *most appropriate* is defined as a fuel alternative which minimises required freight rate (RFR) while maximising overall performance on technological, environmental and other criteria.

A decision support tool was devised combining a decision model based on the simple multi-attribute rating technique (SMART) with a financial model based on discounted cash-flow (DCF). Additionally, an optimisation model was implemented to optimise for minimal required freight rate through slow steaming. The decision tool provides shipowners with a quantified impact on their current business if they do not transition to alternative fuels under a 'market based measure' (MBM) regulatory scenario, as well as best-alternatives if their current fuels do not meet regulations under an 'emission cap' (EC) scenario. The decision tool is evaluated under optimistic, average and pessimistic scenarios in 2020, 2030 and 2050.

Under an emission cap scenario, the results showed an overall preference for Fischer-Tropsch diesel (FTD) as the most promising alternative maritime fuel both in terms of SMART performance and required freight rate, followed by upgraded bio-oil (UBO). Nevertheless, the average difference in required freight rate of alternative fuels compared to HFO remains substantial, at 43% and 38% higher for Fischer-Tropsch diesel under a 'no regulation' scenario and 'market based measures' scenario, respectively. It is therefore evident that without regulatory intervention, heavy fuel oil is expected to retain dominance based on cost. Even under a market based measure (MBM) scenario, the average required freight rate of HFO increases only by 3.4% overall. For LNG, market-based measures lead to an average increase in RFR of 4.1%.

These results suggest that in order for the maritime industry to transition towards sustainable alternative fuels, policymakers, governments, international organisations and lenders need to align their policies to collectively enable a more sustainable shipping industry - not only by enforcing stricter regulations, but also by providing the correct financial incentives.

Acronyms

AD anaerobic digestion. 34, 35
AER Annual Efficiency Ratio. 19

BAF Bunker Adjustment Factor. 56

CCS carbon capture and storage. 40

DCF discounted cash flow. 6, 63
DME Dimethyl Ether. 34, 40, 42

EC European Commission. 18
ECA emission control area. 13, 14, 22, 28
ECD emission control device. 38, 40
EEA European Economic Area. 17
EEDI Energy Efficiency Design Index. 12, 15
EEOI Energy Efficiency Operational Indicator. 15
EEXI Energy Efficiency Existing Ship Index. 15
EIAPP Engine International Air Pollution Prevention. 14
EIV Estimated Index Value. 17
ETS emission-trading scheme. 19, 20
EU European Union. 17

FAME Fatty-Acid Methyl Ester. 31, 32, 33, 40, 41, 49, 50, 59, 118
FONAR Fuel Oil Non-Availability Report. 15
FTD Fischer-Tropsch Diesel. 32, 33, 40, 41, 118

GHG greenhouse gas. 1, 11, 12, 18, 19, 21, 29, 30, 33, 34, 35, 36, 37, 38, 86
GISIS Global Integrated Shipping Information System. 20, 21
GWP Global Warming Potential. 29, 60

HFO Heavy Fuel Oil. 25, 27, 28, 29, 31, 32, 33, 40
HTL Hydrothermal Liquefaction. 33, 40, 41, 118
HVO Hydrotreated Vegetable Oil. 31, 32, 33, 40, 41, 50, 59, 118

ICS International Chamber of Shipping. xv, 21, 23, 24, 117

IFO Intermediate Fuel Oil. 28, 31, 32

ILUC Indirect Land Use Change. 7, 46, 50

IMO International Maritime Organization. xv, 1, 11, 12, 13, 14, 15, 18, 19, 20, 21, 22, 23, 24, 29, 35, 117

IMRB International Maritime Research and Development Board. 18

IMRF International Maritime Research Fund. 18

LBM liquefied bio-methane. 6, 34, 35, 40, 41, 57, 59, 70, 83, 84, 87, 118

LNG Liquefied natural gas. 29, 35, 40, 41, 118

LPG liquefied petroleum gas. 30, 40

LSFO Low Sulphur Fuel Oil. 14, 15, 28

MARPOL The International Convention for the Prevention of Pollution from Ships. 13, 15

MBM market based measure. 12, 18

MCDM multi-criteria decision making. 63

MDO Marine Diesel Oil. 28, 31, 40

MEPC Marine Environment Protection Committee. 12, 15, 18, 19

MGO Marine Gas Oil. 28, 31, 40

MRV EU Monitoring, Reporting and Verification Regulation. 17, 18, 20, 21

ODS ozone depleting substances. 13

PM particulate matter. 13

RF Radiative Forcing. 29

RFNBO Renewable Fuels of Non-Biological Origin. 34

RFR required freight rate. 92, 97

SEEMP Ship Energy Efficiency Management Plan. 15

SMART simple multi-attribute rating technique. 97

SVO Straight Vegetable Oil. 31, 32, 40, 41

TRL technology readiness level. 46, 47, 49

UCO Used Cooking Oil. 31, 32

ULSFO Ultra-Low Sulphur Fuel Oil. 28

UPO Upgraded Pyrolysis Oil. 32, 40, 41, 59, 118

VLSFO Very Low Sulphur Fuel Oil. 28

VOC volatile organic compounds. 12, 13

WACC weighted average cost of capital. 92

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1

Introduction

The International Maritime Organization (IMO) aims for a total greenhouse gas (GHG) emission reduction from international shipping by at least 50% by 2050 compared to 2008, while, at the same time, pursuing efforts towards phasing them out entirely [91]. In this light, international organisations and governments in cooperation with shipowners, ports and distributors are continuously making efforts to reduce greenhouse and toxic gas emissions while ensuring business continuity for the shipping industry. This transition will not only require a large supply of innovative technological solutions, but also require support from a commercial perspective. Technology, finance and law must seamlessly align to form a sustainable basis for the transition towards the maritime fuel of the future. In this process, the industry is expected to face major challenges.

Nevertheless, policymakers are driving the shift towards alternative maritime fuel technologies with various measures implemented to accelerate innovation. From a regulatory perspective, pollution prevention treaties and emission measures are forcing parties to innovate in their fuel and exhaust technologies, while from a financial perspective, subsidies are made available for R&D and implementation of innovative technologies [91, 92]. As can be understood, the maritime sector supports innovation towards alternative maritime fuels as a whole. Therefore, keeping the upcoming fuel transition in mind, this research paper develops a decision support tool that enables shipowners to select the most appropriate alternative fuel technology to comply with possible different imposed emission regulations while ensuring optimal business performance.

The scope of this study is limited to fuels applied in internal combustion engines that are fit for large scale application by 2030 or 2050, can meet proposed GHG reduction targets, and are suitable for deep-sea shipping. As a result, HFO and eight alternative fuels are considered in this study, including liquefied natural gas (LNG), fatty acid methyl esters (FAME), hydrotreated vegetable oil (HVO), upgraded pyrolysis oil (UPO), upgraded bio-oil via hydrothermal liquefaction (UBO), Fischer-Tropsch diesel (FTD), liquefied bio-methane (LBM) and ammonia (NH3).

Alternative fuels are evaluated and compared based on a set of technological, economic, environmental and other criteria. These criteria are assessed and weighted by a selection of shipowners to reflect their degree of importance. Alternative fuels are evaluated based on technological, environmental and other criteria by means of a SMART decision model, and on economic criteria by determining the required freight rate (RFR) through a discounted cash-flow model. Additionally, for each alternative fuel, the optimal economic vessel speed is determined by an optimisation model which aims to minimise required freight rate. The combination of the SMART decision model, DCF model and speed optimisation model constitutes the final decision support tool.

In chapter 2.2, the research objective, methodology, scope and ethical implications of this research are defined. Following this, chapter 3 elaborates on maritime emission regulations and defines regulatory scenarios which will be treated, where-after chapter 4 identifies and elaborates a selection of alternative maritime fuel technologies. Furthermore, chapter 5 investigates and defines evaluation criteria for the decision tool. Finally, chapter 6 analyses bunker cost of present and future maritime fuels and chapter 7 forms an understanding of current literature on the most feasible alternative maritime fuels and decision tools as a means of complex decision making. This concludes the literature study.

The second phase of this research is introduced by chapter 8. Chapter 8 elaborates on the functional design of the decision tool, the model description, the economic speed optimisation model, the investigated scenarios, KPIs and model verification and validation. Following this, chapter 9 presents and elaborates the case study and results of the present thesis, as well as a sensitivity analysis. Thereafter, in chapter 10, conclusions are presented and recommendations for further research are offered. At last, chapter 11 reflects on the research approach, model assumptions, decision tool outcomes and the wider implications of this research.

2

Problem definition

With the introduction and enforcement of IMO2020, regulators have demonstrated their determination in regulating maritime emissions. This development has incurred an uptake in the already increasing research interest towards alternative maritime fuels. Multiple studies have investigated and assessed a broad range of alternative maritime fuels [20, 21, 24, 32, 33, 36, 42, 44, 48, 54, 55, 58–60, 67, 70, 74, 78–80, 82, 108, 109, 112, 118, 119, 122, 128, 129, 131, 133, 137, 151, 152, 154, 170, 171]. Even though existing studies largely overlap on alternative fuel types, no consensus is reached on the optimal maritime fuel for the future. Additionally, no existing study approaches the problem from the perspective of the shipowner. As a result, profitability and optimal business operations are rarely considered when alternative fuels are assessed. For shipowners, these aspects are essential to successfully implement alternative fuels under future regulatory scenarios.

The concerned challenges are summarised in the following problem formulation:

Researchers have not reached a consensus on the optimal maritime fuel of the future. Current studies lack consideration for the perspective of shipowners. As a result, profitability and optimal business operations are rarely considered when alternative fuels are assessed. For shipowners, these aspects are essential to successfully implement alternative fuels under future regulatory scenarios.

2.1. Research objective

Based on reviewed literature and the problem statement, the research objective for the present study is established. Due to the many criteria and external factors impacting the decisions of shipowners, making a substantiated decision is complex. Additionally, no existing study approaches the problem from the perspective of the shipowner.

Therefore, the research objective is formulated as follows:

Develop a decision support tool that enables shipowners to select the most appropriate alternative fuel technology to comply with possible different imposed emission regulations while ensuring optimal business performance.

The research objective can be fulfilled by addressing the following sub-objectives:

i Analyse current and possible future regulatory scenarios and make a selection of regulatory scenarios to consider in the present study. Discard low-probability scenarios.

ii Analyse a broad range of alternative fuel technologies and assess which can be considered feasible options. Discard fuels that do not meet requirements in scalability, GHG reduction targets, or suitability for deep-sea shipping.

iii Evaluate multi-criteria decision methods and modelling techniques to address the specific problem and criteria presented in the present study.

iv Devise a decision support tool which is able to:
a. Rank optimal fuel choices under different regulatory scenarios and
b. Assist shipowners in making substantiated future decisions regarding alternative fuel technologies.

v By conducting a case study, determine the most appropriate fuel alternatives under different regulatory scenarios while ensuring optimal business performance.

2.2. Methodology

The goal of defining a methodology is to be able to break down the research into tasks, each having its distinct priority and deadline.

First, in preparation of developing a decision tool, it is essential to enrich one's knowledge on the subject by analysing previous literature. To develop that knowledge, a literature study is conducted.

After the literature study is concluded, the second phase of the research is started, which focuses on devising the decision support tool. In order to structure the research, several activities are identified and briefly described below.

Literature study

1. *Examine maritime emission regulations*
   In order to decide on a selection of relevant regulatory scenarios, it is necessary to examine current regulatory measures as well as possible future incoming regulations. When this knowledge is collected, regulatory scenarios under which alternative fuel technologies will be assessed are formulated.

2. *Examine alternative maritime fuel technologies*
   For an accurate assessment of alternative fuel technologies, it is important to map the availability of alternative fuel technologies. When the most important fuel alternatives are identified, a selection is made of feasible alternative maritime fuels.

3. *Select evaluation criteria*
   Following this, technical, economic, environmental, and other criteria are assessed to evaluate the selected alternative fuels. In parallel, a set of individual shipowners is approached to assign weights to the criteria they believe are important when considering alternative fuel technologies.

4. *Investigate the current state of research*
   To ensure a valuable contribution to the present research field, it is important to gain insights into which areas have already been researched, and equally important, which areas have not. Therefore, current literature on alternative maritime fuels of the future and on decision tools as a means of complex decision making towards maritime fuel choices is reviewed.

This concludes the literature study, where-after the development of the decision tool is started.

Decision tool

5. *Draft the decision tool architecture*
   This phase of the research consists of developing a decision tool that enables shipowners to select the most appropriate alternative fuel technology to comply with possible different imposed emission regulations while ensuring optimal business performance. To achieve this, it is

necessary to develop a solution that provides a perspective on alternative fuels through financial modelling and multi-criteria decision methodology under different scenarios.

Since developing such a decision tool is a complex task, it is necessary to deeply understand what it is required to perform. Therefore, the decision tool architecture is drafted. In a schematic draft of the decision tool architecture, required model inputs, processes and outputs are identified. Once the tool's requirements are clear, previously gathered literature on decision tools is reviewed in order to finalise the choice of appropriate decision method. The theory on which the design of the decision tool is based is analysed in a literature review in chapter 7. The intention is for the chosen models to complement each other to deliver answers to the defined research questions.

6. *Model the decision tool*
   After the decision tool architecture is devised, the decision tool is modelled. The decision tool consists of a decision model and a financial model which are both modelled in Microsoft Excel. The implemented models are extensively documented in chapter 8.

7. *Determine model parameters*
   After the decision tool is modelled, model parameters are determined. To generate relevant outputs, input parameters require to be defined for all alternative fuels and scenarios. Therefore, technical, economic, environmental and other parameters are compiled from literature. Where data is insufficient, substantiated assumptions are made.

8. *Verify and validate the model*
   Once development is completed, the decision tool requires verification and (as far as possible) validation. Verification is the task of determining if the implementation of a model has been done correctly. Examples of how this can be done include performing balance checks, observing the model under extreme conditions, and reviewing generated data at various points in the model to be compared with logical expected values.

   As real-life validation is not possible for alternative fuels, partial validation is performed on inputs. Input validation is a form of validation where the accuracy of inputs is challenged. Input validation considers the complexity of inputs, the reliability of sources, the degree of manual manipulation of inputs and the relative importance of inputs to the model's output.

9. *Conduct a case study*
   To simulate the performance of the decision tool in a real-world scenario, a case study is developed. Within this case study, the financial performance of a shipping firm under different scenarios is evaluated. Additionally, a sensitivity analysis is performed to examine the influence of critical inputs on model outputs.

10. *Evaluate the decision tool under potential scenarios*
    Once the decision tool has been devised and the case study is applied, it requires evaluation under different potential scenarios. This includes regulatory scenarios, time scenarios and sentiment scenarios. All together, alternative fuels are evaluated under 27 different possible combinations of scenarios.

11. *Analyse results and conclude on findings*
    After the case study is finalised, the results are analysed. Relevant conclusions are drawn and the research questions are answered.

2.3. Scope

Here below, the context of the present research is scoped.

What is included in the scope:

Emissions

Of all emission gases, CO_2 is the greenhouse gas with the largest negative impact on global warming. Therefore, addressing CO_2 emissions from ships is the most effective way to slow down global warming and to contribute towards the goal set in the Paris agreement of 2015, which is limiting global warming by 2100 to <2°C above pre-industrial levels [55, 156]. However, apart from CO_2, there are many other greenhouse gases inducing global warming. Since some of these gases are increasingly present in alternative fuels (methane in LNG, for instance), the present research measures emissions in CO_2-equivalent units, abbreviated as CO_2eq. When calculating in CO_2eq, each quantity of greenhouse gas can be expressed as CO_2eq by multiplying the amount of the specific greenhouse gas by its global warming potential (GWP). Global warming potentials are table values defined for each greenhouse gas and are often defined for time periods of 20 or 100 years. In the present research, the 100-year GWP of GHGs is assumed.

Timeline

The present research investigates alternative fuels in three time scenarios. Due to the availability of recent data, the chosen base year for this research is 2020.

Furthermore, according to DNV GL, a key period of increased R&D activity, piloting, rule development, product development and early commercialisation of alternative fuel technologies is expected towards 2030 [48]. For this reason, 2030 is chosen as the starting year for the medium-term scenarios in this research.

Finally, since many technologies are expected to be piloted by 2030, a selection of these pilot projects are expected to have reached maturity by 2050. Therefore, 2050 is chosen as a basis for the long-term scenarios in this research.

Alternative fuel technologies

In the present research, a broad spectrum of alternative fuel technologies is analysed in order to decide which fuels are most interesting to model considering different regulatory scenarios. Solar and wind power are additionally explored due to their zero-emission capabilities. On the basis of a set of defined criteria, a selection of feasible alternative maritime fuel technologies is considered in the decision tool. This selection includes LNG, fatty-acid methyl ester (FAME), hydrotreated vegetable oil (HVO), upgraded pyrolysis oil (UPO), upgraded bio-oil via HTL (UBO), Fischer-Tropsch diesel (FTD), liquefied bio-methane (LBM/bio-LNG) and ammonia (NH3).

Shipping industry

Alternative fuel solutions which might be feasible for vessels participating in inland or short-sea shipping may not satisfy the requirements of vessels intended for deep-sea shipping. Therefore, the present research is scoped towards one shipping industry. Due to the significant environmental impact and high technical demands of the deep-sea shipping industry, the current research is scoped towards deep-sea vessels.

Decision tool

The aim of the decision tool is to enable shipowners to select the most appropriate alternative fuel technology under different regulatory scenarios. Therefore, the focus of the decision tool lies on comparing alternative fuels in terms of general performance and cost. In the model, fuels are assessed on a selection of technical, economic, environmental, and other criteria. The decision tool aims to rank optimal fuel choices and to assess conditions under which alternative fuels become financially feasible for shipowners. Implemented modelling and decision methods include simple multi-attribute rating technique (SMART) to measure individual fuel performance, discounted cash flow (DCF) to calculate required freight rates (RFR) and optimisation modelling to determine the optimal economic vessel speed for vessels employing alternative fuels.

Case study

To verify the model, a case study is conducted on a 13,500 TEU New-Panamax container vessel. In this case study, the cost impact of using alternative fuels is explored for each scenario and fuel alternative. The foundation of the decision to apply the decision tool on a container vessel descends from two research papers authored by Mazraati (2011) [115] and Bergqvist, Turesson and Weddmark (2015) [25]. These papers identify that container vessels entail the highest fuel cost share of voyage expenses per vessel type. Therefore, the financial impact of employing alternative fuels is expected to be highest in a container vessel.

What is not included in the scope:

Other vessel types

Although the decision tool that is to be made is widely applicable on multiple deep-sea vessel types, the present thesis will only conduct a case study on the impact of using alternative fuels on container vessels. In future research, other use cases may be explored.

Energy saving devices

Due to the limited time available for the execution of the present study, additional energy saving devices will not be considered in the scope of this research. Nevertheless, in the coming decades, additional energy saving devices are expected to become increasingly important in reducing the environmental impact of the maritime industry. It would therefore be of high value to combine the assessment of alternative fuel technologies with additional energy saving devices in a future iteration of the decision tool.

2.4. Ethics

As has been observed throughout history, each significant technological advancement has incurred ethical implications. Therefore, in the development of alternative fuels, ethics should be regarded as an integral part of the process.

Surprisingly, although environmental regulations are considered the primary driver for the transition to alternative fuel technologies, the same transition could also possibly have detrimental effects on the environment. In the following sections, the most important ethical considerations are elaborated.

2.4.1. Feedstock competition with food and Indirect Land Use Change (ILUC)

According to Bergsma et al. (2019) [26], bio-fuels can be split into two groups: those based on edible food crops such as rapeseed, soybean, coconut, palm and corn, and those based on non-food feedstocks such as black liquor, sludge, pulp, manure, residues of fermentation, leaves and sawdust [26, 118].

The sustainability of bio-diesels based on edible feedstocks is often questioned. Critics say that based on simple supply-demand economics, due to the increased demand for edible feedstocks, the price of these products is expected to increase. As a result, food will become more expensive for humans that are not directly dependent on agriculture and live below the poverty line.

Secondly, the cultivation of food crops is also associated with Indirect Land Use Change (ILUC). When ILUC occurs, increased amounts of CO_2 are emitted due to the repression of original vegetation for the production of feedstock crops [26]. In theory, to satisfy demand, such a shift could lead to farmers burning down forests to make place for the cultivation of food crops. When considering global CO_2 emissions, this strongly compromises net emission reductions.

2.4.2. Upstream emissions

Upstream emissions can be defined as emissions emitted during the extraction, processing and transportation of a fuel to the final user [62]. Downstream emissions are defined as the emissions emitted during combustion of a fuel. What is often observed when producers, engine manufacturers and distributors promote alternative fuels, is that the sustainability of alternative fuels is measured by downstream emissions only.

By omitting upstream emissions from the total emission equation, these stakeholders are able to promote 'zero-emission fuels', while their lines of business are still heavily reliant on fossil fuels, causing a significant upstream emission footprint. Because the aim of switching to alternative fuels is not only to use different fuels to comply with regulations but also to actually preserve the environment, it is important to remain critical of the information that is funded or commissioned by stakeholders with implied interests.

2.4.3. Life cycle assessment (LCA)

Life cycle assessment (LCA) is a method to address the potential environmental impact of a product or service from a cradle to grave perspective. In this method, the cradle represents the acquisition of raw material, which is followed by various stages of production, distribution, use, waste management and finally disposal, which represents the grave [23]. The aim of LCA is to avoid problem-shifting from one environmental problem to another, or from one phase in the life cycle to another [23]. This holistic perspective is what makes LCA unique. A schematic representation is shown in figure 2.1.

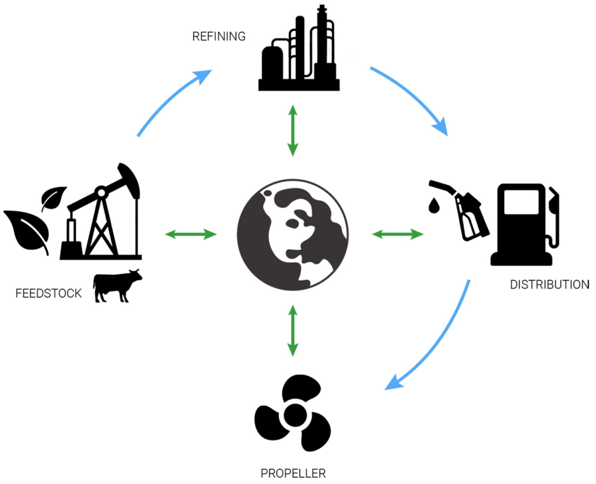

Figure 2.1: 'Cradle to grave' or 'well to propeller' maritime fuel life cycle assessment. Source: Veldhuizen (2020) [161]

In the maritime industry, several studies have conducted life cycle assessments of maritime fuels on present and potential future maritime fuels [22, 23, 31, 73, 168]. When conducting an LCA of maritime fuels, the relevant emissions are often separated into two categories: well-to-tank and tank-to-propeller GHG emissions. Industry-wide, these emission types are named upstream and downstream emissions.

When assessing emissions, one can either focus on a certain greenhouse gas (such as CO_2) or can choose to calculate the so-called Global Warming Potential (GWP). The GWP is a measurement metric that integrates radiative forcing (RF), which is the difference between insolation (sunlight) absorbed by the earth, and energy radiated back to space of a substance over a chosen time horizon, relative to that of CO_2. In other words, the GWP accounts for other gases than CO_2 in combustion emissions and converts them to a CO_2 equivalent unit for ease of GHG emission comparison. Because the detrimental effect of CO_2-equivalent gases on global warming is bound to a time value, researchers often express emission effects over a 20-year or 100-year GWP, varying on the required timeline. In the present research, the industry standard of 100-year GWP is maintained.

However, as Pavlenko et al. (2020) [129] rightfully point out, the industry should consider using the 20-year GWP since the authors believe it better reflects the urgency of reducing GHG emissions than a 100-year GWP.

2.4.4. Ethical consequences

The present research is not only valuable to shipowners towards making the right decision but also to regulators to understand how shipowners might react to future regulations. However, by approaching the problem presented in this research from the perspective of shipowners, opinions and interests of other stakeholders are prioritised lower. This could cause important criteria such as the environmental impact or safety of a fuel technology to be partially disregarded. Nevertheless, ethical implications such as these are observed in every research which aims to approach a problem from a given perspective. It is therefore to the reader to acknowledge that the represented opinions and perspectives are not that of all stakeholders, but rather of a small group with its own priorities and interests. The ethical downside of approaching a problem from a certain perspective can therefore also act as an academic upside to gain valuable insights into a specific stakeholder group.

Furthermore, shipowners can never be certain that the decision that the tool helps them make will offer the best outcome over time. This can be attributed to market uncertainties, but could also be attributed to uncertainties encountered during the development of the decision tool. Although the data and inputs used in this research have been carefully collected from reliable sources, it is inevitable for the author to make assumptions. The most important assumptions are elaborated in section 11.2.

However, to provide a broader view on alternative fuels, discrepancies in data are accounted for by defining sentiment scenarios. As is observed in chapter 4, 6 and 9.3, sentiment scenarios have been developed by categorising data in optimistic, average and pessimistic scenarios. By doing so, shipowners are provided with insights that align with their own perspective towards the future. Additionally, sensitivity analysis is performed on the model outcomes to identify the impact of changes in inputs.

Nevertheless, even when uncertainties are identified and extensively elaborated, proper due diligence should be conducted before basing complex decisions on the present research.

3

Maritime emission regulations

The following chapter elaborates on maritime emission regulations. In section 3.1, an overview of the most important regulators and their imposed regulations is provided, as well as a collection of other facilitators contributing towards the reduction of maritime emissions. Afterwards, in section 3.2, potential future maritime emission regulations are discussed. At last, in section 3.3, an overview of future regulatory scenarios is provided and ranked based on the estimated probability of implementation, where-after a selection is made of regulatory scenarios that will be considered in this research.

3.1. Current regulators on maritime emissions

Today, 90% of the world's trade is carried by sea [6]. Unfortunately, since maritime vessels (primarily) burn fossil fuels, this leads to the emission of greenhouse and toxic gases. In fact, the shipping industry's current CO_2 emissions account for 2-3% of anthropogenic emissions globally [4]. Additionally, a multitude of studies has shown that the share of shipping in global sulphur oxide (SO_x) and nitrogen oxide (NO_x) emissions amounted to approximately 12% and 13% of the global anthropogenic emission share respectively [66, 97, 149]. Therefore, apart from the obvious benefits towards the reduction of global warming, human health also stands to benefit greatly from the current imposed regulations. In fact, a delay in implementation of global sulphur limits from 2020 to 2025 would, according to a 2019 study by Finland for the IMO, contribute to more than 570,000 additional premature deaths compared to the implementation from 2020 [98]. It is thus evident that a radical revision of the shipping industry's fuel technologies is essential.

Rules and regulations around GHG and toxic gas emission reduction are meant for steering shipbuilders, ship-owners and charterers towards cleaner shipping. By joining such organisations and institutions, the involved parties agree to follow the imposed rules and regulations which are proposed by the committee. Violation of regulations can often result in substantial fines and even the detention of ships until the matter is resolved. In this section, the most relevant regulatory bodies and regulations regarding ship emissions will be discussed.

3.1.1. International Maritime Organization (IMO)

GHG reduction strategy

As was mentioned earlier, the IMO aims to reduce GHG emissions from shipping by at least 50% by 2050 compared to 2008, while at the same time, pursuing efforts towards phasing them out entirely [91]. In order to reach this goal, several measures were implemented. These measures can be classified under three terms: short-term for 2018-2023, medium-term for the period between 2023-2030, and long-term for the years after 2030. It is important to note that future measures are still in a conceptual form and would need to be backed by an official IMO convention before being legally binding. An overview is presented in table 3.1.

Measure	**Target group**	**Term**	**Period**
New Energy Efficiency Design Index (EEDI)	Newbuilt vessels	Short-term	2018 - 2023
Operational efficiency measures (e.g. SEEMP, operational efficiency standard)	All vessels	Short-term	2018 - 2023
Existing fleet improvement programme	All vessels	Short-term	2018 - 2023
Speed reduction	All vessels	Short-term	2018 - 2023
Measures to address methane and volatile organic compounds (VOC) emissions	Engines and fuel infrastructure	Short-term	2018 - 2023
Alternative low- and zero-carbon fuel implementation programme	All vessels, fuels	Medium-term	2023 - 2030
Further operational efficiency measures (e.g. SEEMP, operational efficiency standard)	All vessels	Medium-term	2023 - 2030
Development and provision of zero-carbon or fossil-free fuels	All vessels, fuels	Long-term	2030 - …
Market based measures (MBMs)	All vessels, fuels	Long-term	2030 - …

Table 3.1: IMO GHG reduction strategy. Source: (Volger, 2019)

The Marine Environment Protection Committee (MEPC) is a committee under the IMO. As per the IMO website, the MEPC represents IMO's 'senior technical body on marine pollution related matters' [87]. Originally, the focus of the MEPC was the prevention of marine pollution by oil, which led to the introduction of the first ever maritime antipollution convention; the International Convention for the Prevention of Pollution from Ships (MARPOL). Over the last years, the goal of the MEPC has extended beyond just covering oil pollution. In 1997, Annex VI was adopted, aiming to regulate air pollution and emissions from ships.

Table 3.2 provides a timeline of the notable regulatory developments in the IMO's MEPC guidelines towards the prevention of air pollution from ships (Annex VI) which will be elaborated in the following paragraphs.

1997	First adoption of Annex VI
2005	Annex VI enters into force: global sulphur cap is set at 4.50% m/m and ECA sulphur cap is set at 1.50% m/m; NO_x Tier I controls apply
2010	ECA sulphur cap is lowered to 1.00% m/m
2011	NO_x Tier II controls apply
2012	Global sulphur cap is lowered to 3.50% m/m
2013	EEDI mandatory for all ships built after 2013; SEEMP mandatory for all ships
2015	ECA sulphur cap is lowered to 0.10% m/m
2016	NO_x Tier III controls apply in ECAs, Tier II remains the standard outside
2020	Global sulphur cap is lowered to 0.50% m/m

Table 3.2: Timeline of the most relevant developments in- and amendments to MARPOL Annex VI. Own composition

MARPOL Annex VI

The International Convention for the Prevention of Pollution from Ships, 1973 as modified by the Protocol of 1978 and 1997, now known universally as MARPOL, is one of the most important conventions designed by the IMO with the aim of safeguarding the marine environment against ship pollution. As the IMO states: "MARPOL has greatly contributed to a significant decrease in pollution from international shipping and applies to 99% of the world's merchant tonnage" [7]. From its founding in 1973, MARPOL has continuously been updated by amendments throughout the years. Currently, the MARPOL Convention consists of six Annexes: it addresses pollution from ships by oil; by noxious liquid substances carried in bulk; harmful substances carried by sea in packaged form; by sewage; by garbage; and the prevention of air pollution from ships.

MARPOL Annex VI, as first adopted in 1997 and entered into force in 2005, limits the main air pollutants contained in ship exhaust gases. The limited substances include sulphur oxides (SO_x) and nitrous oxides (NO_x), and prohibits the deliberate emission of ozone depleting substances (ODS). Additionally, MARPOL Annex VI regulates shipboard incineration and the emissions of volatile organic compounds (VOC) from tankers [8]. The main recurring developments around MARPOL Annex VI are a global progressive reduction in emissions of SO_x, NO_x, and particulate matter (PM), as well as the introduction of emission control areas (ECAs) to reduce emissions of those air pollutants further in designated sea areas. ECAs are regional areas established to limit vessel emissions near densely populated high-traffic coastal zones. An overview of current and potential future ECAs is shown in figure 3.1, as indicated by DNV GL [48]. Literature by Perera and Mo additionally mentions Australia, the Arctic and Antarctica as potential future ECAs [130].

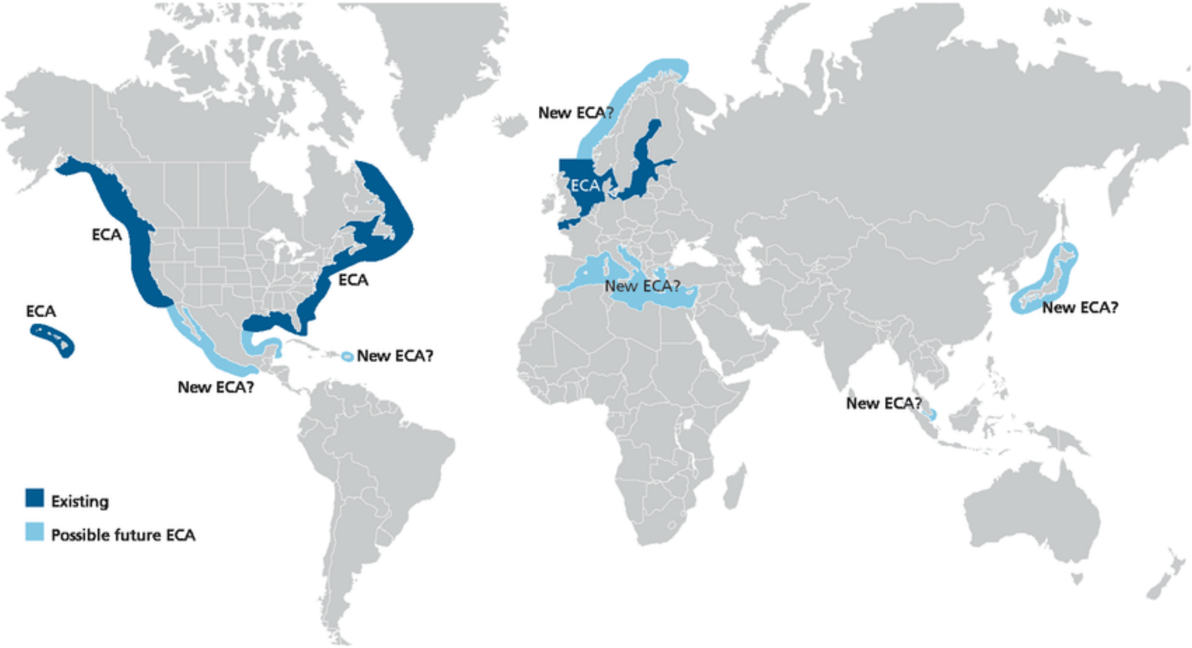

Figure 3.1: Current and potential future emission control areas as indicated by DNV GL. Source: (Bø, 2016)

In order to reach the desired emission limits, a guideline was developed for both sulphur- and nitrogen oxide emissions. The maximum sulphur content in maritime fuels is defined as sulphur mass % by mass fuel (m/m) and is currently capped at 0.5% globally, and 0.1% in ECAs.

For the NO_x emission limits, an Engine International Air Pollution Prevention (EIAPP) Certificate was introduced which can be obtained when building a maritime diesel engine according to the 'NOx Technical Code 2008'[84]. This certification has developed itself into three Tiers, of which currently Tier III controls apply only to specified ships while operating in ECAs, while outside such areas Tier II controls apply [84, 85]. In figures 3.2 and 3.3, the developments of global and ECA SO_x and NO_x emission limits are shown respectively.

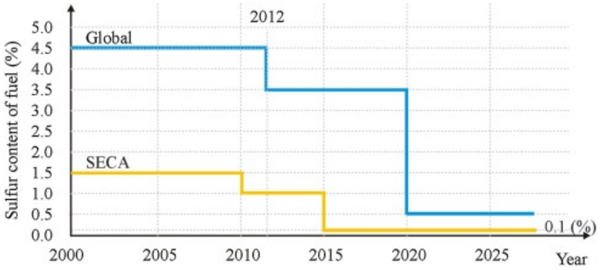

Figure 3.2: Development of SO_x emission limits. Source: (Perera et al., 2016)

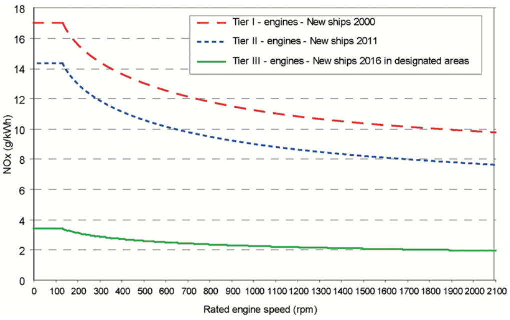

Figure 3.3: Development of NO_x emission limits under Tier I, II and III. Source: (Safety4Sea, 2016)

IMO 2020

The most recent development in MARPOL VI, often abbreviated as IMO 2020 or Sulphur 2020, has kicked up a lot of dust in the maritime industry. The intentions for the implementation of a 0.5% m/m sulphur cap in 2020 were made clear by the IMO as early as in 2008 [86]. The IMO then followed to announce the revised 0.50% m/m sulphur cap in late 2016, effective from 1 January 2020, subject to a feasibility review to be completed no later than 2018 [8]. Industry players initially doubted its feasibility. Many pointed out that the availability of Low Sulphur Fuel Oil (LSFO) or equivalent fuels would fall short of their global demand. Others were afraid that the cost of low sulphur fuels after 2020 would surge, deeming their businesses unprofitable. Alternative solutions such as the retrofitting of scrubbers[1] could provide a solution, would it not be that shipyards were already running at overcapacity to meet demand [9]. To assist ship operators and owners to plan ahead for the 0.50% sulphur 2020 limit, the Marine Environment Protection Committee (MEPC) of the IMO approved various guidance reports and guidelines to facilitate the transition [93]. These guides and guidelines attempt to provide comprehensible information on legislation, as well as solutions to technical challenges that arise such as thermal shock to the fuel system, viscosity changes, combustion concerns and fuel quality control procedures [28]. Additionally, these guidelines include a template for the submission of a Fuel Oil Non-Availability Report (FONAR), meant to facilitate ship operators and owners in the case that regulations can not be met due to the lack of availability of LSFO or an equivalent emission reducing fuel or technology. However, it is important to note that FONAR is not a waiver and that the ship or operator may be subject to more extensive inspections or examinations while in port if the exception is called upon too often.

EEDI, SEEMP and EEOI

The Energy Efficiency Design Index (EEDI), Ship Energy Efficiency Management Plan (SEEMP) and Energy Efficiency Operational Indicator (EEOI) are three important and impactful resolutions of MARPOL VI introduced in July 2011.

The Energy Efficiency Design Index (EEDI) for new ships is the most important technical measure and aims at promoting the use of more energy efficient equipment and engines. As the IMO describes it: "The EEDI is a non-prescriptive, performance-based mechanism that leaves the choice of technologies to use in a specific ship design to the industry. As long as the required energy efficiency level is attained, ship designers and builders are free to use the most cost-efficient solutions for the ship to comply with the regulations. The EEDI provides a specific figure for an individual ship design, expressed in grams of carbon dioxide (CO_2) per ship's capacity-mile (the smaller the EEDI the more energy efficient ship design) and is calculated by a formula based on the technical design parameters for a given ship" [5].

In addition, the Ship Energy Efficiency Management Plan (SEEMP) is an operational measure aimed at establishing a mechanism to improve the energy efficiency of a ship in a cost-effective fashion. The SEEMP provides an approach for shipping companies to manage their fleet efficiency performance over time using monitoring tools such as the EEOI. The guidance provided for the development of the SEEMP additionally incorporates best practices for fuel efficient ship operation and guidelines for voluntary use of the EEOI for new or existing ships [5].

Finally, the Energy Efficiency Operational Indicator (EEOI) measures the fuel efficiency of a ship in operation. The indicator aims to measure the effect of any change in operation such as improved voyage planning, more frequent propeller cleaning, or introduction of technical measures such as waste heat recovery systems or new propellers [5].

Of these resolutions, the EEDI is mandatory for new ships built after 2013, the SEEMP is mandatory for all ships starting from 2013, and the EEOI is to be applied voluntarily. With these measures, for the first time in history, an organisation established a global mandatory GHG emission reduction regime for an entire economic sector. The IMO thereby proved its strong leadership and commitment in addressing GHG emissions from international shipping [5].

EEXI

In November 2020, during MEPC 75, the IMO approved amendments to MARPOL Annex VI, introducing an Energy Efficiency Existing Ship Index. The EEXI will be applicable for all vessels exceeding 400 GT that fall under MARPOL Annex VI. The new measure is subject to adoption at MEPC 76 in June 2021, and is expected to enter into force in 2023 [50]. Guidelines on calculations, surveys and verification of the EEXI are expected to follow and be finalised at MEPC 76. Nevertheless, as EEXI is the extension of EEDI for existing ships, industry experts expect a high resemblance to EEDI, with some adaptations

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[1] Scrubbers in the maritime industry refer to air pollution control devices installed in order to filter undesired particles from engine exhaust gases.

regarding limited access to design data [50]. As DNV GL states, the most important differences between EEDI and EEXI calculations are that for the EEXI, no sea trials are demanded unless these sea trials are performed within the EEDI certification, meaning that for pre-EEDI vessels, the relevant ship speed cannot be determined from on-board measurements. Instead, for these ships, the EEXI reference speed is determined from the speed/power curve determined in model tests of the specific design [50].

In a draft amendment to MARPOL Annex VI by member countries and non-governmental organisations, the group noted that the EEDI-certified ships could use the attained EEDI as an alternative to the attained EEXI, if the attained EEDI satisfied the required EEXI [76].

When a ship's attained EEDI or EEXI does not meet the EEXI threshold, technical modifications may be considered for compliance (e.g. engine power limitation (EPL), retrofit of energy saving devices or alternative fuels). For such cases, the attained EEXI shall be calculated and verified based on the guidelines to be adopted by the IMO [12].

The attained EEXI is calculated by an equation very similar to that for EEDI, although exact guidelines are expected to be finalised at MEPC 76 in June 2021. The required EEXI relies on a reference line value (RLV) based on reference values per ship type. The required and attained EEXI are interrelated as presented in equation 3.1.

$$\text{Attained EEXI} \leq \text{Required EEXI} = (1 - Y/100) \cdot \text{EEXI}_{\text{reference line}} \tag{3.1}$$

Reduction factor Y is a table value ranging between 0 and 50 depending on vessel type and deadweight, defined in draft amendment ISWG-GHG 7/2/6 to MARPOL Annex VI regarding EEXI [76]. The relevant lookup table is presented in appendix B. The reference line for the required EEXI for container vessels is defined by equation 3.2.

$$\text{EEXI}_{\text{reference line}} = a \cdot b^{-c} \tag{3.2}$$

Where for container ships:

$a = 174.22$

$b =$ Vessel deadweight (DWT)

$c = 0.201$

Applying equations 3.1 and 3.2 with table values found in appendix B, the required EEXI (based on the required EEDI) reference value lines for each deadweight (DWT) of container vessels are graphically presented in figure 3.4. One must consider that these figures are based on draft amendments, and not yet on finalised regulations.

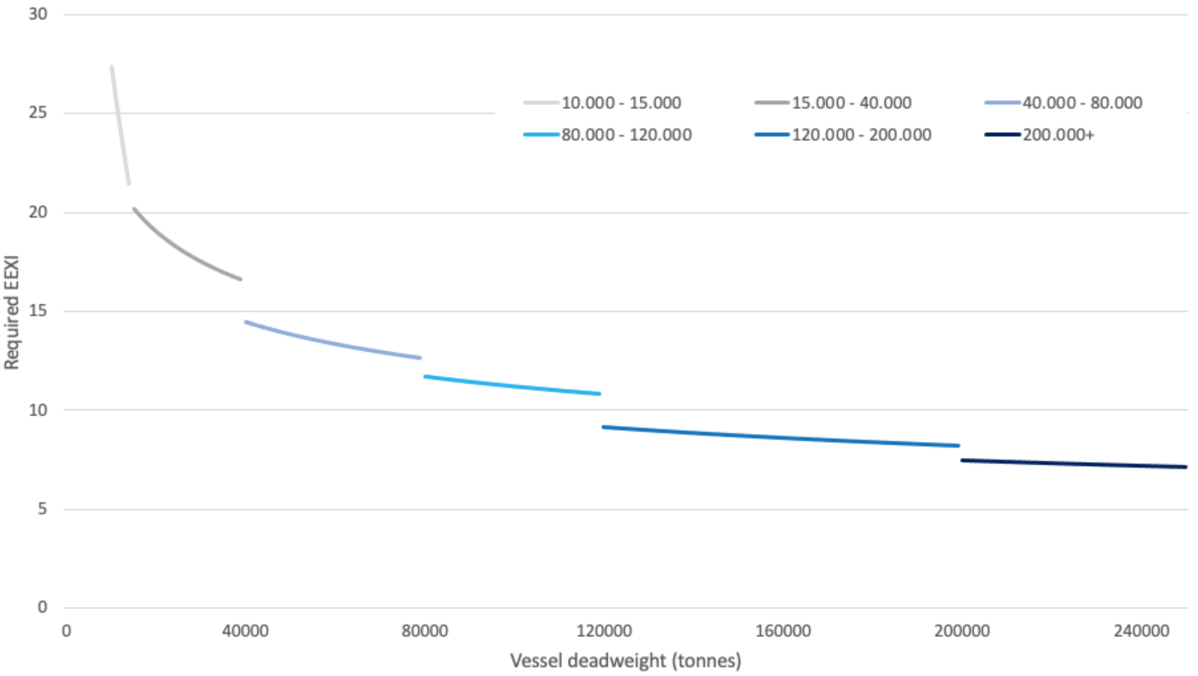

Figure 3.4: EEXI requirements for container vessels of 10.000 tonnes deadweight to 200.000+ tonnes deadweight. Own composition based on equations 3.1 and 3.2, and table data from appendix B

Contrary to calculating the required EEXI, the attained EEXI is more complex. The attained EEXI is vessel-dependent and calculated based on the ship's main and auxiliary engine emissions, energy saving measures, and transport work.

However, as for the EEDI, a simplified calculation method exists: the Estimated Index Value (EIV). The EIV was introduced in 2012 by the International Maritime Organisation through MEPC.215(63) [89]. The EIV uses a number of simplifications and approximations to approach the EEDI or EEXI. This is achieved by means of a set of assumptions, including a constant carbon emission factor, specific fuel consumption and 75% of total installed main engine power, among others. According to an empirical analysis conducted by CE Delft (2016), this method results in an EIV of approximately 10% below the actual EEDI (or EEXI), thus accounting for a margin of error [37]. Therefore, in chapter 11 of this research, the EIV estimation method is used to approach the EEXI and determine the need for additional measures to reach the required EEXI.

The Estimated Index Value (EIV) is calculated by the following formula:

$$\text{Estimated Index Value} = 3.1144 \cdot \frac{190 \cdot \sum_{i=1}^{NME} P_{ME,i} + 215 \cdot P_{AE}}{Capacity \cdot V_{ref}} \tag{3.3}$$

Where for container vessels:

NME = Number of main engines
P_{ME} = Main engine power and defined as 75% of the total installed main power
P_{AE} = Auxiliary engine power
$Capacity$ = For container vessels, capacity is 70% of deadweight

3.1.2. European Union (EU)

EU Monitoring, Reporting and Verification Regulation (MRV)

The MRV Regulation is a regulation enforced by the EU for large ships over 5,000 gross tonnage loading or unloading cargo or passengers at ports in the European Economic Area (EEA). The objective is to make these ships monitor and report their related CO_2 emissions, fuel consumption, and other parameters such as distance travelled, hours underway and cargo carried as per voyage basis [63, 143]. For the inclusion of maritime GHG emissions in the EU's reduction commitment, the gradual approach consisting of three subsequent steps is considered:

1.	Implementing a system for MRV of emissions	Active as of January 2018
2.	Definition of reduction targets for the maritime transport sector	Pending
3.	Application of market based measures (MBMs)	Pending

As can be seen, the European Commission (EC) is in the process of building a structure on which it can apply one or multiple market based measures (MBMs). The most promising MBMs to address GHG emissions of maritime transport measures were identified by an Impact Assessment of the EC. These include a contribution based compensation fund, a target based compensation fund, or an emission trading system. However, as the EC recognises, "the precise design of any option would require further work and design decisions to be taken" [63]. Additionally, the EC emphasises the necessity of aligning its initiatives with the IMO, since without collaboration, enforcement would not be possible.

3.1.3. Other facilitators

International Maritime Research Fund (IMRF)

In December 2019, a group of major industry players including BIMCO, CLIA, ICS, INTERCARGO, INTERFERRY, INTERTANKO, IPTA, and WSC submitted a proposal to the IMO's Marine Environment Protection Committee (MEPC) for the establishment of an International Maritime Research and Development Board (IMRB), and the creation of an International Maritime Research Fund (IMRF). The principal intention of the proposal is to accelerate the introduction of low-carbon and zero-carbon technologies and fuels. The role of the IMRB would be to coordinate and oversee the research and development efforts towards these new technologies, using collective funds secured in the IMRF [27]. As for the method of raising these funds, the proposal states: "The co-sponsors propose that core funding would be provided via a mandatory R&D contribution per tonne of fuel oil purchased for consumption which will be necessary to maintain an appropriate level of funding and to maintain fair competition between shipping companies" [27]. The co-sponsors further emphasise that the fund would require to be of significant size to move the needle; core funding is expected to amount to approximately US$ 5.0bn over the life of the programme, fundamentally altering the current level of investment in maritime R&D focused on the development of low-carbon and zero-carbon technologies [27].

The Poseidon Principles

The Poseidon Principles are a global framework for responsible ship finance which will help incentivise shipping's decarbonisation trajectories to align with the IMO's climate goals. Contrary to the aforementioned initiatives, the Poseidon Principles do not only originate from governments, shipowners, or charterers, but were co-created with major players in the financial industry. The signatories' ambition follows that of the Paris agreement and aims to reduce shipping's total annual GHG emissions by at least 50% by 2050. Important signatories of the Principles include ABN Amro, Amsterdam Trade Bank, BNP Paribas, Bpifrance, Citi, Credit Agricole CIB, Credit Industriel et Commercial, Credit Suisse, Danish Ship Finance, Danske Bank, DNB, DVB, Export Credit Norway, ING, Nordea, Société Générale, Sparebanken Vest and Sumitomo Mitsui Trust Bank. Together, these financiers represent a bank loan portfolio to global shipping of more than US$ 150bn – over a third of the global ship finance portfolio [75, 153].

To measure the decarbonisation trajectory, it is firstly important to understand how climate alignment is assessed. As per the Poseidon Principles website: "Climate alignment is defined as the degree to which a vessel, product, or portfolio's carbon intensity is in line with a decarbonisation trajectory that meets the IMO ambition of reducing total annual GHG emissions by at least 50% by 2050 based on 2008 levels" [153]. More specifically, the Poseidon Principles rely on the Annual Efficiency Ratio (AER) as the carbon intensity metric. The AER relies on parameters such as fuel consumption, distance travelled, and design deadweight tonnage. For the definition of climate alignment for a single vessel, the annual carbon intensity of the vessel is compared with the decarbonisation trajectory for its specific ship type and size class. The climate alignment of a portfolio or product is a weighted average of the vessel carbon intensities in each portfolio or product. As for the definition of the decarbonisation trajectory, it is a representation of how many grams of CO_2 a single ship can emit to move one tonne of goods one nautical mile (gCO_2/tnm) over a time horizon [153]. The Secretariat of the Poseidon Principles has produced standard decarbonisation trajectories for each ship type and size class to offer a targeting basis.

Finally, to ensure enforcement of the Principles, the signatories are expected to contractually implement the Poseidon Principles in their new Business Activities using standardised covenant clauses, thereby ensuring their lenders will focus on hitting the desired alignment targets.

3.2. Potential future maritime emission regulations

Current regulations have put significant pressure on shipowners to alter their vessel emission standards. This has driven the maritime industry towards the use of more innovative and environmentally conscious fuel technology. Nevertheless, stricter emission regulation is imminent.

In the pursuit of reducing GHG emissions from shipping by at least 50% by 2050 compared to 2008, the IMO is considering the implementation of a number of additional measures over the coming years, with a solidified strategy to be produced in 2023 [21]. Nevertheless, the extent of this challenge is not to be underestimated. The IMO's Third GHG Study [148] has projected GHG emission growth between 50% and 250% by 2050 under a business-as-usual scenario - depending on the degree of economic growth and development. Alongside the 2018 IMO agreement [91], various policy measures were suggested for the short- (2018-2023), medium- (2023-2030) and long-term (beyond 2030), as was also displayed in table 3.1 [21].

Although no new decisive measures have yet been put forward, several potential policy considerations are repeatedly mentioned in literature and policy recommendations handed in by IMO member states [162]. In the following paragraphs, several potential policy measures regarding future imposed emission regulations are discussed.

3.2.1. Implementation of market based measures (MBMs)

Market based measures, or market based solutions, are instruments designed to address the climate impact of shipping. MBMs are increasingly called upon as a long-term solution to strongly reduce the maritime industry's GHG emissions. At the Marine Environment Protection Committee (MEPC) 63rd session, the discussion around market-based measures received wide-spread attention; however, opinions between developed and developing countries were divergent, with the latter worrying about the unknown economic impact the measures may bring and the potential ripple effect on the export sector [90, 162].

