Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

Dorthe Alida Arntzen Slotvik

Decision support for future proof ship fuel selection
- *Moving beyond cost-efficiency*

Master's thesis in Marine Technology
Supervisor: Stein Ove Erikstad
Co-supervisor: Øyvind Endresen and Martin Wattum
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Master Thesis in Marine Systems Design

Stud. techn. Dorthe Alida Arntzen Slotvik

Decision Support for Future Proof Ship Fuel Selection
– Moving