Emission trading scheme (ETS)

An emission trading scheme (ETS) is a market based measure relying on the free trade of emission allowances. The IMO has received multiple ETS proposals to tackle CO_2 emissions. The most notable proposals originated from advanced industrialised countries such as Norway, the United Kingdom, France and Germany. The key takeaways of these proposals have been summarised by Wan, el Makhloufi, Chen and Tang (2018) [162]:

1. *Under the total amount control strategy, set a carbon emissions ceiling for a period of time.*
2. *"Ships" are objects subject to regulation. Ship operators, flag states, and port states should jointly validate or supervise the real energy performance of ships.*

3. *During the initial implementation phase, relevant parties in the carbon emission-trading market can freely gain or purchase quotas in the primary market corresponding to their bunker consumption share. They can then trade the quota in the secondary market or access emission allowances from other sectors to offset carbon emissions. Ships must ensure that their possessed emission quotas can cover the actual emissions during the period; otherwise, they will incur a penalty.*

4. *The auction of these emission allowances shall be organised by a recognised national or international entity.*

5. *The revenues generated by the initial auction of the emission allowances are used for climate change funds to support mitigation and adaption efforts.*

As Wan et al. pointed out in their study [162], "carbon trading is favoured by many economists and industries because it lowers the compliance cost while meeting the emission reduction targets". Emission reduction costs under technology advancement in the transport sector are reportedly 3-11 times higher than those under carbon trading [162]. As Wan et al. [162] points out, a policy measure involving a floating carbon emission ceiling can encompass the uncertainties in future maritime trade volumes, reducing the impact from emission quota price volatility.

However, the introduction of a loophole-proof maritime ETS would require significant regulatory and organisational efforts. Additionally, high transactional costs related to trading, monitoring, enforcement and verification accompanying a maritime ETS would put a significant burden on participants and regulators. The allowance trade volume may therefore be lower with higher transaction cost, resulting in sub-optimal trading [21].

A uniform benchmarking and grandfathering rights allocation approach used currently in the EU aviation industry can not be applied to its maritime counterpart. Maritime vessels employ a too large variety of systems, engines, fuels and cargo loads, leading to large variations (up to 10x) in gCO_2/tnm emissions between different vessel and cargo types [162].

A different proposition is offered by Kågeson (2008) [100], which applies an open system to the maritime ETS. An open system has the advantage of allowing trade with entities in other sectors and parts of the world that have a lower cost of CO_2 emission reduction than the shipping sector. The volume of allowances and the number of potential participants would provide greater flexibility in trading emissions, benefiting market transparency and liquidity. Although the shipping industry's pollution levels would in theory be able to remain stable if enough emission allowances are purchased, the effect on the global net emission reduction would be equal.

The main complication with Kågeson's proposition is the need for the establishment of an accurate emission cap for a collection of all vessels in the complete maritime industry. It is needless to say that the estimation of such a number is a highly complex problem, and the effects of inaccuracies on other industries could be significant under an open trading system. Additionally, under an open trading system, the maritime industry would not contribute towards the ship-specific climate goals set by the IMO [91].

A different solution would be to construct a closed maritime emission trading system. In this system, benchmarked floating limits would be identified for each particular vessel type based on past emission data. The deviation between the past emission performance of a vessel and a percentage-based emission reduction target would determine the current emission allowances a shipowner would own. These emission allowances could then be traded within the maritime emission trading scheme. This way, older (more polluting) vessels of a certain type will be required to buy carbon allowances to reach a percentage-wise emission reduction, while newer (cleaner) vessels will have room to sell excess carbon emission allowances they own.

However, a problem with this solution is that the EU MRV system which could provide benchmarked verified emission data for vessels over 5000 GT calling at EU ports has only been implemented since 2018, providing an incomplete data-set for comparison in the short term. Additionally, an IMO-led fuel data collection system (Global Integrated Shipping Information System (GISIS)) that also collects emission data on vessels over 5000 GT has only been enforced from 2019, thus also providing insufficient data for current benchmarking.

Nevertheless, the fact that emission data is widely collected in the EU since 2018 and worldwide since 2019 presents opportunities for data-driven market-based emission regulations in the future.

Maritime carbon tax or 'bunker levy'

Another proposed approach towards GHG emission reduction in the maritime industry is the application of a maritime carbon tax or 'bunker levy'. Currently, maritime fuel prices do not reflect or account for the associated environmental costs and externalities such as climate change and health hazards [71]. The application of a maritime carbon tax could take such external costs into account. The fuel tax associated with the use of maritime fuels would be in proportion with the degree of GHG emissions resulting from their consumption [71, 104]. Vessel emission data on which the tax would be calculated could be verified in the IMO's GISIS database, or the EU's MRV database.

An inevitable complication concerning a maritime carbon tax is the institutional architecture involved with the implementation of such a measure. Since taxes are payable to the country of a ship's vessel registry, the implementation of such a measure may involve battles amongst countries to win tax concessions [71]. Additionally, as Kosmas and Accario (2017) [104] point out, such a policy will inevitably lead to industry profit decline, the extent of which is dependent on the structure of the levy and market conditions. Nevertheless, the core rule - a maritime carbon tax based on greenhouse gas emissions - can form a solid basis for a sustainable emission reduction policy.

If such a carbon tax would be introduced in the maritime industry, shipowners could choose to invest in clean fuel technologies or alternative fuels for their vessels, thus saving tax expenses on emissions. If shipowners on the other hand choose to not comply with the proposed non-taxable emission standards, the produced carbon tax revenues could be used to fund R&D into alternative maritime fuels or to pay for the required port infrastructure to bunker these fuels.

The International Chamber of Shipping (ICS) has published a report in 2018 exploring possibilities for the industry to reach the goals set in the 'Initial Strategy on Reduction of GHG Emissions from Ships' by the IMO [83, 91]. In this report, although the ICS remains sceptical of MBMs due to the high fuel costs that might result from them, a clear preference is shown by the industry towards a bunker levy payable to "some kind of IMO climate fund" [83]. These funds could be deployed to support research into new low carbon technologies, or to support the roll-out of expensive new bunkering infrastructure for the supply of zero-CO_2 fuels, particularly in ports of developing nations [83].

The key advantages of implementing a uniform maritime carbon tax are the extent to which it can be applied, its simplicity, and its ability to build upon existing regulatory frameworks. This is particularly beneficial in a complex industry such as shipping due to the low (transactional) costs involved with the implementation and application of such a measure. As the ICS accurately points out, the shipping industry has a 'sound dislike for unnecessary complications' [71, 83].

3.2.2. Expansion of emission control areas (ECAs)

As was discussed in section 3.1.1, emission control areas are designated sea areas established to limit vessel emissions near densely populated high-traffic coastal zones. In these ECAs, both SO_x and NO_x emission regulations are stricter than the IMO's global standard.

Currently, emission control areas are limited to the dark blue regions marked in figure 3.1. However, not all ECAs employ equal limitations. Although the SO_x and NO_x emission limit within ECAs is set uniformly at sub-0.1% and Tier III respectively, different ECAs enforce regulations on different gases. The ECAs with their respective emission control contents have been summarised by Perera and Mo (2016) [130]: Baltic Sea (SO_x, NO_x from 2021), North Sea (SO_x, NO_x from 2021), North America (SO_x, NO_x) and United States Caribbean Sea ECA (SO_x, NO_x). Furthermore, potential future identified ECAs by Perera et al. include the Norwegian and Barents Sea, Mediterranean Sea, Japan, Mexico and Panama, as well as Australia, the Arctic, and Antarctica [130].

Currently, shipowners sailing and trading in ECAs need to comply with the IMO's strict imposed emission regulations. However, the strategic evasion of such areas is a very viable option for shipowners that prefer not to invest in low-emission technology. The degree to which a shipowner's current operations are disturbed by the existence of ECAs is limited. Nevertheless, this does not mean that such disturbances can not arise in the (near) future. For example, the addition of the Mediterranean Sea and Panama Canal to the list of ECAs could have significant detrimental effects for shipowners relying on non-ECA trading routes.

Since countries have the freedom to add their regional water to the list of ECAs, bureaucratic barriers for the implementation of such measures are much lower. Additionally, as human health and the environment are becoming increasingly important topics in modern society, many governments are expected to be in favour of adding their waters to the list of ECAs. Potential short-term disturbances due to the implications involved with said measures will eventually be offset by the long-term benefits on human health and the environment.

If enough countries choose to implement ECAs, it will become difficult for shipowners to sustain a flexible and profitable business without complying with the imposed regional emission limits. Feasible solutions include the use of dual-fuel engines or the implementation of low emission alternative fuel technologies.

3.2.3. Expansion of SO_x and NO_x emission regulations

While the latest SO_x emission restrictions have only been implemented in January 2020, a possibility exists for regulators to further expand these measures in the (near) future. Since SO_x emissions have only been limited to 0.5% m/m, and the current limit within ECAs rests only at 0.1%, future regulatory measures could expand the global sulphur cap to 0.1%, or even 0%.

In the same way, NO_x Tier III emissions for new-built vessels willing to sail in ECAs have only been in force since 2016. Nevertheless, an expansion of Tier III controls to all new-built vessels built from 2030 or 2050 onward remains an option. However, since compliance with Tier III emission controls is dependent on fuel combustion temperature and engine rpm, the future choice of compliant engine and fuel technology could be restricted [169].

Although the expansion of both SO_x and NO_x emission measures seems feasible in the (near) future, there are currently no signs that the IMO or any other regulatory body aims to pursue this on a global scale. An indication for the approximated date of implementation of such a measure could be found by looking at the past time-span from the date of announcement to the date of enforcement. In the case of both the 0.5% sulphur cap enforced in 2020 and the NO_x Tier III controls enforced in 2016, the IMO amendments in MARPOL Annex VI announcing the measures were published as early as in 2008 [86]. This means that shipowners had 8-12 years to respond to the announced measures. Since no such amendments have been accepted yet, it is highly unlikely one of these measures will be implemented by 2030.

Additionally, since SO_x and NO_x emissions primarily harm human health, governments might prefer to add their regional waters to the list of emission control areas where these emissions are limited to 0.1% and Tier III respectively. This way, the degree of SO_x and NO_x emissions are regulated regionally.

3.3. An overview of future regulatory scenarios

To make a selection of future regulatory scenarios that will be considered in this research, it is first important to create an overview of the range of potential future measures. Therefore, in table 3.3 below, an effort has been made to outline potential regulatory scenarios that can be investigated in this research.

In the table, a distinction is made between the category of the measure and the specific context in which the measure is proposed to be applied. Furthermore, a short description is given of the proposed measure, where-after a selection is made if the scenario could potentially be investigated for implementation in 2030, 2050, or if both timelines could be considered.

Category	*Specificaction*	*Description*	*2030*	*2050*	*Source*
Market based measures	Emission trading scheme (ETS)	Under a carbon emission ceiling or reduction target, vessels can trade allowance quotas in a secondary market to cover their actual emissions	✓	✓	[91, 100, 162]
Market based measures	Bunker levy	A maritime fuel tax in proportion with the degree of GHG emissions resulting from their consumption	✓	✓	[71, 83, 91, 104]
Emission Control Areas	Regional expansion of measures	Expansion of ECAs to the Norwegian and Barents Sea, Mediterranean Sea, Japan, Mexico and Panama, as well as Australia, the Arctic, and Antarctica	✓	✓	[48, 130]
Emission Control Areas	Global expansion of measures	Global expansion of ECAs to all coastal waters		✓	-
GHG emission regulation	50% CO_2eq emission cap	Benchmarked 50% CO_2eq emission cap for all new-built vessels	✓	✓	[91]
GHG emission regulation	100% CO_2eq emission cap	100% CO_2eq emission cap for all new-built vessels (zero-carbon)		✓	[91]
NO_x emission regulation	Tier III emission controls	Tier III controls apply for all new-built vessels built after 2030 or 2050	✓	✓	-
SO_x emission regulation	0.1 % SO_x emission cap	A global 0.1% SO_x emission cap for all vessels		✓	-
SO_x emission regulation	0 % SO_x emission cap	A global 0% SO_x emission cap for all vessels (zero-sulphur)		✓	-

Table 3.3: An overview of potential maritime emission reduction measures that could be implemented by 2030 or 2050. A 'V' marks the possibility of implementation in the involved time frame. Own composition

For relevant research, it is important to investigate regulatory measures that have a high probability of being implemented in the future. Therefore, a selection needs to be made of the measures presented in table 3.3. To facilitate this process, a multi-criteria scoring model (using simple additive weighting (SAW)) is presented in table 3.4, which ranks potential future emission regulations based on their probability of implementation.

To establish this ranking, potential measures are scored on a set of criteria. These criteria include the necessity of a measure, the backing of a measure by the IMO or other regulatory bodies, the regulatory complexity of a measure, the financial burden of a measure on developing countries, the costs involved in the execution of a measure, the uncertainty surrounding the effect of a measure, and finally, the financial burden of a measure on shipowners.

The scores assigned to the aforementioned criteria in table 3.4 are based on opinions reflected in literature reviewed in section 3.2. This includes research by Balcombe et al. [21], Wan et al. [162], Kågeson [100], International Maritime Organization [90, 91], Garcia et al. [71], Kosmas et al. [104], the International Chamber of Shipping (ICS) [83], Perera et al. [130] and Woodyard [169].

In this approach, linguistic terminology used in literature is translated into a normalised score reflecting the contribution of a criterion towards the probability of future application of a regulatory measure. Where information was incomplete, an approximation has been made. The scores represent very low (0.2), low (0.4), medium (0.6), high (0.8) or very high (1.0) contributions towards the future application of a measure.

Additionally, since not all selection criteria carry equal importance towards the probability of implementation of a measure, they are weighed. The weight (expressed in %) assigned to each criterion is therefore proportional to its estimated importance.

Category	*Specification*	*Necessity*	*Backing*	*Regulatory complexity*	*Burden on dev. countries*	*Cost of measure*	*Uncertainty of effect*	*Burden on shipowners*	*Weighted score*	*Ranking*
MBMs	Emission trading scheme	1.0	0.8	0.2	0.4	0.2	0.2	0.4	**0.52**	**5**
MBMs	Bunker levy	1.0	1.0	0.6	0.4	0.6	0.8	0.6	**0.76**	**1**
ECAs	Regional expansion of measures	0.4	0.4	0.8	1.0	0.8	0.8	0.6	**0.65**	**3**
ECAs	Global expansion of measures	0.2	0.2	0.4	0.4	0.8	0.6	0.2	**0.38**	**8**
GHG	50% CO_2eq emission cap	1.0	0.8	0.4	0.6	0.6	0.8	0.4	**0.70**	**2**
GHG	100% CO_2eq emission cap	0.6	0.6	0.6	0.4	0.4	1.0	0.2	**0.57**	**4**
NO_x	Tier III emission controls	0.4	0.4	0.4	0.2	0.8	1.0	0.6	**0.51**	**6**
SO_x	0.1% SO_x emission cap	0.4	0.4	0.6	0.2	0.6	0.4	0.4	**0.43**	**7**
SO_x	0% SO_x emission cap	0.2	0.2	0.8	0.2	0.4	0.6	0.2	**0.37**	**9**
	Weight	*20%*	*20%*	*16%*	*12%*	*12%*	*12%*	*8%*	*100%*	

Table 3.4: Simple additive weighting of the probability of implementation of potential future emission regulations. Own composition based on literature by Balcombe et al. [21], Wan et al. [162], Kågeson [100], International Maritime Organization [90, 91], Garcia et al. [71], Kosmas et al. [104], the International Chamber of Shipping (ICS) [83], Perera et al. [130], Woodyard [169] and the author's approximations.

From the ranking in the right-most column of table 3.4, it is evident that the implementation of a market based measure such as a bunker levy has the highest probability of being applied in the future. A bunker levy would pose a significant incentive for shipowners to switch to cleaner fuels or fuel technologies, while at the same time raising funds for necessary R&D into future technologies. As was previously mentioned in section 3.1.1, the IMO aims to implement market based measures in the medium-term (2023-2030), which underpins the backing of such a measure.

Of the proposed measures, the implementation of a benchmarked 50% CO_2 equivalent (CO_2eq) emission cap for all new-built vessels ranks second in the scoring model of table 3.4, meaning it is the second most probable measure to be implemented in the future. Although no extensive proposal has yet been put forward by the IMO or another regulatory body, the IMO's third GHG emission reduction strategy supports the goal of reducing GHG emissions by 50% by 2050 compared to 2008 levels. A proposal of limiting the CO_2eq emissions from new-built vessels would contribute towards the climate goals set by the IMO as well as those set in the Paris agreement. Additionally, such a measure would carry low uncertainty surrounding its effect on the industry.

As can be seen, the proposal of a regional expansion of ECAs ranks third in the scoring model. Although the necessity of such a measure is limited and it is only supported on a regional level, its low complexity, low uncertainty and the fact that it poses no burden on developing countries results in a high score in its possibility of implementation. However, since the regional expansion of emission control areas would only affect shipowners sailing to these specific regions, it is not necessarily relevant for consideration in this research, where the aim lies on global measures.

Following the ranking of the proposal to expand ECAs regionally, on number four, is the proposed measure of reducing CO_2eq emissions of new-built vessels by 100%. While the aim of incorporating zero-carbon or fossil-free fuels in shipping is only intended for the long-term according to the IMO's third GHG reduction strategy [91], there is a realistic chance that such a measure could be implemented by 2050. The effects of such a measure would be highly predictable, making it a favourable option for future regulators willing to reduce GHG emissions drastically.

In the scoring model, the 'uncertainty of effect' represents the degree of uncertainty towards the effect of a measure on the industry. Since the implementation of an emission trading scheme (ranked fifth) is subject to dynamic market movements, the high degree of uncertainty involved with its execution causes a low score. In the same way, the emission trading scheme scores very low on the 'cost of measure' criterion, since the measure would involve a significant amount of transactional costs, even after successful implementation. Therefore, although an emission trading scheme might sound like a feasible future measure, there is significant doubt that regulators will choose to move forward with its implementation.

The measures ranked from number six to nine are not expected to be implemented in either 2030 or 2050 since they rank low on multiple decisive criteria or their less strict predecessors have been implemented only very recently.

3.4. Conclusion and selection

Measure		Vessel type	Description	Time frame
MBM	Bunker fuel levy	All vessels	A maritime fuel tax in proportion with the degree of GHG emissions resulting from their consumption	2030
MBM	Bunker fuel levy	All vessels	A maritime fuel tax in proportion with the degree of GHG emissions resulting from their consumption	2050
EC	50% CO_2eq emission cap	New-built vessels	Benchmarked 50% CO_2eq emission cap for all new-built vessels	2030
EC	50% CO_2eq emission cap	New-built vessels	Benchmarked 50% CO_2eq emission cap for all new-built vessels	2050

Table 3.5: Selected regulatory scenarios to be considered in this research.

Based on the multi-criteria scoring model of the nine aforementioned proposed measures as well as the scope of this research, a selection has been made of the regulatory scenarios that are to be considered in the decision tool. An overview is provided in table 3.5.

The considered scenarios form the cornerstones of the decision tool that is devised during this research. The basis of the five regulatory scenarios that are considered consist of one base-base 'no regulation' scenario and two proposed regulatory measures, executed either in 2030 or 2050. Because the impact of a 100% CO_2eq emission cap for new-built vessels is equal to the impact of a 50% CO_2eq emission cap on the selected fuels, the 100% scenario is not considered.

Under the scenarios of implementing a bunker levy, the choice of tax structure can have a significant impact on the profitability of shipowners. In a unit-tax approach, the fuel tax consists of a fixed monetary amount per ton of fuel or ton of CO_2eq greenhouse gas emission. Under an *ad-valorem* approach, the tax is enforced as a percentage of fuel price [104]. Under both structures, if a maritime fuel tax is applied that is dependent on the degree of GHG emissions, an emission benchmark requires to be determined. The same holds true for the implementation of CO_2eq emission reduction measures for new-built vessels.

Ideally, a benchmark for defining CO_2eq emission reduction potentials is one that represents the emission levels of the majority of the industry in present times. Therefore, considering that heavy fuel oil (HFO) currently represents the largest part of marine fuel consumption (approximately 77% [116]) and emits large amounts of CO_2eq greenhouse gas per unit of energy produced, it could serve as an appropriate benchmark for future emission reductions. According to Pavlenko et al. (2020) [129], the emission factor for HFO is 81.2 gCO_2eq/MJ.

In the decision tool, the choice is made to enforce a unit-tax approach consisting of a fixed monetary cost per ton of CO_2eq greenhouse gas emissions. By doing so, fuels are effectively taxed proportionally to the environmental harm of their annual greenhouse gas emissions.

4

Alternative maritime fuel technologies

The following chapter elaborates on alternative maritime fuel technologies. In section 4.1, available fuel technologies are investigated, where-after section 4.2 examines emission control devices for maritime vessels. Following this, an overview of the discussed alternative maritime fuel technologies and their key characteristics is presented in section 4.3. Finally, a preliminary selection of feasible alternative fuel technologies for the present research is made and presented in section 4.4.

4.1. Available fuels

From the information and developments mentioned in past section, it is obvious that regulations and emission limits are constantly being tightened. For many years, from the perspective of the shipowner, minor adjustments were sufficient in order to comply with said demands. However, the industry is reaching a point where new fuel technologies must emerge to accompany this change. In the following section, a collection of current and emerging fuel technologies will be discussed that might potentially fill the demand for a cleaner shipping fuel in the future.

4.1.1. Fuel oils

Fuel oils, the most dominant maritime fuels in the past decades, are low-cost crude oil products from refineries. Due to their popularity after the Second World War, power trains of ships have been designed to cope with these highly viscous and often high-sulphur content fuels. However, over time more refined forms have been developed in order to meet the higher emission standards in the market. Here below, the various different types of fuel oils have been identified.

Heavy Fuel Oil (HFO)

Heavy Fuel Oil (HFO), residual fuel oil or Bunker C, is the heaviest and most popular form of fuel oil. As of 2013, approximately 77% of the maritime industry burned HFO [116]. It is characterised by its high viscosity (up to 700 cSt at 50°), density of up to 1010 kg/m^3, and high fuel sulphur content (up to 3.50% m/m). Due to the fuel's high viscosity, HFO requires to be heated before use. Although it is still widely used in the maritime industry, its use has been limited since the sulphur cap of 2020. By limiting the maximum sulphur content of maritime fuels to 0.50%, the IMO implicitly only allows HFO to be used in combination with scrubbers. In this way, the toxic gas emissions generated by the use of HFO are the equivalent of a fuel with a sulphur content below 0.50%.

Commonly, the term 'heavy fuel oils' describes a category containing all heavy marine fossil fuels ranging from intermediate fuel oils to low-sulphur fuel oils with various degrees of sulphur content [2]. Commercially, when a vessel is said to run on heavy fuel oil, it commonly bunkers IFO-380, which consists of 98% residual oil and has a viscosity of 380 cSt. Alternatively, it can run on IFO-180, a heavy fuel oil with a lower viscosity of 180 cSt.

Marine Diesel Oil (MDO)

Marine Diesel Oil (MDO) describes a marine fuel that is composed of distillate blends and Heavy Fuel Oil. The main difference between MDO and HFO is that high distillate MDO does not require heated storage due to its lower viscosity. The use of the terms MDO and IFO for describing the fuel varies according to its respective HFO content. The HFO content in Marine Diesel Oil is generally lower than that in Intermediate Fuel Oil, although there are no strict guidelines on the terminology.

According to Marquard & Bahls oil company [1], their different blending ratios make it possible to use MDO in many different engines. Lighter versions are used to power smaller medium- to high-speed marine engines and auxiliary power units as well as auxiliary engines on very large ships, while the viscous IFO-380 is mainly used in commercial vessels [1]. The sulphur content of marine diesel oils does not exceed 3.5% according to their ISO standards and is also sold in lower, 1% sulphur content variants. However, as can be expected, these fuels are more expensive than HFO [1].

Marine Gas Oil (MGO)

In contrast to MDO, marine gas oil describes marine fuels that consist exclusively of distillates. This means that there is no HFO blend present. MGO consists of components of crude oil that evaporate in fractional distillation and are then condensed into liquid fractions. Just as the other fuel oils, MGO is produced with varying degrees of sulphur content [3]. However, the maximum permissible sulphur content of MGO lies below that of HFO. The maximum permissible sulphur content of MGO sits at 1.5%, while low-sulphur marine gas oil (LSMGO) has a sulphur content of less than 0.1% [40]. This allows LSMGO to be suitable for ships sailing within ECAs or European ports. Additionally, shipowners and charterers can opt for MGO 0.5%, with a sulphur content not exceeding 0.5%.

Again, unlike HFO, MGO does not require any preheating before being pumped into the engine. However, its lower viscosity often means adjustments need to be made to the ship's fuel system. Higher viscosity usually reflects a better calorific value and is suitable for current ship engines [107]. Therefore, many shipowners tend to prefer the use of Very Low Sulphur Fuel Oil (VLSFO) or Ultra-Low Sulphur Fuel Oil (ULSFO) over MGOs.

LSFO, VLSFO and ULSFO

Low Sulphur Fuel Oil (LSFO), Very Low Sulphur Fuel Oil (VLSFO) and Ultra-Low Sulphur Fuel Oil (ULSFO) are three grades of low sulphur bunker fuel, with each grade containing a lower percentage of sulphur compared to the previous. Whereas Heavy Fuel Oil (HFO) generally contains 3.5% sulphur, the sulphur content of these fuels lies lower. Since the terminology surrounding these fuels tends to be used interchangeably in literature, it is important to identify each fuel according to its corresponding sulphur content. The first fuel grade containing a lower sulphur content is LSFO. LSFO generally contains sulphur contents of 1.0%, making it an unpopular choice after 2020 since it does not meet regulatory limits, nor is it cheaper than HFO when used in combination with scrubbers [145]. A more popular choice is VLSFO. Very Low Sulphur Fuel Oil, also known as IMO 2020 grade bunkers, contain a maximum of 0.5% sulphur, thus complying with new regulations under MARPOL VI that are enforced since 1 January 2020 [145]. Furthermore, in order to be compliant with the sulphur limits in ECAs and European ports, shipowners and charterers can also choose to bunker Ultra-Low Sulphur Fuel Oil (ULSFO). ULSFO contains a maximum of 0.1% of sulphur, being the cleanest choice available in fuel oils [145].

All the aforementioned fuel oils are crude oil derivatives and originate from the same base product. The resulting sulphur content is solely dependent on the extensiveness of desulphurisation. During desulphurisation, sulphur and sulphur compounds are extracted with catalysts and chemical additives which lead to a considerable rise in the price of refinery [105]. Therefore, low sulphur fossil fuel oils will always be more expensive than their more polluting alternatives.

4.1.2. Liquefied natural gas (LNG)

Liquefied natural gas is a liquid gas consisting of mostly methane (CH_4) with some mixture of ethane (C_2H_6) that has been cooled to its liquid form for storage. For the last 50 years, boiled-off gas produced inside LNG tanks on LNG carriers has been used for propulsion in traditional boiler/steam turbine systems and dual fuel diesel engines. Nowadays, ship- and engine builders are increasingly working towards using LNG in all sorts of commercial vessels. In one of the scenarios presented by the IMO's Third GHG Study (2015) [148], the share of LNG in the maritime fuel mix is expected to be as high as 25% by 2050.

The use of LNG in maritime vessels emits between 20-30% less CO_2 from tank to propeller relatively to HFO [33]. Although this decrease may not seem significant, the reduction in toxic gases such as SO_x and NO_x is very significant. In fact, by using LNG, NO_x emissions are reduced by approximately 80 to 85%, and as LNG does not contain sulphur, SO_x emissions are almost completely eliminated [33]. Although low toxic gas emissions are important to comply with regulations, the main reason for shipowners to adjust to LNG fuelled ships is low fuel price. CE Delft, Stratas Advisors, UMAS, NMRI, Petromarket Research Group and Shinichi Hanayama [37] found in 2016 that in the future, LNG will likely remain less expensive than VLSFO and might even be less expensive than HFO, depending on how the price of HFO responds to the IMO's 2020 global sulphur cap. Therefore, shipowners are finding that it makes economic sense to invest in an LNG-fuelled ship since LNG currently offers the possibility to comply with IMO 2020 GHG and Tier III NO_x emission regulations at a relatively low cost.

Controversially, when considering upstream emissions, the advantages of using LNG from a GHG emissions perspective remain uncertain. Natural gas fuel production pathways can be relatively energy intensive compared to petroleum pathways, and methane slip during natural gas extraction and distribution may show significant (negative) GHG impacts [24, 32, 154]. In January 2020 the International Council on Clean Transportation (ICCT) published a working paper by Pavlenko, Comer, Zhou, Clark and Rutherford (2020) [129] arguing that LNG does not provide a climate benefit using a 20-year Global Warming Potential (GWP)[1] when factoring in higher upstream emissions. Additionally, Pavlenko et al. (2020) [129] found that when adding the emissions from international transport, average LNG GHG emissions are 20% higher than HFO. The emission data from these studies is plotted in figure 4.1 below. Studies missing adjusted values in the figure lack the data needed to differentiate emissions from CO_2 or CH_4, while studies using the same 100-year GWP as in figure 4.1 have the same original and adjusted numbers.

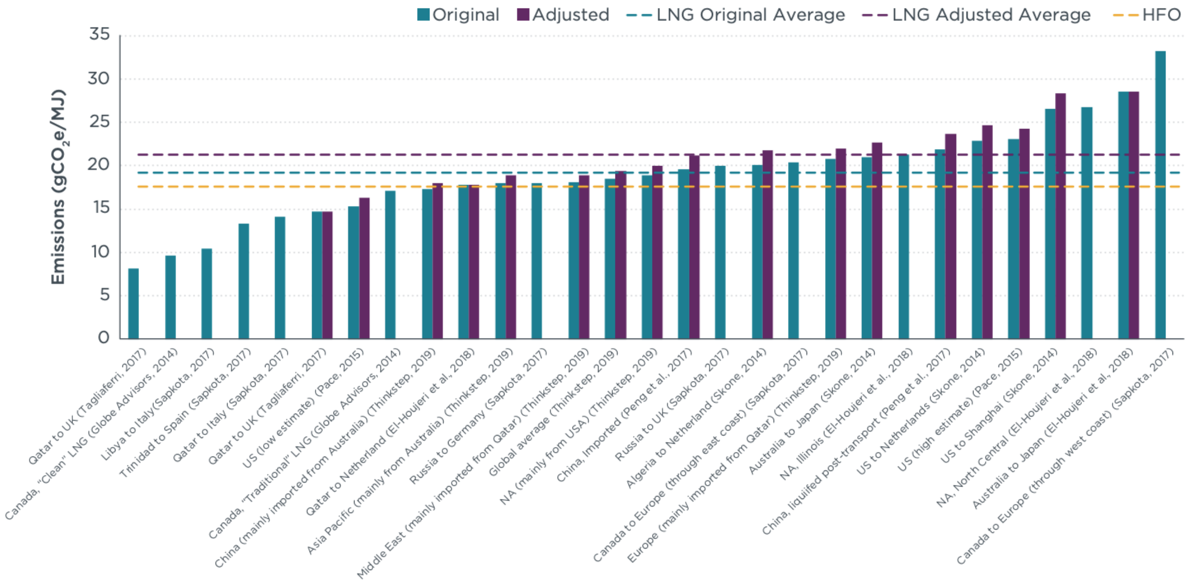

Figure 4.1: Upstream GHG emissions of LNG including international transport, 100-year GWP. Source: (Pavlenko et al., 2020)

On the contrary, Juha Kytölä, Wärtsilä's director of R&D and engineering, states that the claim that

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[1] The Global Warming Potential (GWP) integrates the Radiative Forcing (RF), which is the difference between insolation (sunlight) absorbed by the earth and energy radiated back to space of a substance over a chosen time horizon, relative to that of CO_2.

LNG fails to deliver the required emission reductions is incorrect since the assumptions and data of the ICCT do not reflect those of a modern gas engine. Wärtsilä is a proponent of LNG as ship fuel. Two factors in particular support it, the company says: "The first is the excellent potential that exists for cutting methane-slip emissions from 4-stroke engines even further through the introduction of advanced combustion techniques. Secondly, the LNG technology that has been developed is perfectly suited for burning low-carbon bio- and synthetic fuels that will help the industry to lower its GHG emissions to the levels targeted by the IMO for achievement by 2050 [131]." By emphasising the suitability of their engines for burning low-carbon bio- and synthetic fuels, it is evident that even an LNG proponent as Wärtsilä adheres to the long-term vision of sailing on a cleaner alternative than LNG.

In conclusion, a topic that most researchers and engine builders agree on is that LNG is not the most sustainable fuel solution for the long term, as LNG-powered vessels and natural gas production facilities still emit, and will continue to emit, a significant amount of CO_2 and CH_4 compared to its alternatives [24, 32, 129, 154]. Nevertheless, LNG could provide a decent solution in the meantime.

4.1.3. Liquefied petroleum gas (LPG)

Liquefied petroleum gas (LPG) is a liquid gas consisting of a mixture of primarily propane, and butane. The mixture is a gas under ambient conditions, but under pressure, the gas becomes a liquid. Even though the heating values for propane and butane are higher than those of oil-based fuels, a tank of LPG will typically have three times larger volume that a tank with oil-based fuel due to its low density. LPG is produced as a by-product from two processes: oil and gas production and oil refining.

LPG is currently mostly used for cooking, water heating, or as engine fuel for (backup) generators. Yet, two-stroke engines and gas turbines for marine use are available in LPG versions. Due to its global demand, there are currently about 200 very large gas carriers (VLGCs) in operation that can transport LPG [42]. LPG can be transported refrigerated at close to ambient pressure, semi-refrigerated at 4-8 bar pressure, or under pressure, typically at 17 bar.

According to DNV GL (2017), global LPG production is at the same level as fuel oil consumption in the maritime industry and is increasing by 2-3% per year [42]. However, although a large network of LPG import and export terminals is available to address trade needs, bunkering infrastructure is still lacking.

Nevertheless, LPG's low energy and capital cost (close to LNG) make a compelling economic case for its use. Nonetheless, since operational experience with the use of LPG is very limited, the maturity level of the technology is medium [48]. Additionally, since LPG remains a hydrocarbon produced from fossil sources, its low environmental performance remains a major downside to its use [48].

4.1.4. Bio-fuels

Bio-fuels are fuels that are very similar to fossil fuels, but are created from biomass feedstocks. By using biomass feedstocks that have absorbed CO_2 over their life-cycle, bio-fuels have the potential to be carbon neutral. Carbon neutrality exists when fuel combustion does not cause for net emission of CO_2 in the atmosphere. However, when performing a life cycle assessment (LCA) on bio-fuels, these fuels are far from carbon-neutral. Since processing and transportation of bio-fuels requires a lot of energy, upstream (well-to-tank) emissions for bio-fuels can not be omitted from the emission equation. Nevertheless, a possible method to achieve carbon neutrality for bio-fuels is to either balance carbon emissions through carbon offsetting (theoretical offsetting), or by eliminating GHG emissions altogether throughout the supply chain.

The use of bio-fuels in the maritime sector could present an opportunity to strongly reduce GHG emissions and improve air quality, since bio-fuels do not only cut CO_2 emissions but also contain very little or no sulphur [82]. Although vessels do not yet operate on pure bio-fuel due to the lack of production capacity and higher cost, bio-fuels are increasingly used as drop-in fuels[2] in blends with fossil fuels to reduce emissions [55].

To ensure sustainability along the whole supply chain, bio-fuels must ideally not compete with food crops. To combat the use of food crops to manufacture bio-fuels, the EU has implemented RED-II, a regulation capping the use of certain bio-fuels [26]. The caps are set to 7% bio-fuel from food crops, and 1.7% from Used Cooking Oil (UCO) compared to the total energy content of transport fuels supplied for consumption or use on the market [61]. According to Bergsma et al., although the maritime and aviation industry are currently exempt from RED-II, the permanency for fuels that are made of food crops is poor. However, regulations such as RED-II can have a positive influence on the phasing in of more sustainable bio-fuels.

Therefore, several researchers and organisations have extensively investigated the potential of using bio-fuels for shipping [48, 54, 55, 70, 82, 152]. In the following section, the most important bio-fuels and their applications in shipping are addressed.

Straight Vegetable Oil (SVO)

Straight Vegetable Oil (SVO) is a plant-extracted oil that can be used as a fuel directly, without further processing. According to E4Tech (2018) [55] and Hsieh and Felby (2017) [82], SVO could be a suitable alternative for the use of Intermediate Fuel Oil (IFO) or Heavy Fuel Oil (HFO) in low speed diesel engines. However, due to SVO's high viscosity and boiling point, the use of SVO carries an increased risk of carbon deposits in the engine and gelling of the engine lubricant [82]. Additionally, the low calorific value of SVO would mean that fuel consumption would increase, meaning the vessel would require to bunker more often [137]. Possible solutions to mitigate the risk of carbon deposit buildup include pre-heating the SVO before entering the engine, adjusting fuel injection systems to the higher viscosity of SVO or blending SVO with IFO or HFO [70, 137]. However, Florentinus, Hamelink, Bos et al. (2012) [70] argue that heavy fuel blends including SVO will form an emulsion, rather than a blend and that pre-heating the vegetable oil would not mitigate all challenges. Because of the aforementioned hurdles, the implementation of SVO as a maritime fuel or fuel blend would require significant modifications to the diesel engine and fuel systems, as well as the existing petroleum infrastructure. The risk of reduced engine lifespan due to carbon deposits exceeds the benefit of using SVO as a drop-in fuel [82].

Fatty-Acid Methyl Ester (FAME)

Fatty-Acid Methyl Ester (FAME), otherwise known as bio-diesel, is a processed product of SVO through transesterification, a process in which the vegetable oil reacts with methanol. FAME has a lower viscosity and boiling point compared to SVO, and is therefore more suitable to be used in diesel engines. Currently, FAME is already blended with a concentration of 7% in diesel for road use, forming EN590 diesel [55, 82]. For maritime applications, FAME could be seen as a future alternative for Marine Gas Oil (MGO) or Marine Diesel Oil (MDO) in low- to medium speed diesel engines.

Its current maritime use is however quite limited. According to Hsieh and Felby [82], when FAME is produced from certain feedstocks, the high cloud point could cause filter clogging and poor fuel flow in temperatures <32°C. Additionally, FAME includes acid degradation products which are suspected of causing damage to fuel pumps, injectors and piston rings, leading to an acid number limit in marine fuel specifications [58, 82]. Nevertheless, blending FAME in existing maritime fuels to a certain degree can still be an attractive GHG reduction strategy for deep-sea shipping. According to E4Tech (2018) [55], the GHG reduction potential of FAME can reach as much as 88% when compared to fossil fuel chains.

The production of FAME is not feedstock specific, as long as the feedstock is an oily product. Examples include rapeseed, palm, coconut, soybean, corn, tallow (animal fats), and Used Cooking Oil (UCO) [55, 82]. The degree of sustainability of FAME however, is. Currently, most FAME, SVO and HVO, a bio-fuel which will be treated in the next paragraph, is produced from edible oily product

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[2] Drop-in fuels are fuels that can completely interchangeably be used as a substitute for conventional fossil fuels without adaptation of the engine, fuel system or fuel distribution network.

sources such as rapeseed, soybean, coconut, palm and corn [118]. Since these feedstocks compete with the food industry, their sustainability is questionable. Therefore, FAME is currently only allowed in trace amounts based on the ISO 8217 standards applying to HFO in deep-sea shipping. Ideally, bio-fuels such as FAME and HVO should be produced from non-edible and low cost resources such as curcas, karanja, neem, jatropha, algae and waste oils [118]. By depending on non-edible feedstocks, the production of bio-fuels is able to remain sustainable in the long run.

Hydrotreated Vegetable Oil (HVO)

Hydrotreated Vegetable Oil (HVO), otherwise called renewable diesel, is a product of the process of hydro-treating oily and fatty products such as vegetable oils, tallow, or Used Cooking Oil (UCO). Hydro-treating is a process where the vegetable oil is treated with hydrogen over a special catalyst, resulting in long-term stability [48, 70]. This process removes excess oxygen from the oily feedstocks and leads to higher fuel efficiency, as well as a lower chance of oxidation [82]. Due to its high quality and consistency, HVO can be used as a drop-in diesel fuel. However, in order to reach this quality, its production is more costly than that of FAME and SVO [55]. Additionally, due to this high quality and drop-in characteristic, HVO is likely to attract interest from other sectors such as aviation and road transport [55].

The cross-industry interest towards HVO in combination with its high price will likely cause a competitive disadvantage for the maritime industry. Apart from the economic challenges, the production of HVO is also dependent on feedstocks competing with the food industry, making it a less sustainable option for the long-term in its current form. However, if production cost is reduced and feedstocks are replaced by non-edible, low-cost resources, HVO could form a good candidate for long-term maritime application. According to DNV GL (2019) [48], HVO is one of the most promising substitutes to fossil fuels due to its high compatibility with existing infrastructure and engine systems. Although there is limited operational experience with the use of HVO as a maritime fuel, it is currently used on several Norwegian ferries without reported negative effects [48].

Upgraded Pyrolysis Oil (UPO)

Upgraded Pyrolysis Oil (UPO) is an upgraded form of pyrolysis oil that could potentially become a substitute for HFO and IFO [70]. Pyrolysis oil is a bio-oil that is produced by heating a feedstock in the absence of oxygen in order to thermally decompose into liquid oil, gas and charcoal [55]. This process is called pyrolysis. Pyrolysis is a mature technology that has been used since ancient times for the production of charcoal from wood and is nowadays still commonly used for heat and power applications. Pyrolysis technology can not yet produce synthetic diesel fuel because pyrolysis oil contains too high oxygen levels. This results in pyrolysis oil being very prone to oxidation, having short storage life, and having a lower energy density when compared to bunker fuel [70, 82]. Nevertheless, as Hsieh et al. [82] note, pyrolysis oil can be used as an intermediate material for the production of a substitute fuel for petroleum; especially considering the fact that pyrolysis oil is made from lignocellulosic feedstocks (plant dry matter) or waste material which does not compete with edible feedstock.

This substitute fuel is UPO. The upgrading of pyrolysis oil improves its compatibility significantly, and UPO can therefore become a drop-in fuel with similar characteristics to Fischer-Tropsch Diesel (FTD) [55]. In this process, bio-oil is catalytically upgraded or hydroprocessed to a hydrocarbon fuel. In theory, the upgrading of pyrolysis oil can be done in any intermediate degree between crude and fully upgraded pyrolysis oil to produce a fuel tailored to particular engine types. The well-to-tank GHG emission savings for UPO are high, especially when upgrading takes place on-site at the pyrolysis plant and the hydrogen that is used in the process is not fossil-produced [55].

Currently, there are several organisations working on the upgrading of pyrolysis oil. There are however no commercial plants that are ready for large-scale production, making the future of UPO uncertain.

Upgraded bio-oil via HTL (UBO)

Hydrothermal Liquefaction (HTL) is a process similar to pyrolysis, where feedstock is heated in the absence of oxygen, under moderate temperature and high pressure [82]. The intermediate product resulting from HTL before upgrading to a hydrocarbon fuel is called bio-crude. When compared to pyrolysis, HTL can produce a bio-oil with higher energy density, making it favourable for use as a drop-in fuel [55]. However, due to the lack of research into upgraded bio-oil, no different energy density figures have yet been determined.

Additionally, a benefit of the process of HTL is the lack of need for drying, thus lowering production energy demand and therefore production cost [82]. This also means that HTL can be applied on wet biomass and waste including manure, sewage sludge or algae, of which most is available in abundance and at low cost. According to Hsieh et al. (2017) [82] few companies are working on commercialising HTL technology to bring HTL-produced fuels to market, although Hydrotreated Vegetable Oil (HVO) production technology precedes it.

Nevertheless, there are signs that indicate great potential for upgraded bio-oil via HTL, especially due to its favourable feedstock compatibility and production process compared to pyrolysis.

Fischer-Tropsch Diesel (FTD)

Fischer-Tropsch Diesel (FTD) is a processed diesel product originating from lignocellulosic biomass and waste feedstocks. In the process of making FTD, these feedstocks are first converted into syngas (synthesis gas) by gasification. When the syngas is formed, it is turned in to long-chain hydrocarbon waxes by reactions over metallic catalysts during Fischer-Tropsch (FT) synthesis. Finally, these waxes are then upgraded by standard refinery processes to FT liquids including diesel, gasoline and jet fuel [54]. A benefit of gasification and FT synthesis is that the process is already fully commercialised for use with fossil feedstocks such as coal. However, for use with biomass or waste feedstocks, the technology is less advanced and only expected to be commercially available in limited amounts from 2030 [55].

As with all drop-in diesel fuels, due to their compatibility with the existing diesel infrastructure of Fischer-Tropsch Diesel, strong competition is expected from the road transport and aviation sectors. Additionally, FT diesels tend to contain more impurities than conventional fuels [82].

Nevertheless, Fischer-Tropsch synthesis remains an attractive process to produce near-zero sulphur diesel fuel [128]. Of all bio-fuels, the well to tank GHG emission reduction potential for wood-based FTD is the highest, at 93-95% [152]. Additionally, due to the relative maturity of Fischer-Tropsch synthesis, the external investment costs in R&D, production plants and infrastructure are significantly lower compared to newer technologies.

At last, from a cost perspective, Fischer-Tropsch diesel competes fairly well with other bio-fuels, especially when produced from left-over lignocellulosic residues or waste.

Bio-ethanol

Bio-ethanol is produced by the microbial fermentation of sucrose or starch of cellulose feedstocks such as sugar cane or corn. Bio-ethanol is the most consumed and transported bio-fuel to date, with the majority being used for automotive transportation [82]. Its commercial production is currently nearly twice as high as that of bio-diesel (FAME). The well to tank GHG reduction potential for bio-ethanol lies at approximately 71% when using sugarcane, 32-69% for wheat, 56% for corn and 61% for sugar beet [152]. For advanced bio-ethanol, from straw, for example, the reduction potential could be as high as 87% [152].

An important downside for the use of bio-ethanol is the low energy density and lower volumetric density than HFO or fossil diesel, leading to approximately 40% lower energy density per volume [55]. This strongly reduces the applicability of bio-ethanol for deep-sea shipping, as fuel tanks need to be significantly larger to carry additional fuel for the same distance travelled.

Although bio-ethanol is available today for use in maritime vessels, the engine, fuel injection systems and storage systems are not built to operate on bio-ethanol [55]. It is therefore not a drop-in fuel and would require sizeable investments to become common in the maritime sector. Nevertheless, the advancement of new multi-fuel diesel engine technologies could potentially create an opening in the maritime fuel market for bio-ethanol [82].

Bio-methanol

Methanol is, unlike ethanol, mostly produced via chemical processes. However, early stage commercial production of bio-methanol is underway using feedstocks such as municipal solid waste, waste wood, black liquor (a waste product from paper manufacturing), glycerine and renewable electricity [55]. Bio-methanol synthesis from captured CO_2 is a technology under development to a semi-commercial scale [82].

Bio-methanol has the potential to reduce GHG emissions strongly. According to a directive by the European Parliament published in 2009 [152], reductions could amount to 91-94%, depending on the production route. However, according to Hsieh et al. (2017) and Svanberg, Ellis, Lundgren and Landälv (2018), due to the fuel's low energy density, bunkering of bio-methanol would be required at a 2-3 times higher frequency compared to current liquid fossil fuels [82, 151]. Additionally, methanol is incompatible with current engine and fuel systems, thus requiring additional research and development into compatible system design. At last, apart from a single bunkering station for the Stena Germanica ferry operating between Kiel and Gothenburg, infrastructure and distribution networks for the supply of bio-methanol to marine vessels is not widely available [151].

Considering the aforementioned arguments, bio-methanol is unlikely to persist as an alternative fuel for deep-sea shipping. Nevertheless, with sufficient R&D efforts, it could provide a suitable solution for ferries or inland shipping, since these routes only cover a fraction of the voyage distance compared to deep-sea transport.

Bio-Dimethyl Ether (DME)

Bio-dimethyl ether is a gaseous processed fuel produced through the gasification and conversion of black liquor, a byproduct in the paper and pulp industry or other lignocellulosic material such as farmed wood [69, 152]. Bio-DME's combustion emissions contain very low levels of particulate matter, NOx, and CO_2. Therefore, the GHG emission reduction potential of bio-DME is as high as 92-94% depending on the choice of feedstock and internal energy consumption [152]. Additionally, in contrast to bio-(m)ethanol, its low auto-ignition temperature makes bio-DME more suitable for use in conventional diesel engines, however adaptation of the engine and fuelling system would still be required [55, 82].

Since (bio-)DME is gaseous at ambient temperature, it additionally requires storage under a pressure of at least 5 bar to remain in liquid state. As it is not available globally in the same way as ethanol or methanol, this means that infrastructure and distribution networks would need to be built and adjusted accordingly for its application [55].

Additionally, if bio-DME were to represent a solution towards a future of cleaner shipping, significant amounts of wood biomass would need to be supplied to address the global demand of the maritime industry. Currently, according to Florentinus et al. (2012) [70], there is limited feedstock availability and the technology is still very immature. Additionally, its very low flash point of -41°make it uncertain if bio-DME would be accepted as a maritime fuel under ISO standards [70].

Nevertheless, bio-DME could pose as an interesting alternative fuel solution for the very long term future due to its high adaptability to current systems and high GHG reduction potential. In 2030 or 2050 however, it is not yet expected to be considered a serious alternative for the maritime industry.

LBM (bio-LNG)

Liquefied bio-methane, otherwise called bio-LNG, can be produced via four different routes. These include anaerobic digestion (AD), landfill gas, bio-SNG and RFNBO, which is short for Renewable Fuels of Non-Biological Origin [55]. These routes vary in technological progress from very early stage to full commercial scale operations. Currently, only AD and landfill gas routes are commercially available. Bio-SNG and RFNBO are not expected to become commercially available before 2030 [55].

AD is the process of natural decomposition of biological feedstocks by micro-organisms in the absence of oxygen [55]. The process of AD can run on many feedstocks such as manure, sewage sludge, organic waste and cellulose crops. The biogas that is produced in this process consists of mostly methane (CH_4) and carbon dioxide (CO_2). Since the resulting raw biogas still includes trace gases and CO_2, it is necessary to be upgraded before it can be liquefied into LBM [55]. For landfill gas, the process is identical.

The GHG emission savings from LBM via AD or landfill gas vary depending on the source of electricity used for liquefaction and methane leakage rates. The well to tank GHG emission savings from LBM from organic waste or dry manure range from 71-82% depending on the aforementioned factors [152].

A large benefit of using liquefied bio-methane is that it can be considered a drop-in fuel for use in LNG-fuelled vessels or vessels equipped with a dual fuel LNG engine. In one of the scenarios presented in the IMO's Third GHG study (2015) [148], the share of LNG in the maritime fuel mix is expected to rise to as much as 25% by 2050. In that scenario, LBM could be a relatively simple and feasible solution to reduce GHG emissions from shipping.

Additionally, research carried out by CE Delft for SEA LNG LTD in 2020 concluded that - even when comparing low projected supply values with high demand values - the global supply of liquefied bio-methane in 2030 and 2050 will be more than sufficient to satisfy the demand of the global maritime fleet [36].

Finally, to incentivise shipowners to switch to LBM (bio-LNG), the fuel should be cost-competitive with its fossil counterpart. According to CE Delft (2020), a carbon mark-up of 50-100 USD/t CO_2 is not expected to be sufficient to incentivise a shift in 2030 [36]. However, a 2050 carbon price is consistent with the <2°C mitigation pathway can be expected to incentivise shipowners to make a switch from fossil LNG to LBM; at least if the 2050 fossil LNG price does not decline below 2030 levels, and the production of LBM is sufficiently scaled [36].

4.1.5. Hydrogen

Hydrogen (H_2) is considered as an alternative maritime fuel due to its zero-carbon tank-to-propeller emissions and high conversion efficiency when used in fuel cells.

However, although hydrogen fuel cells exhibit no direct greenhouse gas emissions, the emissions associated with hydrogen production must be considered. Hydrogen is most commonly produced via two pathways: fossil hydrogen through desulphurisation and reforming of natural gas, and renewable hydrogen through electrolysis based on renewable electricity [78]. Currently, most hydrogen is produced through the fossil pathway, resulting in high CO_2 emissions throughout its supply chain. Therefore, in order to commercialise the use of hydrogen as a zero-emission maritime fuel, it is crucial to scale its renewable production.

Although renewable hydrogen is an efficient fuel for producing zero-carbon electricity, its availability and low volumetric density require significant additional infrastructure and system design for maritime application [21]. Contrary to most maritime fuels, hydrogen storage requires very high pressure or very low temperatures. Storage of hydrogen as a compressed gas is typically under a pressure of 250-700 bar, or alternatively as a liquid at -254°C. Even under these conditions, compressed hydrogen requires 30 times larger storage compared to HFO, and 8 times larger storage in liquid condition [21]. The decreased volumetric energy density and need for larger storage would therefore favour inland or short-sea shipping over deep-sea shipping, as these types require less on-board fuel storage [55].

Additionally, there is a high safety risk surrounding the use of hydrogen. Since the gas is highly explosive, leakage should be avoided at all times. This is especially a challenge under high-pressure storage since the molecules are essentially 'pushed' into the storage material at pressures up to 700 bar [48]. Additionally, its small particle size makes it able to diffuse through many materials including metals, making them brittle and subject to sudden fracture [48]. Therefore, hydrogen distribution, storage and bunkering require highly sophisticated systems, which inevitably carry a high cost. All in all, hydrogen fuel costs are higher, potentially by an order of magnitude, compared to conventional fuels, although this gap should decline as the cost of electrolysis declines [133].

4.1.6. Ammonia

In recent years, ammonia (NH_3) has increasingly been proposed as a potential carbon-zero maritime fuel due to its lack of GHG emissions and its ability to efficiently store hydrogen [55]. Its high liquefaction temperature compared to hydrogen (-33°C compared to -253°C for H_2) makes it simpler to store and distribute [48]. Additionally, ammonia is 46% more energy-dense per unit volume than liquid hydrogen, thus saving space and distribution costs compared to H_2 [20].

Although the use of ammonia as a marine fuel produces zero tank-to-propeller CO_2 emissions, the uncertainty surrounding increased NO_x emissions from ammonia combustion should not be left unconsidered [79]. Additionally, its high corrosiveness and toxicity to humans require additional safety and health measures to be taken throughout the supply chain and on board [20, 48].

Furthermore, adjusting global bunkering infrastructure to distribute and handle ammonia demands substantial investments. Although the requirement for such investments may not be a problem for developed countries and ports, it presents significant barriers to adoption in developing countries.

Ammonia has been demonstrated as a fuel in compression ignition (CI) engines, spark ignition (SI) engines, and fuel cells. A recent literature review shows that there is a limited number of tests published on ammonia in combustion engines and that in the tests available, significant amounts of ignition fuel (such as hydrogen, diesel or alcohols) were needed for both CI and SI engines [20, 80]. The review concludes that there are issues remaining with ignition, specific fuel consumption, materials and emissions resulting from ammonia combustion [80]. However, with further R&D and sufficient investments, many can be mitigated [20].

In fuel cells, ammonia can be used directly or it can be split into H_2 and N_2 where-after the hydrogen is used directly in the cell. Although proton-exchange membrane fuel cells (PEM) using purified hydrogen are commercial and tested in maritime applications, alternatives using ammonia directly (e.g. solid oxide fuel cells (SOFC)) have not been tested on board [79]. In any of the two cases, the application of ammonia in fuel cells remains a relatively costly solution.

Ammonia is currently mainly produced from an electricity demanding Haber-Bosch (HB) process using fossil-fuel-based hydrogen, while renewable processes for ammonia production are still under development [79]. Overall, the technology to support ammonia as a marine fuel still shows low maturity, as ammonia production rates can not yet cope with its commercialisation and essential bunkering infrastructure is not in place [48, 79]. Nevertheless, ammonia produced from renewable hydrogen and nitrogen may form a sustainable solution for shipping in the long term, since apart from large amounts of electricity, its production is not dependent on depletable raw materials and, if produced from renewable energy sources, CO_2 emissions are completely eliminated [20, 79].

4.1.7. Nuclear

Nuclear powered vessels have the potential of near-zero-emission sailing due to the lack of combustion process (99% GHG emission reduction according to DNV GL (2015)). Rather than fuelling a combustion engine, small nuclear power plants on board a vessel power a steam generator delivering electricity to the motor. The use of nuclear reactors as a fuel source for maritime applications is well developed through its military use in submarines [55]. As of 2016, there were an estimated 166 naval reactors in operation: 85 owned by the US, 48 by Russia and 33 across the rest of the world [21]. Currently, only one nuclear powered merchant vessel is in operation named the 'SEVMORPUT', a Russian ice-breaking LASH carrier and container ship. The $265m vessel has reportedly been built in 1988 and still operates in the Arctic region, after only needing to refuel its nuclear core twice up to date [110]. Although refuelling frequency may be low, the high cost of the 150kg nuclear cores and complementary systems results in operational expenses of $90k per day [110]. More recently developed nuclear ice-breaking vessels such as the 'NS Arktika' cost approximately $1.9bn per vessel.

Nuclear power offers an extremely high range, very limited need for refuelling and extremely high fuel density, making it theoretically ideal for deep-sea shipping. However, due to its high cost, safety concerns to people and the environment and geopolitical risks related to nuclear powered commercial shipping, it presents very high barriers to commercial adoption [55]. Additionally, there is still no solution presented for the decommissioning of nuclear vessels; all retired units are ultimately still stored afloat [21].

As Balcombe et al. and E4Tech agree, due to the high cost, geopolitical risks, public perception, the lack of precedent and shortfall in legislative frameworks, trained personnel and infrastructure, the potential for large scale deployment of nuclear powered commercial vessels before 2050 is low [21, 55].

4.1.8. Solar

Solar energy is a non-depletable energy source that can power complete households if collected and used efficiently. Since commercial maritime vessels employ very large surfaces that can accommodate solar panels, solar energy could potentially be used to reduce GHG emissions from ships.

However, currently, commercially available photovoltaic panels only produce electrical energy with an efficiency of 15-19%, with a theoretical limit of 33.7% according to the Shockley-Queisser limit [146]. Due to low solar efficiency and very high energy demands for propulsion, marine merchant vessels need large surfaces in order to fully power their propulsion. Additionally, the operation of solar-powered vessels is highly weather-dependent. Since merchant vessels require 24/7 access to power, this means that they must employ very large energy storage devices to endure long nights and dark storms.

Currently, there exist a number of pilot projects on solar-powered vessels combining solar panels and batteries. The most successful project to date is the PlanetSolar Turanor, a passenger vessel with a carrying capacity of 50 passengers which completed a round-the-world trip without using any fossil fuels [132]. Nevertheless, although the pilot was successful, the ratio between panel surface and energy demand of the Turanor was many factors higher than that of a commercial merchant vessel.

As DNV GL predicts in a 2017 study titled 'Low Carbon Shipping Towards 2050', renewable energy systems (such as solar, wind) are not expected to result in more than 0-10% of main engine fuel savings or 0-2% of fuel savings on auxiliary systems [52]. Therefore, the GHG reduction potential for renewable energy sources is also limited. Nevertheless, although solar energy is not expected to become the maritime fuel of the future, solar panels remain a feasible additional energy source on marine vessels, effectively saving fuel and reducing GHG emissions.

4.1.9. Wind

Wind propulsion was the first non-human propulsion method seen on maritime vessels, dating back thousands of years. Nowadays, nearly all commercial maritime vessels are propelled by engines. Nevertheless, wind power is increasingly investigated to reduce fuel consumption and GHG emissions from marine vessels. A number of R&D companies are researching the development of multiple types of sails including soft sails, rigid sails/wingsails or hull sails. The most promising sails for commercial application to date are wingsails, which are wing-shaped foils with varied geometry and configurations, often used in combination with flaps [122]. When applied correctly on large carriers, wingsails can achieve fuel savings from 5-18%. Nevertheless, since (soft or rigid) sails are currently expensive and take up a lot of deck- and overhead space, they are not expected to persist as a widely adopted complement to engine propulsion.

After sails, the most popular wind propulsion method that can be used complementary to traditional engines, are Flettner rotors. Flettner rotors are vertical rotating cylinders that, when immersed in a fluid stream, are able to produce fluid dynamic lift using the Magnus effect [44]. Unlike sails, Flettner rotors are not fragile and take up only a fraction of the overhead space compared to ordinary sails. However, Flettner rotors require additional energy to rotate, and their function remains highly dependent on wind intensity and direction. Additionally, for Flettner rotors to be efficient, they need to have significant height, making them unpractical during on- and offloading of cargo. Nevertheless, according to CE Delft, Flettner rotors can lead to fuel savings of 5-17% depending on carrier type [122].

Another option for wind propulsion assistance is the use of towing kites towards fuel saving on commercial maritime vessels. Experimental studies have been conducted investigating the control and use of towing kites for seagoing vessels, where potential energy savings were determined of 1-9% [60, 122]. However, due to the kite's sensitivity to wind direction and required constant and homogeneous wind fields, the technology is expected to provide too many uncertainties for widespread adoption.

In general, wind and solar are only expected to be applicable to assist the auxiliary powering system of a vessel [108]. The key barriers to wind (assisted) propulsion on commercial vessels identified by CE Delft in 2016 are the lack of (trusted) information on their performance, operability, safety, durability and economic implications, the lack of access to capital for the development of the relevant technology, and the lack of incentive to improve energy efficiency or reduce CO_2 emissions from ships.

4.2. Emission control devices

Emission control devices (or ECDs) are devices designed to reduce gas emissions from industrial processes or engines. The most widely known emission control devices are catalytic converters found in automotive vehicles. Two possible solutions for the maritime industry are discussed below.

4.2.1. Scrubbers

Scrubber systems (or scrubbers) are air pollution control devices that use an alkaline material, commonly in combination with a carrying liquid, to remove toxic gases (SO_x, NO_x) or particulate matter from an exhaust system or gas stream. After passing through the scrubber system, the cleaned exhaust gas is passed out of the system and into the atmosphere.

In open loop scrubbing systems, due to its intrinsic alkalinity, the washing liquid used in scrubbers is seawater. The remaining contaminated wash water is then filtered or diluted and disposed of in the ocean. This process uses up a lot of water, which requires significant space and amounts of energy to power the pumps. A benefit of open loop systems is that there is no need for chemical additives such as caustic soda [119]. Additionally, because toxic substances in open loop systems are ultimately extracted from the air and disposed of in the ocean, there is a lot of discussion around the effectiveness of this method towards reducing emissions. Many researchers believe that disposing of wash water in the sea harms the marine environment by disturbing surface pH levels, which can lead to secondary detrimental effects on the environment [59, 170].

In closed loop maritime scrubber systems, the scrubbing material is chosen such that specific impurities such as SO_x or NO_x can be removed by suitable chemical reactions. In this method, less water needs to be used, but cost and required system volume is higher [119]. Closed loop systems, contrary to their open loop counterpart, do not dispose of wash water in the ocean. Instead, scrubbing residue is stored in a buffer tank until it can be discharged during port operations.

Hybrid systems give the possibility to either use a closed or open loop system on demand. Hybrid scrubbers are mostly used on vessels that commonly operate in open water, but are also prohibited of disposing of wash water in harbours or estuaries [119].

At last, dry scrubbers use a dry chemical such as calcium hydroxide to lock in sulphur, meaning it can not burden the marine environment when disposed. Dry scrubbers do not use any liquid in the process, but rather consist of a bed of granulated filter material. The contaminated granulate can then be disposed of on land during port operations. For dry scrubbers, storage room needs to be created for granulate, which reduces cargo capacity. An advantage of dry scrubbers is the lower energy requirement compared to their wet counterparts [119].

Although all four scrubber technologies work adequately for the extraction of SO_x and NO_x gases from exhaust streams, scrubbers remain ineffective for the reduction of CO_2 emissions. Therefore, scrubbers do not pose a solution for the effective reduction of GHG emissions in the long term.

4.2.2. Carbon capture and storage systems (CCS)

Carbon capture and storage systems (CCS) are emission control devices mostly used in industrial applications. For maritime applications, ship-based carbon capture (SBCC) is an emission control solution that can be implemented on diesel or LNG-fuelled vessels [67]. As the name implies, CCS systems are used to extract CO_2 from exhaust gases, reaching reduction efficiencies of up to 90% [112]. Although the use of CCS systems for industrial applications are slowly gaining traction with 19 large scale facilities in operation as of 2019, the use of the technology on board marine vessels still in very early stages of development [74]. Nevertheless, Feenstra et al. (2019) believe that the technology could provide a transition solution for maritime CO_2 emissions in the short term [67]. However, the research concludes that although the solution is technically feasible, strategies to lower the initial investment must be further developed. A prototype of a ship-based carbon capture system has not yet been realised.

According to literature, the largest hurdles towards the development and adoption of ship-based carbon capture systems are the size of the systems, energy consumption, system OPEX, system CAPEX, storage costs and extensive R&D needed until the system is fit for maritime application [67, 112, 171].

As DNV's head of research and innovation for Greece, Dr. Nikolaos Kakalis, states in an interview (2013) with *ship-technology.com*: "It all comes down to the investment," Kakalis says. "Someone will need to go through the building of a prototype unit, find out more about the real cost and then see what could be a break-even selling price for the CO_2. From what we know of onshore CCS, it costs a lot. This concept will require something like a more integrated value chain, so that somebody could present some contracts selling this CO_2 to the oil and gas industries or to big companies that are producing algae-based biofuel. So someone really needs to have forward contracts to make this a reality" [109]. Dr. Nikolaos Kakalis led a project by DNV that aimed to gauge the theoretical feasibility of implementing carbon capture and storage (CCS) technology on board large vessels [109].

Dr. Kakalis' arguments, in combination with the aforementioned hurdles and the fact that the technology is still far from being widely adopted on land, it is not expected that ship-based carbon capture systems will become commercially available in the short term.

4.3. An overview of alternative maritime fuel technologies

In table 4.1, an overview is presented of the alternative maritime fuel technologies that are discussed in section 4.1 and 4.2. The most notable characteristics of each fuel technology have been summarised.

Category	*Fuel technology*	*Characteristics*	*Primary resource*	*Source*
Fuel oils	HFO	Low cost, carbon heavy, high viscosity bunker fuel; high sulphur content	Crude oil	[116]
	MDO	Cleaner, popular alternative to HFO; varying viscosities; 1-3.5% sulphur content	Crude oil	[1, 2]
	MGO	Distillate fuel, no HFO blend; 0.1-1.5% sulphur content; lower viscosity	Crude oil	[3, 40]
	LSFO	Low-sulphur bunker fuel, 1% sulphur content	Crude oil	[105, 145]
	VLSFO	Low-sulphur bunker fuel, 0.5% sulphur content; suitable for use after IMO2020	Crude oil	[105, 145]
	ULSFO	Low-sulphur bunker fuel, 0.1% sulphur content; suitable for use in ECAs	Crude oil	[105, 145]
Natural gases	LNG	Liquid cooled methane/ethane gas; low nitrogen oxide emissions, sulphur free; low cost; high well-to-propeller GHG output	Crude oil; natural gas	[24, 32, 33, 129, 131, 154]
	LPG	Liquid cooled propane/butane gas; high production level; low environmental performance	Crude oil; natural gas	[42, 48]
Bio-fuels	SVO	Suitable clean alternative to HFO/IFO; risk of carbon deposits and bad blending	Edible or used oils	[55, 70, 82, 137]
	FAME (bio-diesel)	Suitable clean alternative to MDO/MGO; risk of acidic degradation	Edible or used oils	[55, 58, 82, 118]
	HVO	High quality drop-in diesel fuel; higher cost; cross-sector interest	Edible or used oils	[48, 55, 70, 82]
	UPO	Suitable clean alternative to HFO/IFO; high GHG reduction potential; not commercially available	Lignocellulosics; waste	[55, 70, 82]
	UBO via HTL	High potential; low commercialisation; easier production process compared to UPO	Lignocellulosics; wet biomass; waste	[55, 82]
	FTD	Drop-in diesel fuel; more impurities; very high GHG reduction potential	Lignocellulosics; waste	[54, 55, 128, 152]
	Bio-ethanol	Most popular automotive bio-fuel; low energy density; incompatible with current systems	Lignocellulosics	[55, 82, 152]
	Bio-methanol	Low energy density; very high GHG reduction potential; incompatible with current systems	Lignocellulosics; black liquor; waste	[55, 82, 151, 152]
	Bio-DME	Very high GHG reduction potential; pressurised storage; lacking distribution networks	Lignocellulosics; black liquor	[55, 69, 70, 82, 152]
	LBM (bio-LNG)	Renewably sourced drop-in LNG fuel; high GHG reduction potential; potentially cost competitive	Lignocellulosics; landfill gas; waste	[36, 55, 152]
Hydrogen		No tank-to-propeller emissions; very high cost; extreme storage conditions; expensive infrastructure	Natural gas; electricity	[21, 48, 55, 78, 133]
Ammonia		No tank-to-propeller emissions; high cost; toxic; low maturity in marine applications	Hydrogen	[20, 48, 55, 79, 80]
Nuclear		No tank-to-propeller emissions; extremely high cost; geopolitical barriers; safety concerns	Radioactive material	[21, 55, 110]
Solar		Zero-emission cycle; low efficiency; high cost; low energy output	Solar energy	[52, 132]
Wind		Zero-emission cycle; low reliability; high cost; unpractical	Wind energy	[44, 60, 108, 122]
ECDs	Scrubbers	Effectively cut SO_x and NO_x emissions from (fossil) fuels; not applicable to CO_2	-	[59, 119, 170]
	CCS	High CO_2 reduction potential; can be used with many fuels; high cost; high energy consumption; unpractical	-	[67, 74, 109, 112, 171]

Table 4.1: An overview of alternative maritime fuel technologies and their main characteristics. Own composition

4.4. Preliminary selection

In section 3.4, a selection was made of regulatory scenarios that are to be considered in this thesis. In the same way, a selection is now made of alternative fuel technologies that will be considered in the present research.

From the available alternative fuel technologies presented in table 4.1, only a few have the potential to be applied on a large scale by 2030 or 2050. Additionally, only a few fuels can be considered to meet GHG reduction targets, or to be suitable for deep-sea shipping. Therefore, in order to narrow down the list of potential alternative fuel technologies for the future, fuels that do not meet the three following boundary conditions are eliminated:

- The fuel technology is fit for large scale application by 2030 or 2050
- The fuel technology is able to meet proposed GHG reduction targets
- The fuel technology is suitable for deep-sea shipping

On the basis of these three boundary conditions, a preliminary selection of alternative maritime fuels that are to be considered in this research is presented below:

Category	*Fuel technology*	*Characteristics*	*Primary resource*	*Source*
Fuel oils	HFO with scrubbers	Low cost, carbon heavy, high viscosity bunker fuel; Reduced SO_x and NO_x emissions	Crude oil	[59, 116, 119, 170]
Natura gases	LNG	Liquid cooled methane/ethane gas; low nitrogen oxide emissions, sulphur free; low cost; high well-to-propeller GHG output	Crude oil; natural gas	[24, 32, 33, 37, 129, 131, 154]
Bio-fuels	FAME (bio-diesel)	Suitable clean alternative to MDO/MGO; risk of acidic degradation	Edible or used oils	[55, 58, 82, 118]
	HVO	High quality drop-in diesel fuel; higher cost; cross-sector interest	Edible or used oils	[48, 55, 70, 82]
	UPO	Suitable clean alternative to HFO/IFO; high GHG reduction potential; not commercially available	Lignocellulosics; waste	[55, 70, 82]
	UBO via HTL	High potential; low commercialisation; easier production process compared to UPO	Lignocellulosics; wet biomass; waste	[55, 82]
	FTD	Drop-in diesel fuel; more impurities; very high GHG reduction potential	Lignocellulosics; waste	[54, 55, 128, 152]
	LBM (bio-LNG)	Renewably sourced drop-in LNG fuel; high GHG reduction potential; potentially cost competitive	Lignocellulosics; landfill gas; waste	[36, 55, 152]
Ammonia		No tank-to-propeller emissions; high cost; toxic; low maturity in marine applications	Hydrogen	[20, 48, 55, 79, 80]

Table 4.2: Selection of alternative maritime fuels for decision tool. Own composition

As can be seen in the list above, all fuel oils except for HFO have been eliminated from the preliminary fuel selection. This choice was made because fuel oils do not have the capability to meet the IMO's 2030/2050 GHG emission reduction targets in their current form [91]. Despite the fact that the use of HFO with scrubbers will not be able to meet the GHG reduction targets either, it offers an interesting case under a regulatory scenario involving market-based measures and can act as a benchmark.

Moreover, although LNG is considered due to its potential in the medium term, LPG is not considered in this thesis due to its lack of environmental performance compared to traditional HFO.

Concerning bio-fuels, SVO is excluded from the list due to its low calorific value, bad blending capability, high boiling point, high viscosity, and poor compatibility with current systems and infrastructure. Since these challenges can not be mitigated by pre-heating the vegetable oil, the fuel is not considered to be applicable on large scale by 2030 or 2050. In addition, bio-ethanol and bio-methanol are not considered due to their low volumetric energy densities. Vessels using these fuels would require to bunker more often, thus making them unfit for application in deep-sea shipping. Finally, bio-DME is not considered due to its very low technological maturity, uncertainty surrounding its very low flash point and lack of feedstock availability, deeming it unsuitable for large scale application by 2030 or 2050.

Furthermore, despite many research efforts being made towards the development of hydrogen as a maritime fuel, its low volumetric energy density causes hydrogen tanks to take too much space aboard deep-sea vessels.

Also, although nuclear power satisfies the three preliminary boundary conditions, the fuel is omitted from the list due to its geopolitical risks, public perception, lack of precedent and shortfall in legislative frameworks.

Additionally, although solar and wind power are zero-emission energy solutions, their inability to fully power a commercial cargo vessel make these technologies unfit for single-power application in deep-sea shipping. Nevertheless, these technologies are expected to play an integral role in reducing maritime GHG emissions in the future.

At last, although carbon capture and storage systems are increasingly used in land-based applications, the lack of development incentives for maritime applications and impracticality of the installations make the technology unrealistic to be applied by 2030 or 2050.

5

Evaluation criteria

The following chapter studies evaluation criteria for the present research. In section 5.1, relevant literature on evaluation criteria is reviewed. In section 5.2, a selection is made of the criteria to be considered in this research. Section 5.3 evaluates the performance of fuels on technical, environmental and other criteria, where-after in section 5.4 criteria weights are determined according to a survey presented to shipowners. Finally, a preliminary conclusion is drawn in section 5.5.

5.1. Literature on evaluation criteria

Now that a list of feasible alternative maritime fuels is presented, these fuels are assessed based on a set of predefined evaluation criteria.

Since the potential range of criteria that can be used for the evaluation of alternative fuel technologies is very broad, a selection is made. Brynolf (2014) [32], Hansson, Månsson, Brynolf and Grahn (2019) [78], Ren and Lützen (2017) [135], McGill, Remley and Winther (2013) [116], Bergsma, Hart, Pruyn and Verbeek (2019) [26], Deniz and Zincir (2016) [46] and DNV GL (2019) [48] have each defined a distinct set of criteria on which alternative fuels are reviewed in their research. In table 5.1, an overview of these criteria is composed. The terminology used in the table is as quoted in the respective research unless homogenisation was possible without impacting the meaning of a criterion.

Additionally, in order to make a representative selection of evaluation criteria for the present research, it is important to understand the goal and perspective of each cited research paper. Therefore, the concerned literature is reviewed in short paragraphs after table 5.1.

Source	Evaluation criteria			
	Technical	*Economic*	*Environmental*	*Other*
Brynolf [32]	Fuel properties	Engine CAPEX	GHG emissions: well-to-propeller	Safety and safe handling
	Fuel pre-treatment	Engine system OPEX	SO_x emissions	Public opinion
	Engine adaption	Fuel cost	NO_x emissions	Politics and strategy
	Maintenance requirement		Spillage and accident consequences	Ethics
	Logistical criteria		Environmental life cycle performance	
Hansson et al. [78]	Available infrastructure	Engine system CAPEX	Climate change (GWP): well-to-propeller	Upcoming legislation
		Engine OPEX	Health impact	Safety
		Fuel cost	Acidification (SO_x, NO_x)	Long-term global supply
Ren et al. [135]	Technological maturity	Engine system CAPEX	GHG emissions: unspecified	Social acceptability
	Reliability	Fuel cost	SO_x emissions	Government support
	Energy storage efficiency	Training cost	NO_x emissions	Safety
	Available infrastructure	Maintenance cost	PM emissions	
McGill et al. [116]	Available infrastructure	Engine system CAPEX (incl. refit CAPEX)		Long-term global availability
		Fuel cost		
		Maintenance cost		
		Emission abatement cost		
		Training cost		
		Classification cost		
		Insurance cost		
		Indirect cost: reduced range and/or cargo capacity		
Bergsma et al. [26]	Technology readiness level (TRL)	Production cost and routes	Indirect Land Use Change (ILUC)	Feedstock competition with food
	Scalability			
	Engine compatibility			
Deniz et al. [46]	Bunker capability	Fuel cost	Effect on engine emissions	Safety
	Durability	Commercial effects (cargo capacity)	Compliance with emission regulations	Long-term global availability
	Adaptability to current ships			
	Effect on engine performance			
	Effect on engine components			
DNV GL [48]	Energy density	Engine system CAPEX	GHG emissions: well-to-wake	Flammability and toxicity
	Technological maturity	Fuel cost	SO_x emissions	Regulations and guidelines
	Scalability		NO_x emissions	Global production capacity and locations
			PM emissions	Long-term global availability

Table 5.1: Overview of evaluation criteria on alternative maritime fuels as retrieved from literature. Own composition based on Brynolf (2014) [32], Hansson, Månsson, Brynolf and Grahn (2019) [78], Ren and Lützen (2017) [135], McGill, Remley and Winther (2013) [116], Bergsma, Hart, Pruyn and Verbeek (2019) [26], Deniz and Zincir (2016) [46] and DNV GL (2019) [48]

Brynolf

In the PhD dissertation of Selma Brynolf (2014) [32], the author emphasises that factors such as safety, costs, and environmental aspects all have different weights in many alternative perspectives, and the various stakeholders have conflicting views of the importance of these aspects. When Brynolf presents the criteria, the set is divided into four groups: technical, economic, environmental, and other criteria. Certain criteria must satisfy minimum levels and therefore act as boundary conditions, whereas others can be compared mutually.

In Brynolf's dissertation, titled 'Environmental Assessment of Present and Future Marine Fuels', the perspective from which fuels are evaluated is environmental. In this thesis, fuel technologies are evaluated from a shipowner's perspective, and thus primarily account for the views of a shipowner towards an alternative fuel technology. However, although the shipowner's perspective is honoured, boundary conditions are set by regulatory bodies and environmental goals discussed in chapter 3.

Hansson et al.

In Hansson et al. (2019) [78], the goal of the research paper is to find the alternative maritime fuel that is ranked highest considering both the performance of a fuel on different aspects, as well as the importance these aspects carry according to different stakeholders. Additionally, the impact of potential differences in stakeholder preferences is considered by including different maritime stakeholder groups in the examination of cases. These stakeholder groups include authorities, shipowners, fuel manufacturers and engine manufacturers.

Since the present thesis focuses on the shipowner's perspective, Hansson et al. (2019) [78] provides interesting insights into which criteria are important to these stakeholders. Additionally, since authorities create future regulations, analysing the criteria that they consider important can contribute to anticipating which fuels can possibly persist. On the contrary, the views of fuel and engine manufacturers are of less importance to this research.

Ren et al.

Jingzheng Ren and Marie Lützen have written a research paper on the selection of a sustainable alternative energy source for shipping (2017) [135]. In this research paper, the focus lies on sustainable development. Ren et al. suggest that in order to select the most important criteria for sustainability, six principles should be followed: (1) the systemic principle, (2) the consistency principle, (3) the independence principle, (4) the measurability principle, (5) the comparability principle, and (6) the significance principle. These principles are also applicable to the selection of evaluation criteria in the present thesis.

Additionally, the research paper emphasises that to make a complete sustainability assessment, four pillars of technological, economic, environmental and social-political aspects should be considered, since these aspects are intertwined and of mutual influence. Finally, Ren et al. add that users should always choose the most suitable criteria for sustainability assessment according to the actual conditions, which may vary by the perspective from which research is approached. This is particularly relevant for the present thesis.

McGill et al.

The research of McGill et al. (2013) [116] titled 'Alternative fuels for marine applications' examines the use of alternative fuels for use by the marine shipping industry to satisfy or partially satisfy new and future regulations. In assessing alternative fuels, several parameters are evaluated relating to the technical, economic, and environmental implications of the use of each fuel. However, contrary to other research papers examined in this chapter, McGill et al. choose to convert most criteria across these four pillars into costs, thus providing a level basis for comparison [116].

Nevertheless, McGill et al. do not perform any systematic review of the proposed fuel alternatives. Instead, the research report covers alternative marine fuels in separate chapters in which only a few criteria are briefly discussed. The majority of the aforementioned criteria are left unconsidered. Considering that this thesis is aimed at following systematic methodology, the research of McGill et al. is not considered in the selection of appropriate evaluation criteria.

Bergsma et al.

Bergsma et al. (2019) [26] published a report for the Netherlands Maritime Land and Ministry of Economic Affairs on the assessment of alternative fuels for seagoing vessels using heavy fuel oil. In their assessment, Bergsma et al. primarily evaluate fuels based on their current and future technological readiness level (TRL) with regard to fuel production. In this approach, the TRL represents the maturity of a technology. TRL level 1 to 2 indicates basic technology research, 3 to 5 indicates the phase of technology development, TRL level 5 to 7 indicates the phase of technology demonstration, TRL level 6 to 8 indicates the phase of system and subsystem development, TRL level 7 to 9 indicates the phase of systems testing for launching and operations and TRL level 10 indicates proven technology [26].

In addition, Bergsma et al. place emphasis on the sustainability of a feedstock by considering its competition with food and Indirect Land Use Change (ILUC), which causes the repression of original vegetation due to the production of crops. These criteria are especially important when evaluating bio-fuels.

In the present thesis, high priority is given to the sustainability of a fuel technology. Therefore, criteria such as competition with the food industry and ILUC carry high significance when evaluating bio-fuels on their sustainability. Additionally, the TRL of fuel technologies is a realistic criterion for shipowners to consider when evaluating a fuel technology for the future.

Deniz et al.

Deniz and Zincir (2016) [46] have written a research paper on the environmental and economical assessment of alternative maritime fuels. The aim of their study was to make a scientific comparison of alternative fuels which can be used on ships. In this comparative study, the performance of methanol, ethanol, LNG and hydrogen was addressed.

The criteria considered in Deniz et al. manage to capture technical, economic, environmental and social aspects of alternative maritime fuels. In addition, the research paper includes an expert ranking of comparison criteria by a panel of five licensed chief engineers, each with a minimum experience of 8 years. In this ranking, safety is ranked as the highest priority, while global availability is ranked last (11th). This is conflicting with the findings from Hansson et al. (2019) [78], where according to shipowners the reliable supply of a fuel and its safety share the first priority.

However, as was also seen in Hansson et al. (2019) [78], relative rankings of criteria deviate strongly when provided by different stakeholder groups. Therefore, when weighing criteria, it is essential to understand the perspective from which a study is approached. In the case of the present research, that is the perspective of the shipowner.

DNV GL

In a report by DNV GL published in 2019 [48], several alternative marine fuels are compared. As DNV GL states: "the overall ambition of the project has been to carry out a comprehensive study, based on existing academic and industry literature, on the commercial and operational viability of alternative marine fuels." [48].

Although this goal aligns well with the goal of the present thesis, DNV GL additionally chooses to do a deep-dive into combustion methods for each maritime fuel. This deep-dive includes analyses of combustion methods and technologies of very low maturity; something that will not be considered in the current research.

5.2. Criteria selection for multi-criteria decision model

Following the scope of the present research and the insights gained from the aforementioned literature, the criteria that are to be considered in the multi-criteria decision model in this research are presented in table 5.2. These criteria are all relevant to making an optimal choice of fuel technology under the selected regulatory scenarios and are chosen from the perspective of a shipowner. However, since economic criteria are considered in an extensive financial model which produces several financial indicators, they are not considered in this section.

Category		*Evaluation criteria*
Technical	*1*	Technological maturity
	2	Availability of infrastructure
	3	Engine compatibility
	4	Fuel volumetric energy density
Economic	*1*	CAPEX
	2	OPEX
	3	Fuel cost
Environmental	*1*	Compliance with emission regulations
	2	GHG emissions: well-to-tank
	3	GHG emissions: tank-to-propeller
Other	*1*	Safety of fuel technology
	2	Long-term global availability of fuel
	3	Feedstock competition with food (if applicable)

Table 5.2: Overview of final evaluation criteria on alternative maritime fuels for the present research. Own composition

After reviewing numerous criteria from literature in table 5.1, the final evaluation criteria have been formulated such as to encompass as many important aspects as possible. Under the following bullet points, the chosen criteria are described.

Technical (A)

- *Technological maturity*
  Technological maturity defines the degree up to which a technology has been developed. A well-known method of measuring technological maturity is the technology readiness level (TRL). The use of the TRL metric enables consistent and uniform assessment of technological maturity across different types of technology.

- *Availability of infrastructure*
  Availability of infrastructure is a criterion which assesses the degree to which infrastructure is currently available for the transportation and bunkering of a fuel during port operations. Although some fuels that are discussed can be considered drop-in fuels and can therefore utilise existing infrastructure, many alternative fuels require (sometimes major) adjustments to existing systems.

- *Engine compatibility*
  Engine compatibility describes the degree to which an alternative fuel is compatible with existing engines and fuel systems. This criterion is mostly dependent on technical criteria such as density, viscosity, boiling point and flash point of a fuel.

- *Fuel volumetric energy density*
  The volumetric energy density of a fuel represents the amount of energy stored in a fuel per unit of volume. Therefore, vessels that equip fuels with higher energy densities require less fuel

to travel equal distances over sea. With the same analogy, vessels that equip fuels with higher energy densities can travel longer distances on equal amounts of fuel. As the considered fuels are liquid, the unit in which the volumetric energy density is described is in MJ/l.

Environmental (B)

- *Compliance with emission regulations*
  This criterion describes to what extent a fuel technology is compliant with current and/or future emission regulations. This includes regulations limiting NO_x and SO_x emissions, as well as regulations constraining the use of certain bio-fuels in high concentrations.

- *GHG emissions: well-to-tank*
  Well-to-tank GHG emissions, otherwise called upstream emissions, are considered the GHG emissions emitted during the extraction, processing and transportation of a fuel to the final user [62].

- *GHG emissions: tank-to-propeller*
  Tank-to-propeller GHG emissions are the emissions a vessel produces when consuming a fuel for propulsion.

Other (C)

- *Safety of fuel technology*
  The criterion assessing the safety of a fuel technology describes the safety of a fuel towards both humans and the environment. This includes the potential toxicity and flammability of a fuel.

- *Long-term global availability of fuel*
  This criterion assesses the degree to which a fuel will be or remain to be globally available in the long-term.

- *Feedstock competition with food (if applicable)*
  'Feedstock competition with food' describes the degree to which a fuel uses a feedstock in its production cycle that is also used for human consumption. This is relevant when assessing bio-fuels.

The final criteria that are described above are chosen such as to encompass as many elements as possible from the criteria that are retrieved from literature (as presented in table 5.1).

As such, in category A (technical criteria), bunker capability falls under the 'availability of infrastructure' and fuel properties and pre-treatment of fuels fall under the criterion of 'engine compatibility'. Additionally, increased space requirements for larger fuel storage tanks are considered within the 'fuel volumetric energy density' criterion. In the same way, in category B (environmental criteria), SO_x and NO_x emission compliance criteria are not considered separately, as these aspects are accounted for under the 'compliance with emission regulations' criterion. Finally, under C (other criteria), the toxicity and flammability criteria fall under 'safety of fuel technology' and the scalability of a fuel technology falls under the criterion 'long-term global availability of fuel'.

Although financial implications surrounding a fuel technology are of paramount importance to shipowners, these criteria are not statically defined in the literature study. This choice has been made intentionally since costs are dynamic over time and dependent on the maturity and scale of a technology. However, in the decision tool that is devised in the second part of this research, cost development over time of each selected fuel plays a central role. This includes running costs, voyage costs and capital costs. Eventually, the performance parameters assigned to each technology for each criterion are implemented in the decision tool that is devised in the second phase of this research.

5.3. Criteria evaluation

Now that the evaluation criteria have been selected, potential future fuel technologies are evaluated. As was also primarily carried out in the analysis of table 3.4, criteria are evaluated based on literature. Where information was incomplete, an approximation has been made. The results are presented in table 5.3. In the current phase of the research, the terminology or scoring method used in table 5.3 is not yet translated into a normalised score. This is a task that follows in the implementation of the decision tool.

		j	*Unit*	HFO	LNG	FAME	HVO	UPO	UBO	FTD	LBM	NH3	*Source*
(A)	*1*	Technological maturity	*TRL*	10	10	10	10	5.5	4.5	7	10	5.5	[26, 82]
	2	Availability of infrastructure	-	5	5	3	5	5	5	5	5	2	[48, 55]
	3	Engine compatibility	-	5	5	2	5	5	5	5	5	2	[48, 55, 79, 82]
	4	Fuel volumetric energy density	*MJ/l*	41	22.2	33.2	34.4	34	34	34.5	22.2	12.7	[10, 15, 48, 55, 77]
(B)	*1*	Compliance with emission regulations	-	4	5	3	3	5	5	5	5	2	[26, 118, 126]
	2	GHG emissions: well-to-tank	gCO_2eq/MJ	14.3	21.2	32	30	34.5	22	5	19.5	7.0	[55, 129, 152]
	3	GHG emissions: tank-to-propeller	gCO_2eq/MJ	81.2	57.5	0	0	0	0	0	0	0.0	[39, 57, 96, 129]
(C)	*1*	Safety of fuel technology	-	5	4	5	5	5	5	5	4	3	[20, 33]
	2	Long-term global availability of fuel	-	3	3	3	3	4	4	4	4	5	[118, 144, 159]
	3	Feedstock competition with food	-	5	5	2	2	4	4	4	4	5	[26, 82]

Table 5.3: Performance parameters p for each alternative i for the average, unregulated, 2020 base case scenario.

The technology readiness level (TRL) of the various fuel technologies has been determined based on their technological relevance in 2020. In designing a decision tool subject to future scenarios, these TRLs are expected to increase over time as technological development progresses.

Under criteria A2 and A3, which judge the availability of infrastructure and engine compatibility of fuel technologies respectively, FAME and ammonia perform below average. This can be attributed to the fact that both fuel technologies require major adjustments and/or investments in existing systems to ensure safety and durability in the long term. In the case of FAME, the low scores can be attributed to its clogging and acid degradation properties, while with ammonia, the low scores are attributed to its highly corrosive properties affecting infrastructure and engines.

What might seem surprising when reviewing bio-fuels, is that tank-to-propeller emissions (B3) are 0 gCO_2/MJ. This is because under the Kyoto Protocol the emission factor for biomass is always zero [125]. However, this does not mean that the combustion of these bio-fuels does not emit any exhaust gases. The net tank-to-propeller emissions of bio-fuels are zero because they are measured over the bio-fuels' life-cycle, where the growth of the feedstock has absorbed an equal amount of CO_2 from the air. Nevertheless, as Cherubini et al. (2009) [39] explain, bio-fuel production does emit greenhouse gases from well-to-tank: "Biomass use for energy generation is considered “carbon neutral” over its life cycle because combustion of biomass releases the same amount of CO_2 as was captured by the plant during its growth. By contrast, fossil fuels release CO_2 that has been locked up for millions of years. Bio-energy has an almost closed CO_2 cycle, but there are GHG emissions in its life cycle largely from the production stages: external fossil fuel inputs are required to produce and harvest the feedstocks, in processing and handling the biomass, in bio-energy plant operation and in transport of feedstocks and bio-fuels". Figure 5.1 demonstrates the total well-to-propeller emissions of the selected fuels, which include emissions generated during production, distribution and combustion of each fuel.

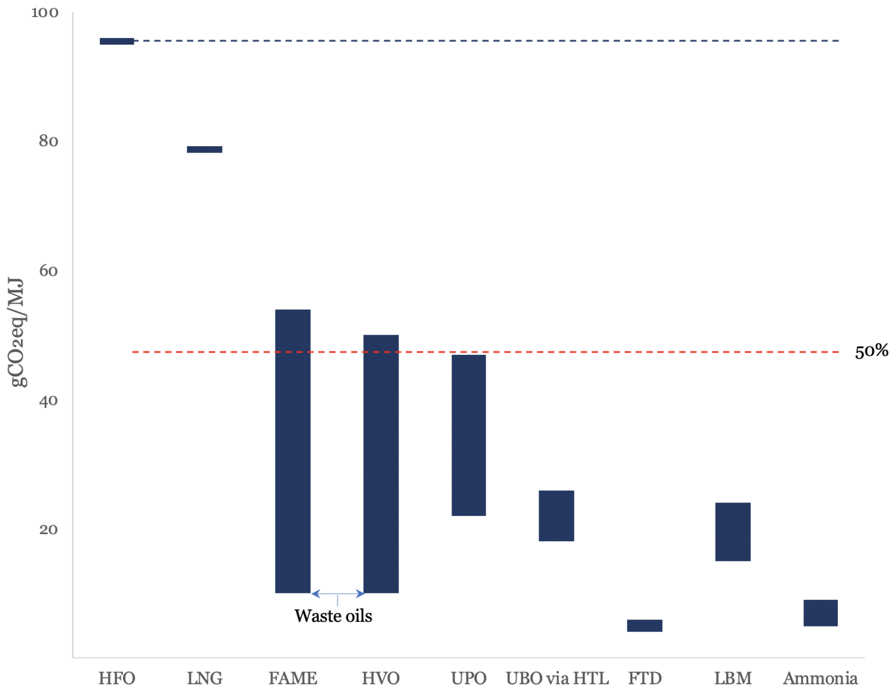


Figure 5.1: Graphic representation of well-to-propeller emissions of selected fuel technologies. Own composition

Under C2, where scores are assigned for the long-term global availability of fuels, fossil fuels, FAME and HVO score lower. According to a paper published by Shafiee and Topal (2009) [144], fossil fuel reserve depletion times for oil, coal and gas amount to approximately 35, 107 and 37 years, respectively. Even though these time spans are evaluated with high uncertainty, they do confirm that the current fossil fuel supply is finite, and is reaching its bottom at present consumption rates.

As for FAME and HVO, the lower score has been assigned due to the present choice of feedstock used. Currently, FAME and HVO production is heavily dependent on edible oily feedstocks that compete with the food industry; meaning these fuels will likely be subject to future regulatory measures [118].

Additionally, under D3, apart from FAME and HVO scoring low due to their dependence on edible oily products, other bio-fuels are not assigned a score of 5 due to the uncertainty surrounding the effects of Indirect Land Use Change (ILUC) [26].

5.4. Criteria weights

In a survey presented to seven deep-sea shipowning entities, shipowners have reviewed the aforementioned evaluation criteria and assigned scores to judge the importance of each criterion for decision-making on alternative fuel technologies in their firm. In the decision tool, these opinions are translated into criteria weights. In the current application, shipowners reviewed criteria categories (technological, economic, environmental and other) and individual criteria on the basis of their importance, ranging from not important at all to extremely important.

For privacy reasons, survey participants are anonymised and identified by their job function, while the associated shipping companies are identified by their primary business line and number of vessels under management. An overview is presented in table 5.4.

Job title	Country of origin	Primary business line	Vessels under management (±)
Senior Manager	Denmark	Tankers, container vessels	700
General Manager	China	Tankers, container vessels, bulk carriers	600
Vice President	Norway	Tankers, gas carriers	370
Head of corporate and business dev.	Greece	Container vessels, bulk carriers	50
Director	Norway	Chemical tankers	25
Senior Manager	Norway	Container vessels	25
Managing Director	Norway	Tankers, container vessels	10
			1780

Table 5.4: Overview of survey participants. Own composition

The received responses were evaluated on a 5-point Likert scale. The Likert scale is a psychometric scale that analyses the opinions of participants on five or seven points [29]. The results from the survey presented to shipowners are visualised in figure 5.2 and 5.3 below.

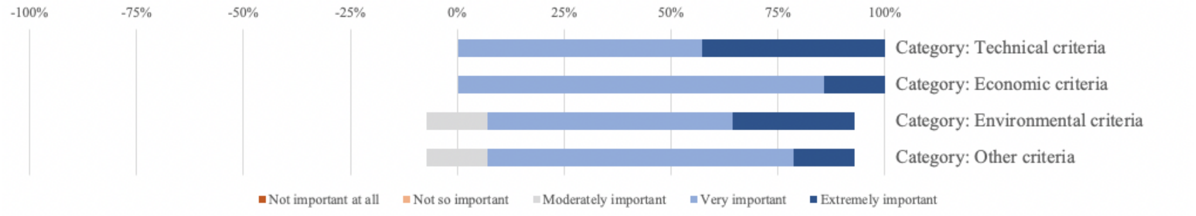


Figure 5.2: Visualised survey results: criteria categories. Own composition

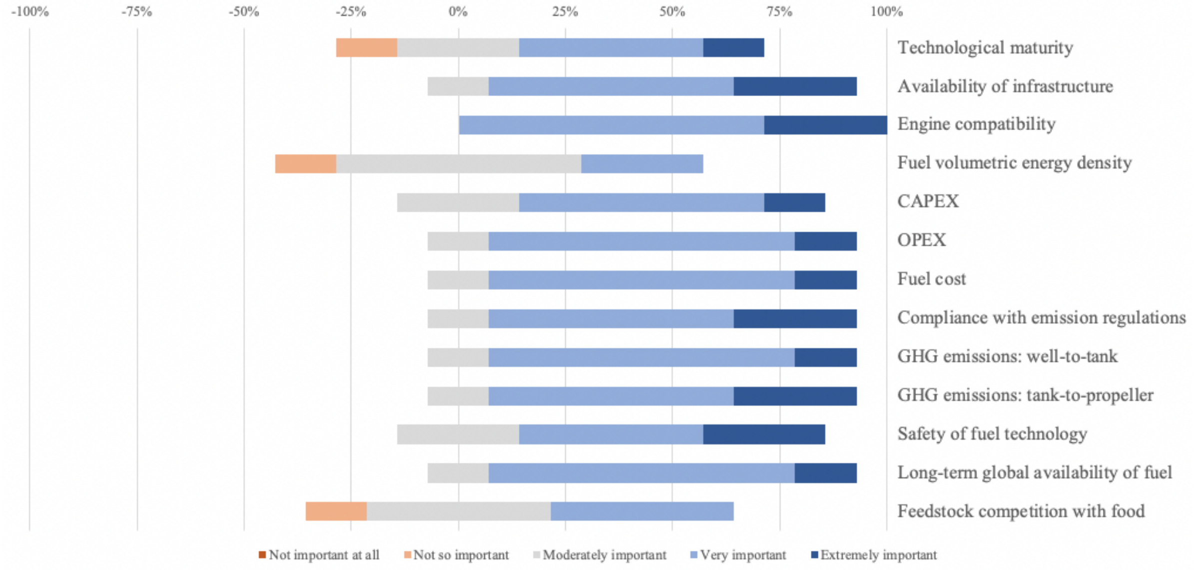


Figure 5.3: Visualised survey results: individual criteria. Own composition

The right-hand side of the figures shows the evaluated criteria and the left-hand side shows the distribution of the responses. From the above figures, one can derive how shipowners have evaluated the importance of the presented criteria on the Likert scale. Although the degree of importance varies between different criteria, the relatively low standard deviation shown in table 5.5 shows high consensus amongst survey respondents.

Criteria	Median	Standard deviation	Consolidated median
Category: Technical criteria	4.0	0.53	-
Category: Economic criteria	4.0	0.38	-
Category: Environmental criteria	4.0	0.69	-
Category: Other criteria	4.0	0.58	-
Technological maturity	4.0	0.98	4.0
Availability of infrastructure	4.0	0.69	4.0
Engine compatibility	4.0	0.49	4.0
Fuel volumetric energy density	3.0	0.69	3.0
CAPEX	4.0	0.69	4.0
OPEX	4.0	0.58	4.0
Fuel cost	4.0	0.58	4.0
Compliance with emission regulations	4.0	0.69	4.0
GHG emissions: well-to-tank	4.0	0.58	4.0
GHG emissions: tank-to-propeller	4.0	0.69	4.0
Safety of fuel technology	4.0	0.82	4.0
Long-term global availability of fuel	4.0	0.58	4.0
Feedstock competition with food	3.0	0.76	3.0

Table 5.5: Criteria weight assessments. Scores are assessed on Likert scale: 1: Not important at all; 2: Not so important; 3: Moderately important; 4: Very important; 5: Extremely important.

In table 5.5, the median, the standard deviation, and the consolidated median of the shipowners' responses are presented. As can be seen, in the two left-most columns, category scores are separated from individual criteria scores, as they assess the general importance of a criteria category. Since all criteria categories receive an equal median score (4.0), they do not influence the weights of the individual criteria. In the right-most column, the consolidated median of each individual criterion is presented. The presented results of the survey are integrated with the SMART decision tool to express the degree of importance shipowners assign to each fuel alternative.

5.5. Preliminary conclusion

On the basis of the criteria assessed in table 5.3, no evident conclusions on the optimal choice of fuel technology can yet be drawn. However, by assessing the most important characteristics and properties of the selected fuel technologies, the relative performance of fuels compared to their peers become evident.

Whereas FAME and HVO are proven technologies and therefore show a benefit over the other (bio-)fuels in terms of maturity and development, these fuels lag behind on other criteria such as regulation, global availability and feedstock competition. This can mostly be attributed to the fact that the majority of FAME and HVO are currently produced from edible oily product sources such as rapeseed, soybean, coconut, palm and corn, which compete with the food industry [118]. However, when these fuels are produced from waste oils, their performance on emissions, long-term global availability and feedstock competition with food drastically improve.

Upgraded pyrolysis oil (UPO) and upgraded bio-oil via hydrothermal liquefaction (UBO via HTL) perform very similarly due to their technological property of being able to be upgraded to the required quality standard. These fuels do not show high maturity, meaning that some properties such as the volumetric energy density can yet only be estimated to be approximately equal to other liquid bio-fuels. Nevertheless, UPO and UBO show great potential in terms of both performance and cost.

In its turn, Fischer-Tropsch diesel (FTD) shows higher maturity and highly similar performance to UPO and UBO via HTL, while maintaining extremely low emission standards.

Liquid bio-methane, or bio-LNG, is a proven technology that can be considered a drop-in fuel in LNG-powered vessels. Apart from the lower volumetric density compared to the aforementioned liquid bio-fuels, bio-LNG shows steady performance on all criteria.

Finally, whereas ammonia production is very mature for applications in the agricultural industry, its maritime counterpart has not yet reached mature stages of development and testing. Additionally, current infrastructure would require major adjustments to be able to provide ammonia to sea-going vessels. At last, engine compatibility with current systems is low, and fuel safety regarding human operators and the environment is still highly uncertain. Nevertheless, ammonia remains a low-emission, non-depletable fuel source, making a very interesting case for its potential as a long-term solution.

Concerning criteria weights, shipowners allocate high importance to technical criteria. Whereas technological maturity and volumetric energy density do not seem to be of highest importance, the availability of infrastructure and especially engine compatibility do. This may be due to the fear of higher costs surrounding fuels that are incompatible with current engine systems. Additionally, what is surprising is that although the economic criteria category is scored relatively high, individual economic criteria (CAPEX, OPEX and fuel cost) do not receive as high scores as one might expect. Finally, environmental criteria and especially compliance with emission regulations and tank-to-propeller GHG emissions receive high scores. Other criteria are valued slightly lower by shipowners, possibly due to the low risk they carry to their business. Nevertheless, the survey results should not be accepted as general industry standards. Although a lot of effort has been put into collecting survey responses, the sample size of n=7 might not be representative of the industry-wide opinion of deep-sea shipowners.

In conclusion, this chapter does not provide closure on which fuel technology represents the optimal choice for a shipowner in the long term. However, it does provide valuable insights regarding the performance of different fuel technologies on technical, environmental and other criteria. When combining these criteria with the economic aspects of fuels, shipowners are able to decide which fuel technology is the preferred choice under different imposed emission regulations. This decision-making process is facilitated in the second phase of this research by means of a decision support tool.

6

Bunker fuel cost

Chapter 7 explores the cost of present and alternative bunker fuels. In section 6.1, the current bunker fuel market is assessed. Following this, section 6.2 researches the cost of feasible alternative fuels, of which most have not yet reached commercial stage. Finally, in section 6.3, preliminary conclusions are drawn.

6.1. Assessment of current bunker fuel market

Currently, global bunker prices of the most popular bunker fuels are published on a daily basis by multiple providers. When analysing bunker price data from different bunkering ports, it is evident that bunker prices can vary significantly between geographical areas. This causes shipowners to invest substantially in their bunkering strategy, as cost-efficient bunkering can significantly increase profit margins. Therefore, for an alternative fuel to successfully penetrate the industry, it does not only require to be cost competitive but also to be globally available with minimal price differentiation between ports. This is a highly challenging matter for alternative fuels.

In figure 6.1, year-to-date bunker price developments of the most popular bunker fuels are demonstrated. The prices shown represent a global average of the top-20 bunkering ports based on volume; consisting of Busan, Canary Islands, Colombo, Durban, Fujairah, Gibraltar, Hong Kong, Houston, Los Angeles, New York, Nigeria, Panama Canal, Piraeus, Rotterdam, Santos, Shanghai, Singapore, St. Petersburg, Suez and Tokyo. As is seen from the graphs, price differentials between various types of heavy fuel oils are fairly constant. Additionally, it is evident that the more refined fuels (in terms of lower viscosity or lower sulphur content) are the most expensive. Finally, it is important to note that the steep decline in bunker prices from February/March 2020 is attributed to COVID-19, which had a severe impact on global trade and consequently bunker fuel demand. The steep decline verifies the price dependency of bunker fuel on local demand.

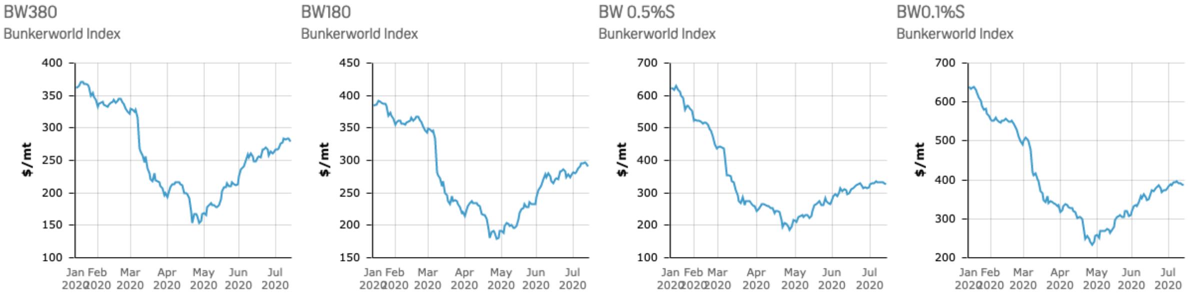


Figure 6.1: Global 20-port average price charts for IFO-380, IFO-180, VLSFO-0.5% and LSMGO-0.1% YTD-2020. Source: S&P Global Platts

Finally, since natural gas has been internationally traded since the late 1960s, regional price indices have been established. Generally, LNG has always been more cost competitive compared to heavy fuel oils. However, liquefaction cost for liquid storage aboard marine vessels should not be forgotten. Currently, the cost of liquefaction in the U.S. comes down to approximately 3 $/MMBtu, although lower spreads of 2 $/MMBtu have been observed in the past [157, 158].

According to MAN (2011) and DNV GL (2020), the total cost of liquefaction and small scale distribution of natural gas are expected to range between approximately 3-5 $/MMBtu [49, 53]. Production costs average from 3 $/MMBtu to 4 $/MMBtu. Taking these costs into account, the cost of bunkering LNG in present time would come down to approximately 6-9 $/MMBtu, which translates to approximately 310-465 $/mt LNG.

Local bunker price differentiation and global bunker price fluctuation is dependent on many factors, ranging from supply and demand dynamics in the short run to more complex relationships with oil markets in the long run. Additionally, static factors such as vicinity to oil refinery plants and oil reserves form an important basis for price setting. As Alizadeh, Kavussanos and Menachof accurately summarise in an article researching the effectiveness of hedging against bunker price fluctuations using petroleum futures contracts (2004) [18]: "Differences between the short-run dynamics of bunker prices and energy futures appear to be due to the changes in regional supply and demand in the bunker market, while the long-run co-movements between spot bunkers and energy futures are due to the fact that all these prices are driven by the same underlying factor, which are the conditions prevailing in the world oil markets."

Nevertheless, unlike hedging opportunities presented by Forward Freight Agreements (FFAs) in the freight market, Alizadeh et al. see low hedging effectiveness with forward energy contracts in the bunker market [18]. This can be attributed to the fact that bunker prices mainly reflect the regional balance of supply and demand for bunker fuel, rather than leaning on the present or future condition of the global oil market.

Although forward hedging is not found to be effective on bunker prices, a common measure shipowners take to shield themselves against surging bunker prices is the implementation of the so-called Bunker Adjustment Factor (BAF). The BAF is an additional surcharge levied on ship operators to compensate or protect the shipowner for unexpected fluctuations in fuel prices. Bunker adjustment factors are not considered in this thesis.

6.2. Cost of feasible alternative fuels

One of the most important criteria for shipowners when considering alternative fuels is fuel cost. In this section, fuel cost ranges for feasible alternative fuels are derived from literature. Following this, a preliminary conclusion is drawn based on the findings.

As with all new and upcoming technologies, the single biggest obstacle towards market penetration is to get the product to a competitive price point with the lack of scale. In encountering this challenge, alternative fuels are not different. Due to low-scale production, low availability of resources and lack of technical know-how, prices for alternative fuels remain high. In table 6.1, present production and distribution costs of alternative fuel technologies are demonstrated.

Alternative	*Production cost*		*Distribution cost*		*Total cost*		*Source*
	$/MWh		*$/MWh*		*$/MWh*		
	Minimum	*Maximum*	*Minimum*	*Maximum*	*Minimum*	*Maximum*	
HFO (IFO-380)	30.5	34.8	-	-	30.5	34.8	Clarksons; [41]
LNG	11.3	15.1	11.3	18.9[1]	22.6	34.0	[49, 53, 72, 157]
FAME (bio-diesel)	67.6	100.5	0.0	0.6	67.6	101.1	[14, 68, 106, 123]
HVO	58.7	146.9	0.0	0.6	58.7	147.5	[64, 68, 124, 139]
UPO	58.0	136.6	0.0	0.6	58.0	137.2	[11, 55, 139, 165]
UBO via HTL	60.3	145.5	0.0	0.6	60.3	146.1	[45, 155]
FTD	61.0	165.6	0.0	0.6	61.0	166.2	[55, 64, 106, 139]
LBM (bio-LNG)	46.0	144.9	11.3	18.9[2]	46.0	144.9	[55, 64, 72, 139]
Ammonia	39.0	118.8	19.8	73.3[3]	58.7	192.1	[48, 77, 81]

[1] LNG distribution costs include cost of liquefaction.

[2] Distribution and liquefaction costs of LBM are assumed equal to LNG.

[3] Ammonia is assumed to be stored and distributed under 1 bar and -33°C or 10 bar and 20°C at equal cost.

Table 6.1: Fuel production and distribution cost of alternative fuel technologies. Own composition

For the sake of comparison, the cost for HFO (IFO-380) bunker fuel is added to the list of alternative fuels. As one might notice, the distribution cost of IFO-380 is left blank. This is due to the fact that for IFO-380, distribution cost is included in the production cost.

For LNG, production costs range from 3 $/MMBtu to 4 $/MMBtu and according to DNVL GL and MAN, distribution and liquefaction costs range from 3-5 $/MMBtu [49, 53]. Due to the fact that the same distribution networks can be used to transport and bunker liquefied bio-methane as LNG, distribution costs for LBM are assumed equal.

For bio-fuels that can be distributed via present distribution networks (FAME, HVO, UPO, UBO and FTD), distribution costs are found to range from zero to approximately 0.6 $/MWh [56].

Furthermore, for FAME, the lower bound of the production cost range is achieved when the bio-diesel is produced from waste streams, while the upper bound of the range is reached when it is produced from rapeseed oil [68]. Due to the low technological maturity of bio-fuel production from waste streams, the current market price for FAME remains close to the upper bound of the price range [123].

Similarly, for Fischer-Tropsch diesel, the lower bound is achieved when the bio-fuel is produced from waste streams, while the upper bound is reached when the FTD is produced from biomass. However, as is the case with FAME, current FTD production is heavily reliant on biomass, which maintains very high costs. In fact, according to Kesieme et al. (2019) the average cost of raw material for bio-diesel production is nearly 60 to 75% of the total production cost [101].

For ammonia, the production cost range is not so heavily dependent on resources, but rather the choice of production process. The lower end of the cost range is achieved via traditional Haber-Bosch, the middle range via direct electrochemical nitrogen reduction and the upper range via electrolysis of water, followed by Haber-Bosch. The distribution cost for ammonia is derived by assuming equal distribution cost as for LNG and correcting for the difference in volumetric energy density.

6.3. Preliminary conclusion

Figure 6.2 demonstrates the total cost range of the selected alternative fuels, including production and distribution costs.

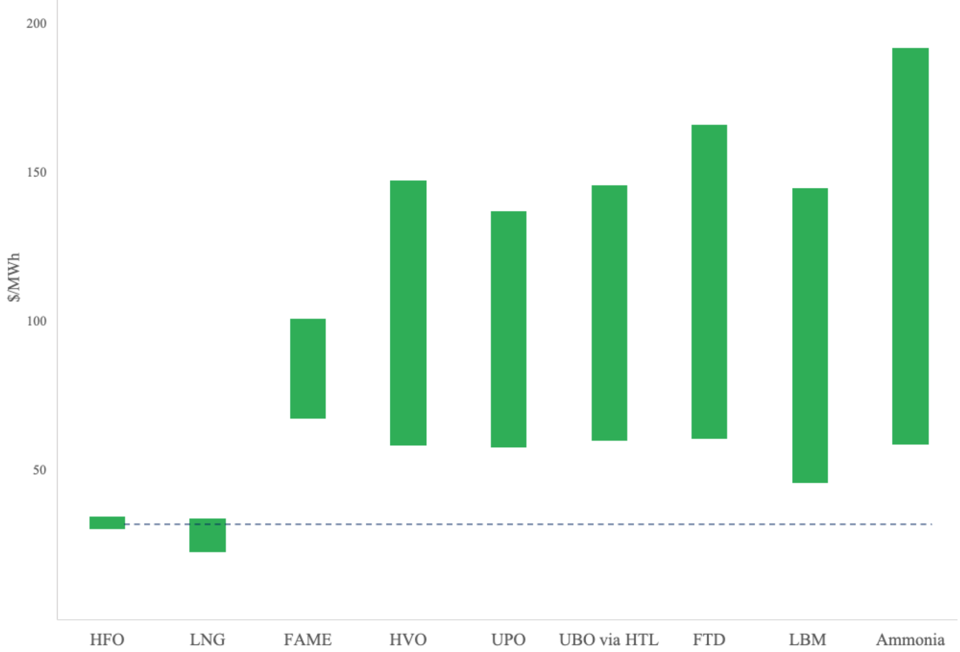


Figure 6.2: Total fuel cost range of alternative fuel technologies. Own composition

As is evident, alternative fuel technologies still need to bridge a significant price gap before shipowners are expected to switch their bunkering strategy based on fuel cost. Nevertheless, it is not unthinkable that with significant scale, sufficient financial support from governments and regulators and supportive tax schemes, this can be achieved.

Especially when considering the fact that with the current lack of scale and technological know-how, (relatively) low-cost alternative fuels can be produced from waste streams. This may indicate that the door to a more sustainable future for the maritime industry starts to open.

Nevertheless, the lower cost scenarios for the selected alternative fuels still remain too high compared to current fuel solutions. As was suggested in chapter 4, LNG could present a sufficient bridging opportunity to defer from heavy fuel oils. If prices are maintained low -something that is bound to happen when the technology is scaled- LNG presents a competitive opportunity compared to traditional heavy fuels. Additionally, if the industry decides to initiate a mass transition towards LNG, the threshold towards the adoption of liquefied bio-methane (bio-LNG) is lowered.

However, this strategy would not necessarily speed up the adoption of an environmentally friendly fuel. As was presented in figure 5.1, LNG still emits far more gCO_2eq/MJ than is desirable to cut emissions by 50%.

In conclusion, shipowners are currently not incentivised to switch their bunkering strategy to the use of a more sustainable fuel due to fuel cost. Additionally, the added CAPEX that would be required to refit vessels in order to burn alternative fuels would add to the total switching cost.

However, with the implementation of the correct tax schemes and other economic incentives, the current price gap may possibly be bridged. The conditions under which this is possible will be examined in the decision tool.

7

Current state of research

This chapter is intended to form an understanding of current literature on alternative maritime fuels of the future and of decision tools as a means of complex decision-making towards maritime fuel choices. Relevant literature is reviewed and the conclusions are summarised. Additionally, this chapter provides insights into which areas have already been researched, and equally important, which areas have not. In section 7.1, existing literature on alternative maritime fuels is reviewed, where-after in section 7.2, literature is reviewed on decision tools. Finally, in section 7.3, conclusions are drawn and the knowledge gap in the current field of research is identified.

7.1. Literature on alternative maritime fuels

The current section reviews literature on alternative maritime fuels of the future. The literature review is limited to the chosen set of alternative fuel technologies (LNG, FAME, HVO, UPO, upgraded bio-oil via HTL, FT-diesel, LBM (bio-LNG) and ammonia.

Literature considering multiple maritime fuels

In 2019, DNV GL [48], the largest Norwegian registrar and classification society, did an extensive review of alternative marine fuels in 2019 for SEA\LNG. From the interpretation of the results presented by DNV GL, HVO and LNG show promising prospects, although these fuels do not sufficiently manage to reduce GHG emissions. On the other hand, whereas ammonia performs very well in terms of emissions, the fuel lacks in commercial readiness, technological maturity, bunkering availability and safety [48]. The report concludes that it is not likely that any major uptake of expensive alternative fuels with significant GHG reduction potential can be expected until required by regulations or unless it is heavily incentivised. Towards 2030, however, DNV GL says there will be a key period of increased R&D activity, piloting, rule development, product development and early commercialisation [48]. Additionally, DNV GL published a position paper in 2014 on alternative fuels for shipping [47]. In this paper, DNV GL articulates that it expects an acceleration in the development of bio-fuels produced from locally available waste biomass [47]. However, DNV GL continues, acceptance of bio-fuels in deep-sea transportation can only take place if these can be produced globally in sufficiently large volumes and competitive prices [47].

Balcombe et al. (2019) [21] wrote a paper on methods of decarbonising shipping, where options for fuels, technologies and policies are examined. According to the authors, with LNG being economically feasible and achieving moderate environmental benefits, it might be promising in the short-term with minor policy intervention [21]. The paper concludes that longer-term, deep decarbonisation can only be achieved with strong financial incentives.

In a report executed for the Netherlands Maritime Land and Ministry of Economic Affairs by the Maritime Knowledge Centre, TNO, and TU Delft (2019) [26], alternative fuels for seagoing vessels using

HFO are reviewed. According to the report, which expresses a clear preference for the use of bio-fuels that do not compete with the food industry, bio-methanol and bio-LNG are the preferred options [26]. This is mainly because these fuels can be produced at a similar cost as the food based bio-diesels (HVO, FAME, SVO) [26]. However, as is also concluded in the present research, bio-methanol is unfit for deep-sea shipping due to its low energy density [82].

Hansson et al. (2019) [78] assess the prospects for seven alternative fuels for the shipping sector in 2030, including bio-fuels. In their study, the researchers apply a multi-criteria decision-making approach based on fuel performance and a panel of maritime stakeholders. Commercial stakeholders such as shipowners, fuel producers and engine manufacturers, rank LNG and HFO the highest, followed by fossil methanol, and then various bio-fuels (liquefied bio-gas, bio-methanol, and HVO) [78]. Stakeholder groups involving Swedish government authorities rank renewable hydrogen the highest, followed by renewable methanol, and then HVO [78]. As Hansson et al. therefore conclude, policy initiatives are needed to promote the introduction of renewable marine fuels [78].

In a dissertation by Selma Brynolf which performs an environmental assessment of present and future maritime fuels (2014) [31], the author concludes that natural gas-based fuels are the most likely replacements through 2050, whereas bio-fuels are unlikely to play a major role in the shipping sector due to their limited supply and competition for bio-energy from other energy sectors [31]. However, in this consideration, Brynolf does not consider policy instruments and regulations which are able to allocate or redistribute resources between industries.

Furthermore, researchers that have written extensive papers scoped towards a specific fuel or fuel category for future maritime applications include Pavlenko et al. (2020) [129] on LNG, Hansson et al. (2020) [79] on ammonia, and E4Tech (2018) [55], Hsieh et al. (2017) [82], Kesieme et al. (2019) [101] and Florentinus et al. (2012) [70] on bio-fuels.

Literature considering LNG

Pavlenko et al. (2020) [129] have written a paper in which the climate implications of using LNG as a marine fuel are analysed. In this paper, the authors conclude that when using a 20-year GWP -which Pavlenko et al. believe better reflects the urgency of reducing GHGs than a 100-year GWP- there is no climate benefit for using LNG, regardless of engine technology used. Pavlenko et al. add that even when using a 100-year time frame, the maximum life-cycle GHG benefit of LNG is 15% reduction compared to MGO.

Additionally, Burel et al. (2013) [33] wrote a paper aimed at increasing the sustainability of maritime transport through the utilisation of LNG for propulsion. In their investigation, the first part is aimed at identifying the ship type which would most benefit from switching to LNG propulsion, where-after operational costs and pollutant emission reduction following LNG implementation are calculated [33]. The authors claim that LNG leads to a reduction of 35% of operational costs (although no calculation is provided) and 25% of downstream CO_2 emissions compared to vessels on HFO [33].

Literature considering ammonia

Hansson et al. (2020) [79] have written a paper in which a synthesis of knowledge is presented on the potential role of ammonia as a marine fuel. Hansson et al. conclude that in the short term, natural gas-based fuels such as LNG represent the most cost-effective fuel choice [79]. Furthermore, they add that even in a long-term scenario of more stringent climate targets, the use of hydrogen represents a more cost-effective option. This is due to the fact that although ammonia carries significantly lower storage cost, this does not outweigh the additional cost of converting hydrogen to ammonia from a systems perspective [79]. Nevertheless, although hydrogen may be more cost-effective, it can still not provide a feasible solution for deep-sea shipping due to its low volumetric energy density [55].

Literature considering bio-fuels E4Tech (2018) [55], an energy and sustainability strategy consultancy, has written a very extensive report for Platform Duurzame Bandstoffen in which it presents a master plan for CO_2-reduction in the Dutch shipping sector through the use of bio-fuels. Additionally, E4Tech differentiates between short- and deep-sea shipping, which is of high value for the present research. According to the authors, HVO is the only 'drop-in' bio-fuel that is currently available at commercial scale and allows for high GHG emission reduction when using waste oils [55]. Its drawback, as was also mentioned in chapter 4, lies in the limited availability of waste oils and fats. Additionally, E4Tech sees potential in liquefied bio-methane (bio-LNG) due to the high GHG reduction potential when produced from organic waste or manure, and in FT-diesel and upgraded pyrolysis oil due to their full compatibility with current diesel engines and marine fuel infrastructure [55]. However, the low commercial readiness of FT-diesel and upgraded pyrolysis oil is expected to limit their availability in 2030.

Kesieme et al. (2019) [101] perform a technological, environmental and economic assessment on alternative shipping fuels, with an emphasis on bio-fuels. According to Kesieme et al., existing and upcoming environmental restrictions can be met by alternative fuels such as SVO, bio-diesel and bio-LNG [101]. However, the researchers recognise limiting parameters in the uptake of bio-fuels in the maritime industry. According to Kesieme et al., key issues in the application of alternative fuels in the maritime industry need to be resolved through the introduction of marine-grade fuel specifications, lower manufacturing costs, beneficial tax regimes and government subsidies [101].

Additionally, Hsieh and Felby (2017) [82] map the current supply of bio-fuels and bio-fuel related technologies to investigate how and if bio-fuels can be integrated into the shipping industry. According to the authors, with the current fuel volumes demanded by the merchant shipping industry and new regulatory fuel requirements, there is a strong market potential for bio-fuels, and particularly bio-fuel blends [82]. However, apart from the fact that bio-fuels are and will remain more expensive than fossil fuels in the foreseeable future, Hsieh and Felby conclude that the largest operational drawback at the moment is the lack of long-term data on bio-fuel use, as they are still relatively new in the sector [82].

Finally, Florentinus et al. (2012) [70] confirm that there is a market for bio-fuels to be introduced in ships based on current policy and support schemes, high operational costs and environmental benefits. However, although the market incentives are there and it is technologically possible, multiple factors are limiting the implementation of bio-fuels in the maritime sector. In accordance with Hsieh and Felby (2017) [82], Florentinus et al. identify the largest boundaries to include the higher production cost, lack of experience in long-term use, and threats to current fuel supply chain market players [70].

7.2. Literature on decision tools

Both in academics and business, decision tools have been applied for decades. For this reason, the total span of decision methods is enormous. However, it is not the intention of this research to explain the large variety of decision methods available. Therefore, for reasons of brevity, this section focuses on the review of decision methods that fit the specific use case of this thesis.

The aim of the present thesis is to design and devise a decision tool that accounts for a broad range of both qualitative and quantitative criteria while respecting criteria weights assigned by decision-makers. Additionally, the decision tool should include the possibility of running on different scenarios. The methodology by which the design tool for the present thesis is devised is discussed in chapter 2.

Multi-criteria decision-making (MCDM)

To successfully design and devise a decision tool, it is first necessary to decide on an appropriate decision-making method.

Within the category of multi-criteria decision-making methods, various theories exist, each with its own distinctive applications and properties. In this regard, Velasquez and Hester (2013) [160] have performed an extensive analysis of the most commonly used multi-criteria decision-making methods. In table 7.1 below, an overview including a description, advantages, and limitations of each method is presented based on Velasquez et al. (2013) [160], Saaty (2008) [138] and Konidari et al. (2007) [103].

Method	*Description*	*Advantages*	*Limitations*
Multi-attribute utility theory (MAUT)	MAUT is an expected utility theory that decides on the best course of action by assigning a utility to every possible consequence	Takes uncertainty into account; can incorporate preferences	Needs a lot of input; preferences need to be precise
Analytic hierarchy process (AHP)	AHP is a theory of measurements through pairwise comparisons by the judgement of experts to derive priority scales	Easy to use; scalable; hierarchy can easily adjust to fit many sized problems; not data-intensive	Long comparison process for complex decisions; does not handle interdependence well; only allows for comparative criteria grading
Case-based reasoning (CBR)	CBR retrieves cases similar to a problem from an existing database of cases, and proposes a solution based on the most similar cases	Requires little maintenance; can improve over time; can adapt to changes in environment; not data-intensive	Sensitive to inconsistent data; requires many cases to achieve reliability
Data envelopment analysis (DEA)	DEA compares the relative efficiency of alternatives that perform the same tasks to identify inefficiencies and room for improvement	Capable of handling multiple in- and outputs; efficiency can be analysed and quantified	Does not deal with imprecise data; assumes that all in- and outputs are precisely known
Fuzzy set theory	Fuzzy set theory is a theory that is able to deal with imprecise and uncertain data to encompass complex problems	Allows for imprecise input; takes insufficient information into account	Difficult to develop; requires numerous simulations and iterations before use
Simple multi-attribute rating technique (SMART)	SMART relies on utility and preferential independence and allows for any type of weight assignment techniques (i.e. relative, absolute, etc.)	Simple; allows for any type of weight assignment technique; requires minimal effort by decision-makers	Procedure for determining weights can become inconvenient in complicated frameworks
Goal programming (GP)	Goal Programming is a pragmatic programming method that is able to choose from an infinite number of alternatives	Capable of handling large-scale problems; can produce infinite alternatives	Inability to weigh coefficients; typically requires to be combined with other MCDM
ELECTRE	ELECTRE is an outranking method based on concordance analysis through many iterations	Takes uncertainty and vagueness into account	Outranking limits the identification of strengths and weaknesses of alternatives; process not transparent
PROMETHEE	Similar to ELECTRE, PROMETHEE consists of a family of outranking methods in various applications	Easy to use; does not require assumption that criteria are proportionate	Does not provide clear method to assign weights; process not transparent
Simple additive weighting (SAW)	SAW consists of a value function based on a simple addition of scores that represent the goal achievement under each criterion, multiplied by the particular weights	Ability to compensate among criteria; intuitive to decision-makers; simple calculation method	Estimates revealed do not always reflect the actual situation; results obtained may lack logic; does not allow minimisation or negative values
TOPSIS	TOPSIS is an approach to identify an alternative closest to the ideal solution and farthest to the negative ideal solution in a multidimensional computing space	Simple process; easy to use and program; number of steps remains equal regardless of the number of attributes	Its use of Euclidean distance does not consider the correlation of attributes; difficult to address weight and keep consistency of judgement

Table 7.1: Overview of most common multi-criteria decision methods. Own composition based on Velasquez et al. (2013) [160], Saaty (2008) [138] and Konidari et al. (2007) [103]

Literature on the application of MCDM methods for alternative fuel decision-making
As can be perceived from table 7.1, not all multi-criteria decision methods are applicable to the problem presented in the present thesis. Therefore, several examples of literature including multi-criteria decision-making methods for alternative fuel decision-making are reviewed below.

Rousos and Lee (20012) [136] discuss the needs and possibilities of widening the traditional perspective through which shipping investment decisions are taken by embedding them in a multi-criteria environment. Rousos et al. argue that shipping decision-makers faced with ship investment decision-making are commonly influenced by factors that are not clearly financial or cannot be easily quantified in financial terms [136]. Therefore, they apply an 'integrated' analytical hierarchy process (AHP) - discounted cash flow (DCF) approach. In this integrated AHP-DCF approach, DCF outcomes are set as some of the criteria in the AHP hierarchy. By integrating these methods, the researchers were able to combine both financial criteria (further detailed as the net present value (NPV) and internal rate of return (IRR)) as well as other, less quantifiable criteria.

Ren and Lützen (2017) [135] investigate sustainable alternative energy sources for shipping under incomplete information. The authors use novel multi-criteria decision-making method that combines Dempster-Shafer theory and a trapezoidal fuzzy analytic hierarchy process (TFAHP) for alternative energy source selection under incomplete information conditions [135]. Additionally, Ren and Liang (2017) [134] applied fuzzy 'Technique for Order of Preference by Similarity to Ideal Solution' (TOPSIS) to determine the order of sustainability of marine fuels.

Hansson et al. (2019) [78] assessed alternative maritime fuels under Swedish stakeholders by employing an AHP. The authors decided to do so due to the possibility to mix quantitative and qualitative input data and to consider the views of different stakeholders specifically engaged for this purpose [78]. In a different study by Hansson, Fridell and Brynolf (2020) [79], the researchers use the analytic hierarchy process (AHP) to combine estimated fuel performance and input on criteria importance from a panel of maritime stakeholders.

Other assessment methods
Other popular assessment methods in decision analysis include decision trees, cost-benefit analysis, real-options analysis, life-cycle assessment and the even-swap method. Although these methods offer many individual benefits towards decomposing a decision-making process, they lack the property of considering criteria weights assigned by relevant stakeholders. Therefore, the optimal and only method that is able to assist decision-makers in assessing qualitative and quantitative criteria while respecting criteria weights, is MCDM.

Nevertheless, this does not mean that other methods can not be introduced in order to assist in the multi-criteria decision analysis. For instance, life-cycle assessment (LCA), as reviewed in chapter 4, is a method that is particularly useful in assessing the environmental performance of alternative over their lifetime. In the present research, LCA is applied to assess GHG emissions.

Additionally, real-options analysis can attach a value to flexibility in strategic decisions. This is particularly valuable in the present research where multiple future regulatory scenarios are considered. According to Buurman and Babovic (2016) [35], the fact that a different pathway can be taken or that a policymaker can adopt a strategy to wait until more information is available, allows one to limit the downside of making a wrong decision, and capture the upside of new information and opportunities. In practice, this translates to flexibility in an assumed discount rate in a discounted cash flow. Mun (2002) [121] has written a book on real options analysis, including numerous industry examples. Using Mun's analogies, in the present research, the application of real options analysis could quantify the added value of choosing an engine that supports multiple (alternative) fuel technologies, thus reducing uncertainty surrounding the success of the present fuel choice [121].

7.3. Conclusions

Most of the reviewed literature on alternative maritime fuels concludes that at the time of research, only natural gas-based fuels such as LNG are considered an appropriate alternative fuel choice. Although bio-fuels gain popularity on many fronts, their high production costs, lack of technological maturity and lack of experience in their long term application are boundaries that yet need to be overcome before the industry is ready to adapt to these new fuels. Nevertheless, according to literature, a lot of potential is seen in the selected alternative fuels. Ammonia is also often mentioned as a possible alternative fuel for the maritime industry. However, it is difficult to find independent literature concluding that ammonia indeed represents a feasible fuel choice in the short- to medium term. The current cost of switching to an alternative fuel other than LNG is currently expected to be very high, and thus not economically competitive.

On the topic of decision tools, each method has its own distinct characteristics, advantages and limitations, as presented in table 7.1. In the current architecture describing the decision tool that is to be built, the simple multi-attribute rating technique (SMART) forms the best basis for development. Although similar to AHP, in SMART, decision-makers are not required to grade criteria comparatively (which would be too extensive in this case) but rather directly based on their perceived importance. Nevertheless, the sole use of SMART is not able to capture the full extent of the requirements of the decision tool that is devised in the present thesis. Therefore, a combination of SMART, discounted cash flow (DCF) and optimisation modelling is integrated to form the final decision support tool.

Knowledge gap

On the author's insight, the current literature evaluating alternative maritime fuels does not sufficiently consider the perspective of the final decision-maker: the shipowner. For the successful adoption of an alternative fuel technology, shipowners need to be able to make a substantiated business decision that will not defy profitability. Therefore, it is necessary to acknowledge and consider the critical importance of various technical, economic, environmental and other criteria.

Additionally, although several studies have investigated potential future regulatory scenarios for the maritime industry, there is a lack of literature on how shipowners might revise their future fuel choice depending on the regulatory climate. Furthermore, the financial performance of alternative fuels has not been analysed over the lifetime of a vessel.

All in all, there is a lack of knowledge on how shipowners can optimally respond to different imposed emission regulations by selecting the most appropriate fuel technology. This information is not only important for shipowners, but also for regulators and governments to ensure affordable and reliable global trade under stricter emission regulations. Without this (or similar) knowledge, it would be irresponsible for shipowners to make decisions towards employing alternative fuel technologies.

Therefore, the present study aims to fill the gap by developing a decision support tool which enables shipowners to select the most appropriate alternative fuel technology to comply with possible different imposed emission regulations while ensuring optimal business performance.

8

Decision tool

This chapter presents the decision support tool (otherwise called 'decision tool') that is devised in this research. A decision tool is built in order to assist decision-makers in applying the work of this research on different use cases. The current chapter aims to provide the reader with an understanding of how results are produced, which assumptions are made and how the work can be reproduced.

The decision tool is produced to realise research objective four (vi.):

Devise a decision support tool which is able to:
a. Rank optimal fuel choices under different regulatory scenarios and
b. Assist shipowners in making future decisions regarding their choice of (alternative) fuel technology.

Section 8.1 describes the functional design of the decision tool. Section 8.2 provides the reader with an elaborate model description, diving into the architecture of the decision tool. Section 8.4 explains how the various regulatory scenarios are implemented throughout the model. Section 8.5 elaborates on the key performance indicators (KPIs) used to assess which alternatives qualify as *optimal* under various scenarios. Finally, section 8.6 addresses the verification of the decision tool to assure that it is correctly implemented with respect to the conceptual model, and section 8.7 discusses the partial validation of the tool to check the accuracy of inputs.

8.1. Functional design

The functional design describes the functionalities and user experience throughout the decision tool. Firstly, 8.1.1 describes the intended use case and user of the decision tool. Following this, derived from the use case, 8.1.2 describes the goal of the decision tool. Finally, 8.1.3 describes the workflow of the decision tool. In this section, the reader is made familiar with the necessary data for the proper operation of the decision tool, the required user inputs, the outline of the process and the produced outputs the user receives from the tool. After this section, the reader should have an idea of the various applications of the decision tool but does not yet require to understand the background architecture. The latter is explained in further detail in section 8.2.

8.1.1. Use case of decision tool

The devised decision tool is intended to be applied by shipowners involved in the deep-sea shipping trade. By means of this tool, shipowners are assisted in their decision-making process regarding the choice of (alternative) fuel technology in a new-built vessel. The tool provides valuable insights concerning the estimated costs incurred per different choice of fuel technology over the lifetime of the vessel, as well as the optimal economic speed the vessel should sail when employing different fuel alternatives. Additionally, the decision tool accounts for other (non-financial) criteria in the decision-making process. Several scenarios are examined by the tool including a pessimistic, average and optimistic outlook based on varying model parameters, as well as outcomes under various future regulatory scenarios in 2020, 2030 or 2050.

The information obtained by using this decision tool is most valuable in the investigative phase of making a decision regarding the choice of fuel alternative for a new-built vessel. Due to the high pace of developments in the alternative fuel technology space, it is highly recommended to regularly re-evaluate and double-check model parameters.

8.1.2. Goal of decision tool

The goal of the decision tool can be formulated from the definition of the use case.

The goal of the decision support tool is to enable shipowners to select the most appropriate alternative fuel technology to comply with possible different imposed emission regulations while ensuring optimal business performance.

The decision tool should support shipowners in making substantiated decisions on questions such as whether they should choose to implement an alternative fuel technology in their new-built vessels and to what extent these choices might impact their business performance. Therefore, the purpose of the decision tool is to assist shipowners in making decisions by analysing the provided insights for each considered alternative fuel.

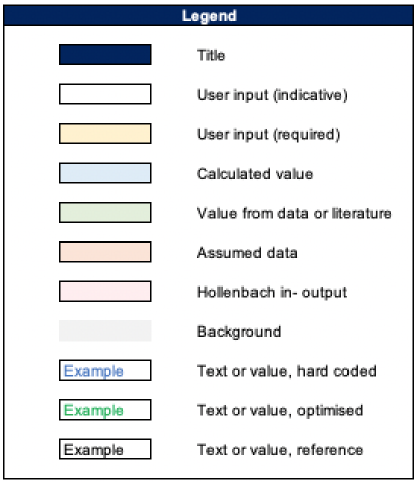
8.1.3. Workflow of decision tool

The workflow of the decision tool describes which data is necessary for its proper operation, which inputs are required to be inserted by the user, the outline of the process and the most relevant outputs subsequently provided to the user. The parameter categories are labelled according to the processes they are involved in. A schematic overview of the decision tool architecture is provided in figure 8.1, where-after the following sections elaborate on the applied model.

Figure 8.1: Schematic overview of decision tool architecture. Own composition

Legend

Since the decision tool consists of a complex combination of inputs, calculations, data and assumptions, colour coding has been used to simplify its interpretation. The legend is presented in figure 8.2 below.



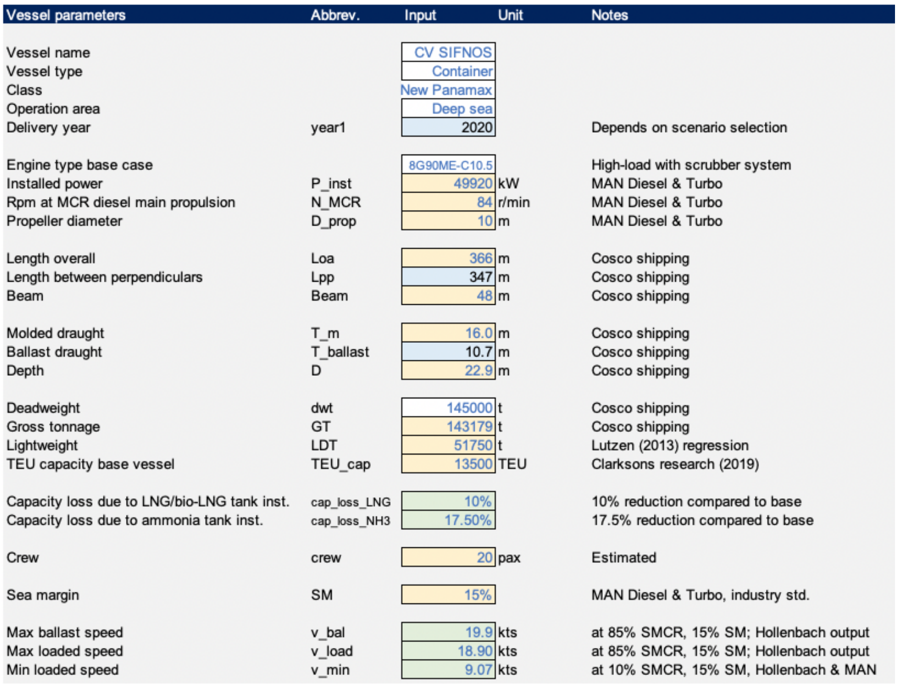
Legend	
■	Title
☐	User input (indicative)
🟨	User input (required)
🟦	Calculated value
🟩	Value from data or literature
🟧	Assumed data
☐	Hollenbach in- output
▨	Background
Example	Text or value, hard coded
Example	Text or value, optimised
Example	Text or value, reference

Figure 8.2: Legend of clarifying cell and text colours used throughout the model.

Input

In the following paragraphs, model inputs are defined which originate from both shipowner inputs and available data. The combination of these inputs is required to operate the decision tool successfully and to provide the shipowner with relevant insights.

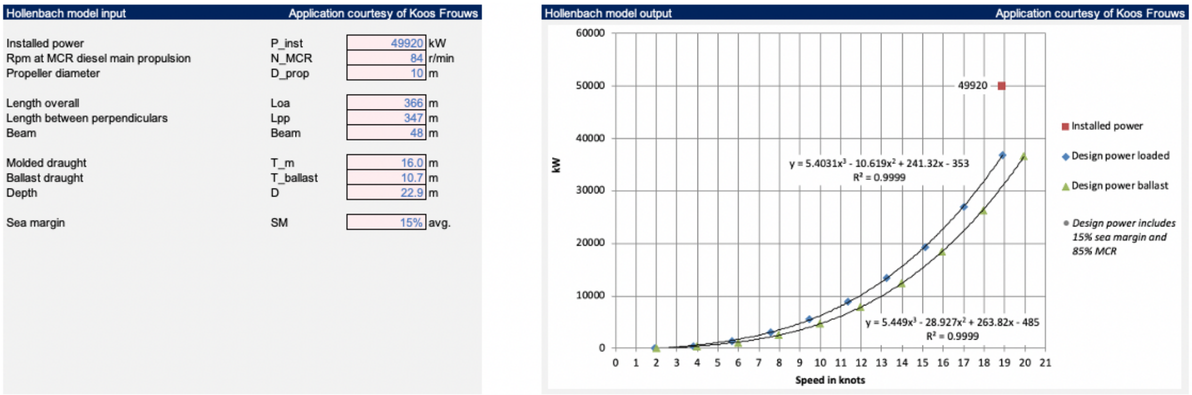
The first part of the inputs consists of input parameters including delivery year, installed power, rpm at MCR, propeller diameter, vessel sizing, gross tonnage, lightweight, TEU capacity, capacity loss due to LNG/bio-LNG/ammonia tank installations, crew number, maximum ballast speed and maximum loaded speed. Other vessel details are added for clarity and case study detail but are not required for the calculations performed by the model. An example of the vessel parameter input is provided in figure 8.3 below.



Vessel parameters	Abbrev.	Input	Unit	Notes
Vessel name		CV SIFNOS		
Vessel type		Container		
Class		New Panamax		
Operation area		Deep sea		
Delivery year	year1	2020		Depends on scenario selection
Engine type base case		8G90ME-C10.5		High-load with scrubber system
Installed power	P_inst	49920	kW	MAN Diesel & Turbo
Rpm at MCR diesel main propulsion	N_MCR	84	r/min	MAN Diesel & Turbo
Propeller diameter	D_prop	10	m	MAN Diesel & Turbo
Length overall	Loa	366	m	Cosco shipping
Length between perpendiculars	Lpp	347	m	Cosco shipping
Beam	Beam	48	m	Cosco shipping
Molded draught	T_m	16.0	m	Cosco shipping
Ballast draught	T_ballast	10.7	m	Cosco shipping
Depth	D	22.9	m	Cosco shipping
Deadweight	dwt	145000	t	Cosco shipping
Gross tonnage	GT	143179	t	Cosco shipping
Lightweight	LDT	51750	t	Lutzen (2013) regression
TEU capacity base vessel	TEU_cap	13500	TEU	Clarksons research (2019)
Capacity loss due to LNG/bio-LNG tank inst.	cap_loss_LNG	10%		10% reduction compared to base
Capacity loss due to ammonia tank inst.	cap_loss_NH3	17.50%		17.5% reduction compared to base
Crew	crew	20	pax	Estimated
Sea margin	SM	15%		MAN Diesel & Turbo, industry std.
Max ballast speed	v_bal	19.9	kts	at 85% SMCR, 15% SM; Hollenbach output
Max loaded speed	v_load	18.90	kts	at 85% SMCR, 15% SM; Hollenbach output
Min loaded speed	v_min	9.07	kts	at 10% SMCR, 15% SM, Hollenbach & MAN

Figure 8.3: Vessel parameter input excluding fuel consumption.

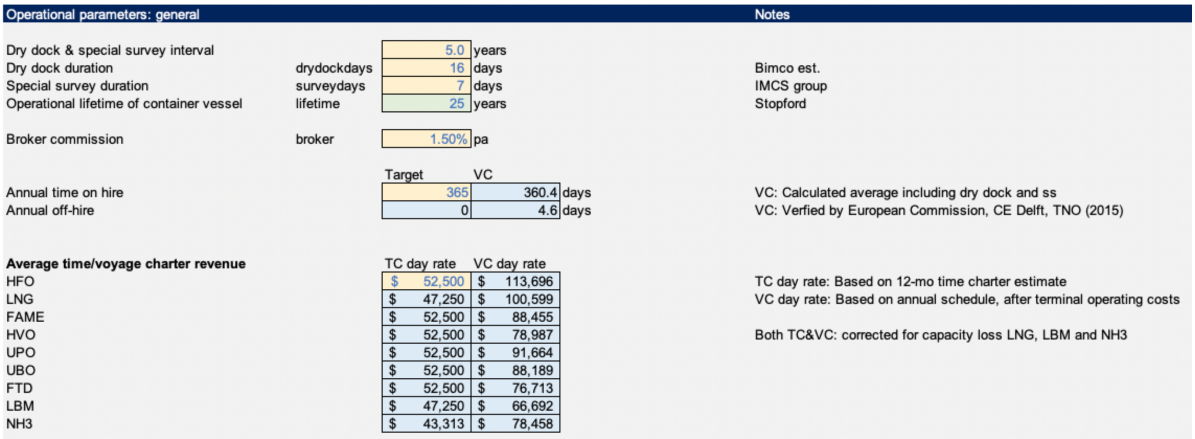
After the vessel parameters have been defined, the vessel's speed-power curve is determined using the Hollenbach Method as found in Fundamentals of Ship Hydrodynamics (2019) [111]. The Hollenbach Method is based on an analysis of model tank tests for 400+ ships performed by the Vienna Ship Model Basin from 1980 to 1995 to improve the reliability of the performance prognosis for modern cargo ships in the preliminary design stage [140]. The Hollenbach Method is applied to the current vessel with the help of a model provided by Prof. Koos Frouws (TU Delft). The related in- and outputs are displayed in figure 8.4 below and applied in calculations of fuel consumption and vessel speed.



Hollenbach model input			Application courtesy of Koos Frouws
Installed power	P_inst	49920	kW
Rpm at MCR diesel main propulsion	N_MCR	84	r/min
Propeller diameter	D_prop	10	m
Length overall	Loa	366	m
Length between perpendiculars	Lpp	347	m
Beam	Beam	48	m
Molded draught	T_m	16.0	m
Ballast draught	T_ballast	10.7	m
Depth	D	22.9	m
Sea margin	SM	15%	avg.

Figure 8.4: Hollenbach shipowner in- and output. Application model courtesy of Prof. Koos Frouws (TU Delft).

Following Hollenbach, the operational parameters of the vessel and its trajectories are inserted by the shipowner. When on both time or voyage charter, operation parameters consist of charter day rate, dry dock and special survey interval, dry dock duration, special survey duration, operational lifetime of the vessel, broker commission, the annual target time on hire and the average time charter day rate received. An overview of the general operational parameters is provided in figure 8.5.



Operational parameters: general				Notes
Dry dock & special survey interval		5.0	years	
Dry dock duration	drydockdays	16	days	Bimco est.
Special survey duration	surveydays	7	days	IMCS group
Operational lifetime of container vessel	lifetime	25	years	Stopford
Broker commission	broker	1.50%	pa	

	Target	VC		
Annual time on hire	365	360.4	days	VC: Calculated average including dry dock and ss
Annual off-hire	0	4.6	days	VC: Verfied by European Commission, CE Delft, TNO (2015)

Average time/voyage charter revenue	TC day rate	VC day rate	
HFO	$ 52,500	$ 113,696	TC day rate: Based on 12-mo time charter estimate
LNG	$ 47,250	$ 100,599	VC day rate: Based on annual schedule, after terminal operating costs
FAME	$ 52,500	$ 88,455	
HVO	$ 52,500	$ 78,987	Both TC&VC: corrected for capacity loss LNG, LBM and NH3
UPO	$ 52,500	$ 91,664	
UBO	$ 52,500	$ 88,189	
FTD	$ 52,500	$ 76,713	
LBM	$ 47,250	$ 66,692	
NH3	$ 43,313	$ 78,458	

Figure 8.5: General operational parameters for both time and voyage charters.

For time charters, the relevant operational parameters are hereby concluded. However, for voyage charters, operational parameters extend further in order to contribute to the calculation of voyage expenses. In the decision tool, these parameters are defined as voyage charter specific operational parameters. In figures 8.6 and 8.7 below, an example is provided for the voyage charter specific operational parameters in the average, 2020, unregulated scenario.

To calculate the net revenue generated by the vessel, cargo handling costs paid by shipper to shipowner and terminal operating costs paid from shipowner to ports are deducted from the freight rates received. These costs are deducted from initial revenue by a fixed percentage. For the model to account for port time on each voyage, the maximum time loading and discharging is input by the shipowner. Because this figure may vary from port to port, an average value is maintained. Furthermore, indicators for annual time in transit, port arrivals and canal exits are included, which are calculated according to the voyage specifications shown in figure 8.7 and used to determine fuel consumption as well as port and canal costs.

Following this, a number of rows is dedicated to vessel speed and annual fuel consumption. In green numbers, the optimal economic vessel speed for each alternative can be found. The optimal economic vessel speed is calculated by an optimisation model that aims to minimise required freight rate (RFR) for each fuel under each different scenario. As the vessel speed changes, the working point of the engine is determined by the regression formula produced by the Hollenbach Model provided by Prof. Koos Frouws (TU Delft). The devised speed optimisation model is described in detail in section 8.3.

In the large blue tables with green text, the optimal economic speed outputs from the optimisation model are displayed for each scenario. On the right side of the sheet, a button is placed to recalculate the optimal economic speed when inputs are changed.

As fuel consumption is not constant across the power curve, each engine working point corresponds to a different specific fuel oil consumption level (SFOC). With the help of a power-SFOC data table provided by MAN Diesel & Turbo[1], the SFOC corresponding to each alternative fuel and engine working point is determined. For all diesel-like fuels, the engine efficiency curve is assumed equal. For gas-like fuels such as LNG and liquefied bio-methane (LBM), a 9.5% higher engine efficiency is assumed [114, 163]. This difference is further elaborated in section 8.2.2. With this available information, annual fuel consumption for propulsion and auxiliary equipment is calculated for all alternatives.

After the speed and SFOC data tables, an optional input field is added to address a deviation in specific fuel oil consumption (SFOC) in case a shipowner wishes to implement other, additional efficiency measures. Additionally, because auxiliary energy consumption contributes to the total fuel cost, the vessel's additional auxiliary fuel consumption is input as a function of propulsion fuel

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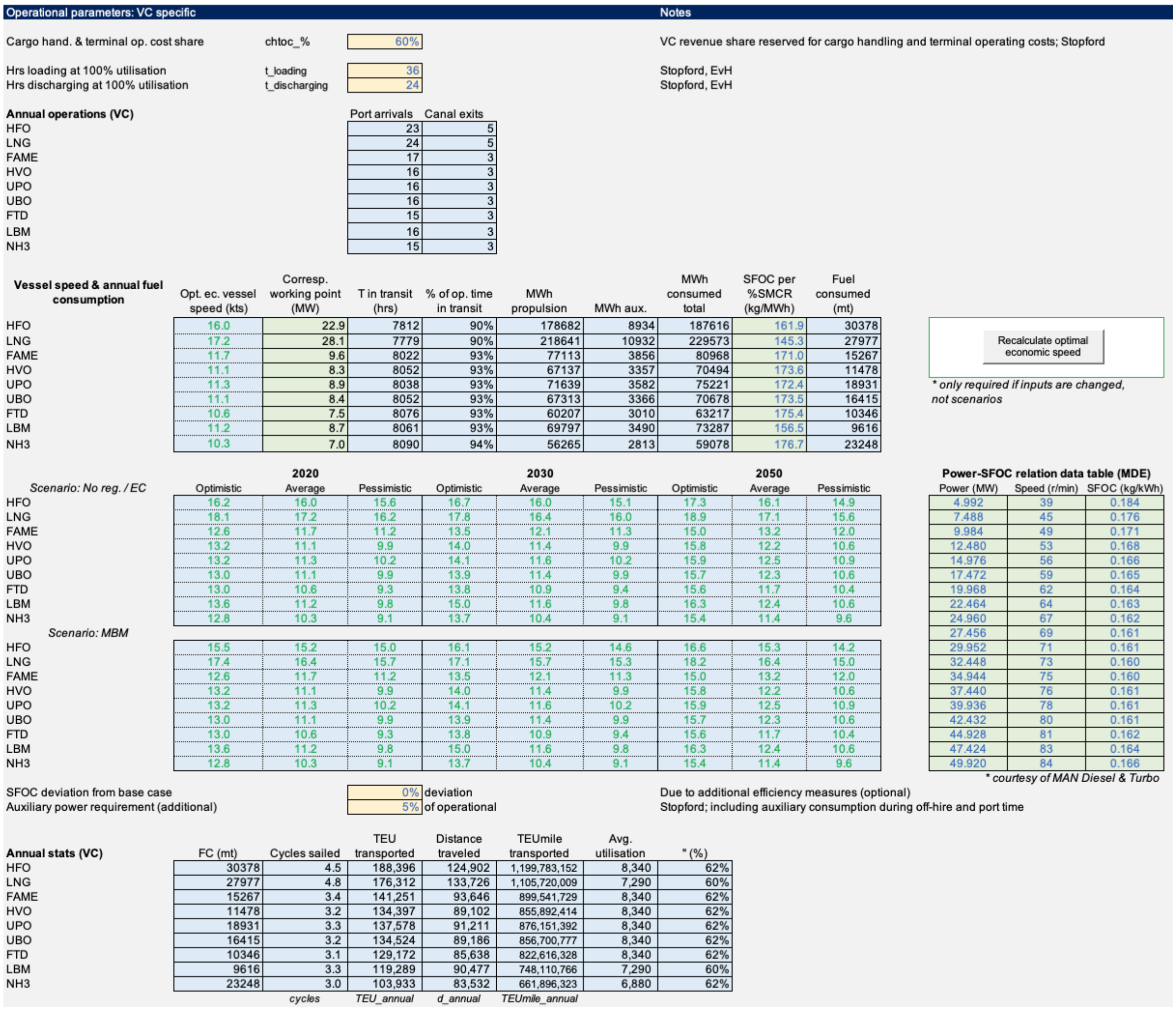
[1] It is important to note that MAN Diesel & Turbo are incentivised to provide highly optimistic SFOC figures as these double as marketing material for their engines.

consumption. This includes auxiliary energy consumption during off-hire and port time. Finally, an overview of annual statistics such as fuel consumption, cycles sailed, TEU transported, distance travelled, TEU-mile transported and average TEU utilisation is added for clarity and cost calculations in the financial model.



Operational parameters: VC specific — **Notes**

Cargo hand. & terminal op. cost share — chtoc_% — 60% — VC revenue share reserved for cargo handling and terminal operating costs; Stopford

Hrs loading at 100% utilisation — t_loading — 36 — Stopford, EvH
Hrs discharging at 100% utilisation — t_discharging — 24 — Stopford, EvH

Annual operations (VC)	Port arrivals	Canal exits
HFO	23	5
LNG	24	5
FAME	17	3
HVO	16	3
UPO	16	3
UBO	16	3
FTD	15	3
LBM	16	3
NH3	15	3

Vessel speed & annual fuel consumption	Opt. ec. vessel speed (kts)	Corresp. working point (MW)	T in transit (hrs)	% of op. time in transit	MWh propulsion	MWh aux.	MWh consumed total	SFOC per %SMCR (kg/MWh)	Fuel consumed (mt)
HFO	16.0	22.9	7812	90%	178682	8934	187616	161.9	30378
LNG	17.2	28.1	7779	90%	218641	10932	229573	145.3	27977
FAME	11.7	9.6	8022	93%	77113	3856	80968	171.0	15267
HVO	11.1	8.3	8052	93%	67137	3357	70494	173.6	11478
UPO	11.3	8.9	8038	93%	71639	3582	75221	172.4	18931
UBO	11.1	8.4	8052	93%	67313	3366	70678	173.5	16415
FTD	10.6	7.5	8076	93%	60207	3010	63217	175.4	10346
LBM	11.2	8.7	8061	93%	69797	3490	73287	156.5	9616
NH3	10.3	7.0	8090	94%	56265	2813	59078	176.7	23248

Recalculate optimal economic speed

** only required if inputs are changed, not scenarios*

	2020			2030			2050		
Scenario: No reg. / EC	Optimistic	Average	Pessimistic	Optimistic	Average	Pessimistic	Optimistic	Average	Pessimistic
HFO	16.2	16.0	15.6	16.7	16.0	15.1	17.3	16.1	14.9
LNG	18.1	17.2	16.2	17.8	16.4	16.0	18.9	17.1	15.6
FAME	12.6	11.7	11.2	13.5	12.1	11.3	15.0	13.2	12.0
HVO	13.2	11.1	9.9	14.0	11.4	9.9	15.8	12.2	10.6
UPO	13.2	11.3	10.2	14.1	11.6	10.2	15.9	12.5	10.9
UBO	13.0	11.1	9.9	13.9	11.4	9.9	15.7	12.3	10.6
FTD	13.0	10.6	9.3	13.8	10.9	9.4	15.6	11.7	10.4
LBM	13.6	11.2	9.8	15.0	11.6	9.8	16.3	12.4	10.6
NH3	12.8	10.3	9.1	13.7	10.4	9.1	15.4	11.4	9.6
Scenario: MBM									
HFO	15.5	15.2	15.0	16.1	15.2	14.6	16.6	15.3	14.2
LNG	17.4	16.4	15.7	17.1	15.7	15.3	18.2	16.4	15.0
FAME	12.6	11.7	11.2	13.5	12.1	11.3	15.0	13.2	12.0
HVO	13.2	11.1	9.9	14.0	11.4	9.9	15.8	12.2	10.6
UPO	13.2	11.3	10.2	14.1	11.6	10.2	15.9	12.5	10.9
UBO	13.0	11.1	9.9	13.9	11.4	9.9	15.7	12.3	10.6
FTD	13.0	10.6	9.3	13.8	10.9	9.4	15.6	11.7	10.4
LBM	13.6	11.2	9.8	15.0	11.6	9.8	16.3	12.4	10.6
NH3	12.8	10.3	9.1	13.7	10.4	9.1	15.4	11.4	9.6

Power-SFOC relation data table (MDE)

Power (MW)	Speed (r/min)	SFOC (kg/kWh)
4.992	39	0.184
7.488	45	0.176
9.984	49	0.171
12.480	53	0.168
14.976	56	0.166
17.472	59	0.165
19.968	62	0.164
22.464	64	0.163
24.960	67	0.162
27.456	69	0.161
29.952	71	0.161
32.448	73	0.160
34.944	75	0.160
37.440	76	0.161
39.936	78	0.161
42.432	80	0.161
44.928	81	0.162
47.424	83	0.164
49.920	84	0.166

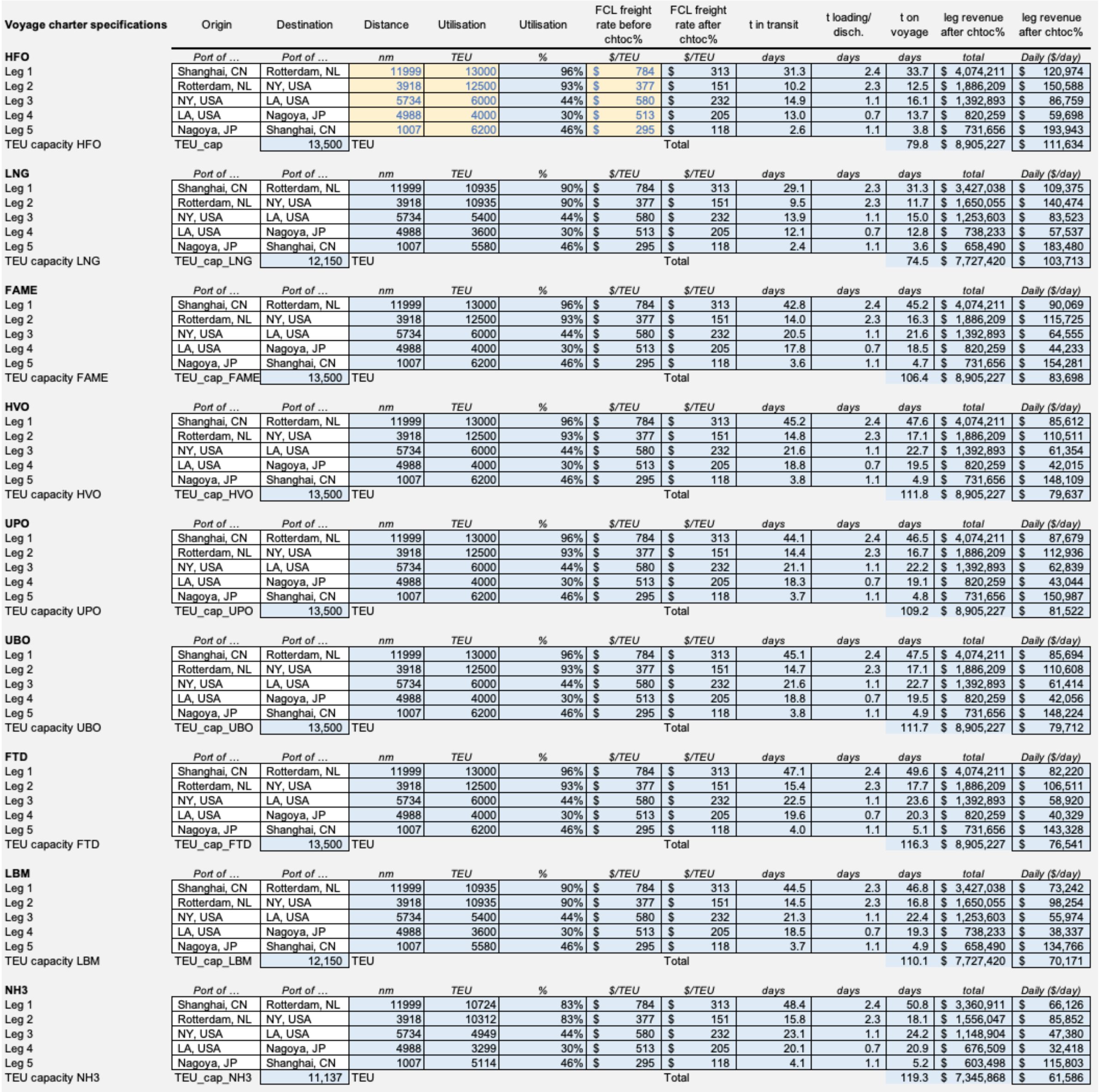
** courtesy of MAN Diesel & Turbo*

SFOC deviation from base case — 0% deviation — Due to additional efficiency measures (optional)
Auxiliary power requirement (additional) — 5% of operational — Stopford; including auxiliary consumption during off-hire and port time

Annual stats (VC)	FC (mt)	Cycles sailed	TEU transported	Distance traveled	TEUmile transported	Avg. utilisation	" (%)
HFO	30378	4.5	188,396	124,902	1,199,783,152	8,340	62%
LNG	27977	4.8	176,312	133,726	1,105,720,009	7,290	60%
FAME	15267	3.4	141,251	93,646	899,541,729	8,340	62%
HVO	11478	3.2	134,397	89,102	855,892,414	8,340	62%
UPO	18931	3.3	137,578	91,211	876,151,392	8,340	62%
UBO	16415	3.2	134,524	89,186	856,700,777	8,340	62%
FTD	10346	3.1	129,172	85,638	822,616,328	8,340	62%
LBM	9616	3.3	119,289	90,477	748,110,766	7,290	60%
NH3	23248	3.0	103,933	83,532	661,896,323	6,880	62%
		cycles	*TEU_annual*	*d_annual*	*TEUmile_annual*		

Figure 8.6: Voyage charter specific operational parameters. Voyage charter specifications for all alternatives follow in figure 8.7.

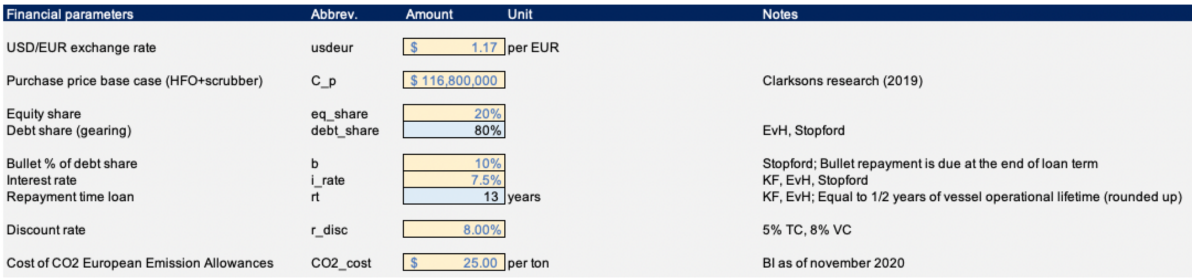
To optimise for optimal economic speed and to determine fuel cost and voyage charter revenues, the model requires specific voyage specifications. These specifications include the origin and destination of the voyage, the distance travelled, the TEU utilisation, charter day rate per voyage, time in transit, time loading and time discharging per voyage. An example of operational parameters and voyage charter specifications as presented in the model are shown in figure 8.7.



Voyage charter specifications	Origin	Destination	Distance	Utilisation	Utilisation	FCL freight rate before chtoc%	FCL freight rate after chtoc%	t in transit	t loading/ disch.	t on voyage	leg revenue after chtoc%	leg revenue after chtoc%
HFO	*Port of ...*	*Port of ...*	*nm*	*TEU*	*%*	*$/TEU*	*$/TEU*	*days*	*days*	*days*	*total*	*Daily ($/day)*
Leg 1	Shanghai, CN	Rotterdam, NL	11999	13000	96%	$ 784	$ 313	31.3	2.4	33.7	$ 4,074,211	$ 120,974
Leg 2	Rotterdam, NL	NY, USA	3918	12500	93%	$ 377	$ 151	10.2	2.3	12.5	$ 1,886,209	$ 150,588
Leg 3	NY, USA	LA, USA	5734	6000	44%	$ 580	$ 232	14.9	1.1	16.1	$ 1,392,893	$ 86,759
Leg 4	LA, USA	Nagoya, JP	4988	4000	30%	$ 513	$ 205	13.0	0.7	13.7	$ 820,259	$ 59,698
Leg 5	Nagoya, JP	Shanghai, CN	1007	6200	46%	$ 295	$ 118	2.6	1.1	3.8	$ 731,656	$ 193,943
TEU capacity HFO	TEU_cap	13,500	TEU				Total			79.8	$ 8,905,227	$ 111,634
LNG	*Port of ...*	*Port of ...*	*nm*	*TEU*	*%*	*$/TEU*	*$/TEU*	*days*	*days*	*days*	*total*	*Daily ($/day)*
Leg 1	Shanghai, CN	Rotterdam, NL	11999	10935	90%	$ 784	$ 313	29.1	2.3	31.3	$ 3,427,038	$ 109,375
Leg 2	Rotterdam, NL	NY, USA	3918	10935	90%	$ 377	$ 151	9.5	2.3	11.7	$ 1,650,055	$ 140,474
Leg 3	NY, USA	LA, USA	5734	5400	44%	$ 580	$ 232	13.9	1.1	15.0	$ 1,253,603	$ 83,523
Leg 4	LA, USA	Nagoya, JP	4988	3600	30%	$ 513	$ 205	12.1	0.7	12.8	$ 738,233	$ 57,537
Leg 5	Nagoya, JP	Shanghai, CN	1007	5580	46%	$ 295	$ 118	2.4	1.1	3.6	$ 658,490	$ 183,480
TEU capacity LNG	TEU_cap_LNG	12,150	TEU				Total			74.5	$ 7,727,420	$ 103,713
FAME	*Port of ...*	*Port of ...*	*nm*	*TEU*	*%*	*$/TEU*	*$/TEU*	*days*	*days*	*days*	*total*	*Daily ($/day)*
Leg 1	Shanghai, CN	Rotterdam, NL	11999	13000	96%	$ 784	$ 313	42.8	2.4	45.2	$ 4,074,211	$ 90,069
Leg 2	Rotterdam, NL	NY, USA	3918	12500	93%	$ 377	$ 151	14.0	2.3	16.3	$ 1,886,209	$ 115,725
Leg 3	NY, USA	LA, USA	5734	6000	44%	$ 580	$ 232	20.5	1.1	21.6	$ 1,392,893	$ 64,555
Leg 4	LA, USA	Nagoya, JP	4988	4000	30%	$ 513	$ 205	17.8	0.7	18.5	$ 820,259	$ 44,233
Leg 5	Nagoya, JP	Shanghai, CN	1007	6200	46%	$ 295	$ 118	3.6	1.1	4.7	$ 731,656	$ 154,281
TEU capacity FAME	TEU_cap_FAME	13,500	TEU				Total			106.4	$ 8,905,227	$ 83,698
HVO	*Port of ...*	*Port of ...*	*nm*	*TEU*	*%*	*$/TEU*	*$/TEU*	*days*	*days*	*days*	*total*	*Daily ($/day)*
Leg 1	Shanghai, CN	Rotterdam, NL	11999	13000	96%	$ 784	$ 313	45.2	2.4	47.6	$ 4,074,211	$ 85,612
Leg 2	Rotterdam, NL	NY, USA	3918	12500	93%	$ 377	$ 151	14.8	2.3	17.1	$ 1,886,209	$ 110,511
Leg 3	NY, USA	LA, USA	5734	6000	44%	$ 580	$ 232	21.6	1.1	22.7	$ 1,392,893	$ 61,354
Leg 4	LA, USA	Nagoya, JP	4988	4000	30%	$ 513	$ 205	18.8	0.7	19.5	$ 820,259	$ 42,015
Leg 5	Nagoya, JP	Shanghai, CN	1007	6200	46%	$ 295	$ 118	3.8	1.1	4.9	$ 731,656	$ 148,109
TEU capacity HVO	TEU_cap_HVO	13,500	TEU				Total			111.8	$ 8,905,227	$ 79,637
UPO	*Port of ...*	*Port of ...*	*nm*	*TEU*	*%*	*$/TEU*	*$/TEU*	*days*	*days*	*days*	*total*	*Daily ($/day)*
Leg 1	Shanghai, CN	Rotterdam, NL	11999	13000	96%	$ 784	$ 313	44.1	2.4	46.5	$ 4,074,211	$ 87,679
Leg 2	Rotterdam, NL	NY, USA	3918	12500	93%	$ 377	$ 151	14.4	2.3	16.7	$ 1,886,209	$ 112,936
Leg 3	NY, USA	LA, USA	5734	6000	44%	$ 580	$ 232	21.1	1.1	22.2	$ 1,392,893	$ 62,839
Leg 4	LA, USA	Nagoya, JP	4988	4000	30%	$ 513	$ 205	18.3	0.7	19.1	$ 820,259	$ 43,044
Leg 5	Nagoya, JP	Shanghai, CN	1007	6200	46%	$ 295	$ 118	3.7	1.1	4.8	$ 731,656	$ 150,987
TEU capacity UPO	TEU_cap_UPO	13,500	TEU				Total			109.2	$ 8,905,227	$ 81,522
UBO	*Port of ...*	*Port of ...*	*nm*	*TEU*	*%*	*$/TEU*	*$/TEU*	*days*	*days*	*days*	*total*	*Daily ($/day)*
Leg 1	Shanghai, CN	Rotterdam, NL	11999	13000	96%	$ 784	$ 313	45.1	2.4	47.5	$ 4,074,211	$ 85,694
Leg 2	Rotterdam, NL	NY, USA	3918	12500	93%	$ 377	$ 151	14.7	2.3	17.1	$ 1,886,209	$ 110,608
Leg 3	NY, USA	LA, USA	5734	6000	44%	$ 580	$ 232	21.6	1.1	22.7	$ 1,392,893	$ 61,414
Leg 4	LA, USA	Nagoya, JP	4988	4000	30%	$ 513	$ 205	18.8	0.7	19.5	$ 820,259	$ 42,056
Leg 5	Nagoya, JP	Shanghai, CN	1007	6200	46%	$ 295	$ 118	3.8	1.1	4.9	$ 731,656	$ 148,224
TEU capacity UBO	TEU_cap_UBO	13,500	TEU				Total			111.7	$ 8,905,227	$ 79,712
FTD	*Port of ...*	*Port of ...*	*nm*	*TEU*	*%*	*$/TEU*	*$/TEU*	*days*	*days*	*days*	*total*	*Daily ($/day)*
Leg 1	Shanghai, CN	Rotterdam, NL	11999	13000	96%	$ 784	$ 313	47.1	2.4	49.6	$ 4,074,211	$ 82,220
Leg 2	Rotterdam, NL	NY, USA	3918	12500	93%	$ 377	$ 151	15.4	2.3	17.7	$ 1,886,209	$ 106,511
Leg 3	NY, USA	LA, USA	5734	6000	44%	$ 580	$ 232	22.5	1.1	23.6	$ 1,392,893	$ 58,920
Leg 4	LA, USA	Nagoya, JP	4988	4000	30%	$ 513	$ 205	19.6	0.7	20.3	$ 820,259	$ 40,329
Leg 5	Nagoya, JP	Shanghai, CN	1007	6200	46%	$ 295	$ 118	4.0	1.1	5.1	$ 731,656	$ 143,328
TEU capacity FTD	TEU_cap_FTD	13,500	TEU				Total			116.3	$ 8,905,227	$ 76,541
LBM	*Port of ...*	*Port of ...*	*nm*	*TEU*	*%*	*$/TEU*	*$/TEU*	*days*	*days*	*days*	*total*	*Daily ($/day)*
Leg 1	Shanghai, CN	Rotterdam, NL	11999	10935	90%	$ 784	$ 313	44.5	2.3	46.8	$ 3,427,038	$ 73,242
Leg 2	Rotterdam, NL	NY, USA	3918	10935	90%	$ 377	$ 151	14.5	2.3	16.8	$ 1,650,055	$ 98,254
Leg 3	NY, USA	LA, USA	5734	5400	44%	$ 580	$ 232	21.3	1.1	22.4	$ 1,253,603	$ 55,974
Leg 4	LA, USA	Nagoya, JP	4988	3600	30%	$ 513	$ 205	18.5	0.7	19.3	$ 738,233	$ 38,337
Leg 5	Nagoya, JP	Shanghai, CN	1007	5580	46%	$ 295	$ 118	3.7	1.1	4.9	$ 658,490	$ 134,766
TEU capacity LBM	TEU_cap_LBM	12,150	TEU				Total			110.1	$ 7,727,420	$ 70,171
NH3	*Port of ...*	*Port of ...*	*nm*	*TEU*	*%*	*$/TEU*	*$/TEU*	*days*	*days*	*days*	*total*	*Daily ($/day)*
Leg 1	Shanghai, CN	Rotterdam, NL	11999	10724	83%	$ 784	$ 313	48.4	2.4	50.8	$ 3,360,911	$ 66,126
Leg 2	Rotterdam, NL	NY, USA	3918	10312	83%	$ 377	$ 151	15.8	2.3	18.1	$ 1,556,047	$ 85,852
Leg 3	NY, USA	LA, USA	5734	4949	44%	$ 580	$ 232	23.1	1.1	24.2	$ 1,148,904	$ 47,380
Leg 4	LA, USA	Nagoya, JP	4988	3299	30%	$ 513	$ 205	20.1	0.7	20.9	$ 676,509	$ 32,418
Leg 5	Nagoya, JP	Shanghai, CN	1007	5114	46%	$ 295	$ 118	4.1	1.1	5.2	$ 603,498	$ 115,803
TEU capacity NH3	TEU_cap_NH3	11,137	TEU				Total			119.3	$ 7,345,868	$ 61,586

Figure 8.7: Voyage charter specifications for all alternatives.

At last, the financial input is inserted. The financial input includes the current EUR/USD exchange rate, the purchase price of the base case vessel (employing HFO diesel engines and scrubbers), the equity share the shipowner is expecting to contribute to the purchase of the vessel, the bullet % (or balloon) of debt share he is able to negotiate to pay at the end of the payback period as a lump sum, the interest rate he is demanded on his loan from his lenders, the discount rate representing the shipowner's weighted average cost of capital (WACC) and the cost of CO_2 European Emission Allowances. An overview is presented in table 8.8.



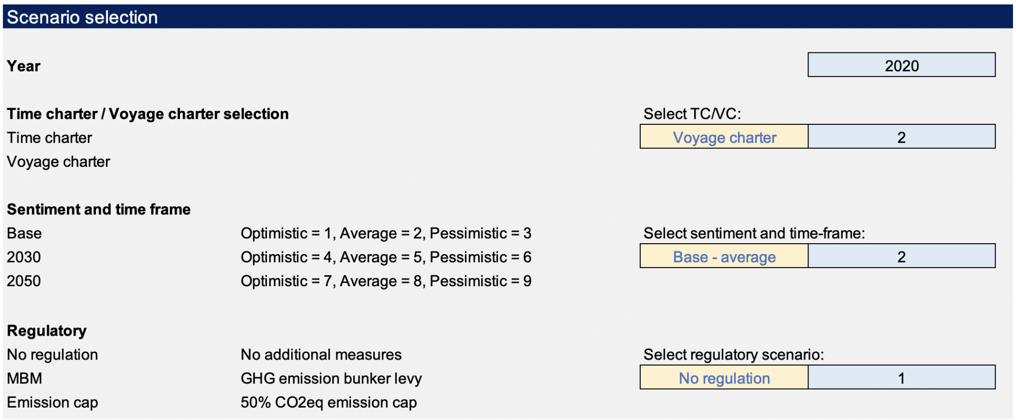
Financial parameters	Abbrev.	Amount	Unit	Notes
USD/EUR exchange rate	usdeur	$ 1.17	per EUR	
Purchase price base case (HFO+scrubber)	C_p	$ 116,800,000		Clarksons research (2019)
Equity share	eq_share	20%		
Debt share (gearing)	debt_share	80%		EvH, Stopford
Bullet % of debt share	b	10%		Stopford; Bullet repayment is due at the end of loan term
Interest rate	i_rate	7.5%		KF, EvH, Stopford
Repayment time loan	rt	13	years	KF, EvH; Equal to 1/2 years of vessel operational lifetime (rounded up)
Discount rate	r_disc	8.00%		5% TC, 8% VC
Cost of CO2 European Emission Allowances	CO2_cost	$ 25.00	per ton	BI as of november 2020

Figure 8.8: Example of financial parameter input.

Scenarios

In this thesis, several scenarios are treated which can be applied in a large number of combinations. Each scenario has a distinct impact on the output of the decision tool. A distinction can be made between so called ’sentiment’ scenarios, time scenarios, and regulatory scenarios. The sentiment scenarios describe the ’optimistic’, ’average’ or ’pessimistic’ perspective from which the criteria are evaluated, the time scenarios make a distinction between the starting years 2020, 2030 and 2050 and at last, the regulatory scenarios include ’no regulation’, ’market-based measures’ and ’emission cap’ scenarios.

As the sentiment, time and regulatory scenarios can produce 27 different combinations, a scenario selection module is implemented in the decision tool to allow shipowners to produce outputs for each desired scenario. An overview of the selection module is presented in figure 8.9. The impact of each scenario is further elaborated in section 8.4.



Scenario selection			
Year			2020
Time charter / Voyage charter selection		Select TC/VC:	
Time charter		Voyage charter	2
Voyage charter			
Sentiment and time frame			
Base	Optimistic = 1, Average = 2, Pessimistic = 3	Select sentiment and time-frame:	
2030	Optimistic = 4, Average = 5, Pessimistic = 6	Base - average	2
2050	Optimistic = 7, Average = 8, Pessimistic = 9		
Regulatory			
No regulation	No additional measures	Select regulatory scenario:	
MBM	GHG emission bunker levy	No regulation	1
Emission cap	50% CO2eq emission cap		

Figure 8.9: Overview of the scenario selection module as found in the decision tool.

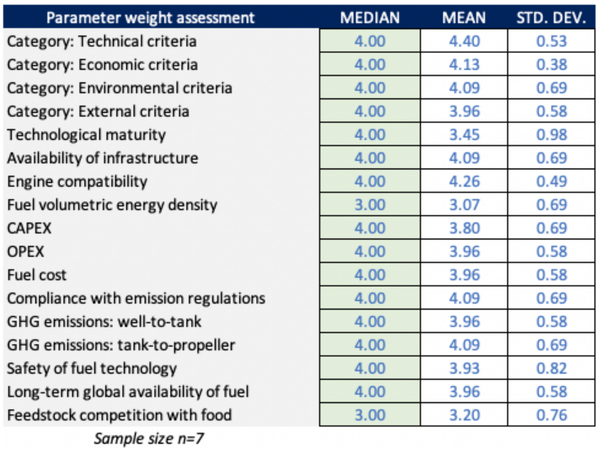
In table 8.1, all possible scenarios are identified with a checkmark. The most important results in chapter 9 are presented in the same format.

	2020			2030			2050		
	O	A	P	O	A	P	O	A	P
NR	✓	✓	✓	✓	✓	✓	✓	✓	✓
MBM	✓	✓	✓	✓	✓	✓	✓	✓	✓
EC	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 8.1: Illustration of all possible scenarios presented in the model. O = optimistic, A = average, P = pessimistic scenario. NR = no regulation, MBM = market-based measure, EC = 50% GHG emission cap compared to 2020 levels.

Data

The foundation of an accurate decision tool lies in the reliability of the data it is fed. For this research, data is collected on aspects such as technical specifications, development levels or costs, among others. As can be read in chapter 5, several criteria have been established to assess the selected fuel technologies. In order to weigh the importance of these criteria in the SMART decision tool, a survey is presented to a set of shipowners managing over 1780 deep-sea vessels collectively (see table 5.4 for overview). The results from this survey are presented in figure 8.10 below. As can be seen, the median of the survey results is used in the SMART decision model due to the relatively small sample size of $n = 7$. If a larger survey would be conducted, the author would recommend using mean values to more accurately represent the sample. If the user of the decision tool prefers to assign his own weights to the importance of the presented criteria, this can be adjusted manually in the leftmost column. The model will adjust accordingly.

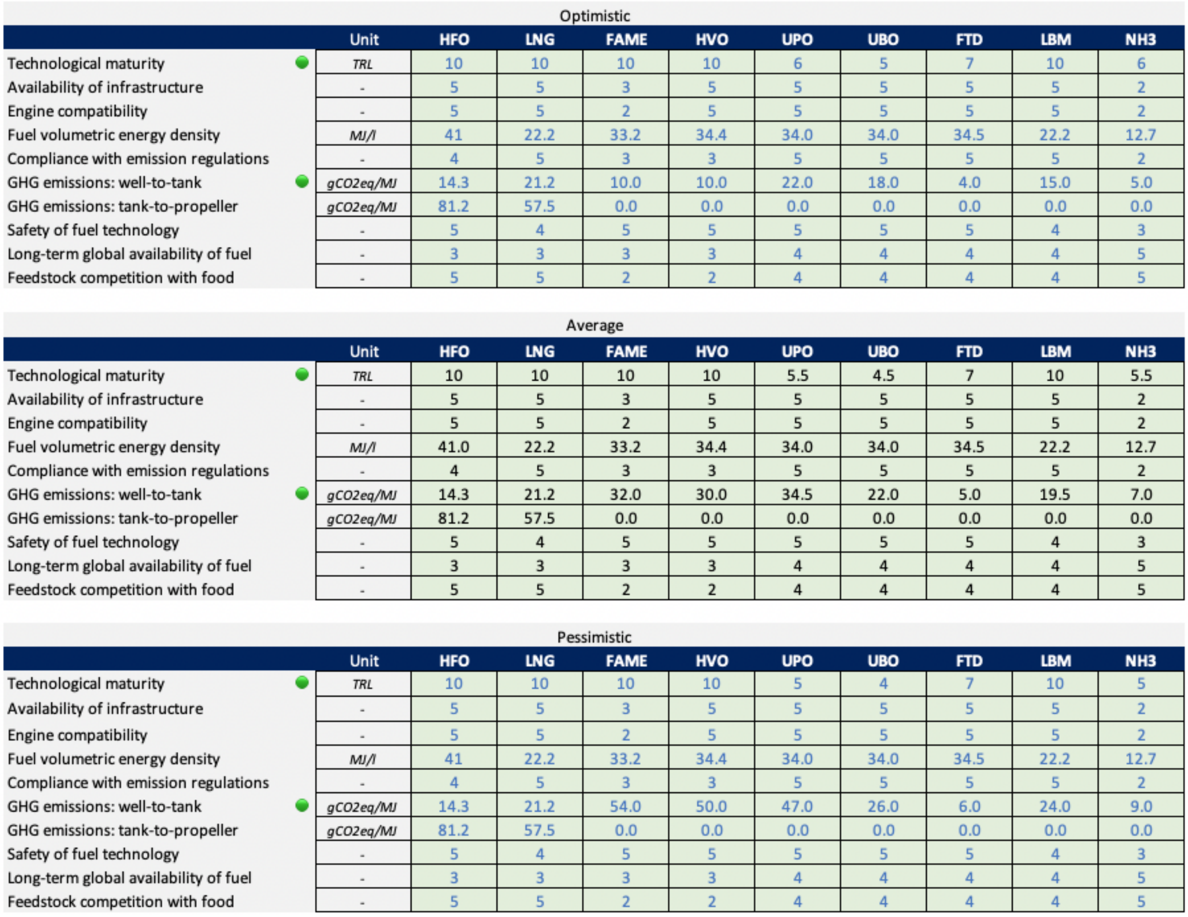


Parameter weight assessment	MEDIAN	MEAN	STD. DEV.
Category: Technical criteria	4.00	4.40	0.53
Category: Economic criteria	4.00	4.13	0.38
Category: Environmental criteria	4.00	4.09	0.69
Category: External criteria	4.00	3.96	0.58
Technological maturity	4.00	3.45	0.98
Availability of infrastructure	4.00	4.09	0.69
Engine compatibility	4.00	4.26	0.49
Fuel volumetric energy density	3.00	3.07	0.69
CAPEX	4.00	3.80	0.69
OPEX	4.00	3.96	0.58
Fuel cost	4.00	3.96	0.58
Compliance with emission regulations	4.00	4.09	0.69
GHG emissions: well-to-tank	4.00	3.96	0.58
GHG emissions: tank-to-propeller	4.00	4.09	0.69
Safety of fuel technology	4.00	3.93	0.82
Long-term global availability of fuel	4.00	3.96	0.58
Feedstock competition with food	3.00	3.20	0.76

Sample size n=7

Figure 8.10: Shipowner survey results as presented in the decision tool. Scores are given from 1 (Not important at all) to 5 (Extremely important). Mean and standard deviation values are only included indicatively, they do not contribute to the model.

As data is collected on each assessment criterion, an optimistic, average and pessimistic scenario is defined. However, these different perspectives on data are not applicable to all criteria. For instance, whereas a (dynamic) future price of an alternative fuel can be approached in an optimistic, average or pessimistic scenario, the safety of a fuel technology is approached invariable, meaning this specific score is assumed equal in all three sentiment scenarios. The choice to approach some criteria invariably is made on the basis of available literature. If different sources agree on the performance of an alternative fuel on a specific criterion, it is assumed invariable throughout the scenarios.



Optimistic

		Unit	HFO	LNG	FAME	HVO	UPO	UBO	FTD	LBM	NH3
Technological maturity	●	TRL	10	10	10	10	6	5	7	10	6
Availability of infrastructure		-	5	5	3	5	5	5	5	5	2
Engine compatibility		-	5	5	2	5	5	5	5	5	2
Fuel volumetric energy density		MJ/l	41	22.2	33.2	34.4	34.0	34.0	34.5	22.2	12.7
Compliance with emission regulations		-	4	5	3	3	5	5	5	5	2
GHG emissions: well-to-tank	●	gCO2eq/MJ	14.3	21.2	10.0	10.0	22.0	18.0	4.0	15.0	5.0
GHG emissions: tank-to-propeller		gCO2eq/MJ	81.2	57.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Safety of fuel technology		-	5	4	5	5	5	5	5	4	3
Long-term global availability of fuel		-	3	3	3	3	4	4	4	4	5
Feedstock competition with food		-	5	5	2	2	4	4	4	4	5

Average

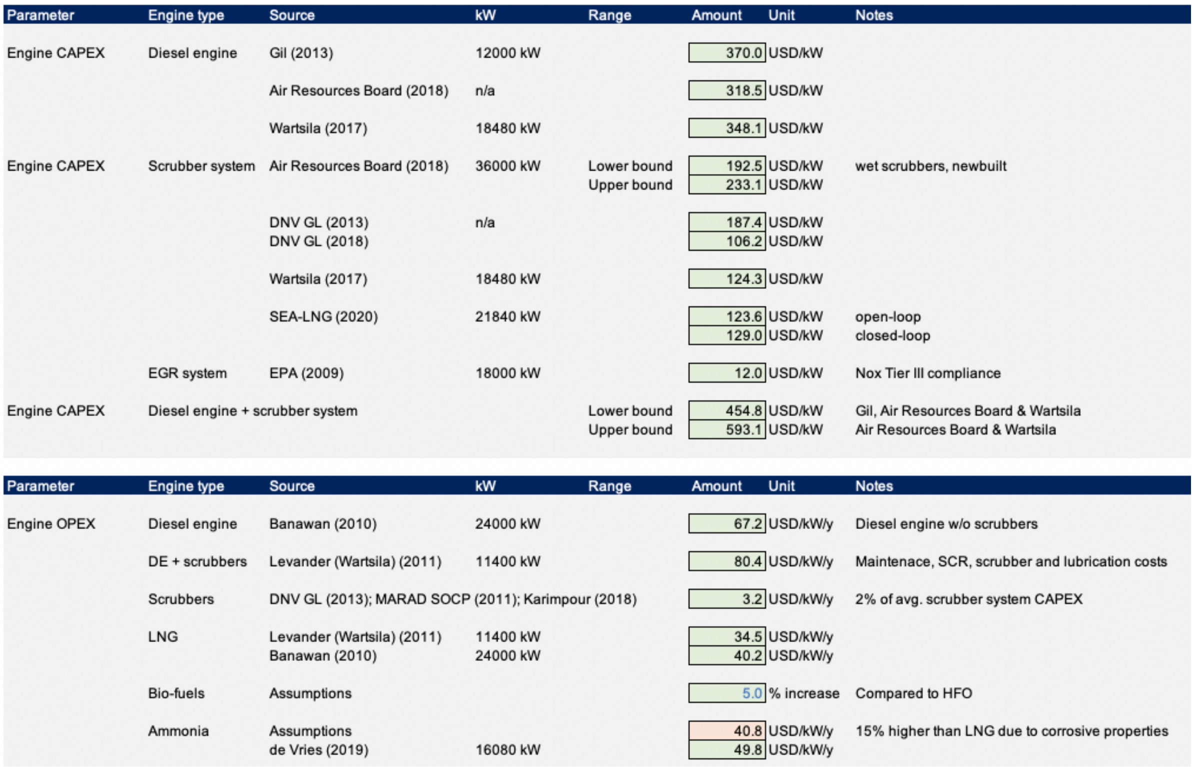
		Unit	HFO	LNG	FAME	HVO	UPO	UBO	FTD	LBM	NH3
Technological maturity	●	TRL	10	10	10	10	5.5	4.5	7	10	5.5
Availability of infrastructure		-	5	5	3	5	5	5	5	5	2
Engine compatibility		-	5	5	2	5	5	5	5	5	2
Fuel volumetric energy density		MJ/l	41.0	22.2	33.2	34.4	34.0	34.0	34.5	22.2	12.7
Compliance with emission regulations		-	4	5	3	3	5	5	5	5	2
GHG emissions: well-to-tank	●	gCO2eq/MJ	14.3	21.2	32.0	30.0	34.5	22.0	5.0	19.5	7.0
GHG emissions: tank-to-propeller		gCO2eq/MJ	81.2	57.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Safety of fuel technology		-	5	4	5	5	5	5	5	4	3
Long-term global availability of fuel		-	3	3	3	3	4	4	4	4	5
Feedstock competition with food		-	5	5	2	2	4	4	4	4	5

Pessimistic

		Unit	HFO	LNG	FAME	HVO	UPO	UBO	FTD	LBM	NH3
Technological maturity	●	TRL	10	10	10	10	5	4	7	10	5
Availability of infrastructure		-	5	5	3	5	5	5	5	5	2
Engine compatibility		-	5	5	2	5	5	5	5	5	2
Fuel volumetric energy density		MJ/l	41	22.2	33.2	34.4	34.0	34.0	34.5	22.2	12.7
Compliance with emission regulations		-	4	5	3	3	5	5	5	5	2
GHG emissions: well-to-tank	●	gCO2eq/MJ	14.3	21.2	54.0	50.0	47.0	26.0	6.0	24.0	9.0
GHG emissions: tank-to-propeller		gCO2eq/MJ	81.2	57.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Safety of fuel technology		-	5	4	5	5	5	5	5	4	3
Long-term global availability of fuel		-	3	3	3	3	4	4	4	4	5
Feedstock competition with food		-	5	5	2	2	4	4	4	4	5

Figure 8.11: SMART performance parameters defined in an optimistic, average and pessimistic scenario. The green dots clarify SMART criteria that vary throughout scenarios.

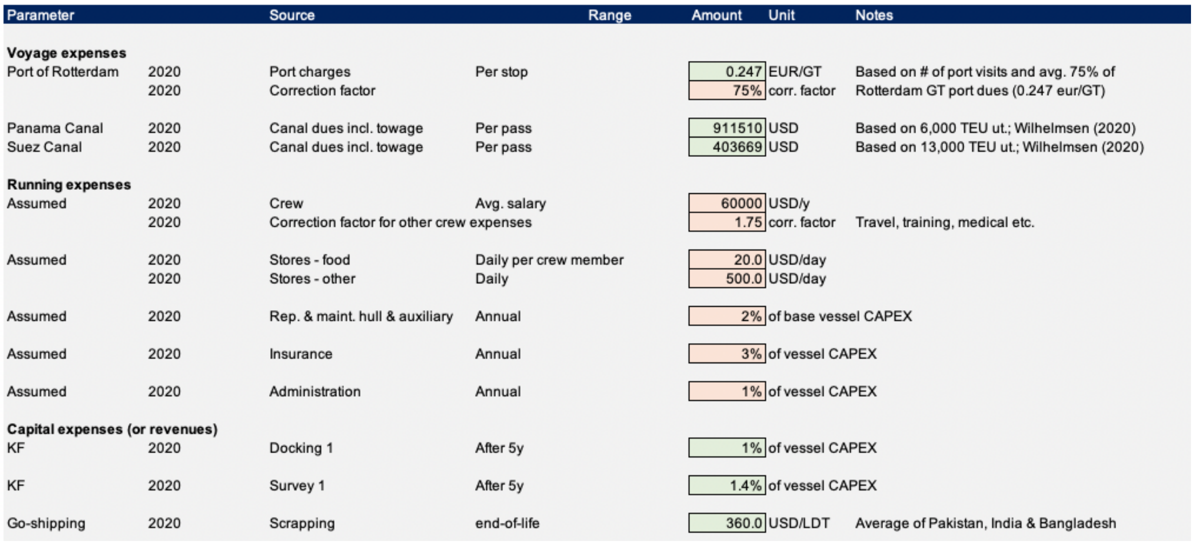
Although most performance parameters are established in section 5.3, financial parameters have been established alongside the construction of the model. This process is detailed in the top section of the 'Cost parameter info' tab, as is demonstrated in figure 8.12. In addition to the engine CAPEX and OPEX data, this tab also includes other expenses, as is presented in figure 8.13. These other costs include voyage expenses such as port and canal dues, as well as running expenses for crew, stores, repairs and maintenance, insurance and administrative expenses. Although repair and maintenance costs for the engine are already accounted for in the performance parameters, the model additionally accounts for maintenance and repairs to the hull and auxiliary equipment, something that is not fuel-dependent. Furthermore, data is collected on capital expenses. This includes costs for docking and special survey as well as cash generated from the scrapping of the vessel. To improve the accuracy of the model, all collected cost data is corrected for inflation to reflect the unit cost in the year of new-building. This is achieved by correcting past cost data with the global inflation of G20 OECD countries up to the equivalent cost in the year of new building [127]. It goes without saying that when more recent data is available, this is preferred and used.



Parameter	Engine type	Source	kW	Range	Amount	Unit	Notes
Engine CAPEX	Diesel engine	Gil (2013)	12000 kW		370.0	USD/kW	
		Air Resources Board (2018)	n/a		318.5	USD/kW	
		Wartsila (2017)	18480 kW		348.1	USD/kW	
Engine CAPEX	Scrubber system	Air Resources Board (2018)	36000 kW	Lower bound	192.5	USD/kW	wet scrubbers, newbuilt
				Upper bound	233.1	USD/kW	
		DNV GL (2013)	n/a		187.4	USD/kW	
		DNV GL (2018)			106.2	USD/kW	
		Wartsila (2017)	18480 kW		124.3	USD/kW	
		SEA-LNG (2020)	21840 kW		123.6	USD/kW	open-loop
					129.0	USD/kW	closed-loop
	EGR system	EPA (2009)	18000 kW		12.0	USD/kW	Nox Tier III compliance
Engine CAPEX	Diesel engine + scrubber system			Lower bound	454.8	USD/kW	Gil, Air Resources Board & Wartsila
				Upper bound	593.1	USD/kW	Air Resources Board & Wartsila

Parameter	Engine type	Source	kW	Range	Amount	Unit	Notes
Engine OPEX	Diesel engine	Banawan (2010)	24000 kW		67.2	USD/kW/y	Diesel engine w/o scrubbers
	DE + scrubbers	Levander (Wartsila) (2011)	11400 kW		80.4	USD/kW/y	Maintenace, SCR, scrubber and lubrication costs
	Scrubbers	DNV GL (2013); MARAD SOCP (2011); Karimpour (2018)			3.2	USD/kW/y	2% of avg. scrubber system CAPEX
	LNG	Levander (Wartsila) (2011)	11400 kW		34.5	USD/kW/y	
		Banawan (2010)	24000 kW		40.2	USD/kW/y	
	Bio-fuels	Assumptions			5.0	% increase	Compared to HFO
	Ammonia	Assumptions			40.8	USD/kW/y	15% higher than LNG due to corrosive properties
		de Vries (2019)	16080 kW		49.8	USD/kW/y	

Figure 8.12: Engine CAPEX and OPEX parameters used in the model.



Parameter		Source		Range	Amount	Unit	Notes
Voyage expenses							
Port of Rotterdam	2020	Port charges	Per stop		0.247	EUR/GT	Based on # of port visits and avg. 75% of
	2020	Correction factor			75%	corr. factor	Rotterdam GT port dues (0.247 eur/GT)
Panama Canal	2020	Canal dues incl. towage	Per pass		911510	USD	Based on 6,000 TEU ut.; Wilhelmsen (2020)
Suez Canal	2020	Canal dues incl. towage	Per pass		403669	USD	Based on 13,000 TEU ut.; Wilhelmsen (2020)
Running expenses							
Assumed	2020	Crew	Avg. salary		60000	USD/y	
	2020	Correction factor for other crew expenses			1.75	corr. factor	Travel, training, medical etc.
Assumed	2020	Stores - food	Daily per crew member		20.0	USD/day	
	2020	Stores - other	Daily		500.0	USD/day	
Assumed	2020	Rep. & maint. hull & auxiliary	Annual		2%	of base vessel CAPEX	
Assumed	2020	Insurance	Annual		3%	of vessel CAPEX	
Assumed	2020	Administration	Annual		1%	of vessel CAPEX	
Capital expenses (or revenues)							
KF	2020	Docking 1	After 5y		1%	of vessel CAPEX	
KF	2020	Survey 1	After 5y		1.4%	of vessel CAPEX	
Go-shipping	2020	Scrapping	end-of-life		360.0	USD/LDT	Average of Pakistan, India & Bangladesh

Figure 8.13: Other cost parameters used in the model.

Output

For the shipowner, the output is the most important aspect of the decision tool when considering employing alternative fuels. In the current decision tool, a SMART decision model is devised to provide the user with an overview on the proposed ranking of alternative fuel technologies under the selected scenario. Additionally, the user is provided with an overview of financial indicators such as NPV, required freight rate and optimal economic speed, as well as clarifying charts in order to be able to analyse each potential choice and scenario in more depth. Figure 8.14 provides an example of the outputs generated for HFO under the 2020, average, no regulation scenario.

From top to bottom, the generated outputs include:

1. The weighted scores and SMART ranking of all alternatives under the selected scenario.
2. The SMART ranking for a specific alternative (in this case, HFO) under each combination of sentiment, time and regulatory scenario.
3. The optimal economic speed at which RFR is minimised for a specific alternative (in this case, HFO) under each combination of scenarios.
4. The required freight rate to achieve NPV=0 for a specific alternative (in this case, HFO) under each combination of scenarios.
5. Chart outputs of NPV over time for the optimistic, average and pessimistic scenarios in 2020, 2030 and 2050 for a specific alternative (in this case, HFO).

The following paragraphs each provide a brief explanation on their related decision tool outputs:

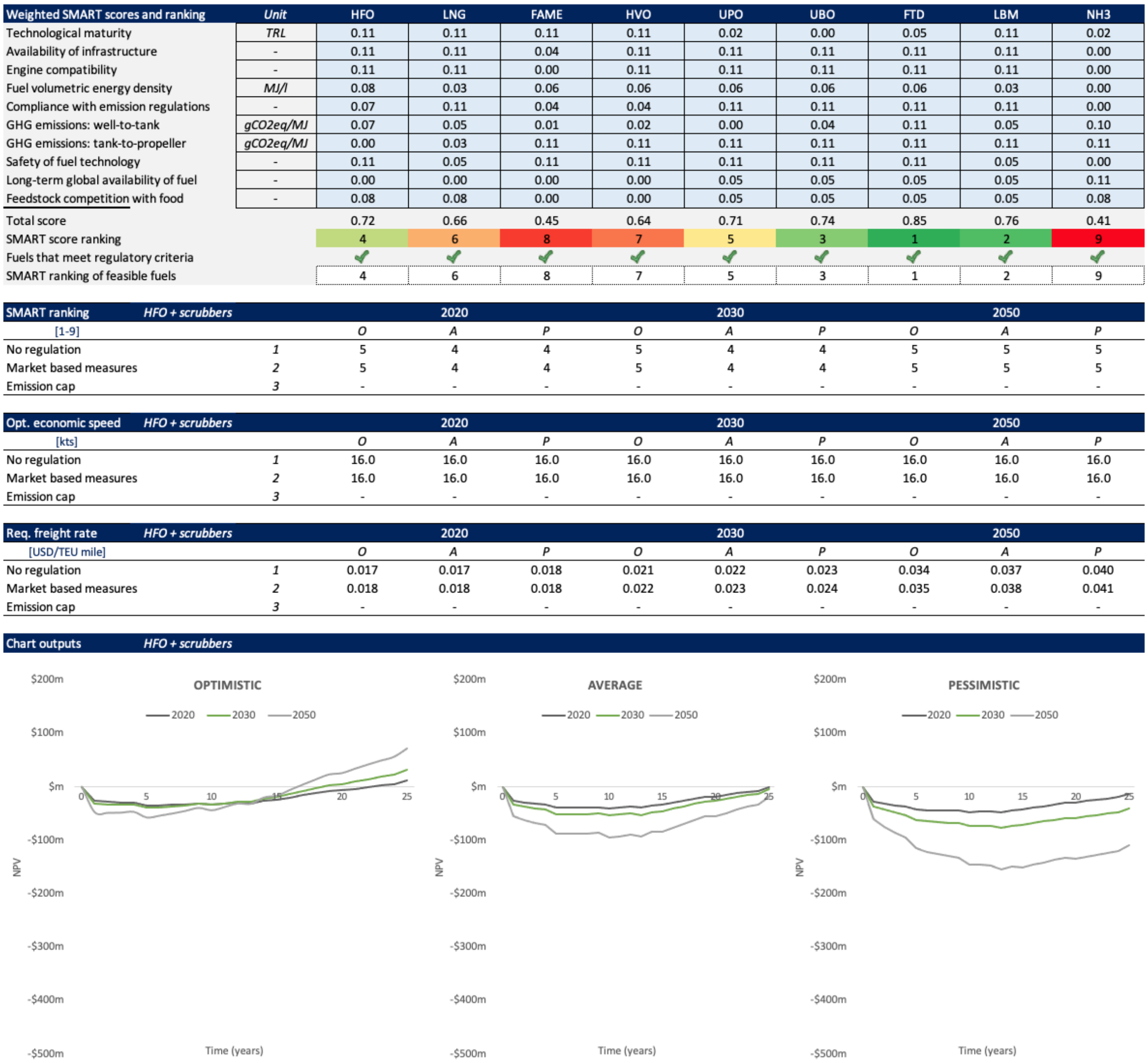
1. The weighted scores and SMART ranking outputs of all alternatives under the selected scenario provide the shipowner with insights in how each of the fuel alternatives performs on each criterion. The performance scores (in black, on blue background) add up to the total score, which ranges between 0.00 - 1.00. The highest score represents the most favourable alternative under the chosen criteria. Following this, each of the alternatives is ranked in order of preference according to its score: from 1 for the highest-ranking alternative to 9 for the lowest ranking alternative. However, boundary conditions apply under different regulatory scenarios. Therefore, when an alternative does not satisfy regulatory requirements, it is assumed infeasible and eliminated from the ranking. Infeasible alternatives are marked with a dash '–'.

2. The SMART ranking output table is a data table showing the SMART ranking output of an alternative under each combination of scenarios. Contrary to the weighted scores and SMART ranking output which only shows outputs for the selected scenario, this data table is able to provide insights into how an alternative ranks under each different scenario. Again, where an alternative does not satisfy regulatory requirements (such as HFO under an emission cap scenario) it is assumed infeasible and marked with a dash '–'.

3. The optimal economic speed data table shows the vessel speed at which required freight rate (RFR) is minimised for a specific alternative under each combination of scenarios. The economic speed outputs are the result of an optimisation model which is further elaborated in section 8.3. Contrary to HFO and LNG, for other 'new' fuels the economic speed only changes for each sentiment and time scenario. The newer alternatives are not affected by regulation, and their optimal economic speed is therefore constant for each regulatory scenario.

4. The last data table shows the required freight rate to achieve NPV=0 for a specific alternative under each combination of scenarios. The required freight rate is the freight rate per TEU-mile the shipowner needs to earn to achieve NPV=0. The required freight rate is defined in '$\$/TEU-mile$' and is not calculated for fuels that do not meet regulatory requirements. More information on the required freight rate (RFR) is provided in sections 8.2.2 and 8.5.

5. To provide insights into the development of NPV over time, chart outputs are produced for the optimistic, average and pessimistic scenarios in 2020, 2030 and 2050 for a specific alternative. From these charts, shipowners can deduct under which scenarios a specific alternative produces a positive return, as well as the approximate payback period of their investment.



Weighted SMART scores and ranking	Unit	HFO	LNG	FAME	HVO	UPO	UBO	FTD	LBM	NH3
Technological maturity	TRL	0.11	0.11	0.11	0.11	0.02	0.00	0.05	0.11	0.02
Availability of infrastructure	-	0.11	0.11	0.04	0.11	0.11	0.11	0.11	0.11	0.00
Engine compatibility	-	0.11	0.11	0.00	0.11	0.11	0.11	0.11	0.11	0.00
Fuel volumetric energy density	MJ/l	0.08	0.03	0.06	0.06	0.06	0.06	0.06	0.03	0.00
Compliance with emission regulations	-	0.07	0.11	0.04	0.04	0.11	0.11	0.11	0.11	0.00
GHG emissions: well-to-tank	gCO2eq/MJ	0.07	0.05	0.01	0.02	0.00	0.04	0.11	0.05	0.10
GHG emissions: tank-to-propeller	gCO2eq/MJ	0.00	0.03	0.11	0.11	0.11	0.11	0.11	0.11	0.11
Safety of fuel technology	-	0.11	0.05	0.11	0.11	0.11	0.11	0.11	0.05	0.00
Long-term global availability of fuel	-	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.11
Feedstock competition with food	-	0.08	0.08	0.00	0.00	0.05	0.05	0.05	0.05	0.08
Total score		0.72	0.66	0.45	0.64	0.71	0.74	0.85	0.76	0.41
SMART score ranking		4	6	8	7	5	3	1	2	9
Fuels that meet regulatory criteria		✓	✓	✓	✓	✓	✓	✓	✓	✓
SMART ranking of feasible fuels		4	6	8	7	5	3	1	2	9

SMART ranking	*HFO + scrubbers*	2020			2030			2050		
[1-9]		*O*	*A*	*P*	*O*	*A*	*P*	*O*	*A*	*P*
No regulation	*1*	5	4	4	5	4	4	5	5	5
Market based measures	*2*	5	4	4	5	4	4	5	5	5
Emission cap	*3*	-	-	-	-	-	-	-	-	-

Opt. economic speed	*HFO + scrubbers*	2020			2030			2050		
[kts]		*O*	*A*	*P*	*O*	*A*	*P*	*O*	*A*	*P*
No regulation	*1*	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0
Market based measures	*2*	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0
Emission cap	*3*	-	-	-	-	-	-	-	-	-

Req. freight rate	*HFO + scrubbers*	2020			2030			2050		
[USD/TEU mile]		*O*	*A*	*P*	*O*	*A*	*P*	*O*	*A*	*P*
No regulation	*1*	0.017	0.017	0.018	0.021	0.022	0.023	0.034	0.037	0.040
Market based measures	*2*	0.018	0.018	0.018	0.022	0.023	0.024	0.035	0.038	0.041
Emission cap	*3*	-	-	-	-	-	-	-	-	-

Figure 8.14: SMART and financial outputs based on the currently provided inputs. In the current example, the 2020, average, no regulation scenario is selected to print outputs for HFO + scrubbers.

Details on the calculations behind the discussed outputs are provided in section 8.2.

8.2. Model description

The goal of the following section is to provide the reader with an accurate description of the model behind the decision tool in order to allow them to understand the underlying principles and to be able to reproduce what is desired. Section 8.2.1 describes the SMART decision method, the relevant calculations and how it is applied and linked in the current decision tool. Section 8.2.2 describes how the financial model is built up, which costs are included and calculated and how they are accumulated. Additionally, clarification is provided on the calculations behind the financial indicators presented in the decision tool.

8.2.1. SMART decision model

The simple multi-attribute rating technique, otherwise called SMART decision method, is a method of multi-criteria decision making. SMART is applied in situations where different criteria carry weights but minimal input is demanded from decision-makers. SMART relies on utility and preferential independence and allows for any type of weight assessment technique. In the present research, absolute weight assessments have been used after presenting a survey to a set of shipowners. Section 5.4 expands on the presented survey and the methodology applied to assess these weights. The current section elaborates on the implementation of the SMART decision model in the current model.

SMART is a linear additive model with the goal of calculating the score of each alternative while accounting for individual values and criteria weights. The SMART decision method relies on the theory that each alternative consists of some criteria that have values. On their turn, each criterion has been assigned a weight that describes how important it is compared to other criteria. This weighting is used to assess each alternative to obtain the best choice for the decision-maker.

The SMART decision method consists of five processing steps:

1. Assessment of criteria weights w (carried out in section 5.4).
2. Calculation of relative weights W.
3. Assessment of performance parameters p for each alternative i (carried out in section 5.3).
4. Calculation of relative evaluation factors v_{ij} for each alternative i under each criterion j.
5. Calculation of total score received by each alternative i under criteria j with relative weights W.

To demonstrate the working principle of the SMART decision model, an example of the method is reproduced for the average, unregulated, 2020 scenario:

1. As was determined in section 5.4, the median weights assigned to each criterion by the set of shipowners that participated in the survey are displayed below:

Criteria	Consolidated median
Technological maturity	4.0
Availability of infrastructure	4.0
Engine compatibility	4.0
Fuel volumetric energy density	3.0
Compliance with emission regulations	4.0
GHG emissions: well-to-tank	4.0
GHG emissions: tank-to-propeller	4.0
Safety of fuel technology	4.0
Long-term global availability of fuel	4.0
Feedstock competition with food	3.0
$\sum_j w$	50

Table 8.2: Criteria weight assessment w of each criterion j. Scores are assessed on Likert scale: 1: Not important at all; 2: Not so important; 3: Moderately important; 4: Very important; 5: Extremely important.

2. Going off table 8.2, relative weights W are assessed by dividing each weight w_j over the sum of all criteria weights. The results are shown in table 8.3:

Criteria	Relative weight W
Technological maturity	0.08
Availability of infrastructure	0.08
Engine compatibility	0.08
Fuel volumetric energy density	0.06
Compliance with emission regulations	0.08
GHG emissions: well-to-tank	0.08
GHG emissions: tank-to-propeller	0.08
Safety of fuel technology	0.08
Long-term global availability of fuel	0.08
Feedstock competition with food	0.06

Table 8.3: Relative weights W for criteria j.

3. Following step 2, performance parameters p are assessed for each alternative i under criteria j. These performance parameters are not yet defined as a relative score, as this conversion is only performed in step 4. The performance parameters p for each alternative i under criteria j for the average, unregulated, 2020 scenario are presented in figure 8.4.

j	*Unit*	HFO	LNG	FAME	HVO	UPO	UBO	FTD	LBM	NH3	*Source*
Technological maturity	*TRL*	10	10	10	10	5.5	4.5	7	10	5.5	[26, 82]
Availability of infrastructure	-	5	5	3	5	5	5	5	5	2	[48, 55]
Engine compatibility	-	5	5	2	5	5	5	5	5	2	[48, 55, 79, 82]
Fuel volumetric energy density	*MJ/l*	41	22.2	33.2	34.4	34	34	34.5	22.2	12.7	[10, 15, 48, 55, 77]
Compliance with emission regulations	-	4	5	3	3	5	5	5	5	2	[26, 118, 126]
GHG emissions: well-to-tank	gCO_2eq/MJ	14.3	21.2	32	30	34.5	22	5	19.5	7.0	[55, 129, 152]
GHG emissions: tank-to-propeller	gCO_2eq/MJ	81.2	57.5	0	0	0	0	0	0	0.0	[39, 57, 96, 129]
Safety of fuel technology	-	5	4	5	5	5	5	5	4	3	[20, 33]
Long-term global availability of fuel	-	3	3	3	3	4	4	4	4	5	[118, 144, 159]
Feedstock competition with food	-	5	5	2	2	4	4	4	4	5	[26, 82]

Table 8.4: Performance parameters p for each alternative i for the average, unregulated, 2020 base case scenario.

4. Step 4 aims to calculate the relative evaluation factors v_{ij} for each alternative i under each criterion j. Relative evaluation factors are determined by applying formulas 8.1 and 8.2 to each of the performance parameters p_{ij}. Formula 8.1 is used when preference is given to high scores (i.e. fuel volumetric energy density), whereas formula 8.2 is applied when preference is given to low scores (i.e. GHG emissions). $Max(p_j)$ represents the maximum parameter value found under criterion j, whereas $Min(p_j)$ represents the minimum parameter value found under criterion j. Furthermore, p_{ij} describes performance parameter p for alternative i under criterion j.

$$\frac{p_{ij} - Min(p_j)}{Max(p_j) - Min(p_j)} = v_{ij} \tag{8.1}$$

$$\frac{Max(p_j) - p_{ij}}{Max(p_j) - Min(p_j)} = v_{ij} \tag{8.2}$$

To be able to calculate v_{ij} for all parameters p_{ij}, the model automatically determines the Min and Max range for each criterion j under each different regulation, scenario and timeline.

5. Finally, the total score received by each alternative i under criterion j with relative weight W is calculated. The total score ranges from 0.00 - 1.00 and is determined by summing all relative evaluation factors v_j received by alternative i. As the goal of the SMART decision method is to maximise the total score, the alternatives i which receive the highest total score are the most preferred alternatives. An example is provided in table 8.5.

j	HFO	LNG	FAME	HVO	UPO	UBO	FTD	LBM	NH3
Technological maturity	0.11	0.11	0.11	0.11	0.02	0.00	0.05	0.11	0.02
Availability of infrastructure	0.11	0.11	0.04	0.11	0.11	0.11	0.11	0.11	0.00
Engine compatibility	0.11	0.11	0.00	0.11	0.11	0.11	0.11	0.11	0.00
Fuel volumetric energy density	0.08	0.03	0.06	0.06	0.06	0.06	0.06	0.03	0.00
Compliance with emission regulations	0.07	0.11	0.04	0.04	0.11	0.11	0.11	0.11	0.00
GHG emissions: well-to-tank	0.07	0.05	0.01	0.02	0.00	0.04	0.11	0.05	0.10
GHG emissions: tank-to-propeller	0.00	0.03	0.11	0.11	0.11	0.11	0.11	0.11	0.11
Safety of fuel technology	0.11	0.05	0.11	0.11	0.11	0.11	0.11	0.05	0.00
Long-term global availability of fuel	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.11
Feedstock competition with food	0.08	0.08	0.00	0.00	0.05	0.05	0.05	0.05	0.08
Total score	0.72	0.66	0.45	0.64	0.71	0.74	0.85	0.76	0.41

Table 8.5: Relative evaluation factors v for each alternative i under criteria j and total SMART score of each alternative i for the average, unregulated, 2020 scenario.

As can be seen in table 8.5, the SMART decision model evaluates fuel alternatives in terms of technical, environmental and other criteria j. For a shipowner to make an informed assessment of the optimal fuel alternative, it is necessary to consider economic criteria as well. Therefore, it does not suffice to only look at the results from the SMART decision model to decide on the choice of optimal alternative for the shipowner.

To evaluate the fuel alternatives on economic criteria, a financial model is devised. This model is elaborated in section 8.2.2 below.

8.2.2. Financial model

The financial model that is incorporated in the decision tool accounts for operating revenues, voyage expenses, running expenses and capital expenses according to the annual cash flow accounting method explained in Maritime Economics by Martin Stopford (2013) [150]. In the following sections, all cost line items are described and elaborated such as to be able to reproduce the model.

Furthermore, it should be noted that all cost line items covered in the following sections represent operations in year 1 (Y1), and are afterwards escalated individually with a fixed escalation factor 'ef'. This factor is free to be input by the shipowner. The escalation factor may be positive or negative and should be considered when certain costs are expected to increase or decline over time. Escalation factors are further elaborated in the last paragraph of this section. The equations below demonstrate how annual cash flow is calculated in the present model.

$$ACF_{tc,i} = R_{tc} - C_{running,i} - C_{capital,i} \tag{8.3}$$

$$ACF_{vc,i} = R_{vc,i} - C_{voyage,i} - C_{running,i} - C_{capital,i} \tag{8.4}$$

with:

$$C_{voyage,i} = C_{port,i} + C_{canal,i} + C_{fuel,i} \tag{8.5}$$

$$C_{running,i} = C_{crew,i} + C_{stores} + C_{r\&m,h\&a} + C_{eOPEX,i} + C_{insurance,i} + C_{admin,i} \tag{8.6}$$

$$C_{capital,i} = C_{purchase,i} + C_{interest,i} + C_{principal,i} + C_{bullet,i} + C_{dd,i} + C_{ss,i} - C_{scrap} \tag{8.7}$$

where:

i	Index i specifies each of the different alternative fuels (with their corresponding engine type).

$ACF_{tc,i}$	Annual cash flow of vessel employing fuel i on time charter.
$ACF_{vc,i}$	Annual cash flow of vessel employing fuel i on voyage charter.
R_{tc}	Annual time charter revenue earned by vessel, in USD.
$R_{vc,i}$	Annual voyage charter revenue earned by vessel employing fuel i after cargo handling and terminal operating cost cost revenue share, in USD.
$C_{voyage,i}$	Annual voyage expenses of vessel employing fuel i.
$C_{running,i}$	Annual running expenses of vessel employing fuel i.
$C_{capital,i}$	Annual capital expenses of vessel employing fuel i.
$C_{port,i}$	Annual port charges of vessel employing fuel i.
$C_{canal,i}$	Annual canal dues of vessel employing fuel i.
$C_{fuel,i}$	Annual fuel cost of vessel employing fuel i.
$C_{crew,i}$	Annual crew expenses of vessel employing fuel i.
C_{stores}	Annual stores expenses.
$C_{r\&m:h\&a}$	Annual expenses for repairs and maintenance of hull and machinery.
$C_{eOPEX,i}$	Annual expenses for engine OPEX, including repairs, maintenance and lubricants for engine of vessel employing fuel i.
$C_{insurance,i}$	Annual total insurance expenses dependent on each fuel type.
$C_{admin,i}$	Annual administrative expenses of vessel employing fuel i.
$C_{purchase,i}$	One-time capital expense for purchase of vessel. Only contains shipowner's equity contribution, not debt.
$C_{interest,i}$	Annual interest expense over the remaining debt portion of vessel employing fuel i.
$C_{principal,i}$	Annual principal payment of vessel employing fuel i as a fraction of the total debt as agreed in the loan term agreement.
$C_{bullet,i}$	Bullet debt to be paid at the end of the agreed loan term.
$C_{dd,i}$	Dry docking expense of vessel employing fuel i at the end of each dry dock interval.
$C_{ss,i}$	Special survey expense of vessel employing fuel i at the end of each special survey interval.
C_{scrap}	Scrapping income received upon the end of the vessel's lifetime.

All mentioned revenue categories, expense categories and specific cost line items are further elaborated in the sections below.

Regarding taxation, the international nature of the business makes it possible to avoid taxes by registering vessels and companies under one of many open registry flag states which exempt shipping companies from tax [150]. Common examples of such flag states include Panama, Liberia, Marshall Islands and Hong Kong, among others. Therefore, taxation is merely included in the model's discount rate, as it does not figure prominently in the accounts of most shipping companies [150].

Time charter and voyage charter

Chartering within the shipping industry refers to the activity whereby a shipowner offers the hire of his vessel. In this model, two charter types are implemented: time charter and voyage charter. Bare-boat charters are not covered in this model. The main difference between time- and voyage charters is the distribution of responsibilities and cost among the charterer and the shipowner. Whereas a time charter is a time-bound agreement, often contracted for periods of 12 or 36 months, a voyage charter is a one-time agreement for the transport of goods from A to B. This means that when on time charter, the charterer is responsible for the voyage costs. Voyage costs include fuel, port charges and canal dues, and in the present model amount to approximately 42% of the total costs when on voyage charter: in line with the expected 40% cost share retrieved from Maritime Economics (2013) [150]. The similarities and differences in shipowner charges when sailing on each covered contract type are presented in table 8.6 below. Although analysis on time chartered vessels could be interesting, the focus of the present research lies on voyage charters due to the large influence of fuel cost on financial performance.

Category	Cost line item	Time charter	Voyage charter
Voyage expenses	Port charges		✓
	Canal dues		✓
	Fuel		✓
	GHG emissions		✓
Running expenses	Crew	✓	✓
	Stores	✓	✓
	R&m: hull & auxiliary	✓	✓
	Engine OPEX	✓	✓
	Insurance	✓	✓
	Administration	✓	✓
Capital expenses	Base vessel: equity	✓	✓
	Engine CAPEX	✓	✓
	Financial cost: interest	✓	✓
	Financial cost: principal	✓	✓
	Financial cost: bullet	✓	✓
	Dry dock	✓	✓
	Special survey	✓	✓
	Scrapping (income)	✓	✓

Table 8.6: Similarities and differences in shipowner charges when sailing on time or voyage charter contract types. Own composition

Revenue buildup

To calculate the net present value of an alternative, it is necessary to determine the vessel's revenue. In the present model, the revenue varies dependent on the charter type the shipowner chooses to put his vessel up for. In both a time or voyage charter, annual revenue is calculated by multiplying the number of chartered days per year with the vessel's average daily charter rate. However, in this thesis, the emphasis will lie on voyage charters as they provide a better view of the cost effects of employing alternative fuel technologies.

In voyage charters, total freight rates per TEU '$FR_{TEU,n,i}$' on voyage 'n' for fuel type 'i' are calculated over each leg 'l' of the route that the freight travels on board of the vessel. For example, the charter rate received for freight that needs to travel from A to C consists of two legs: from A to B and B to C. As such, legs 'l' are chosen as the basis for daily voyage charter revenues.

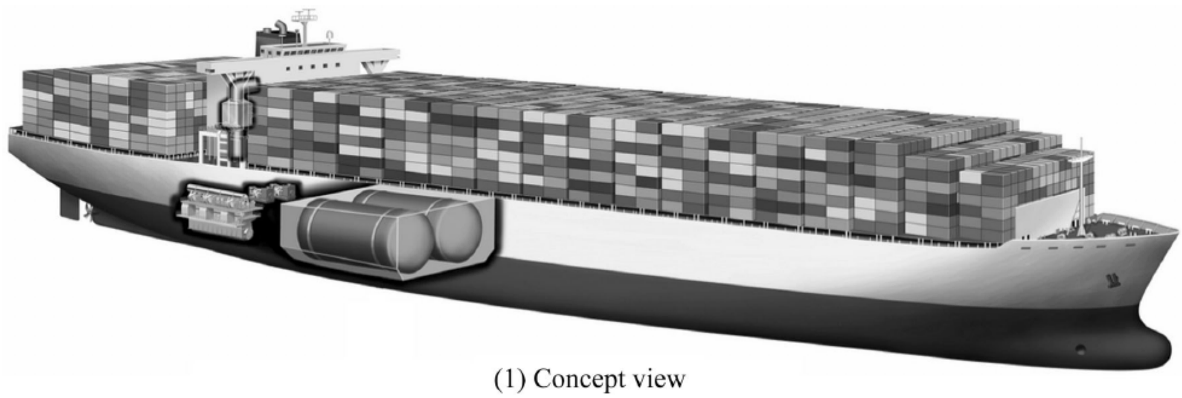
It is important to consider that the daily voyage charter rates (revenues) received by the shipowner include cargo handling and terminal operating costs. In the present model, it is assumed that cargo handling costs from shipper to shipowner and terminal operating costs from shipowner to port are directly passed on through the shipowning entity. Therefore, a fixed percentage of the average daily charter rate 'cr_{vc}' is subtracted for cargo handling and terminal operating costs; hereby expressed as '$chtoc_{\%}$'.

At last, revenues are not assumed equal for vessels that make use of different fuel types. Since each vessel employing different fuel types sails at a different optimal economic speed, charter revenues are subject to variations between the fuel alternatives. Additionally, due to the higher volume requirement of LNG, LBM or ammonia tanks, the container vessel loses a part of its full load capacity. Research by TNO and CE Delft for the European Commission (2015) states that to decrease load capacity loss, LNG-equipped vessels need to be 5% longer than vessels equipping traditional diesel engines and tanks [65]. The report assumes a maximum time at sea of 14 days.

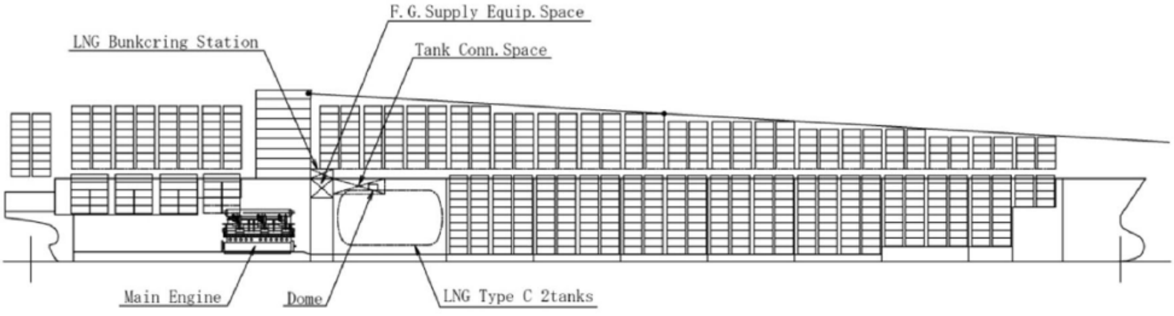
However, in the present study, the vessel sizing is assumed constant due to the limitations of the

New Panama canal. Since the LNG and LBM tanks still require more space on board, the case study vessel's load capacity is necessarily decreased. To account for this capacity loss, the case study vessel's maximum load capacity is reduced by 5% to account for the LNG and LBM higher system volume requirement [65].

Additionally, the case study vessel's maximum load capacity is reduced by another 5% due to the requirement of spending approximately double the time at sea compared to the container vessel investigated in the 2015 study [65]. Therefore, in the present thesis, LNG and LBM tanks reduce maximum load capacity by 10% in total. This way the model accounts for 5% length not added, as well as 5% for extra tank capacity to account for the longer time at sea. An illustration of the proposed setup was rendered by Adachi (2014) and is provided in figure 8.15 [13]. The LNG tanks are cylindrical type C tanks intended for storage at -160°C and at a design pressure in ranges above 2 bar [38].



(1) Concept view



(2) General arrangement

Figure 8.15: Schematic overview of proposed LNG configuration aboard container vessel. Source: (Adachi, 2014)

For ammonia, the same reasoning is followed. However, due to its 1.75 times lower volumetric energy density compared to LNG or LBM, the case study vessel's maximum load capacity is reduced by 17.5%[2] compared to the base case.

It should not be forgotten that the 10% and 17.5% capacity losses are only of influence on the legs where the vessel has a capacity utilisation above 90% and 82.5% respectively, since net transport demand on each leg is assumed constant for all fuels. In the present model, the affected legs include Shanghai - Rotterdam and Rotterdam - New York. In practice, capacity loss for both LNG/LBM and ammonia could potentially be reduced by employing fewer fuel tanks and sailing through multiple bunkering ports. However, as this implies a complex bunkering strategy, this is not considered in the present thesis.

At last, in order to account for deferred revenue during dry dock and special survey, the duration of the docking and survey periods is subtracted from the total number of days per year the vessel

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[2] Although the discrete steps in which load capacity aboard container vessels can scale varies per ship size and arrangement, in the current case it is assumed that capacity can be increased or reduced in steps of 2.5% compared to the base case. This assumption is based on a seven-tank arrangement (three double tanks as seen in figure 8.15 and one single tank).

is chartered in the respectful maintenance years. This correction is automatically implemented by calculating the annual average days on charter. In the following equations, the revenue buildup as found in the model is presented for both time and voyage charters.

$$R_{tc} = cd_a \cdot cr_{tc} \tag{8.8}$$

$$R_{vc,i} = cd_a \cdot cr_{vc,i} \cdot (1 - chtoc_{\%}) \tag{8.9}$$

with:

$$cr_{vc,i} = \frac{\sum_{l_i=1}^{l_i} FR_{TEU,l} \cdot u_{l,i}}{cd_a} \tag{8.10}$$

$$cd_a = cd_w - \frac{cd_{dd} + cd_{ss}}{int_{dd,ss}} \tag{8.11}$$

where:

i	Index i specifies each of the different alternative fuels (with their corresponding engine type).
R_{tc}	Annual time charter revenue earned by vessel, in USD.
$R_{vc,i}$	Annual voyage charter revenue earned by vessel employing fuel i after cargo handling and terminal operating cost revenue share, in USD.
cr_{tc}	Average daily charter rate earned by the vessel on time charter, in USD. Decided on contract with charterer.
$cr_{vc,i}$	Average daily charter rate earned by the vessel on voyage charter before cargo handling and terminal operating cost cost revenue share, in USD.
$chtoc_{\%}$	Cargo handling and terminal operating cost revenue share. Expressed in % of charter rate.
$FR_{TEU,l}$	Freight rate per TEU on leg l.
cd_a	Number of days per year the vessel is chartered on average. Includes correction for deferred days due to dry dock and special survey.
cd_w	Number of target days per year the shipowner wishes to charter the vessel.
cd_{dd}	Number of days vessel spends on each dry dock.
cd_{ss}	Number of days vessel spends on each special survey.
$int_{dd,ss}$	Dry dock and special survey interval, in years.

Voyage expenses buildup

Voyage expenses are expenses related to a specific voyage that is sailed. These expenses include port charges, canal dues, fuel costs and GHG emission costs. Port charges are calculated by ports based on a vessel's gross tonnage. In the present model, annual port charges are calculated based on the port charge per GT, gross tonnage and average annual port visits. As for canal passages, the Panama and Suez canal use different calculation methods for their canal dues. The Panama canal calculates canal dues based on vessel type, maximum cargo capacity (TEU), length overall (LOA) and beam [166]. The Suez canal bases its canal dues on vessel type, draft, 'Suez canal net tonnage' (measured every time a vessel passes the Suez canal), sailing direction (north- or southbound) and gross tonnage [167]. In the decision tool, canal dues are assumed to be paid upon exit of the canal. Therefore, total annual canal dues are calculated by multiplying the sum of the Panama and Suez canal dues with the number of annual canal exits. The number of annual port arrivals and canal exits varies per vessel employing a different fuel type due to the different average transit speed of each vessel. A vessel sailing with a lower average transit speed results in less annual port arrivals and canal exits than a vessel sailing with a higher average transit speed.

Although port charges and canal dues contribute significantly to a vessel's annual voyage expenses, the largest annual voyage expense is fuel cost. Annual fuel cost is calculated by multiplying annual fuel consumption (in mt) with the specific fuel cost per unit of mass per fuel type (in \$/mt). The method with which the present model establishes annual fuel consumption is further elaborated under 'Fuel consumption'. The different fuel cost established for each alternative fuel is presented in table 6.1 in chapter 6.

At last, annual GHG cost is dependent on the total energy consumption, CO_2eq emissions per fuel type, and the cost of CO_2eq emissions. However, under current regulations, greenhouse gas emission offsetting by certificate purchase is not mandatory. Therefore, GHG emission costs are only relevant under one of the investigated regulatory scenarios which considers market-based measures. Thus, under the base case scenario, $C_{GHG,i}$ is zero for all fuels. The different regulatory scenarios and their implementation are further elaborated under section 8.4. In the following equations, the voyage expenses buildup as found in the model is presented.

$$C_{voyage,i} = C_{port} + C_{canal} + C_{fuel,i} + C_{GHG,i} \tag{8.12}$$

with:

$$C_{port,i} = GT \cdot c_{GT} \cdot port_{a,i} \tag{8.13}$$

$$C_{canal,i} = (c_{ce,NP} + c_{ce,S}) \cdot canal_{e,i} \tag{8.14}$$

$$C_{fuel,i} = FC_{total,i} \cdot c_{mt,i} \tag{8.15}$$

$$C_{GHG,i} = EC_{total,i} \cdot E_{CO2eq,i} \cdot c_{CO2eq,i} \tag{8.16}$$

where:

i	Index i specifies each of the different alternative fuels (with their corresponding engine type).
$C_{voyage,i}$	Annual voyage expenses of vessel employing fuel i.
$C_{port,i}$	Annual port charges of vessel employing fuel i.
$C_{canal,i}$	Annual canal dues of vessel employing fuel i.
$C_{fuel,i}$	Annual fuel cost of vessel employing fuel i.
$C_{GHG,i}$	Annual greenhouse gas emission cost of vessel employing fuel i. Only applicable under regulatory scenario employing market-based measures. Further elaborated in section 8.4.
GT	Vessel gross tonnage.
c_{GT}	Port charges per gross tonnage charged by ports. Expressed in US dollar per gross tonnage (\$/GT).
$c_{ce,NP}$	Canal dues per New Panama canal exit including towage. Expressed in US dollar per canal exit (\$/exit).
$c_{ce,S}$	Canal dues per Suez canal exit including towage. Expressed in US dollar per canal exit (\$/exit).
c_{CO2eq}	Cost per ton of CO_2-equivalent GHG emissions. Expressed in US dollar per ton (\$/ton).
$port_{a,i}$	Average annual port arrivals.
$canal_{e,i}$	Average annual canal exits of vessel employing fuel i. Counted upon exit of the canal.

$c_{mt,i}$	Cost per unit of mass per fuel type. Expressed in US dollar per metric tonne ($/mt).
$FC_{total,i}$	Annual fuel consumption by vessel employing fuel i. Further specified under 'Fuel consumption'.
$EC_{total,i}$	Total annual propulsion and auxiliary energy consumption, expressed in mega joule (MJ).
$E_{CO2eq,i}$	Ton CO_2-equivalent GHG emissions emitted per mega-joule energy by vessel employing fuel i. Expressed in ton CO_2eq/MJ.

Fuel consumption

As the fuel-dependent cost per mt has already been calculated in chapter 6, the vessel's annual fuel consumption remains to be determined. Once annual fuel consumption $FC_{total,i}$ is calculated, it is multiplied by the specific fuel cost per mt for each fuel type to determine the annual fuel cost for each fuel type.

The vessel's annual fuel consumption is the sum of the annual propulsion fuel consumption and the annual auxiliary fuel consumption. The total propulsion fuel consumption is dependent on the propulsion energy consumption and the specific fuel oil consumption (SFOC) at each percentage of engine power output per fuel type. The propulsion energy consumption is dependent on the time the vessel spends in transit and the vessel's cruising speed. The vessel's cruising speed is optimised for each fuel alternative in order to minimise required freight rate: the devised optimisation model to determine the optimal economic cruising speed is elaborated in section 8.3. The vessel's dimensions are assumed constant.

For diesel-like fuels such as HFO and bio-fuels, the use of conventional marine diesel engines is assumed. For gas-like fuels such as LNG and liquefied bio-methane (LBM), the use of dual-fuel engines is assumed. Dual-fuel engines allow being operated on either conventional liquid marine fuels or LNG. For dual-fuel engines, a 9.5% higher engine efficiency is assumed. The 9.5% higher efficiency figure is derived from research conducted by Wärtsilä[3] and Shell (2017) [163]. As for ammonia, of which there are no reliable engine efficiency figures available for ICEs, engine efficiency is assumed equal to when using diesel-like fuels due to its poor combustion characteristics such as high auto-ignition temperature, low flame speed, narrow flammability limits and high heat of vaporisation [19].

The equations below show the calculation method for arriving at the annual fuel consumption for each fuel i.

$$FC_{total,i} = FC_{prop,i} + FC_{aux,i} \tag{8.17}$$

with:

$$FC_{prop,i} = EC_{prop,i} \cdot SFOC_{P,i} \cdot (1 - ECF_i) \tag{8.18}$$

$$FC_{aux,i} = pFC_{aux} \cdot FC_{prop,i} \tag{8.19}$$

and:

$$EC_{prop,i} = t_{t,i} \cdot P_{vc_i} \tag{8.20}$$

$$t_{t,i} = \sum_{l=1}^{l} \frac{td_l}{vc_i} \tag{8.21}$$

$$P_{vc_i} = 5.4031 \cdot vc_i^3 - 10.619 \cdot vc_i^2 + 241.32 \cdot vc_i - 353 \qquad \text{Regression formula, } R^2 = 0.999 \tag{8.22}$$

where:

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[3] It is a known fact that Wärtsilä invests heavily on the development of dual-fuel engines. Therefore, the proclaimed 9.5% higher engine efficiency might be subject to bias.

i	Index i specifies each of the different alternative fuels (with their corresponding engine type).
$FC_{total,i}$	Annual fuel consumption of vessel employing fuel i, in metric tonnes (mt).
$FC_{prop,i}$	Propulsion fuel consumption of vessel employing fuel i, in metric tonnes (mt).
$FC_{aux,i}$	Auxiliary fuel consumption of vessel employing fuel i including off-hire, in metric tonnes (mt). Auxiliary equipment is assumed to be powered by the same fuel as used in the main engine.
$EC_{prop,i}$	Propulsion energy consumption of vessel employing fuel i, in megawatt hour (MWh).
$SFOC_{P,i}$	Specific fuel (oil) consumption (SFOC) at each percentage of engine power output per fuel type, in metric tonnes per megawatt (mt/MW).
ECF_i	Engine efficiency correction factor for fuel i in %. For LNG and liquefied bio-methane, dual-fuel engines provide 9.5% efficiency gains.
pFC_{aux}	Percentage of propulsion fuel consumption additionally spent on auxiliary equipment.
P_{vc_i}	Engine power output of a vessel employing fuel i at optimal economic speed vc_i, in megawatt (MW). Regression formula produced with the Hollenbach Model provided by Prof. Koos Frouws (TU Delft).
$t_{t,i}$	Annual time a vessel employing fuel i spends on transit. Excludes time spent loading and discharging.
vc_i	Optimal economic vessel cruising speed for vessel employing fuel i in knots (kts) as determined by the optimisation model of section 8.3.
td_l	Transit distance sailed on leg l expressed in nautical miles (nm).

In the present model, the data input for specific fuel oil consumption per engine load $SFOC_{P,i}$ is taken from an 8-cylinder two-stroke diesel engine provided by MAN Diesel & Turbo [114]. The engine is equipped with scrubbers to comply with global SO_x emission regulations and an exhaust gas recirculation (EGR) system to comply with Tier III NO_x emission regulations. The specifications of the specific engine type used in the present model are presented in table 8.7 and are assumed equal for all diesel-like fuel types.

Engine parameters	Value	Unit
Engine type	8G90ME-C10.5	
Scrubber	Yes	
Exhaust Gas Recirculation (EGR)	Yes	
NO_x emission compliance	Tier III	
100% SMCR power	49920	kW
100 % SMCR speed	84	r/min
Sea margin	15%	
Propeller diameter	10.0	m
Propeller type	FPP	
Cooling system	Central	
Hydraulic power supply	Mechanical	
Turbocharger type	High eff.	

Table 8.7: Engine specifications for the engine assumed to calculate fuel efficiency for all diesel-like fuels.
Own composition based on data from MAN Diesel & Turbo [114].

The power-SFOC relation data table used in the present model for calculations of specific fuel oil consumption of diesel-like fuels and ammonia is presented in table 8.8. For dual-fuel engines employing LNG and liquefied bio-methane, SFOC is adjusted accordingly.

Power	Speed	SFOC$_{SMCR}$
kW	r/min	g/kWh
49920	84.0	165.5
47424	82.6	163.8
44928	81.1	162.4
42432	79.6	161.2
39936	78.0	160.9
37440	76.3	160.7
34944	74.6	160.3
32448	72.8	160.2
29952	70.8	160.5
27456	68.8	160.9
24960	66.7	161.5
22464	64.4	162.6
19968	61.9	163.7
17472	59.2	165.1
14976	56.2	166.1
12480	52.9	168.1
9984	49.1	171.1
7488	44.6	176.1
4992	39.0	184.1

Table 8.8: Power-SFOC relation data table used in the present model for calculations of specific fuel oil consumption of diesel-like fuels and ammonia. Own composition based on data from MAN Diesel & Turbo [114].

Running expenses buildup

Running expenses are all expenses related to the operation of a vessel regardless of its voyage. Running expenses include crew, stores, repairs & maintenance of the hull and auxiliary equipment, repairs & maintenance & lubrication of the engine (so called 'Engine OPEX'), insurance and administration. Of all running expenses, expenses for stores and repairs & maintenance of the hull and auxiliary equipment are not fuel-dependent. In the equations below, the running expenses buildup as found in the model is presented.

$$C_{running,i} = C_{crew,i} + C_{stores} + C_{r\&m,h\&a} + C_{eOPEX,i} + C_{insurance,i} + C_{admin,i} \tag{8.23}$$

with:

$$C_{crew,i} = c_{cm,i} \cdot cm \tag{8.24}$$

$$C_{stores} = (c_{food} \cdot cm + c_{other}) \cdot cd_a \tag{8.25}$$

$$C_{r\&m:h\&a} = C_b \cdot pc_{b,r\&m:h\&a} \tag{8.26}$$

$$C_{eOPEX,i} = P_{inst} \cdot c_{ekW,i} \tag{8.27}$$

$$C_{insurance,i} = C_{tv,i} \cdot pc_{tv,insurance} \tag{8.28}$$

$$C_{admin} = C_{tv,i} \cdot pc_{tv,admin} \tag{8.29}$$

where:

i	Index i specifies each of the different alternative fuels (with their corresponding engine type).
$C_{running,i}$	Annual running expenses of vessel employing fuel i.
$C_{crew,i}$	Annual crew expenses of vessel employing fuel i.

C_{stores}	Annual stores expenses.
$C_{r\&m:h\&a}$	Annual expenses for repairs and maintenance of hull and machinery.
$C_{eOPEX,i}$	Annual expenses for engine OPEX, including repairs, maintenance and lubricants for engine of vessel employing fuel i.
$C_{insurance,i}$	Annual total insurance expenses dependent on each fuel type.
$C_{admin,i}$	Annual administrative expenses of vessel employing fuel i.
$c_{cm,i}$	Average annual cost per crew member including travel, insurance and other. A higher cost per crew member is assumed for vessels employing alternative fuels due to premiums paid for trained and specialised personnel.
cm	Number of crew members employed on vessel.
c_{food}	Average daily food cost per crew member.
c_{other}	Average daily cost for other stores. Includes additional outfit, furniture, furnishings, appliances, spare and replacement parts and tools.
cd_a	Number of days per year the vessel is chartered on average.
C_b	Cost of base vessel. Further elaborated under Capital expenses buildup.
$pc_{b,r\&m:h\&a}$	Annual percentage of base vessel cost spent on repairs and maintenance of hull and machinery.
P_{inst}	Installed power on vessel, in kilowatt (kW).
$c_{okW,i}$	Annual engine OPEX per kW installed engine power of vessel employing fuel i. Expressed in US dollar per kilowatt (\$/kW).
$C_{tv,i}$	Cost of total vessel dependent on each vessel employing fuel i.
$pc_{tv,insurance}$	Annual percentage of total vessel cost spent on insurance.
$pc_{tv,admin}$	Annual percentage of total vessel cost spent on administration.

Capital expenses buildup

Capital expenses are expenses related to the financing and periodic maintenance of the vessel. Periodic maintenance costs are incurred when the ship is dry docked for major repairs and special survey, which carries considerable expenditure. For this reason, these expenses are not generally treated as part of operating expenses [150]. Financing costs include the shipowner's cash contribution to the vessel's purchase, interest expenses over the remaining debt, principal debt payments during the repayment time agreed in the loan agreement and a single bullet payment of a fixed portion of the agreed debt at the end of the repayment time. Additionally, scrap value is accounted for under capital expenses as an income. In the equations below, the capital expenses buildup as found in the model is presented.

$$C_{capital,i} = C_{purchase,i} + C_{interest,i} + C_{principal,i} + C_{bullet,i} + C_{dd,i} + C_{ss,i} - C_{scrap} \tag{8.30}$$

with:

$$C_{purchase,i} = (1-g) \cdot C_{tv,i} \tag{8.31}$$

$$C_{interest,i} = i_{rate} \cdot d_{lt,i} \tag{8.32}$$

$$C_{principal,i} = \frac{d_{lt,i} - C_{bullet,i}}{rt} \tag{8.33}$$

$$C_{bullet,i} = b \cdot d_{lt,i} \tag{8.34}$$

$$C_{dd,i} = pc_{dd} \cdot C_{tv,i} \tag{8.35}$$

$$C_{ss,i} = pc_{ss} \cdot C_{tv,i} \tag{8.36}$$

$$C_{scrap} = LDT \cdot v_{LDT} \tag{8.37}$$

$$\tag{8.38}$$

and:

$$d_{lt,i} = g \cdot C_{tv,i} \tag{8.39}$$

$$C_{tv,i} = C_b + C_{eCAPEX,i} \tag{8.40}$$

$$C_{eCAPEX,i} = c_{ckW,i} \cdot P_{inst} \tag{8.41}$$

$$\tag{8.42}$$

where:

i	Index i specifies each of the different alternative fuels (with their corresponding engine type).
$C_{capital,i}$	Annual capital expenses of vessel employing fuel i.
$C_{purchase,i}$	One-time capital expense for purchase of vessel. Only contains shipowner's equity contribution, not debt.
$C_{interest,i}$	Annual interest expense over the remaining debt portion of vessel employing fuel i.
$C_{principal,i}$	Annual principal payment of vessel employing fuel i. Represents a fixed fraction of the total debt as agreed in the loan agreement. Bullet debt is subtracted as it does not require to be paid in the principal terms, but rather in its whole at the end of the loan term.
$C_{bullet,i}$	Bullet debt to be paid at the end of the agreed loan term.
$C_{dd,i}$	Dry docking expense of vessel employing fuel i at the end of each dry dock interval.
$C_{ss,i}$	Special survey expense of vessel employing fuel i at the end of each special survey interval.
C_{scrap}	Scrapping income received upon the end of the vessel's lifetime.
$d_{lt,i}$	Total long-term debt of vessel employing fuel i.
i_{rate}	Interest rate on debt.
g	Gearing, otherwise named 'debt share' of total vessel cost expressed in %. Represents the percentage of debt the shipowner takes on to finance the total vessel.
$C_{tv,i}$	Cost of total vessel dependent on each fuel type.
C_b	Cost of base vessel. The base vessel is the portion of the total vessel cost excluding engine cost. Base vessel cost is therefore equal for all fuel types.
$C_{eCAPEX,i}$	Engine CAPEX of vessel employing fuel i.
$c_{ckW,i}$	Engine CAPEX per kW of vessel employing fuel i. Expressed in US dollar per kilowatt (\$/kW).
P_{inst}	Installed power on vessel, in kilowatt (kW).
rt	Repayment time for the agreed debt as found in the loan agreement, in years.
b	Bullet portion of debt to be paid at the end of the agreed loan term, in %.
pc_{dd}	Percentage of total vessel cost spent on dry dock at end of dry dock interval.
pc_{ss}	Percentage of total vessel cost spent on special survey at end of special survey interval.
LDT	Vessel lightweight tonnage.
v_{LDT}	Value per lightweight tonnage in \$/LDT.

Escalation factor
In order for the model to be able to account for changes in future cost, the possibility for applying an escalation factor 'ef' is built in. Escalation factors are annual percentage adjustments to how the cost of a certain item develops over the years. Their application is best understood when thinking of inflation, or of technologies that become more affordable with increasing scale. In the current application, the price of alternative fuels is expected to decline with increasing scale of production, while inflation is assumed constant at 2.5% per annum. The resulting formula for determining an arbitrary cost 'C' in year 'Y' is presented below.

$$C_Y = C_{Y-1} \cdot (ef)^{Y-1} \tag{8.43}$$

The above formula is applied to all line items that are subject to inflation and (if desired) additional escalation. These include revenues, port charges, canal dues, and expenses for fuel, crew, stores, repairs, maintenance, lubrication, insurance, administration, dry docking, special survey and scrapping.

Financial indicators
In order to make financial decisions, shipowners commonly resort to a number of financial indicators. In the present thesis, the net present value (NPV), the internal rate of return (IRR) and the required freight rate (RFR) are discussed. The NPV and IRR are general indicators used for judging the attractiveness of a business opportunity or project in a wide variety of applications and industries. The required freight rate is a specific indicator used in the transportation industry. In the present thesis, the 'projects' that are evaluated consist of a container vessel employing different alternative fuels.

The NPV is a method of balancing the current value of all future cash flows generated by a project against the initial capital investment. A positive NPV of a project or investment means that the discounted present value of all future cash flows related to that project or investment will be positive, and therefore attractive. In simpler words, the NPV is the difference between the present value of cash inflows and the present value of cash outflows, including initial investment, over a period of time. The method of converting future cash flows to present cash flows is called discounted cash flow. Discounted cash flow is a component of the net present value calculation. In the DCF, future cash flows are discounted to present cash flows by means of the discount rate 'r'. The discount rate should equal the weighted average cost of capital, or WACC. The WACC is the discount rate that should be used for cash flows with a risk that is similar to that of the overall firm [95]. The term discount rate in investments is often used interchangeably with 'opportunity cost'. Equations 8.44 and 8.45 demonstrate how the NPV is calculated, and which portion of this calculation consists of the discounted cash flow [94].

$$NPV = \sum_{Y=1}^{lt} DCF_Y \tag{8.44}$$

$$DCF_Y = \frac{CF_Y}{(1+r)^Y} \tag{8.45}$$

where:

lt	Vessel lifetime.
CF_Y	Cash flow in year Y.
r	Discount rate r represents the interest rate used to discount any future value to its present value.

The internal rate of return (IRR) is a second indicator shipowners use to evaluate the attractiveness of a business opportunity. In terms of return, the IRR represents the percentage rate earned on each dollar invested for each period it is invested (in this case, years Y). Therefore, a project is attractive and adds value if the internal rate of return is higher than the discount rate, and becomes unattractive when the IRR is lower than the discount rate. On a lower IRR, the shipowner might just as well choose to invest in a higher yielding opportunity elsewhere.

The IRR represents the interest rate at which the net present value of all future cash flows equal to zero. The IRR is thus determined by back-solving equation 8.46 for 'IRR'.

$$0 = \sum_{Y=1}^{lt} \frac{CF_Y}{(1+IRR)^Y} \tag{8.46}$$

The required freight rate is a common financial indicator in commercial shipping. The required freight rate is the freight rate that must be obtained so that all expenses are covered, with a remainder sufficient for the returns on investment [30]. As David Watson defines in Practical Ship Design (1998) [164]: "The required freight rate (RFR) is that which will produce a zero NPV, i.e. the break-even rate". In the present thesis, the required freight rate is expressed in '$\$/TEU-mile$'. The general formula for calculating the required freight rate as defined in Watson [164] is as follows:

$$RFR = \sum_{Y=1}^{N} \left[\frac{\text{NPV (Operating costs + Ship acquisition costs)}}{\text{Cargo tonnage}} \right] \tag{8.47}$$

Watson's formula for the required freight rate is subsequently adapted for the specific use case of the present thesis, being a container vessel transporting TEUs:

$$RFR_i = \frac{\sum_{Y=1}^{lt} \left[\frac{C_{voyage,i} + C_{running,i} + C_{capital,i}}{(1+r)^Y} \right]}{\sum_{Y=1}^{lt} \left[TEU_{annual,i} \cdot d_{annual,i} \right]} \tag{8.48}$$

where:

i	Index i specifies each of the different alternative fuels (with their corresponding engine type).
RFR_i	Required freight rate per TEU-mile, in $\$/TEU-mile$.
$C_{voyage,i}$	Annual voyage expenses of vessel employing fuel i.
$C_{running,i}$	Annual running expenses of vessel employing fuel i.
$C_{capital,i}$	Annual capital expenses of vessel employing fuel i.
r	Discount rate r represents the interest rate used to discount any future value to its present value.
$TEU_{annual,i}$	Average annual TEU transported by fuel type.
$d_{annual,i}$	Average annual distance sailed by fuel type, in nautical miles.
lt	Vessel lifetime, in years Y.

8.3. Economic speed optimisation

In order to minimise costs, shipowners are recommended to optimise their vessel's cruising speed to the optimal economic speed. The optimal economic speed is the speed at which a vessel employing fuel 'i' demands the lowest required freight rate to meet the shipowner's target return on investment. In the present model, the optimal economic vessel speed for a vessel employing fuel 'i' is determined by a non-linear optimisation model that aims to minimise required freight rate (RFR) by adjusting vessel cruising speed. Therefore, in this optimisation, the objective is to minimise required freight rate 'RFR_i' by changing cruising speed, subject to constraints of the cruising speed being greater than

'v_{min}' and smaller than the maximum cruising speed at loaded condition 'v_{load}'. The minimum vessel speed is constrained due to the minimum required engine running load [114]. The maximum cruising speed at loaded condition is constrained by the engine's operating limits and sea margin. The decision variable is constrained to be non-negative. The conceptual notations and descriptions of the speed optimisation model are presented in table 8.9.

Notations	Descriptions
Index	
$\mathscr{F}$	Set of alternative fuels i, $i = 1,\ldots,n; n = \lvert\mathscr{F}\rvert$
Parameters	
RFR_i	Required freight rate per TEU-mile for vessel employing fuel i
v_{load}	Maximum vessel speed in loaded condition
v_{min}	Minimum vessel speed in loaded condition
Decision variable	
vc_i	Optimal economic vessel cruising speed for vessel employing fuel i

Table 8.9: Notations and descriptions for speed optimisation model.

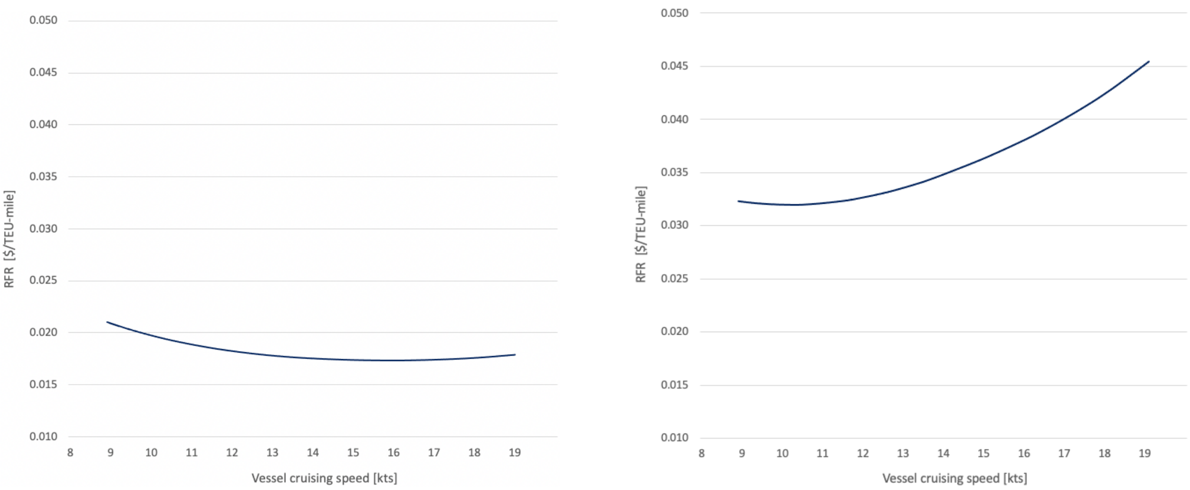
The optimisation model is thus described by:

$$\textbf{minimise:} \quad RFR_i \tag{8.49}$$

$$\textbf{subject to:} \quad v_{load} \geq vc_i \geq v_{min} \qquad \forall i \in \mathscr{F} \tag{8.50}$$

$$vc_i \geq 0 \qquad \forall i \in \mathscr{F} \tag{8.51}$$

The calculation method for the required freight rate is described by the modified Watson's formula (8.48) found in section 8.2 [164]. By varying vessel speed, not only cost parameters such as fuel cost, emission cost, port charges and canal dues are influenced on an annual basis, but also other parameters such as annual distance sailed and TEU transported. The resulting non-linear relationship between vessel cruising speed and required freight rate is different for each vessel employing fuel i due to each alternative's different cost structure. An example of the relationship between required freight rate and vessel speed for both HFO and ammonia (NH3) is demonstrated in figure 8.16. HFO is selected as the base case to compare to ammonia, which is the most expensive of the investigated fuel alternatives.



(a) HFO with scrubbers.

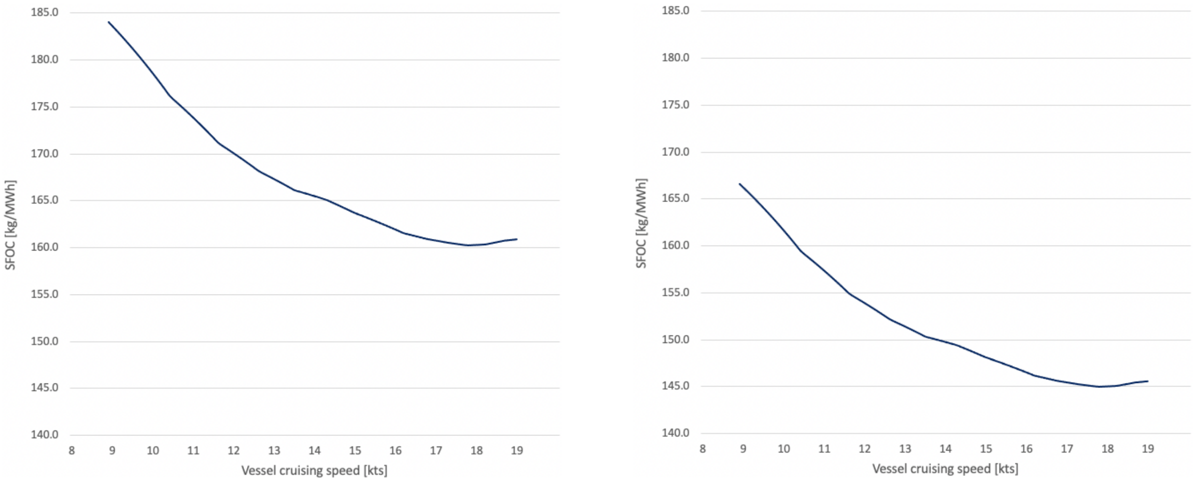
(b) Ammonia.

Figure 8.16: Example of the RFR-speed curve under the average, 2020, unregulated scenario.

From figure 8.16, a number of interesting observations can be made. Firstly, as is evident in both figures 8.16a and 8.16b, required freight rate is only calculated for cruising speeds above and below approximately 9 and 19 knots, respectively. These speeds have been determined to be 'v_{min}' and 'v_{load}': the minimum speed at which the vessel is able to sail in loaded condition (at 10% engine load), and the maximum speed at which the vessel can sail while accounting for the engine's nominal continuous rating (NCR = 85% SMCR) and sea margin.

Additionally, in the case of HFO, the required freight rate can be observed to be slightly elevated at the lower speed range. This can be attributed to the fact that by excessively slow steaming, it is more difficult to generate sufficient revenues (or transporting sufficient TEU-mile) to cover fuel costs and generate desirable returns. As sailing speed increases, in the case of HFO, the RFR-speed curve flattens and required freight rate decreases. This observation can be attributed to the increase of annual TEU-mile transported at lower marginal cost. On the other hand, in the case of ammonia (an expensive fuel), one finds that the required freight rate significantly increases with increasing speed. The conclusion that can be drawn from this observation is that for expensive fuels, the increase in annual TEU-mile transported due to sailing at high speed does not compensate for the associated marginal cost. It should not be forgotten that although the RFR-speed relationship demonstrated in figures 8.16a and 8.16b is primarily dependent on fuel cost and TEU-mile transported, it also depends on other voyage expenses such as emission costs, port charges and canal dues.

In figure 8.17a and 8.17b, the SFOC-speed relationship is demonstrated for both diesel and dual-fuel engines respectively. All diesel-like fuels are assumed to be employed by marine diesel engines, while LNG and liquefied bio-methane (LBM) are assumed to be employed by dual-fuel engines. As is demonstrated in figure 8.17 the present model assumes that dual-fuel engines show a 9.5% higher fuel efficiency compared to their diesel counterpart [163].



(a) Marine diesel engine.

(b) Dual-fuel engine.

Figure 8.17: SFOC-speed relationship for both marine diesel and dual-fuel engines. Own composition based on Sarker (2010), Man Diesel & Turbo (2020) and Wartsila (2017) [114, 140, 163].

8.4. Scenarios

In this section, the impact of scenarios and method of scenarios implementation in the decision tool is elaborated. As shown in table 8.1, each scenario has its own distinct impact on the decision tool. The methods with which scenarios are implemented in the decision tool and the parameters that are influenced are summarised in the following paragraphs.

For the 'sentiment' scenarios, the impact on each of the models is dependent on the range of data that has been collected. For each of the criteria mentioned in table 8.10 that are impacted by the optimistic, average or pessimistic scenario, a lower bound (LB), average (AVG) and upper bound (UB) value is chosen. These so-called 'bounds' are the maximum or minimum values for each criterion that are determined during the literature study.

For the 2020, 2030 and 2050 time scenarios, two types of criteria are varied. These criteria include fuel cost and technical relevance level (TRL). In the 2020 time scenario, the base case for both fuel cost and TRL are assumed. In the 2030 scenario, HFO and LNG fuel cost is varied by -10% in the lower bound and +10% in the upper bound. For the other ('new') fuels, fuel cost is varied by -20% in the lower bound and 0% in the upper bound compared to 2020 levels. In the 2050 scenario, HFO and LNG fuel cost is varied by -20% in the lower bound and +20% in the upper bound. 'New' fuels are varied by -40% in the lower bound and -20% in the upper bound compared to 2020 levels.

In the case of mature fuels such as HFO and LNG, price variances are applied to current fuel prices due to a degree of price uncertainty over time. For the newer fuels, lower fuel prices are expected over time due to efficiencies achieved by economies of scale. The applied variances are chosen as test assumptions. In section 9.5, a sensitivity analysis is performed on fuel price to determine its influence over time on financial outputs such as required freight rate (RFR).

As for the technical relevance level (TRL), the level is expected to increase over time following developments in each respective fuel technology. In 2030, the current TRL (lower, average, and upper bound where applicable) is expected to increase by two points. In 2050, as two decades will have passed, TRL is expected to increase by 6 points. These figures are based on the assumption that developments in these fuel technologies will continue to progress at a moderate pace, as no clear winner has yet been chosen by shipowners, fuel producers and engine manufacturers. In the case that the industry decides on a preferred fuel alternative, TRL is expected to increase at a much higher pace. In that case, shipowners can adjust the assumptions in the model to reflect their views.

At last, the impact of regulatory scenarios on the general feasibility of fuels is studied as well as on the GHG emission cost. In the 'no (additional) regulation' (NR) scenario, the base case for all fuels is assumed. Under market-based measures (MBM), a bunker levy per emitted annual ton CO_2 is charged to shipowners. However, this levy only impacts the selected fossil fuels (HFO and LNG). As agreed under the Kyoto Protocol, the emission factor for biomass is always zero [125]. This is because CO_2 emissions are measured over the bio-fuels' life-cycle, where the growth of the feedstock has absorbed an equal amount of CO_2 from the air. Therefore, the net tank-to-propeller emissions of bio-fuels are zero. In the case of ammonia, the bunker levy does not apply since ammonia combustion does not emit any detrimental greenhouse gases apart from fossil pilot fuel. Due to the very low consumption of pilot fuel or the option to opt for a bio-fuel alternative, this levy is assumed negligible. Nevertheless, in practice, fossil pilot fuel used for ammonia combustion is expected to be levied. For the 'emission cap' (EC) scenario, a feasibility check is performed on all alternatives. If an alternative fails to comply with the emission cap of emitting less than 50% tank-to-propeller GHG emissions per MJ energy compared to 2008 levels, it is deemed infeasible. This measure impacts HFO and LNG, which both fail to deliver the desired 50% GHG emission reductions. More information on the chosen regulatory scenarios can be found in chapter 3. In table 8.10, an overview of all considered scenarios and their impact on the respective model is presented.

Category	*Scenario*	*Impact*									
		General feasibility	GHG emission cost	Fuel cost: HFO, LNG	Fuel cost: new fuels	Engine CAPEX	Engine OPEX	GHG em.: WTT	GHG em.: TTP	Fuel energy density	TRL
	Optimistic			*LB*	*LB*	*LB*	*LB*	*LB*	*LB*	*UB*	*UB*
Sentiment	Average			*AVG*	*AVG*	*AVG*	*AVG*	*AVG*	*AVG*	*AVG*	*AVG*
	Pessimistic			*UB*	*UB*	*UB*	*UB*	*UB*	*UB*	*LB*	*LB*
	2020										
Time	2030			*-10% to +10%*	*-20% to 0%*						*TRL +2*
	2050			*-20% to +20%*	*-40% to -20%*						*TRL +6*
	NR										
Regulatory	MBM		Bunker levy per ton CO_2								
	EC	<50% GHG emission cap									
Affects SMART:		✓						✓	✓	✓	✓
Affects fin. model:		✓	✓	✓	✓	✓	✓				

Table 8.10: Overview of sentiment, time and regulatory scenarios and their impact on the respective model.

8.5. KPIs

To answer research objective four:

> *Devise a decision support tool which is able to:*
> *a. Rank optimal fuel choices under different regulatory scenarios and*
> *b. Assist shipowners in making substantiated future decisions regarding alternative fuel technologies.*

it is necessary to determine the KPIs that define *optimal*. In the current thesis, two mechanisms have been devised to define and rank the performance of a fuel compared to its peers: the simple multi-attribute rating technique (SMART) decision model, which is based on the relative evaluation factors received by each fuel on nine criteria, and the required freight rate (RFR), which is based on financial modelling of the discounted cash flow of a container vessel and the annual distance sailed and TEU transported. An overview of the specific criteria and (financial) items these methods take into account is presented in table 8.11.

Category	Evaluation criteria
Technical	Technological maturity
	Availability of infrastructure
	Engine compatibility
	Fuel volumetric energy density
Environmental	Compliance with emission regulations
	GHG emissions: well-to-tank
	GHG emissions: tank-to-propeller
Other	Safety of fuel technology
	Long-term global availability of fuel
	Feedstock competition with food

Category	Item	Fuel-dependent
Revenues	Operating revenues	✓
Voyage expenses	Port charges	✓
	Canal dues	✓
	Fuel	✓
	GHG emissions	✓
Running expenses	Crew	✓
	Stores	
	R&m: hull & auxiliary	
	Engine OPEX	✓
	Insurance	✓
	Administration	✓
Capital expenses	Base vessel: equity	✓
	Engine CAPEX	✓
	Financial cost: interest	✓
	Financial cost: principal	✓
	Financial cost: bullet	✓
	Dry dock	✓
	Special survey	✓
	Scrapping (income)	
Other	Discount rate	
	Annual distance sailed	✓
	Annual TEU transported	✓

Table 8.11: Left: Evaluation criteria taken into account to produce SMART total scores and ranking. Right: Financial items taken into account to produce net present value (NPV) for each fuel. Fuel-dependent items carry different values for each fuel type.

SMART ranking

As explained in section 8.2.1, the SMART decision model produces an output score between 0.00 - 1.00, where the highest score represents the most favourable alternative under the chosen criteria. Following this, each of the alternatives is ranked in order of preference according to its score: from 1 for the highest-ranking alternative to 9 for the lowest ranking alternative. However, boundary conditions apply under different regulatory scenarios. Therefore, when an alternative does not satisfy regulatory requirements, it is assumed infeasible and eliminated from the ranking.

Required freight rate (RFR)

As explained in section 8.2.2, the required freight rate is a unified measure with which different alternatives can be compared to one another. The required freight rate is defined as the freight rate in USD per TEU-mile[4] required for the container vessel to return a positive net present value. In other words, the required freight rate is the minimum freight rate a (container) vessel needs to earn to make its operation attractive. According to the shipowner's personal insights, he or she might choose to proceed with a project depending on their expected freight rate and the required freight rate calculated by the decision tool. The RFR is found to be a more attractive indicator than the NPV or IRR due to its expression in '$\$/TEU - mile$'. By normalising the earnings per TEU-mile, shipowners can better compare returns and required freight rates with their current performance, as well as among the considered alternatives in the present thesis. As is also the case for the SMART ranking, required freight rates are not calculated when regulatory requirements are not met by the selected fuel alternatives.

In conclusion, the SMART ranking and required freight rate are chosen as the two KPIs due to the amount of information they are able to provide to the shipowner about the *optimal* choice of fuel alternative. Under the different time-frames, regulatory scenarios and optimistic, average and pessimistic scenarios, these indicators provide the shipowner with valuable information on the optimal choice regarding technical, environmental and other criteria, as well as financial criteria. In addition,

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[4] The required freight rate is defined as the freight rate per TEU-mile after cargo handling and terminal operating costs '$chtoc_{\%}$'. More information regarding cargo handling and terminal operating cost costs is provided in section 8.2.2.

all other relevant indicators such as the individual SMART output scores, cost specifications for each financial line item, NPVs, IRRs and optimal economic sailing speed can be found in the output tab of the decision tool. It is eventually up to the shipowners to decide which of the outputs are most important to them. The general results, economic speeds and a sensitivity analysis are discussed in chapter 9.

8.6. Model verification

Sections 8.2, 9.4 and 8.4 have presented the methodology behind the creation of the presented decision tool. In these sections, a considerable number of implementation steps are described. As with any model, implementing allows for significant possibilities of human error. Therefore, it is important to verify the decision tool and the related models to ensure correct implementation. Since the decision tool can not be compared to any known benchmark (as far as known no similar tools or models exist on this subject with the same scope), it is verified in parts. When verifying in parts, different model components with known relationships between in- and output are isolated and tested. When this is performed systematically for all components of a model, a model can be considered verified. To achieve this, the following methods are deployed:

- *Structured walkthroughs*
  The model is carefully and thoroughly inspected by following all input parameters through all calculations steps to the resulting outputs.
- *Balance checks*
  Balance checks are completed by performing isolated or simplified calculations of parameters and benchmarking them against model values.
- *Testing of extreme conditions*
  The model's performance and robustness are tested under extreme conditions by evaluating outputs for extreme inputs.

8.6.1. Structured walkthroughs

During the structured walkthroughs, each alternative fuel is inspected by following the calculation steps from each input to final output. Special care has been taken when reviewing LNG, liquefied bio-methane and ammonia. In the case of LNG and LBM, this was due to the differences in dual-fuel engine efficiency and resulting lower fuel consumption, as well as lower vessel capacity due to the larger volume requirement for tank installations. For ammonia, special care was taken when reviewing vessel capacity due to the larger tank volume requirement. For all alternative fuels, inputs and outputs, the walkthroughs did not generate any surprises.

8.6.2. Balance checks

During the balance checks, simple, isolated calculations are performed with parameters and benchmarked against model values. If large errors occur, this might point to inaccuracies in the model implementation. In table 8.12, an overview is provided of performed balance checks and the corresponding errors.

Balance check	Description	Max. error	Verified
Fuel consumption	Fuel consumption represents a reasonable portion of voyage expenses	-	✓
Utilisation	Average vessel utilisation corresponds to industry standard	-	✓
Economic vessel speed	Economic vessel speed falls within reasonable margins of design speed	-	✓
Voyage expenses	Sum of individual voyage expenses matches to total voyage expenses	0.0%	✓
Running expenses	Sum of individual running expenses matches to total running expenses	0.0%	✓
Capital expenses	Sum of individual capital expenses matches to total capital expenses	0.0%	✓
Emissions	Total emission cost corresponds to total emission output	0.0%	✓
Cash-flows	Sum of individual cash flows matches to total cash flows	0.0%	✓

Table 8.12: Balance checks to verify outputs and intermediate calculated values.

Looking at charter specifications, balance checks are carried out on fuel consumption, utilisation and economic vessel speed. For fuel consumption, the cost share of fuel in total voyage expenses is compared to industry standards. For HFO and LNG, this share is approximately 60%, similar to the industry standard according to Mazraati (2011) and Bergqvist (2015) [25, 115]. Furthermore, average vessel utilisation is calculated at approximately 60-62% for all fuel alternatives, which aligns with industry standards according to experts. Looking at the speed optimisation model, optimised economic vessel speed is observed to be calculated within reasonable margins of design speed for fuels with conventional fuel prices (HFO, LNG). For more expensive alternative fuels, optimal economic vessel speed is observed to be lower, as expected. At last, concerning cash-flow balance checks, simplified manual calculations do not report any discrepancies with modelled expenses. In conclusion, the presented balance checks verify the described calculations successfully.

8.6.3. Extreme conditions

By testing the model under extreme conditions, its robustness is verified. In this thesis, extreme conditions are evaluated under section 9.5, where a sensitivity analysis is performed on SFOC & fuel cost, vessel speed, and interest rate. Under all aforementioned conditions, the model performs as expected. Table 8.13 demonstrates the lower and higher bounds of the examined parameters. The performed sensitivity analysis is elaborated in more detail in section 9.5.

Test parameter	Lower bound	Higher bound	Verified
SFOC & fuel cost	-50%	+50%	✓
Vessel speed	9.1 kts	18.9 kts	✓
Interest rate	0%	15%	✓

Table 8.13: Verification of extreme conditions.

8.6.4. Logical interpretation of results

By interpreting results and testing them against logic, significant discrepancies can potentially be noticed. Although this method could be argued to allow room for bias, it offers an uncomplicated opportunity for the model to be challenged from a logical perspective. In sections 9.3 and 9.4, the generated results and their interpretations are further elaborated. In the present decision tool, results were not found to deviate from logical expectations.

8.7. Model validation

Although the outcomes of the present decision tool can not be compared to real life results due to the hypothetical nature of this research, input validation can still be performed. Input validation is a form of partial validation where the accuracy of inputs is determined. In this process, there is no one-size-fits-all technique. The method with which input validation is approached depends on multiple facets, including:

- The complexity of inputs
- The reliability of sources
- The degree of manual manipulation of inputs from source to model input
- The relative importance of input to the model's output (overlaps with sensitivity)

When considering the complexity of model inputs and assumptions, the greater the complexity, the greater the risk of errors. For example, by aggregating inputs such as the power-SFOC data table provided by MAN Diesel & Turbo [114] with the power-speed curve generated by a model devised by Prof. Koos Frouws (TU Delft) based on the Hollenbach Method, the model will be inherently subject to more risk of inaccuracy compared to binary inputs such as "0" to "1". In general, the more complex an input is, the more profound its sources require to be reviewed to verify its origin and reliability. Validating complex model inputs can be performed by comparing partial model inputs to the corresponding partial source outputs, thus ensuring that each computation in the input of the model corresponds to the partial results of the source model.

Additionally, the degree of manual manipulation of inputs from source to model increases the risk of inaccuracy. For instance, converting source data units of measurement to fit the desired model input units attains more risk than simply copy-pasting data in the correct input units. The most simple method of validating manual operations is by increasing sample size. Therefore, it is wise to individually repeat manual operations from source to manipulation to input to detect and eliminate any potential inaccuracies.

Finally, it is important to recognise and differentiate between inputs with significant impact on model outputs, and inputs with minimal influence. For the inputs which are expected to have a significant impact on model outputs, a sensitivity analysis can be performed. Extreme values (such as minimums or maximums) can then be compared with expected logical values to partially validate the model. An example of such form of validation would be that a modelled vessel with vessel speed zero does not incur any voyage costs.

At last, through presenting models, calculations and intermediate steps to industry experts, results are verified against their industry knowledge.

Although the process of input validation does not provide guarantees for a completely validated model, it does significantly reduce risk by internally auditing inputs. The present model has successfully been partially validated by the method of input validation.

9

Results

This chapter presents the case study and the results of the devised decision tool. The aim of this chapter is to achieve the fifth research objective:

> *By conducting a case study, determine the most appropriate fuel alternatives under different regulatory scenarios while ensuring optimal business performance.*

First, the case study vessel and decision tool inputs are presented in sections 9.1 and 9.2. Thereafter, section 9.3 presents the general results of the evaluated case study. In section 9.4, the optimal economic speed for each fuel alternative under each different regulatory scenario is evaluated. At last, in section 9.5, a sensitivity analysis is conducted on several parameters to demonstrate their impact on the results of the decision tool. All mentioned results originate from output generated by the decision tool.

9.1. Case study vessel

As is briefly mentioned in chapter 2, the present decision tool is built around a fictional vessel. The vessel in question is defined as a 13,500 TEU New-Panamax container liner operating on a round the world sailing route. Therefore, it is categorised as a deep-sea vessel and limited to the sizing of the New Panama canal. Inspired by the engine configuration of the COSCO Shipping Azalea, the container liner in the present model is equipped with a 49.920 kW marine diesel engine and a 10m fixed pitch propeller. The exact dimensions, configuration and other relevant vessel specifications are summarised in table 9.1.

Specification	Value	Unit	Source
Vessel name	CV Sifnos		
Vessel type	Container		
Class	New Panamax		
Operation area	Deep sea		
Installed power	49920	kW	MAN Diesel & Turbo
Engine speed at 100% SMCR	84	rpm	MAN Diesel & Turbo
Propeller diameter	10.0	m	MAN Diesel & Turbo
Length overall	366	m	COSCO Azalea
Beam	48	m	COSCO Azalea
Molded draught	16.0	m	COSCO Azalea
Ballast draught	10.7	m	Hollenbach
Depth	22.9	m	COSCO Azalea
Deadweight	145,000	t	COSCO Azalea
Gross tonnage	143,197	t	COSCO Azalea
Lightweight	51,750	t	Regression [113]
TEU capacity base	13,500	TEU	COSCO Azalea
Crew	20	pax	Estimated
Max. ballast speed	19.9	kts	Hollenbach [111]
Max. loaded speed	18.9	kts	Hollenbach [111]
Min. loaded speed	9.1	kts	Hollenbach [111]

Table 9.1: Case study vessel specifications.

9.2. Decision tool input

To run the decision tool, the shipowner is required to provide inputs. For the case study, a set of example inputs has been devised. As is elaborated in section 8.1, required inputs are displayed in yellow cells. In addition to the vessel specifications mentioned in table 9.1, shipowners are required to provide operational and financial inputs.

9.2.1. Operational input

In table 9.2, an overview of the operational case study inputs is provided. For the dry dock and special survey interval, it is assumed that the case study vessel is compliant with SOLAS (1974) regulations and follows the normal dry docking interval schedule[1] every 5 years [88]. Special survey is carried out concurrently. Broker commission for both time- and voyage charters is set at 1.5%, a general industry standard. Cargo handling and terminal operating cost revenue share is set at 60%, as suggested by Martin Stopford in Maritime Economics (2013) [150]. Time spent loading and discharging at full capacity are established at 36 and 24 hours on average respectively, following rules of thumb in Maritime Economics (2013) and suggestions by E. van Hassel (TU Delft, UAntwerpen). The fraction of additional power required for auxiliary equipment is set at an average of 5% of propulsion power and assumed to be produced by the vessel's main engine following guidelines in Maritime Economics (2013) [150].

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[1] Additional options such as extended dry docking periods are available. However, a variety of complex factors are taken into consideration before approving a ship for extended dry-docking. Therefore, for this case study, the normal dry docking interval schedule is maintained.

Operational input	Value	Unit	Source
Dd & ss interval	5	years	SOLAS [88]
Dd & ss duraton	16	days	Bimco estimate
Broker commission	1.50	%	Industry std.
Cargo handling and terminal op. cost %	60	%	Stopford (2013) [150]
Time loading at full utilisation	36	hours	Stopford (2013) [150]
Time discharging at full utilisation	24	hours	Stopford (2013) [150]
Additional auxiliary power requirement	5	%	Stopford (2013) [150]

Table 9.2: Case study operational input.

9.2.2. Charter specifications

Table 9.3 provides an overview of the charter specification inputs required to generate a revenue model. In the case study, a round the world liner route is considered which starts and ends in Shanghai, China. The case study vessel is assumed to continuously repeat this cycle during the year. For each route, sailing distance is calculated with assistance from SEAROUTES and average TEU utilisation and FCL freight rates are estimated and checked alongside spot rates [142]. Figure 9.1 illustrates the modelled liner route.

Origin port	Origin country	Destination port	Destination country	Distance (nm)	Utilisation (TEU)	FCL freight rate ($/TEU)
Shanghai	CN	Rotterdam	NL	11,999	13,000	810
Rotterdam	NL	New York	USA	3,918	12,500	390
New York	USA	Los Angeles	USA	5,734	6,000	600
Los Angeles	USA	Nagoya	JP	4,988	4,000	530
Nagoya	JP	Shanghai	CN	1,007	6,200	305

Table 9.3: Case study charter specifications.

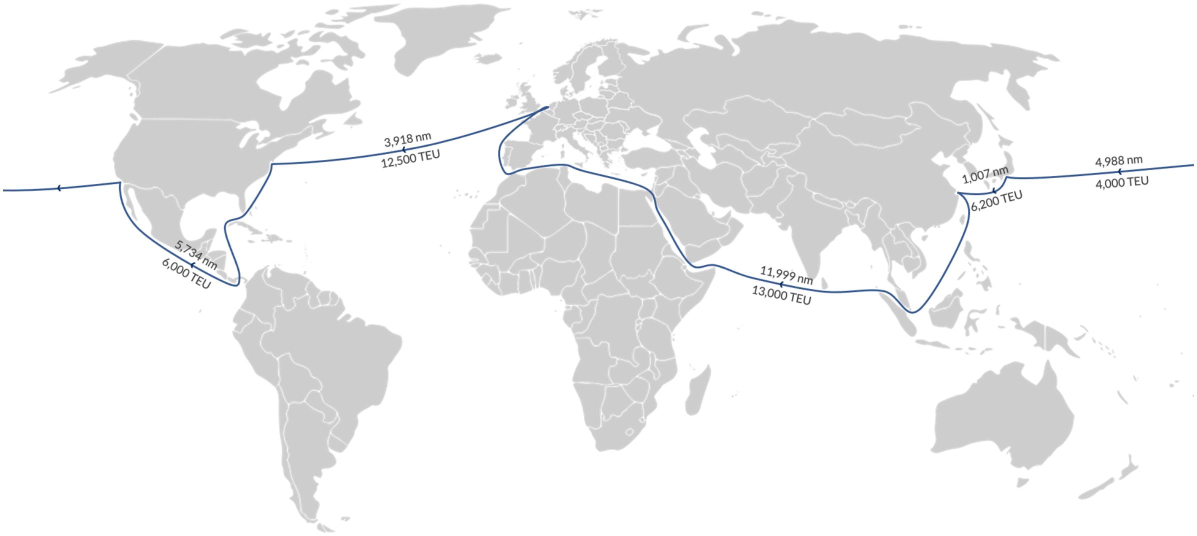


Figure 9.1: Case study liner route. Own composition

9.2.3. Financial input

An overview of the financial case study input is provided in table 9.4. The USD/EUR exchange rate is set at the July 2020 rate: 1.17 $/EUR. The case study vessel's base case purchase price is determined at $116.8 million, equal to the reported purchase price of COSCO Azalea as reported by Clarksons Research Container Intelligence (2020) [43]. The equity share contributed by the shipowner and the corresponding gearing provided by the bank is set at 20% and 80% respectively, an industry standard [150]. The bullet percentage share of debt that is to be repaid at the end of the loan term is set at 10%, a percentage commonly used in the shipping industry. Interest rate is set at 7.5%, which corresponds to current shipping interest rates according to industry experts and Maritime Economics (2013) [150]. The discount rate, representing the risk of the overall firm sits at 8%. Finally, a CO_2 cost of $25 per ton is assumed based on the cost of European CO_2 Emission Allowances.

Financial input	Value	Unit	Source
EUR/USD exchange rate	1.17	per USD	As of July 2020
Base case vessel purchase price	116.8	$m	Clarksons Research (2020) [43]
Equity share	20	%	Stopford (2013) [150]
Gearing	80	%	Stopford (2013) [150]
Bullet % of debt share	10	%	Stopford (2013) [150]
Interest rate	7.5	%	Stopford (2013) [150]
Discount rate	8	%	Industry experts
European CO_2 Emission Allowance cost	25	$/ton	Business Insider (2020) [34]

Table 9.4: Case study financial input.

9.3. General results

According to SMART ranking, Fischer-Tropsch diesel (FTD) scores highest in all sentiment, time and regulatory scenarios. This can be attributed to the fuel's good overall score on most parameters with remarkably high scores in technology readiness level (TRL), GHG emissions and volumetric energy density. In terms of cost, as can be observed in table 9.6, FTD performs slightly below average. However, the cost differences compared to other alternatives are not extensive. In fact, on average, Fischer-Tropsch diesel's required freight rate is only 3% higher compared to UBO which ranks third in the SMART model, and even 10% lower compared to LBM, which ranks second. Therefore, if shipowners value the SMART ranking of Fischer-Tropsch diesel more than the 3% cost markup, FTD deserves a solid overall preference.

If, on the other hand, shipowners do believe that a lower required freight rate could significantly benefit their business at the cost of slightly lower SMART performance, upgraded bio-oil (UBO) represents a good choice of alternative fuel. Regarding SMART performance, UBO ranks third on the list, only lagging slightly behind LBM due to its relatively low technological maturity. However, UBO outperforms LBM in energy density and safety. As is observed from the optimistic 2050 scenarios, if the technology readiness level of UBO increases, it is even preferred to liquefied bio-methane.

Noticeably, while being the second most expensive alternative (ammonia is the most expensive by a relatively large difference), LBM scores second on SMART ranking under most scenarios. It precedes Fischer-Tropsch diesel in TRL, but lags behind in terms of safety, GHG emissions and energy density. Under the optimistic 2050 scenarios, LBM gives up its second place to upgraded bio-oil (UBO) and upgraded pyrolysis oil (UPO), both upgraded bio-mass products. Nevertheless, if the high price is overcome (perhaps by financial support from governments or international organisations), LBM could be a promising drop-in fuel for LNG, which is currently gaining popularity as an alternative to HFO. A transition period where LBM is blended with LNG in increasing proportions would give time to fuel producers and researchers to further increase production efficiency and reduce cost.

An overview of the percentage difference in required freight rate of UBO, FTD and LBM compared to HFO is provided in table 9.5.

Alt.	Result	Reg.	2020			2030			2050		
			O	*A*	*P*	*O*	*A*	*P*	*O*	*A*	*P*
$\frac{UBO}{HFO}-1$	ΔRFR	*NR*	25%	47%	64%	20%	43%	59%	14%	32%	43%
		MBM	21%	42%	59%	16%	39%	55%	9%	28%	39%
		EC	-	-	-	-	-	-	-	-	-
$\frac{FTD}{HFO}-1$	ΔRFR	*NR*	25%	52%	72%	21%	49%	67%	14%	37%	50%
		MBM	21%	47%	67%	16%	44%	63%	10%	32%	46%
		EC	-	-	-	-	-	-	-	-	-
$\frac{LBM}{HFO}-1$	ΔRFR	*NR*	39%	68%	90%	34%	65%	85%	27%	52%	66%
		MBM	34%	63%	84%	29%	60%	80%	22%	47%	62%
		EC	-	-	-	-	-	-	-	-	-

Table 9.5: Percentage difference in required freight rate of UBO, FTD and LBM compared to HFO in all scenarios.

Regarding upgraded pyrolysis oil (UPO), its SMART performance is similar to that of UBO and HFO. When comparing UPO to HFO, HFO scores higher on well-to-tank GHG emissions, energy density and TRL, and UPO scores higher on compliance with emission regulations, GHG emissions and long term global availability. Evidently, these criteria are likely to become more important in the future.

Comparing UPO to UBO, the main differences are technological maturity (developments in commercial production of UPO slightly exceed those of UBO) and well-to-tank GHG emissions (UPO production generates more than 50% higher GHG emissions compared to UBO). Although technological maturity plays an important role in choosing an alternative maritime fuel for the future, the current development gap of TRL 1 can easily be overcome. On the contrary, GHG emissions of industrial production processes are expected to play an increasingly important role in future technological and regulatory developments. In terms of cost, sailing on UBO bears on average 39% and 34% more cost compared to HFO under the no regulation and market-based measures regulatory scenarios, respectively. For UPO, the difference is smaller at 36% and 32%, respectively. As can be observed from table 9.6, the average cost difference of both UBO and UPO compared to HFO decreases under the selected time scenarios as the alternative fuels benefit from cost advantages due to scale.

Furthermore, although LNG scores noticeably poor on SMART ranking, a substantial uptake in LNG as propulsion fuel is observed in the past decade. Apart from LNG carriers using boil-off gas from their LNG tanks, approximately 400 vessels are being ordered or in service as of March 2020 [117]. Although LNG is a controversial fuel due to its (according to critics) low GHG benefits, it does provide a reasonable short-term solution until more sustainable fuels are developed to scale [129]. In the decision tool, LNG primarily under performs in terms of long-term global availability, GHG emissions and energy density. Nevertheless, its low cost, slightly improved emission performance compared to HFO, and the technology's maturity has attracted the interest of shipowners in the past years. Especially the value of a mature technology should not be underestimated, since successfully mitigating risk is at the core of running a high performing shipping firm.

The remaining results to be discussed are that of FAME, HVO, and ammonia (NH_3). As none of these fuels score exceptionally good in SMART ranking, they are not considered the most promising alternative fuels for the future. FAME, HVO and ammonia generate lower scores in a significant number of criteria, and are not a significantly more economic choice either.

Nevertheless, ammonia remains an interesting alternative to watch due to its exceptional emission performance. Not only does ammonia not emit any greenhouse gasses on combustion, but its production is also highly energy efficient and carries a small carbon footprint. That, along with its wide availability, cause for enthusiasm among researchers. However, as this study intends to demonstrate, practical hurdles can not be overlooked.

On a more general note, three important observations can be made regarding the results presented in table 9.6. First, considering the emission cap (EC) scenario, HFO and LNG are not considered feasible alternative fuels and are thus marked with a dash ’–’. This is due to the fact that the tank-to-propeller GHG emissions per MJ energy produced by both HFO and LNG exceed the benchmarked emission cap of less than 50% GHG emissions compared to 2008 levels. Therefore, in the emission cap scenario, the SMART ranking of a number of alternative fuels increases.

Additionally, table 9.6 demonstrates the impact of market-based measures (MBM) on required freight rate of each alternative fuel. As can be observed, bio-fuels and ammonia remain unaffected by this scenario. This can be attributed to their nature of producing net-zero GHG emissions. On the contrary, in the case of HFO, market-based measures lead to an average increase in required freight rate of 3.4%. For LNG, market-based measures lead to an average increase in RFR of 4.1%. Although these cost increases do not provide shipowners with a significant enough financial incentive to transition to (cleaner) alternative fuels, the results prove that the impact of market-based measures is substantial and measurable. This could mean that potentially, in a future where the price of CO_2 emission credits increases, the cost-gap between HFO or LNG and more sustainable alternative fuels can be reduced.

At last, in all fuels, an increase in required freight rate over time is observed. This can be attributed to the implementation and application of different price scenarios, as well as cost escalation over time implemented by an escalation factor ’ef’.

Alt.	Result	Reg.	2020			2030			2050		
			O	*A*	*P*	*O*	*A*	*P*	*O*	*A*	*P*
HFO	*Smart ranking*	*NR*	5	4	4	5	4	4	5	5	5
		MBM	5	4	4	5	4	4	5	5	5
		EC	-	-	-	-	-	-	-	-	-
	RFR	*NR*	0.017	0.017	0.018	0.021	0.022	0.023	0.034	0.037	0.040
		MBM	0.017	0.018	0.018	0.022	0.023	0.024	0.035	0.038	0.041
		EC	-	-	-	-	-	-	-	-	-
LNG	*Smart ranking*	*NR*	7	6	6	7	6	6	7	6	6
		MBM	7	6	6	7	6	6	7	6	6
		EC	-	-	-	-	-	-	-	-	-
	RFR	*NR*	0.018	0.019	0.020	0.023	0.025	0.027	0.036	0.041	0.045
		MBM	0.019	0.020	0.021	0.024	0.026	0.027	0.038	0.043	0.046
		EC	-	-	-	-	-	-	-	-	-
FAME	*Smart ranking*	*NR*	8	8	8	8	8	8	8	8	8
		MBM	8	8	8	8	8	8	8	8	8
		EC	6	6	6	6	6	6	6	6	6
	RFR	*NR*	0.022	0.024	0.025	0.026	0.030	0.033	0.040	0.045	0.050
		MBM	0.022	0.024	0.025	0.026	0.030	0.033	0.040	0.045	0.050
		EC	0.022	0.024	0.025	0.026	0.030	0.033	0.040	0.045	0.050
HVO	*Smart ranking*	*NR*	6	7	7	6	7	7	6	7	7
		MBM	6	7	7	6	7	7	6	7	7
		EC	5	5	5	5	5	5	5	5	5
	RFR	*NR*	0.021	0.025	0.029	0.025	0.032	0.037	0.038	0.049	0.057
		MBM	0.021	0.025	0.029	0.025	0.032	0.037	0.038	0.049	0.057
		EC	0.021	0.025	0.029	0.025	0.032	0.037	0.038	0.049	0.057

Continued on next page

Table 9.6: SMART ranking (1-9) and required freight rate ($/TEU mile) for all alternatives under optimistic (O), average (A), pessimistic scenarios (P), as well as no regulation (NR), market-based measures (MBM), and emission cap (EC) regulatory scenarios in 2020, 2030 and 2050.

Alt.	Result	Reg.	2020			2030			2050		
			O	*A*	*P*	*O*	*A*	*P*	*O*	*A*	*P*
UPO	*Smart ranking*	*NR*	4	5	5	3	5	5	3	3	3
		MBM	4	5	5	3	5	5	3	3	3
		EC	4	4	4	3	4	4	3	3	3
	RFR	*NR*	0.021	0.025	0.028	0.025	0.031	0.036	0.038	0.048	0.056
		MBM	0.021	0.025	0.028	0.025	0.031	0.036	0.038	0.048	0.056
		EC	0.021	0.025	0.028	0.025	0.031	0.036	0.038	0.048	0.056
UBO	*Smart ranking*	*NR*	3	3	3	4	3	3	2	4	4
		MBM	3	3	3	4	3	3	2	4	4
		EC	3	3	3	4	3	3	2	4	4
	RFR	*NR*	0.021	0.025	0.029	0.025	0.032	0.037	0.038	0.049	0.057
		MBM	0.021	0.025	0.029	0.025	0.032	0.037	0.038	0.049	0.057
		EC	0.021	0.025	0.029	0.025	0.032	0.037	0.038	0.049	0.057
FTD	*Smart ranking*	*NR*	1	1	1	1	1	1	1	1	1
		MBM	1	1	1	1	1	1	1	1	1
		EC	1	1	1	1	1	1	1	1	1
	RFR	*NR*	0.021	0.026	0.031	0.025	0.033	0.039	0.039	0.050	0.060
		MBM	0.021	0.026	0.031	0.025	0.033	0.039	0.039	0.050	0.060
		EC	0.021	0.026	0.031	0.025	0.033	0.039	0.039	0.050	0.060
LBM	*Smart ranking*	*NR*	2	2	2	2	2	2	4	2	2
		MBM	2	2	2	2	2	2	4	2	2
		EC	2	2	2	2	2	2	4	2	2
	RFR	*NR*	0.023	0.029	0.034	0.028	0.037	0.043	0.043	0.056	0.066
		MBM	0.023	0.029	0.034	0.028	0.037	0.043	0.043	0.056	0.066
		EC	0.023	0.029	0.034	0.028	0.037	0.043	0.043	0.056	0.066
NH3	*Smart ranking*	*NR*	9	9	9	9	9	9	9	9	9
		MBM	9	9	9	9	9	9	9	9	9
		EC	7	7	7	7	7	7	7	7	7
	RFR	*NR*	0.024	0.032	0.038	0.029	0.040	0.049	0.045	0.062	0.074
		MBM	0.024	0.032	0.038	0.029	0.040	0.049	0.045	0.062	0.074
		EC	0.024	0.032	0.038	0.029	0.040	0.049	0.045	0.062	0.074

Table 9.6: SMART ranking (1-9) and required freight rate ($/TEU mile) for all alternatives under optimistic (O), average (A), pessimistic scenarios (P), as well as no regulation (NR), market-based measures (MBM), and emission cap (EC) regulatory scenarios in 2020, 2030 and 2050 (continued).

In conclusion, as can be observed from table 9.6, alternative fuels are not expected to compete on cost with HFO or LNG. The reality remains that although some alternative fuels are preferred in terms of SMART performance, shipowners do not have the financial freedom to transition towards sustainable alternatives.

However, if governments and international organisations were to incentivise or financially support the uptake of these sustainable alternatives, Fischer-Tropsch diesel (FTD) and upgraded bio-oil (UBO) seem to offer the best balance between SMART performance and cost. In table 9.6, FTD's SMART ranking is 1 across all scenarios, and UBO's SMART ranking ranges from 2-4 depending on the selected time and sentiment scenario. Additionally, as demonstrated in table 9.5, under an optimistic scenario in 2030 or 2050, the differences in required freight rate between FTD and UBO compared to HFO are reasonable.

Under an emission cap scenario, the combination of SMART and RFR places FTD and UBO in a unique position of high preference over other alternatives in terms of both performance and cost. Therefore, FTD and UBO can confidently be entitled the 'most promising' alternative maritime fuels of the future.

9.4. Economic speed

As elaborated in section 8.3, the optimisation model that runs the decision tool to determine the optimal economic speed is constrained by minimum and maximum speeds. The maximum speed is determined at 18.9 knots, limited by the maximum continuous rating for the engine and sea margin. The minimum speed is determined at 9.1 knots, limited by the engine's inability to run below 10% SMCR.

As can be deducted from table 9.7, each alternative has its own specific economic speed which varies per scenario. The difference between each alternative's economic speed can be attributed to different fuel cost, energy density and engine choice. The RFR-speed curve presents the required freight rate of a vessel against its cruising speed and varies per alternative. In figure 9.2, the RFR speed-curves for the optimistic and pessimistic scenario are demonstrated for Fischer-Tropsch diesel (FTD). Comparing the RFR-speed curve of the optimistic and pessimistic scenarios, two key observations can be made: at lower (fuel) cost, the required freight rate drops to lower base levels, and the RFR-speed curve gradient decreases, demonstrating its preference towards higher economic speed. At higher fuel cost, the opposite effect is observed. These observations underpin the results of table 9.7, which show that vessels sailing on more expensive fuels have lower optimal economic speeds, and vessels sailing on cheaper fuels have higher optimal economic speeds. Similar relationships between required freight rate and vessel speed are observed for all alternatives and are further elaborated in section 9.5.2.

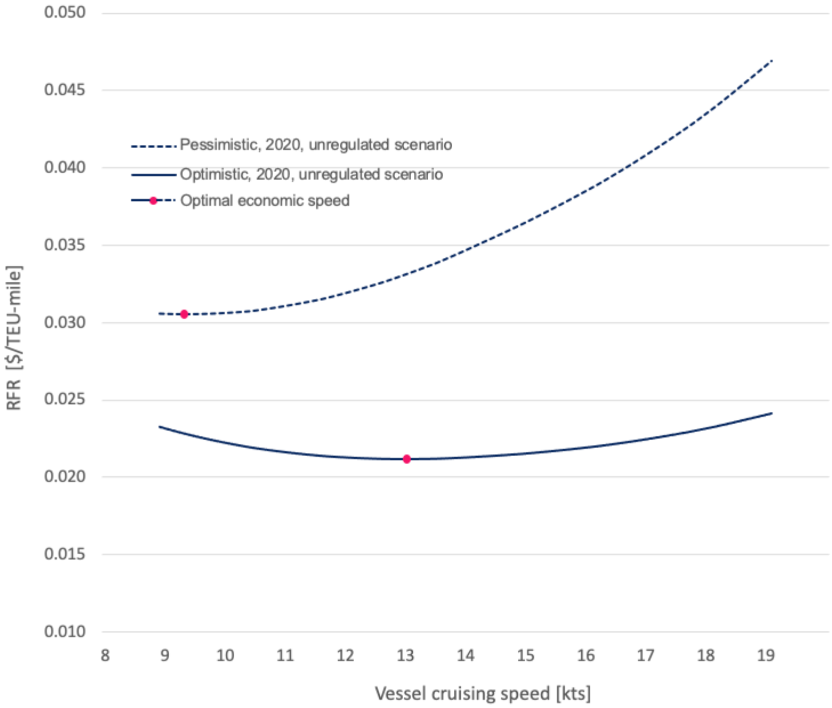


Figure 9.2: RFR-speed curves for Fischer-Tropsch diesel (FTD) in the optimistic and pessimistic 2020, unregulated scenario.

As is evident from both table 9.7 and figure 9.2, the transition towards alternative fuels in the maritime industry will most likely lead to a shift towards lower sailing speeds. Assuming equal transport demand, slow steaming will increasingly be applied to vessels employing expensive alternatives, as the marginal cost when sailing at high speed exceeds the marginal returns from the increase in annual TEU-mile transported.

Alt.	Result	Reg.	2020			2030			2050		
			O	*A*	*P*	*O*	*A*	*P*	*O*	*A*	*P*
HFO	vc_{HFO}	*NR*	16.2	16.0	15.6	16.7	16.0	15.1	17.3	16.1	14.9
		MBM	15.5	15.2	15.0	16.1	15.2	14.6	16.6	15.3	14.2
		EC	-	-	-	-	-	-	-	-	-
LNG	vc_{LNG}	*NR*	18.1	17.2	16.2	17.8	16.4	16.0	18.9	17.1	15.6
		MBM	17.4	16.4	15.7	17.1	15.7	15.3	18.2	16.4	15.0
		EC	-	-	-	-	-	-	-	-	-
FAME	vc_{FAME}	*NR*	12.6	11.7	11.2	13.5	12.1	11.3	15.0	13.2	12.0
		MBM	12.6	11.7	11.2	13.5	12.1	11.3	15.0	13.2	12.0
		EC	12.6	11.7	11.2	13.5	12.1	11.3	15.0	13.2	12.0
HVO	vc_{HVO}	*NR*	13.2	11.1	9.9	14.0	11.4	9.9	15.8	12.2	10.6
		MBM	13.2	11.1	9.9	14.0	11.4	9.9	15.8	12.2	10.6
		EC	13.2	11.1	9.9	14.0	11.4	9.9	15.8	12.2	10.6
UPO	vc_{UPO}	*NR*	13.2	11.3	10.2	14.1	11.6	10.2	15.9	12.5	10.9
		MBM	13.2	11.3	10.2	14.1	11.6	10.2	15.9	12.5	10.9
		EC	13.2	11.3	10.2	14.1	11.6	10.2	15.9	12.5	10.9
UBO	vc_{UBO}	*NR*	13.0	11.1	9.9	13.9	11.4	9.9	15.7	12.3	10.6
		MBM	13.0	11.1	9.9	13.9	11.4	9.9	15.7	12.3	10.6
		EC	13.0	11.1	9.9	13.9	11.4	9.9	15.7	12.3	10.6
FTD	vc_{FTD}	*NR*	13.0	10.6	9.3	13.8	10.9	9.4	15.6	11.7	10.4
		MBM	13.0	10.6	9.3	13.8	10.9	9.4	15.6	11.7	10.4
		EC	13.0	10.6	9.3	13.8	10.9	9.4	15.6	11.7	10.4
LBM	vc_{LBM}	*NR*	13.6	11.2	9.8	15.0	11.6	9.8	16.3	12.4	10.6
		MBM	13.6	11.2	9.8	15.0	11.6	9.8	16.3	12.4	10.6
		EC	13.6	11.2	9.8	15.0	11.6	9.8	16.3	12.4	10.6
NH3	vc_{NH3}	*NR*	12.8	10.3	9.1	13.7	10.4	9.1	15.4	11.4	9.6
		MBM	12.8	10.3	9.1	13.7	10.4	9.1	15.4	11.4	9.6
		EC	12.8	10.3	9.1	13.7	10.4	9.1	15.4	11.4	9.6

Table 9.7: Economic speed (kts) for all alternatives under optimistic (O), average (A), pessimistic scenarios (P), as well as no regulation (NR), market-based measures (MBM), and emission cap (EC) regulatory scenarios in 2020, 2030 and 2050.

From table 9.7, several conclusions can be drawn.

First, as can be deducted from the differences between optimistic, average and pessimistic scenarios, the optimal economic speed declines with higher fuel cost. This observation is confirmed by figure 9.2. Additionally, following scenarios of future price reductions for alternative fuels, the optimal economic speed can be observed to gradually increase.

Looking at specific fuels, significant differences are noticed in economic speed between high and low cost alternatives. For instance, comparing FTD to HFO, average economic speed lies approximately 28% and 24% lower under the no regulation or market-based measures scenarios. An evident correlation can be observed between required freight rate and economic speed.

At last, although LNG, LBM and ammonia do not necessarily carry lower required freight rate, their economic speed can be observed to average at slightly higher levels compared to bio-fuels with similar RFR. This can be attributed to higher capital costs which cause a proportionally smaller share of voyage costs in RFR.

In conclusion, the optimal economic speed for alternative as well as fossil fuels lies significantly lower than the intended design speed. Therefore, if regulators incite a transition towards alternative fuels, slow steaming can be expected to become increasingly common.

9.5. Sensitivity analysis

Sensitivity analysis is an analysis technique that aims to determine how target variables are affected based on changes in input variables. By conducting a sensitivity analysis on multiple input parameters in the present decision tool, shipowners gain insights in several 'what-if' scenarios. In this section, sensitivity analysis will be performed on multiple input parameters including SFOC & fuel cost in section 9.5.1, vessel speed in section 9.5.2, and interest rate in section 9.5.3.

In addition to the 'most promising' alternatives identified in section 9.3, four fuels are chosen as the 'most interesting': heavy fuel oil, Fischer-Tropsch diesel (FTD), upgraded bio-oil (UBO), and liquefied bio-methane (LBM). The most interesting fuels are chosen as a basis for comparison in the sensitivity analysis of the decision tool. HFO is selected due to its current presence in the maritime industry designating it as an ideal benchmark, Fischer-Tropsch diesel is selected due to its exceptional SMART ranking (#1) in all scenarios, upgraded bio-oil is chosen due to its favourable balance between SMART ranking and required freight rate, and liquefied bio-methane is selected due to its high SMART ranking (#2) and high potential as a drop-in alternative to LNG. In all analyses, the target variable is required freight rate (RFR) and each of the four most interesting fuels is evaluated.

9.5.1. SFOC & fuel cost

In this section, a sensitivity analysis is performed to demonstrate the relationship between required freight rate and specific fuel (oil) consumption (SFOC) during transit for the four most interesting fuels (HFO, UBO, FTD and LBM) and NH3. NH3 is added to demonstrate how changes in a high-cost fuel impact change in RFR.

As can be deducted from figure 9.3, the relationship between required freight rate and SFOC is nearly linear in all discussed fuels. However, the gradient of the slope is different between the presented fuel alternatives. Noticeably, in the alternatives where fuel expenses take up a larger proportion of total cost, the gradient is significantly larger. This is made clear when looking at the gradient of NH3, a more expensive alternative. Furthermore, UBO, FTD and LBM seem to overlap due to their similar cost levels. However, upon closer inspection, small differences in their sensitivity are observed.

For fuel cost, the sensitivity analysis produces very similar results due to the correlation of SFOC and fuel cost. Nevertheless, although a >50% improvement in SFOC is highly unlikely, a >50% reduction in fuel cost may not be as ambitious. In many industries, cost advantages due to the increasing scale of operations have proven to have a significant impact on production cost and prices. It is therefore not impossible that in the future, alternative fuels could potentially become cost-competitive with current fossil fuel prices due to increasing scale of production.

In conclusion, figure 9.3 demonstrates that if SFOC were to decline in the future thanks to, for instance, energy saving devices or more efficient engines, the impact would be larger on the required freight rate of more expensive fuels than on their more affordable counterparts.

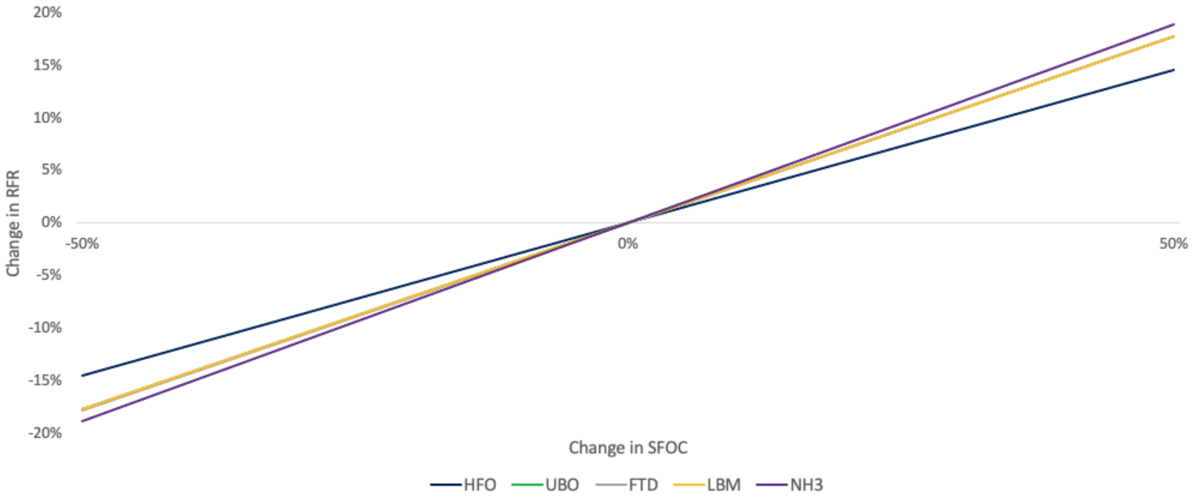


Figure 9.3: Sensitivity analysis on SFOC for HFO, UBO, FTD, LBM and NH3 under the average, 2020, no regulation scenario.

Additionally, one must consider that the sensitivity analysis of figure 9.3 is performed based on a static optimised vessel speed. This means that during the sensitivity analysis, vessel speed remains constant and equal to the optimal economic vessel speed determined at 0% SFOC. When performing a sensitivity analysis based on a dynamically determined optimal economic vessel speed, the optimised economic RFR-SFOC relationship proves to be non-linear. In figure 9.4, an illustrative comparison between the RFR with dynamic optimised speed and the RFR with static optimised speed is demonstrated. The non-linear relationship between speed-optimised RFR and SFOC is evident.

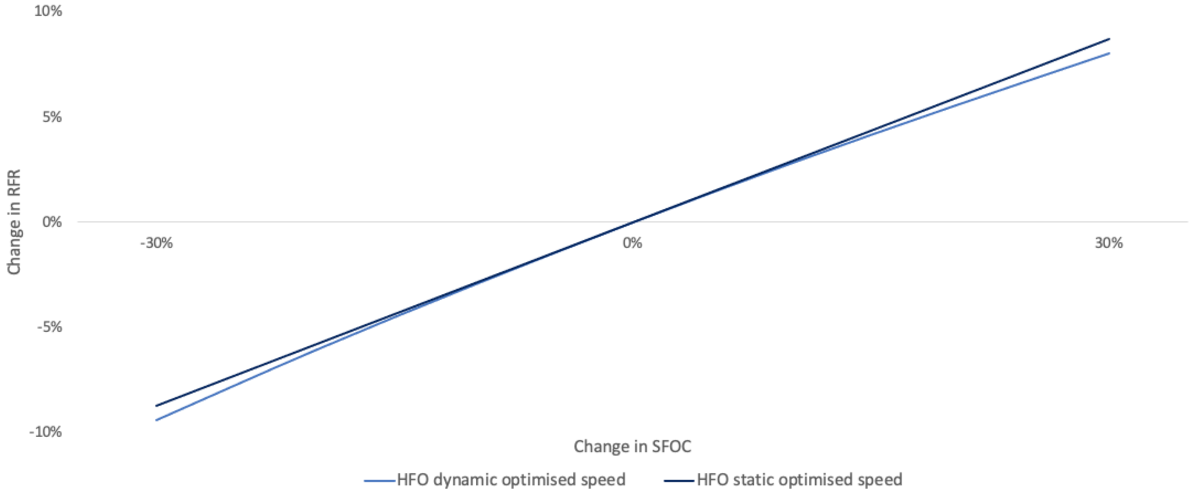


Figure 9.4: Comparison of SFOC sensitivity of HFO between dynamic optimised speed and static optimised speed.

9.5.2. Vessel speed

As discussed in section 9.4, vessel speed has significant impact on fuel consumption and total cost. In figure 9.5, a sensitivity analysis is performed to demonstrate the relationship between required freight rate and vessel speed for the four most interesting fuels under the average, 2020, no regulation scenario. Additionally, the optimal economic speed (at minimum RFR) is demonstrated. As was earlier determined from tables 9.6 and 9.7, the choice of fuel alternative leads to significant differences in RFR and optimal economic speed. For more expensive fuels, the minimum RFR is observed to be significantly higher than that of HFO. Additionally, as is observed in all alternatives, deviating from economic speed has a significant impact on required freight rate. The parabolic curves indicate a non-linear RFR-speed relationship, which can be attributed to the ’cubic law’ of the power-speed curve displayed in figure 8.4.

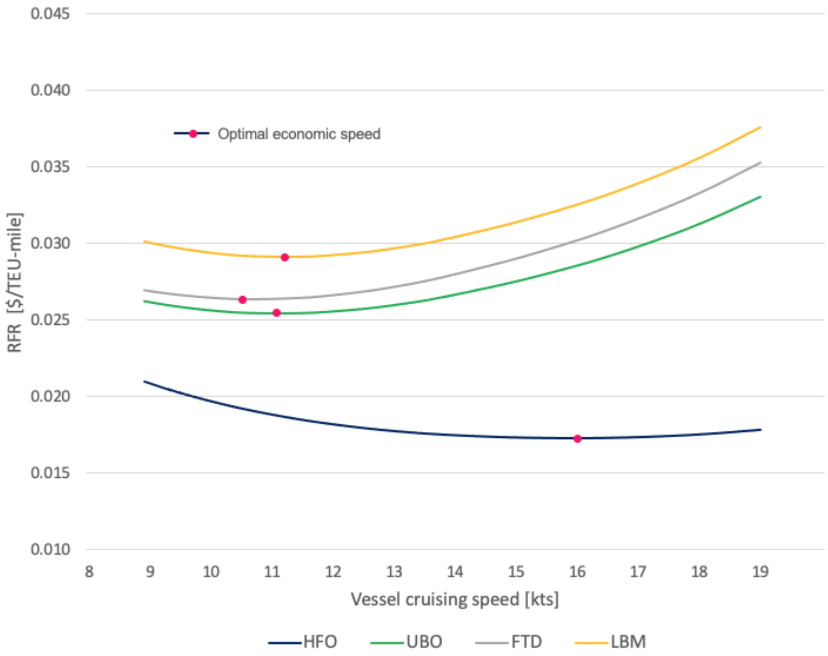


Figure 9.5: Sensitivity analysis on vessel speed for HFO, UBO, FTD and LBM under the average, 2020, no regulation scenario. Both RFR and vessel speed are displayed in absolute values.

To better demonstrate the parabolic shape of the curves and the differences in cost dominance between expensive and more economical fuels, figure 9.6 is devised. In this figure, the optimal vessel speed has been chosen as the baseline for RFR (at 0% change). By doing so, the difference in dominance between voyage expenses or fixed expenses at each vessel speed is demonstrated for each displayed alternative. The dominance of voyage expenses or fixed expenses at each speed can be determined by observing the RFR at each cruising speed compared to the optimal economic speed. At the optimal economic speed, fixed and voyage expenses have found a balance in which the vessel produces the lowest possible total cost per TEU-mile (RFR). When the cruising speed is below the optimal economic speed, fixed expenses become dominant. When cruising speed exceeds the optimal economic speed, voyage expenses become dominant. This relationship can be attributed to the reduction of voyage expenses per TEU-mile at lower cruising speeds, such as less fuel consumption, fewer port visits, and fewer canal passes, as well as the increase of fixed expenses per TEU-mile due to the reduction in TEU-mile transported.

Therefore, the position of the optimal economic speed on the RFR-speed curve demonstrates the relationship between voyage expenses and fixed expenses in each alternative fuel. As can be observed in figure 9.6, voyage expenses weigh heavier in fuels such as UBO, FTD and LBM due to their high fuel cost, whereas in the case of HFO, fixed expenses weigh heavier due to the fuel's relatively low cost.

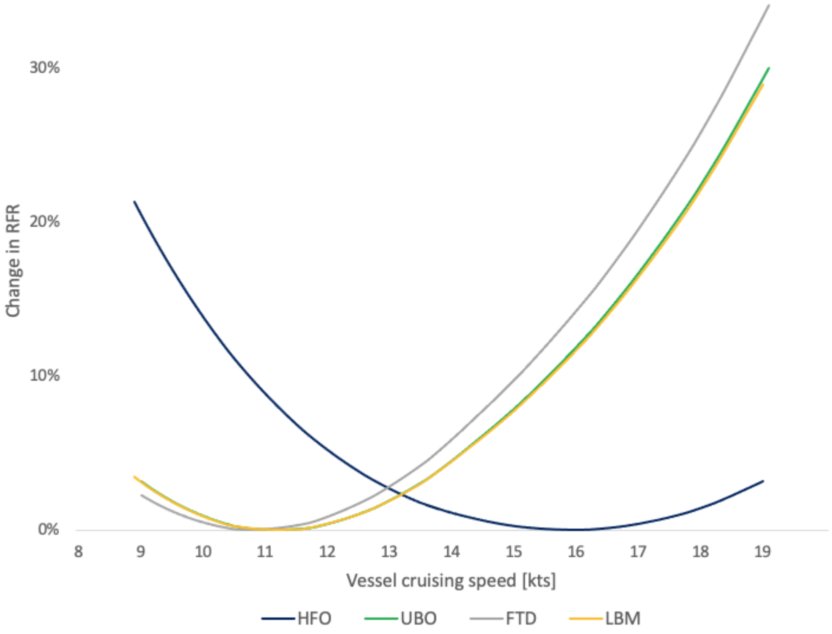


Figure 9.6: Sensitivity analysis on vessel speed for HFO, UBO, FTD and LBM under the average, 2020, no regulation scenario. Base vessel speed is the economic speed for a vessel employing each fuel alternative.

9.5.3. Interest rate

The interest rate is the amount the bank and other lenders charge shipowners for the use of their capital. Interest rate is charged as a percentage of the principal loan amount, and in the shipping industry hovers around approximately 7.5% according to industry experts and Maritime Economics (2013) [150]. Interest rate can vary depending on the risk of the loan and is often judged on the borrower's past performance. Due to the variable basis of interest rates and the case-by-case approach of lenders, it is valuable for shipowners to have an understanding of the impact of different interest rates on the required freight rate of each alternative fuel. In figure 9.7, a sensitivity analysis is performed to understand the model's relationship between interest rate and required freight rate. As can be derived from the figure, required freight rate correlates closely with changes in interest rate. This can be attributed to the fact that the share of total interest expense compared to total expenses is approximately equal to the percentage interest charged by lenders.

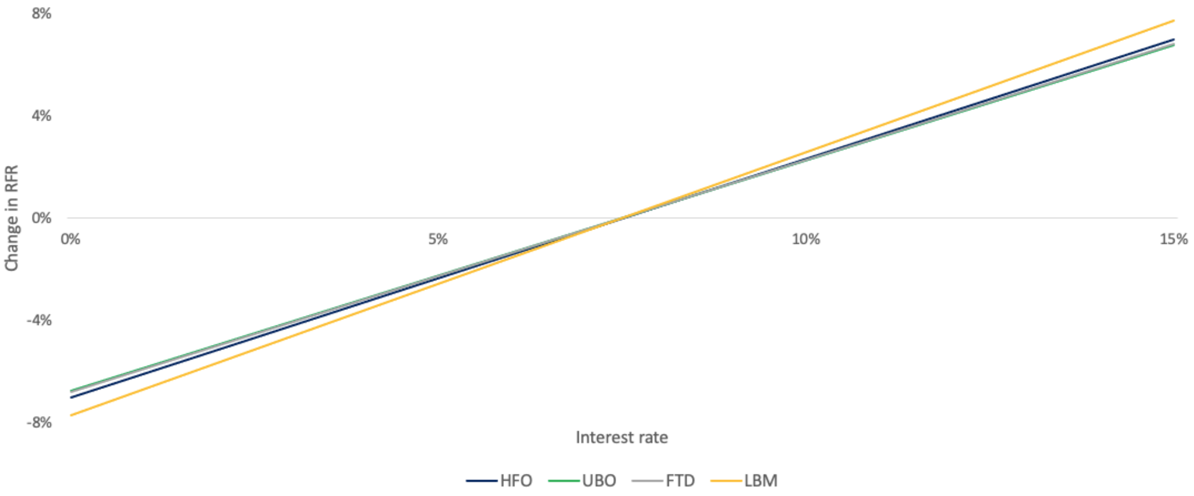


Figure 9.7: Sensitivity analysis on interest rate for HFO, UBO, FTD and LBM under the average, 2020, no regulation scenario. Base case interest rate is set at 7.5% and displayed in absolute values.

9.5.4. Conclusions

Several conclusion can be drawn from the sensitivity analysis performed on SFOC & fuel cost, vessel speed, and interest rate.

First, figure 9.3 examines the relationship between SFOC & fuel cost and required freight rate. SFOC and fuel cost are mentioned together since the effect of each percentage change in either one of the two variables has an equal effect on required freight rate. In figure 9.3, a near-linear relationship between SFOC or fuel cost and required freight rate can be derived at constant speed. However, for alternatives where fuel cost takes up a higher portion of total cost, the gradient of the line is significantly larger. This means that in a scenario of lower SFOC or fuel cost, the proportional decline in required freight rate would be larger for expensive fuels than for more affordable fuels. Although a large decline in SFOC due to energy saving devices or more efficient engines is unlikely, a substantial reduction in fuel cost of alternative fuels thanks to R&D and scale efficiencies is not unthinkable. As can be concluded from the sensitivity analysis, this would significantly improve the economics of employing more sustainable, alternative fuels.

Additionally, figure 9.4 demonstrates the difference between the static optimised linear RFR-SFOC relationship and the dynamic optimised economic RFR-SFOC relationship. As can be observed, when dynamically optimising for economic vessel speed at each different percentage SFOC, the RFR-SFOC relationship becomes non-linear.

In section 9.5.2, a sensitivity analysis demonstrates the relationship between required freight rate and vessel speed. One can conclude from the steep parabolic relationship, a deviation from economic speed has a significant impact on required freight rate. Additionally, figures 9.5 and 9.6 underpin the results of section 9.4, where the optimal economic speed of more expensive fuels can be observed to be close to the minimum speed.

At last, in section 9.5.3, a sensitivity analysis is performed on interest rate. As can be concluded from figure 9.7, required freight rate correlates closely with changes in interest rate. This can be attributed to the fact that the share of total interest expense compared to total cost is approximately equal to the percentage interest charged by lenders.

10

Conclusions and recommendations

10.1. Conclusions

To collectively achieve the goals set in the Paris agreement of 2015, the maritime industry must change. Therefore, the International Maritime Organisation has drafted the initial IMO strategy on reduction of GHG emissions from ships [91]. In this strategy, alternative fuels are considered essential in achieving the emission reduction targets set by the United Nations. However, due to the many criteria and external factors impacting the decisions of shipowners, no consensus has been reached on the most appropriate choice of alternative fuel to comply with possible different imposed emission regulations. Additionally, no existing study has approached the problem from the perspective of the shipowner. To fulfil this research gap, the following research objective was formulated:

"Develop a decision support tool that enables shipowners to select the most appropriate alternative fuel technology to comply with possible different imposed emission regulations while ensuring optimal business performance."

To achieve the main research objective, five sub-objectives were developed and addressed. The sub-objectives and the methods with which they were achieved as well as the key conclusions made are elaborated below.

i *Analyse current and possible future regulatory scenarios and make a selection of regulatory scenarios to consider in the present study. Discard low-probability scenarios.*

The first sub-objective was approached by conducting a literature study on possible future regulatory scenarios. The considered measures included market-based measures in the form of an Emission Trading Scheme (ETS) or bunker levy, regional or global expansion of Emission Control Areas (ECAs), greenhouse gas emission caps of 50% or 100% compared to a predefined benchmark, NO_x emission regulations, or SO_x emission regulations. Based on literature by Balcombe et al. [21], Wan et al. [162], Kågeson [100], International Maritime Organization [90, 91], Garcia et al. [71], Kosmas et al. [104], the International Chamber of Shipping (ICS) [83], Perera et al. [130], Woodyard [169], the probability of different regulations being enforced in 2030 or 2050 was assessed and a selection of four future regulatory scenarios was made. An overview is presented in table 10.1.

Measure		Vessel type	Description	Time frame
MBM	Bunker fuel levy	All vessels	A maritime fuel tax in proportion with the degree of GHG emissions resulting from their consumption	2030
MBM	Bunker fuel levy	All vessels	A maritime fuel tax in proportion with the degree of GHG emissions resulting from their consumption	2050
EC	50% CO_2eq emission cap	New-built vessels	Bench-marked 50% CO_2eq emission cap for all new-built vessels	2030
EC	50% CO_2eq emission cap	New-built vessels	Bench-marked 50% CO_2eq emission cap for all new-built vessels	2050

Table 10.1: Selected regulatory scenarios to be considered in this research.

ii *Analyse a broad range of alternative fuel technologies and assess which can be considered feasible options. Discard fuels that do not meet requirements in scalability, GHG reduction targets, or suitability for deep-sea shipping.*

The second sub-objective was also approached by conducting a literature study on a broad range of alternative fuel technologies. Based on literature by McGill [116], Mohseni [119], Endres [59], Ytreberg [170], Burel [33], CE Delft [37], Pavlenko [129], Thomson [154], Brynolf [32], Bengtsson [24], Einemo [58], Mohd Noor [118], Hsieh [82], Florentinus [70], DNV GL [48], E4Tech [55], Parraga [128], E4Tech [54], the European Parliament and Council [152], Ash [20] and Hansson [80], several options were discarded based on a lack of scalability, GHG reduction potential or suitability for deep-sea shipping. A selection of nine feasible alternatives remained. This includes HFO, LNG, FAME, HVO, UPO, UBO via HTL, FTD and LBM. An overview is presented in table 10.2.

Fuel technology		Characteristics	Primary resource	Source
Fuel oils	HFO (IFO-380) with scrubbers	Low cost, carbon heavy, high viscosity bunker fuel; Reduced SO_x and NO_x emissions	Crude oil	[59, 116, 119, 170]
Natural gases	LNG	Liquid cooled methane/ethane gas; low nitrogen oxide emissions, sulphur free; low cost; high well-to-propeller GHG output	Crude oil; natural gas	[24, 32, 33, 37, 129, 131, 154]
Bio-fuels	FAME (bio-diesel)	Suitable clean alternative to MDO/MGO; risk of acidic degradation	Edible or used oils	[55, 58, 82, 118]
	HVO	High quality drop-in diesel fuel; higher cost; cross-sector interest	Edible or used oils	[48, 55, 70, 82]
	UPO	Suitable clean alternative to HFO/IFO; high GHG reduction potential; not commercially available	Lignocellulosics; waste	[55, 70, 82]
	UBO via HTL	High potential; low commercialisation; easier production process compared to UPO	Lignocellulosics; wet bio-mass; waste	[55, 82]
	FTD	Drop-in diesel fuel; more impurities; very high GHG reduction potential	Lignocellulosics; waste	[54, 55, 128, 152]
	LBM (bio-LNG)	Renewably sourced drop-in LNG fuel; high GHG reduction potential; potentially cost competitive	Lignocellulosics; landfill gas; waste	[36, 55, 152]
Ammonia		No tank-to-propeller emissions; high cost; toxic; low maturity in marine applications	Hydrogen	[20, 48, 55, 79, 80]

Table 10.2: Selection of alternative maritime fuels for decision tool.

iii *Evaluate multi-criteria decision methods and modelling techniques to address the specific problem and criteria presented in the present study.*

Sub-objective iii was the last objective of the literature study and included identifying and evaluating multi-criteria decision methods and modelling techniques to address the research objective of developing a decision support tool. Through selecting, defining and weighing evaluation criteria with the help of shipowners, the appropriate decision methods and modelling techniques were determined. The chosen methods for devising the decision tool include the simple multi-attribute rating technique (SMART) found in Siregar (2017) [147], alongside a financial model based on the annual cash flow accounting method in Maritime Economics by Martin Stopford (2013) [150].

iv *Devise a decision support tool which is able to:*
a. Rank optimal fuel choices under different regulatory scenarios and
b. Assist shipowners in making substantiated future decisions regarding alternative fuel technologies.

Based on the findings of sub-objectives i to iii, a decision support tool was devised that is able to rank optimal fuel choices under different regulatory scenarios and assist shipowners in making future decisions regarding alternative fuel technologies. The decision support tool relies on a set of shipowner inputs including vessel parameters, revenue parameters, operational parameters and financial parameters, as well as compiled data on costs, SMART criteria, and scenarios.

The decision tool evaluates inputs and data and generates output for both the financial and SMART decision model. For the financial model, relevant outputs include the optimal economic vessel speed, required freight rate (RFR) and NPV and IRR projections for each alternative. For the SMART model, the main output consists of a ranking of fuel alternatives based on the selected criteria under each scenario.

v *By conducting a case study, determine the most appropriate fuel alternatives under different regulatory scenarios while ensuring optimal business performance.*

Finally, the sub-objective of conducting a case study to determine the most appropriate fuel alternatives under different regulatory scenarios was achieved. As presented in chapter 9, two main KPIs were selected to judge the performance of each alternative: the SMART ranking and the required freight rate (RFR). Since the SMART ranking considers only technical, environmental and other criteria, financial consequences of each alternative are reflected in the required freight rate. Therefore, the preferred alternatives are different for each evaluation method.

In terms of SMART performance, which evaluates fuels based on technical, environmental and other criteria, Fischer-Tropsch diesel (FTD) and liquefied bio-methane (LBM) capture first and second place respectively. Upgraded bio-oil (UBO) and upgraded pyrolysis oil (UPO) share third and fourth place depending on the selected scenario. HFO follows the list with a shared fourth and fifth position, again depending on the selected scenario.

In terms of required freight rate, HFO performs best, followed by LNG in the medium term and UPO and UBO in the longer term. Nevertheless, the average difference in required freight rate of UPO and UBO compared to HFO remains substantial, at 36% and 39% under a no regulation scenario, and 32% and 34% under market-based measures, respectively. For FTD, the average difference in required freight rates compared to HFO is even higher at 43% and 38% under a no regulation and market-based measures scenario, respectively.

Therefore, without regulations or financial incentives from policymakers, HFO is expected to remain the dominant fuel of the maritime industry. However, if policymakers do take action to drive and support the uptake of sustainable alternative fuels, Fischer-Tropsch diesel (FTD) and upgraded bio-oil (UBO) offer the best balance between SMART performance and cost. Additionally, if the maritime industry undergoes a transition towards LNG as a short-term solution to reduce greenhouse gas emissions compared to HFO, liquefied bio-methane (LBM) could prove to be a suitable future drop-in alternative that offers good performance both in terms of SMART ranking and required freight rate.

In conclusion, Fischer-Tropsch diesel (FTD) and upgraded bio-oil (UBO) can be entitled the 'most promising' alternative maritime fuels of the future, whereas HFO and LNG remain the 'most probable' to retain dominance without regulatory intervention. This suggests that in order for the maritime industry to transition towards sustainable alternative fuels, policymakers, governments, international organisations and lenders need to align their policies to collectively enable a more sustainable shipping industry. Not only by enforcing stricter regulations, but also by providing the correct financial incentives.

10.2. Recommendations for further research

One of the higher-level intentions of this thesis was to introduce a new perspective from which the choice of alternative fuels can be approached. In that light, this thesis aims to establish a base from which knowledge on the subject of this research can further be expanded. Therefore, this section contains a set of recommendations for further research and expansion of the devised decision tool.

In this thesis, decision tool inputs and data have been collected from reliable sources and processed with great care. However, as with all research, higher quality data is always aspired. As the reality remains that such data is not always available, informed assumptions are made where necessary. If higher quality data becomes available in the future, it would be recommended to collect inputs and data from centralised verified sources to increase the accuracy and reliability of the decision tool. This way, the basis for comparison of alternative fuels is even.

Furthermore, concerning future price developments of (alternative) fuels, assumptions have been made and processed in scenarios. Although the decision tool leaves room for the user to insert and adjust his or her assumptions, it would greatly benefit this research if a more detailed approach would be taken to future price developments of alternative fuels.

Additionally, although slow steaming strongly reduces fuel cost, the present decision tool assumes freight rates to remain unaffected by longer transit times. In reality, this may be different. Since it is currently unknown to what extent freight rates are influenced by transit time, it would be recommended to investigate this relationship in further research.

Moreover, concerning criteria evaluation, the sample size of shipowners participating in the questionnaire was n=7. Although this sample size includes a substantial number of vessels under management, it would benefit this research to collect input from more participants.

In a broader sense, this research could be expanded further into other fields than what is touched upon in this thesis. Adjacent fields could include different vessel types such as bulk carriers or tankers, different vessel sizes such as Suezmax or Capesize, different operational areas such as short-sea or inland shipping, other propulsion types such as fuel cells, or additional alternative fuels which were eliminated in chapter 4.

Finally, in terms of the future potential of alternative fuels, it would be interesting to explore and quantify the incentives required to justify the employment of alternative fuels compared to their fossil counterparts. By doing so, policymakers could better channel their regulatory strategies to provide the industry with the correct incentives to accurately accelerate the transition to more sustainable alternative fuels.

11

Reflections

The intention of this chapter is to reflect on the implications and limitations following this research and the obtained results. Limitations are specifically discussed on the research approach, model assumptions and obtained results. The wider implications of this research are elaborated upon, a disclaimer is made, and finally the added value of this research from both a societal and scientific point of view is addressed.

11.1. Reflection on the research approach

The goal of this section is to reflect on the research approach.

First, the approach towards accounting for emission costs focuses solely on greenhouse gas emissions (C_{GHG}). Therefore, external emission costs such as the cost of general human health due to air pollution or the cost of damages to sea life are left unconsidered in this research. On the one hand, since external emission costs are complex to quantify and levy, it is highly unlikely that policymakers will tax shipowners based on these costs. On the other hand, external costs should always be considered by policymakers when drafting new regulations to ensure that the detrimental external effects of new regulations do not exceed the positive effects they aim to achieve.

Concerning freight rates, this research assumes spot freight rates to be settled at a uniform rate per leg, independent of transit time. However, optimised economic vessel speeds show that vessels employing expensive alternative fuels bear significantly higher transit times. As a result, in the future, shippers' willingness to pay might decrease when transit times increase, leading to disturbances in the current relationship between generated revenues and optimal vessel speed. A model which is able to account for dynamic pricing that depends not only on transit routes but also on transit times might improve optimal economic vessel speed calculations.

Additionally, if vessel sizing would not be a limiting factor in the present thesis due to the maximum dimensions of the Panama canal, the financial performance of alternative fuels could significantly be improved by determining the optimal economic vessel size. However, this is not included in the scope of this research.

11.2. Reflection on the model assumptions

When building a tool or model of substantial size in a limited time-frame, it is difficult or even impossible to capture the full complexity of a process without making assumptions. Therefore, in this thesis, assumptions are present in the approach of the model and input parameters. Due to the importance of communicating these assumptions, an overview is presented in table 11.1 where assumptions and their consequences are elaborated.

Assumption	Consequence
Engine efficiency is assumed equal for all diesel-like fuels and 9.5% higher for gas fuels.	Differentiation in engine efficiency due to employing different alternative gas or diesel-like fuels is not accounted for. Although no evidence was found of a statistically significant difference for engine brake thermal efficiency among blended fuels compared to mineral diesel, the effects of employing pure alternative diesel-like or gas-like fuels on engine efficiency are still unknown [17].
Bunker price is averaged over ports and no bunkering strategy is applied.	An efficient bunkering strategy could potentially reduce fuel cost, although past research has not yet provided clear figures.
FCL freight rates are assumed fixed over each route and independent of time in transit.	In the future, shippers' willingness to pay might decrease when transit times increase, resulting in disturbances in the current relationship between generated revenues and optimal vessel speed.
Vessel sizing is assumed constant due to limitations of the New-Panama canal.	Implementing flexible vessel sizing might present the need for larger vessels to decrease the impact of higher fuel cost.
Global transport demand is presumably satisfied.	Slow steaming at equal vessel sizes causes a shortage of container transport. More newbuilt vessels would be required to satisfy equal transport demand.
Port slots are optimally met.	Delays could cause longer average loading and discharging times, thus negatively impacting required freight rate.
Discount rate is assumed equal for all alternatives, independent of risk.	Shipowners might choose to assume a higher discount rate when employing alternative fuels due to increased risk.
Vessel speed-power relationship is calculated and applied as if vessel is sailing at full loaded condition, independent of actual utilisation.	This results in a potential maximum deviation in required freight rate of 5% between loaded and ballast condition.

Table 11.1: Key assumptions and their expected consequences.

11.3. Reflection on the decision tool outcomes

The following sections reflect on the decision tool outcomes and if the results fall within expectations. Where possible, findings are compared to literature. Furthermore, inherent limitations around the decision tool outcomes are discussed and areas that leave room for interpretation are argued.

It can be acknowledged that the expected research outcomes have been obtained. A decision support tool has been devised which enables shipowners to comply with possible different imposed emission regulations while ensuring optimal business performance. The decision tool is able to aggregate and process collected data and inputs and convert them to meaningful and uncomplicated insights. The devised decision tool produces outputs that provide valuable insights in the ranking of alternative fuels against a curated set of criteria, in the financial performance and required freight rate over the lifetime of a vessel employing each alternative fuel, and in the optimal economic speed of each vessel employing an alternative fuel under each scenario.

11.3.1. SMART decision model

Elaborating on the ranking of alternative fuels, the SMART decision model accounts for ten evaluation criteria in three categories: technological criteria, environmental criteria, and other criteria. The criteria selection has been presented to and weighed by a panel of seven shipowners with a total of approximately 1780 vessels under management. The concerned shipowners have reviewed the evaluation criteria and assigned scores to judge the importance of each criterion for decision-making on alternative fuel technologies in their firm. The collected feedback has been converted to criteria weights, assigning relative weights to each criterion. Performance scores have been identified for each alternative under each evaluation criterion and the fuel alternatives have been ranked in order of preference. However, as with all model outcomes, SMART results are subject to limitations and leave room for interpretation. These aspects are argued below for the SMART decision model in this thesis:

- Results from the SMART decision model show a preference for a number of alternative fuels over HFO and LNG when economic criteria are not considered. Although these outcomes do not surprise due to the low environmental performance of HFO and LNG, it would be wrong to assume economic criteria can be left unconsidered. It is therefore critical that SMART output results are studied alongside required freight rates and other financial indicators to get an overall view of the performance of an alternative fuel compared to its peers.
- For the SMART decision model to produce meaningful output, it requires uniform input parameters for all criteria. Since the input parameters for each criterion and alternative fuel are collected from a large number of sources, the author carries the responsibility to interpret and convert literature to the required input parameter units. Although this task has been carried out with great care and data has been processed from reliable sources, other interpretations of literature than those of the author could lead to different results.
- Although general consensus is observed around criteria weighting provided by the seven participating shipowning entities, a larger sample size would significantly increase confidence in its accuracy. Additionally, although the present sample represents shipowners from Denmark, China, Norway and Greece, a larger and more diverse sample would better reflect global views. By attracting more diverse participants, possible cultural bias towards (for instance) environmental policy can be eliminated. Nevertheless, since the participating shipowning entities do represent a substantial amount of vessels and operate globally, the reliability of the weighting is not questioned.

11.3.2. Required freight rate (RFR)

In this thesis, the required freight rate over the lifetime of each vessel employing a different alternative fuel has been devised. The required freight rate per TEU-mile is calculated by a combination of voyage expenses, running expenses, capital expenses, TEU transported, distance sailed, vessel lifetime, and discount rate. The formula used to calculate the required freight rate is found in section 8.2. Voyage, running and capital expenses are extensively modelled in a financial model ranging for the complete lifetime of the vessel and include all relevant cost items as found in Maritime Economics by Stopford (2013) [150]. TEU transported and distance sailed are functions of vessel utilisation, vessel capacity, time loading, time discharging and vessel cruising speed. Vessel lifetime is assumed to be 25 years and discount rate is assumed at 8%. The required freight rate represents the freight rate in USD per TEU-mile required for the container vessel to return a positive net present value over its lifetime. In other words, the required freight rate is the minimum freight rate a (container) vessel needs to earn to make its operation attractive. Therefore, the required freight rate provides a solid ground for comparison of alternative fuels under similar operating conditions. Nevertheless, one should always be aware of the limitations of the model and should take care when interpreting results. In the paragraphs below, these elements are discussed for the financial model and resulting required freight rate:

- The required freight rate is determined under a no regulation, market-based measure and emission cap scenario. Although these regulatory scenarios have been carefully selected in chapter 3, they only impact the required freight rate of HFO and LNG. Since other fuels do not emit any tank-to-propeller GHG emissions (at least on paper), they are not affected by market-based measures. In the same way, since they do not emit any tank-to-propeller GHG emissions, these alternatives are not affected by the emission cap scenario. Therefore only HFO and LNG are deemed infeasible. Nevertheless, the change in required freight rate of HFO and LNG under a market-based measure regulatory scenario indicates the relative impact such a regulatory measure can have. Additionally, it provides insight into how such a measure can be extended to increase the competitiveness of alternative fuels compared to the status quo.

- When evaluating fuel cost of alternative fuels, government subsidies and tax exemptions are left unconsidered. Nevertheless, it is possible that governments and international organisations will provide financial incentives to facilitate the shift towards more sustainable maritime fuels. By doing so, sustainable fuel alternatives will become more cost-competitive, thus reducing required freight rate. Although such possibilities are not implemented in the model, it can easily be adapted to include lower fuel prices. The new required freight rate is automatically recalculated.
- Due to the lack of literature and uncertainty surrounding future cost developments of (alternative) maritime fuels, current projections of 2030 and 2050 fuel costs are based on basic assumptions of decreasing cost with economies of scale. However, as accurately pointed out by van der Kroft (2020) [159], (bio-)fuels could become a victim of their own success: "While increasing production volumes could decrease fuel costs, it also induces the need for feedstocks that are increasingly difficult to access and collect. These increasing efforts could lead to increasing feedstock costs, potentially driving up fuel prices". The present thesis does not consider the secondary price-effects mentioned by van der Kroft. Therefore, although the insights produced by the current model regarding future time scenarios are valuable, they are subject to significant uncertainty. Shipowners are recommended to review these assumptions and adjust them as more information comes available in due time. More information on the implemented time scenarios is provided in section 8.4.

11.3.3. Economic speed

In order to minimise cost and maximise returns, shipowners are recommended to optimise their vessel's cruising speed to the optimal economic speed. In the present model, the economic vessel speed for a vessel employing each fuel alternative is determined by a non-linear optimisation model that minimises required freight rate through adjusting vessel cruising speed. More information on the optimisation model is provided in section 9.4. Although the economic speed optimisation model provides solid recommendations to shipowners, results should always be considered with care. Some limitations are discussed below:

- The optimal economic cruising speed is calculated for each vessel employing each alternative fuel under all sentiment, regulatory and time-scenarios. In these calculations, an economic cruising speed is determined which is constant over the course of the vessel's lifetime based on their annual voyage. However, in reality, optimal economic cruising speed is different for each leg of the voyage depending on utilisation, voyage distance and freight rate. Therefore, ideally, the economic speed should be recalculated for each leg of the route a vessel sails during the course of a year to maximise returns on each leg. Although this is not included in the present research due to time limitations, this means that there is room for improvement in the economic speed for each leg to achieve higher annual returns.
- When calculating optimal economic speed, the present model assumes a power-speed relationship under loaded condition. However, the vessel's utilisation varies on each leg of the voyage. A vessel with lower utilisation can in practice achieve higher speeds on the same power consumption. Therefore, a model which accounts for the exact utilisation on each leg could potentially more accurately determine fuel consumption, and therefore better approach optimal economic

speed on each leg. Nevertheless, since the present implementation accounts for a vessel in loaded condition, the actual fuel consumption on partial utilisation can only be better. The potential maximum deviation in required freight rate between loaded and ballast condition is determined at 5%.

- The economic vessel speed is undoubtedly the optimal speed to be sailed by a vessel in the model environment. However, in reality, failing to meet a port slot due to bad weather or delaying a shipment could lead to substantial damages. Therefore, shipowners should always ensure flexibility in their schedule or vessel speed to account for delays.

11.4. Reflection on the wider implications of this research

In this section, the wider implications of this research are reflected upon. This includes implications for shipowners, shippers, fuel producers, consumers and policymakers.

11.4.1. Implications for shipowners

During a transition towards alternative fuels, shipowners need to account for a number of implications.

First, due to the global nature of the shipping industry, a global bunkering network would require to be in place. Since alternative fuels have not yet reached global maturity, shipowners need to be aware of their dependence on global fuel availability. This is especially problematic for highly specialised fuels such as ammonia since fuel switching (if even possible) comes at a high cost. When employing liquefied bio-methane, shipowners can choose to divert to LNG in the case of a supply drop, although LNG also is not yet globally available. In the case of drop-in bio-fuels, shipowners are less dependent on the reliability of global bunkering facilities, since shipowners can always choose to bunker HFO where more sustainable alternatives are not available. All in all, higher dependence on global fuel availability is inevitable for shipowners, at least until an alternative fuel captures significant global market share.

Additionally, alternative fuels could be subject to higher price instability than their fossil counterparts due to their immature nature. Although alternative fuels are not dependent on global oil markets, minor interferences in production capacity or logistics can cause significant price fluctuations. As alternative fuels mature, fuel prices are expected to become more resilient, although large fluctuations will always remain possible (as has been observed historically in HFO). For shipowners, this could imply the necessity for the implementation of various risk mitigation strategies such as locking in future bunker prices by means of future energy contracts.

Furthermore, as was concluded in chapter 9, slow steaming can significantly reduce required freight rate for vessels employing alternative fuels. However, slow steaming also reduces the annual TEU-mile transport capacity of a vessel. Under the assumption that vessel size does not increase significantly, this would imply the requirement of more vessels to fulfil equal transport demand. Although ordering more new-built vessels is not impossible, the societal and environmental impact of such a transition should not be left unconsidered. Shipowners would also be required to order and manage more vessels, requiring larger investments and fixed costs.

Regarding investments, the implications from increased investment costs per vessel are two-fold: higher investment costs require higher net equity contributions in year 1, and higher investment costs result in a higher risk profile in the beginning of a vessel's lifetime, potentially also impacting loan conditions from lenders. However, as technologies mature, investment costs are expected to decline. Additionally, an industry transition to slow steaming could mean that shipowners can transition towards employing smaller engines, since power demand declines with lower design speed. Subsequently, investment costs per vessel could decline.

Unfortunately, this is not enough to incentivise 'first movers'. First movers inevitably bear the highest cost and risk, as technologies have not yet achieved scale for producers to lower prices, and it is unknown how alternative fuels perform over a vessel's lifetime. Therefore, policymakers, governments, international organisations and lenders should align their policies and incentives to collectively bear the risk alongside first movers to enable the transition towards a more sustainable shipping industry.

11.4.2. Implications for shippers

Due to the large dependence on shipowners to deliver their goods, a transition towards alternative fuels is also expected to have significant implications for shippers. As a result of overall higher required freight rates for vessels employing alternative fuels, shipowners could contemplate collectively forwarding this cost to their clients. By doing so, shipowners would remain able to generate desired returns while employing more sustainable alternative fuels.

However, it is up to shippers rather than shipowners to either accept or reject higher transportation costs. If shippers accept higher transportation cost due to, for instance, certain sustainability goals set by themselves or their clients, they are presented with the choice of either cutting costs in other parts of their supply chain, or further forwarding the additional expenses to their clients. If, on the other hand, shippers decline to carry the burden of additional transportation costs, shipowners that sail on alternative fuels will have difficulties finding cargo.

Additionally, if shipowners decide to slow steam to cut costs, longer transit times will impact the supply-chain of shippers. As a result, shippers will be required to increase supply chain flexibility, agility and responsiveness to absorb longer delivery times. As the downside of longer transit times compounds with higher cost, shippers are unlikely to accept a transition towards alternative fuels without resistance. However, if shipowners manage to mitigate at least one of these two consequences, shippers would possibly be more inclined to sacrifice some margins under the guise of goodwill.

11.4.3. Implications for fuel producers

If a transition towards alternative fuels is incited, fuel producers will be required to satisfy demand. However, due to the novel nature of alternative fuels, it is not only the classic oil majors that can become future market leaders. As is observed, several start-ups and scale-ups across the globe are currently working on scaling the production for alternative fuels. Nevertheless, both types of fuel producers will need to account for the implications of a fuel transition.

To develop alternative fuels on large scale, fuel producers are required to build large production facilities. The investment cost and associated risk of developing these new production facilities is much higher than it is for established technologies. As a result, the assumed discount rate fuel producers will use in their project forecasts will also be higher. A higher discount rate only justifies the investment if the projected internal rate of return exceeds it. In the case of alternative fuels, this can only be realised if they are sold at higher prices than their current fossil counterparts. For the maritime industry, this results in higher fuel prices, complicating the transition towards alternative fuels.

However, fuel producers can significantly reduce risk and investment cost by initiating talks with governments and international organisations. Apart from the obvious climate benefits, local governments are keen on attracting innovators and pioneers in sustainable energy technologies to accelerate innovation and create jobs in their country. Governments are therefore often willing to support these companies in their missions by providing substantial subsidies and tax benefits. Additionally, on a broader scale, international organisations are often willing to financially support innovators that contribute to the long-term prosperity of the participating (industry) stakeholders.

Although attempting to disrupt an industry by allocating resources towards R&D goes hand-in-hand with increased risk, successful pioneers can expect to capture substantial market share through the first-mover advantage. As demonstrated in the automotive industry in the past ten years, it's often entrepreneurial-minded companies with daring and bold ideas who are on pace to redefine the status quo.

11.4.4. Implications for consumers

For consumers, the negative implications of the transition to alternative fuels are minimal. In terms of cost, sea freight accounts for approximately 2% of the consumer retail price for fast-moving consumer goods such as shoes and clothing according to industry experts [102]. For gadgets and general tech, this cost-share easily drops below 1% due to higher total cost. Therefore, even if shipping costs would theoretically increase by 50% and shipowners, shippers and retailers would forward this cost to consumers, the impact would be minimal.

In terms of transit time, slow steaming could lead to longer delivery times for containerised goods. For consumers that directly source products overseas, this is a negative implication. However, as most products that are shipped overseas are not required to reach their destination urgently, the impact is insignificant.

11.4.5. Implications for policymakers

Policymakers are the drivers of change in large international industries such as the maritime industry. In order to accomplish a shift in the type of fuel consumed, policymakers should draft new regulations and directives that limit or eliminate the use of high-emission fuels. For policymakers, it is important to incentivise stakeholders to employ alternative fuels that have a smaller climate footprint. In this thesis, market-based measures as well as an emission cap scenario are examined.

Under market-based measures which impose a bunker levy according to the annually emitted CO_2-equivalent GHG emissions, required freight rate is found to be an average of 3-5% higher for HFO and LNG compared to the no regulation scenario. This cost is calculated using the November 2020 cost of CO_2 European Emission Allowances [34]. Although the resulting change in required freight rate is significant, it does not come close to the cost gap between HFO or LNG and other fuel alternatives. Therefore, it is not significant enough to incite a shift towards more sustainable fuel alternatives. Other options for policymakers include a separate emission trading system for the maritime industry, as is done in aviation and proposed by Wan (2018) [162] and Balcombe (2019) [21], or further iterating on a bunker levy scheme as proposed by Garcia (2020) [71] and Kosmas (2017) [104].

At last, even if alternative fuel prices drop to current HFO levels due to large scale adoption or external incentives, the drop in market share of HFO could cause a collapse in its price. This effect could create a 'last mover advantage' for shipowners which have not yet transitioned to alternative fuels. Although such price interactions have not been implemented in the model, similar market effects are not improbable. For policymakers, it thus remains important to protect first movers from lacking behind of competition.

11.5. Disclaimer

When concluding scientific research, it remains important to take a step back and get a bird's eye view of the future developments that might impact the presented research. In this disclaimer, two potential future developments are discussed which could impact both the conclusions of this research and the maritime landscape as we know it.

11.5.1. Bio-fuel regulation

The present research has demonstrated the importance of bio-fuels in the future decarbonisation of the maritime industry. However, the large-scale adoption of bio-fuels entails significant complications on a global scale. The most important complications are related to the requirement for additional farmland to produce feedstocks to satisfy demand. As concluded through research by Ajanovic (2011), even if all crops, forests and grasslands currently not used were used for bio-fuel production, it would be impossible to substitute all fossil fuels used today in transport [16]. Such an observation underlines the high probability of farmland conversion to cater to the increased demand for bio-fuel feedstocks, even though maritime fuels do not account for all fossil fuels used today in transport. Naturally, this conversion could induce detrimental secondary effects. As Morone, Strzałkowski and Tani (2019) accurately state: "Key problems associated with the bio-fuel transition include indirect land use change (ILUC), [elevated] food crop prices and associated food security issues, as well as equality and gender issues stemming from lack of access to resources deriving from increasing land pressure" [120].

For these reasons, researchers and industry experts have expressed their scepticism towards the feasibility of large-scale adoption of bio-fuels by the maritime industry without proper policy guidelines and blending limits [141]. This puts pressure on both the maritime and (alternative) fuel industry, as in the case of stringent restrictions on bio-fuels, an economically and regulatory feasible fuel alternative that is able to reach the IMO's current reduction targets has yet to be discovered.

11.5.2. EEXI

As elaborated in section 3.1.1, the Energy Efficiency Existing Ship Index, or EEXI, is a design index established by the IMO during MEPC 75 in November 2020 as an amendment to MARPOL Annex VI to regulate carbon emissions from ships [50]. The measure is expected to enter into force in 2023, after being finalised and adopted at MEPC 76 in June 2021.

The EEXI limit is enforced by means of a required EEXI to be satisfied by a vessel's attained EEXI. The required EEXI relies on a reference line value (RLV) based on reference values per ship type. When a ship's attained EEXI does not meet the EEXI threshold, technical modifications may be considered for compliance (e.g. engine power limitation (EPL), retrofit of energy saving devices or alternative fuels). The most feasible technical modification to comply with EEXI regulations is engine power limitation (EPL), as this is carried out with less effort compared to other proposed measures and significantly reduces a ship's running costs [51].

The attained EEXI is calculated and verified based on the guidelines proposed by the IMO in the draft amendments presented at MEPC 75 [12, 99]. The relevant calculation methods for both the required and attained EEXI have been described in section 3.1.1. For the present research, the EEXI is calculated by applying the estimated index value (EIV) to the case study vessel. It is then compared to the power-speed curve determined by the Hollenbach method to determine the need for technical modifications to reach required EEXI levels [50, 89].

As the goal of the EEXI is to regulate CO_2-equivalent emissions from existing ships, it is essential to understand the consequences for shipowners. For vessels sailing on alternative fuels producing low GHG emissions, EEXI compliance is comfortably achieved. However, for vessels sailing on HFO, necessary steps to achieve EEXI compliance might be required. An application of engine power limitation could potentially cap maximum vessel speed or economic vessel speed. In figure 11.1, the intersection of the power-speed curve is presented for the case study vessel sailing on HFO, and the EEXI-imposed engine power limit is charted. As can be observed, the specific case study vessel is compliant with EEXI requirements in both loaded and ballast condition under operational limitations of 85% MCR and 15% sea margin.

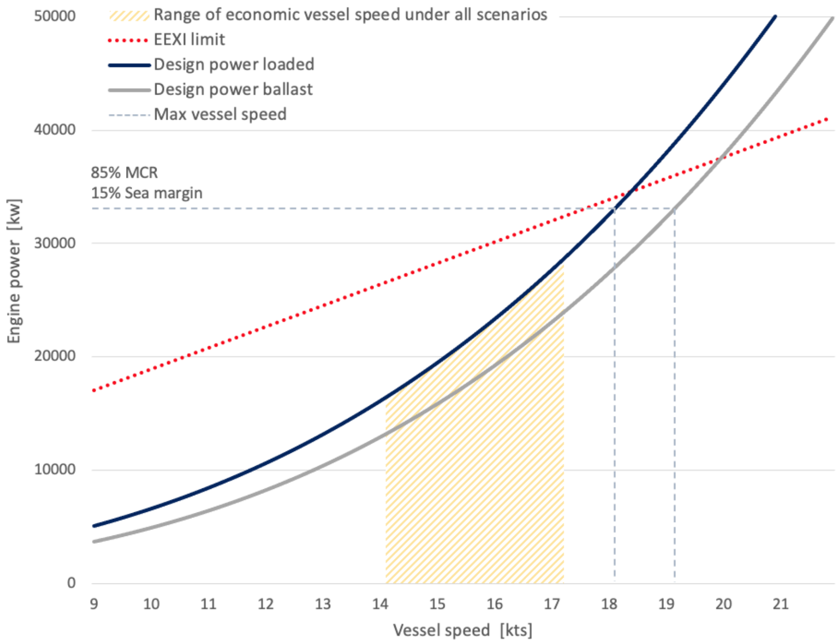


Figure 11.1: Demonstration of the intersection of the power-speed curve of the case study vessel sailing on HFO and the EEXI limit. Own composition

However, one must keep in mind that figure 11.1 represents a case study vessel that is designed to comply with EEDI regulations. Therefore, it is not representative for most existing container vessel configurations: as derived from literature, most of the (older) existing vessels of the same capacity employ significantly larger engines [99]. Therefore, for the majority of the existing container fleet, engine power limitation is expected to be required to comply with EEXI limits, as was also concluded from a case study conducted by Japan and Norway in preparation for MEPC 76 [99].

Nevertheless, from the economic vessel speed indicated in figure 11.1, it becomes evident that the new EEXI regulation is not expected to pose a limitation on economic speed. It will rather act as a catalyst towards lower emissions and lower cost shipping, something that is bound to benefit both the environment and shipowners.

11.6. Societal relevance

The present thesis provides insights into the choices of alternative maritime fuel technologies under different imposed emission regulations. In this process, current and possible future regulatory scenarios have been considered and analysed. The most probable scenarios have been selected and elaborated in a decision tool aimed at assisting shipowners in making (future) decisions in choosing (alternative) fuel technologies for their vessels. In the process of selecting regulatory scenarios, devising the decision tool and processing results, a number of interesting insights have been produced.

First, it is certain that governments and regulators will be required to play a central role in the transition towards more sustainable maritime fuel technologies. As can be concluded from the results, there are no financial incentives for shipowners to transition from fossil fuels towards sustainable fuel alternatives, while many of these alternatives perform at least as good as the status quo in terms of non-economic criteria. It is up to governments and regulators to incite or push the transition by providing financial incentives or penalties on sustainable or polluting maritime fuel technologies.

Furthermore, the various scenarios showed that optimising for economic speed does not only provide financial benefits, but also benefits the climate by reducing exhaust gas emissions. It is therefore not only the responsibility of the maritime industry to embrace slow steaming as the new standard, but also up to shippers and consumers to accept longer transit times. Although it is very difficult to incite a paradigm shift in a time where globalisation has pushed boundaries in terms of efficiency and speed, it is undoubtedly necessary to 'slow down' to collectively achieve the goals set in the Paris agreement of 2015 [156].

At last, a transition towards sustainable alternative fuels would not only benefit the planet, but would also create a large number of technology-driven jobs. Since innovation in alternative fuels is primarily driven by R&D, human capital is at the core of a successful transition. Countries without oil and gas reserves now have an opportunity to differentiate and become a key player in the energy transition. It is up to them to seize that opportunity by providing the right incentives.

11.7. Scientific relevance

To identify the scientific relevance of this research, the knowledge gap of chapter 7 is addressed. The knowledge gap that was discovered can be summarised in the following items:

- There was no insight into how (alternative) fuels compared in the view of shipowners.
- The financial performance of alternative fuels had not been analysed over the lifetime of a vessel.
- The impact of alternative fuels on a shipowner's business performance was unknown.
- There was no view on the impact of regulatory scenarios on the future fuel choice of shipowners.

First, a SMART decision model was developed to assess the preference of shipowners towards alternative fuels. Shipowners provided their input through a survey stating which criteria they found most important in judging an alternative fuel technology. By combining this knowledge with performance parameters from literature, insight could be provided in the views of shipowners towards different alternative fuels.

Second, the financial performance of alternative fuels has previously primarily been analysed on fuel cost. However, fuel cost is not the only cost item influencing the financial performance of alternative fuels over a vessel's lifetime. In the present decision tool, a financial model has been composed accounting for all involved cost items per fuel alternative. This includes different expenses per fuel alternative for port charges, canal dues, fuel, emissions, crew, engine OPEX, insurance, administration, engine CAPEX, financing, dry dock and special survey. Additionally, the decision tool has demonstrated that return can be improved by optimising for economic speed.

Third, financial indicators such as the required freight rate have been devised to provide insight into the impact of alternative fuels on a shipowner's business performance. As demonstrated in table 9.6, shipowners are now able to compare the performance of (alternative) fuels against each other.

At last, there was no clear view of how different regulatory scenarios might impact a shipowner's current business performance. The decision tool provides shipowners with a quantified impact on their current business if they do not transition to an alternative fuel under a market-based measure scenario, as well as best-alternatives if their current fuels do not meet regulations under an emission cap scenario.

A

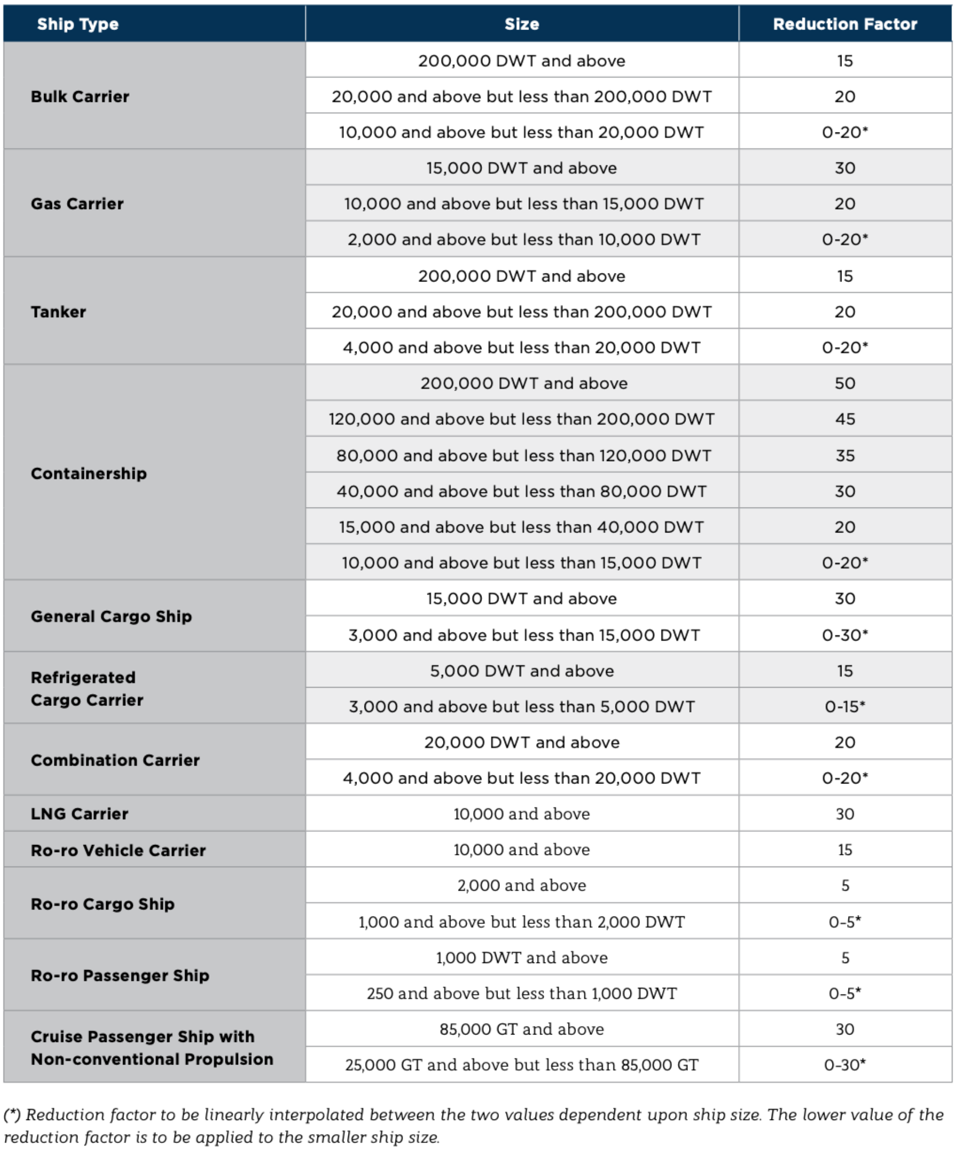
Criteria units

Criteria units			
Technical	Technological maturity	10	10: Proven technology
		7 to 9	7 to 9: Systems testing for launch and operations
		6 to 8	6 to 8: System and subsystem development
		5 to 7	5 to 7: Technology demonstration
		3 to 5	3 to 5: Technology development
		1 to 2	1 to 2: Basic technology research
	Availability of infrastructure	5	Fully available
		4	Available after minor adjustments
		3	Available after moderate adjustments
		2	Available after major adjustments
		1	Not available at all
	Engine compatibility	5	Fully compatible with current engines
		4	Compatible after minor afjustments
		3	Compatible after moderate afjustments
		2	Compatible after major afjustments
		1	Not compatible at all
Environmental	Fuel volumetric energy density	MJ/l	Megajoule per litre
	Compliance with emission regulations	5	Fully compliant with current emission regulations
		4	Fully compliant with minor exceptions
		3	Moderately compliant
		2	Hardly compliant
		1	Not compliant at all
	GHG emissions: well-to-tank	gCO_2eq/MJ	Gram CO_2 equivalent GHG emissions per MJ energy
	GHG emissions: tank-to-propeller	gCO_2eq/MJ	Gram CO_2 equivalent GHG emissions per MJ energy
Other	Safety of fuel technology	5	As safe as current technologies
		4	Slightly less safe than current technologies
		3	Moderately safe
		2	Not really safe
		1	Not safe at all
	Long-term global availability of fuel	5	Fully available in the long-term
		4	Available with slight shortage in the long-term
		3	Moderately available in the long-term
		2	Poorly available in the long-term
		1	Not available in the long-term
	Feedstock competition with food (if applicable)	5	No competition with food
		4	Minor competition with food
		3	Moderate competition with food
		2	Major competition with food
		1	Critical competition with food

Table A.1: Units describing each criterion. Own composition

B

Reduction factors



Ship Type	Size	Reduction Factor
Bulk Carrier	200,000 DWT and above	15
	20,000 and above but less than 200,000 DWT	20
	10,000 and above but less than 20,000 DWT	0-20*
Gas Carrier	15,000 DWT and above	30
	10,000 and above but less than 15,000 DWT	20
	2,000 and above but less than 10,000 DWT	0-20*
Tanker	200,000 DWT and above	15
	20,000 and above but less than 200,000 DWT	20
	4,000 and above but less than 20,000 DWT	0-20*
Containership	200,000 DWT and above	50
	120,000 and above but less than 200,000 DWT	45
	80,000 and above but less than 120,000 DWT	35
	40,000 and above but less than 80,000 DWT	30
	15,000 and above but less than 40,000 DWT	20
	10,000 and above but less than 15,000 DWT	0-20*
General Cargo Ship	15,000 DWT and above	30
	3,000 and above but less than 15,000 DWT	0-30*
Refrigerated Cargo Carrier	5,000 DWT and above	15
	3,000 and above but less than 5,000 DWT	0-15*
Combination Carrier	20,000 DWT and above	20
	4,000 and above but less than 20,000 DWT	0-20*
LNG Carrier	10,000 and above	30
Ro-ro Vehicle Carrier	10,000 and above	15
Ro-ro Cargo Ship	2,000 and above	5
	1,000 and above but less than 2,000 DWT	0-5*
Ro-ro Passenger Ship	1,000 DWT and above	5
	250 and above but less than 1,000 DWT	0-5*
Cruise Passenger Ship with Non-conventional Propulsion	85,000 GT and above	30
	25,000 GT and above but less than 85,000 GT	0-30*

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

Figure B.1: EEXI reduction factors Y. Source: ABS (2020) [12]

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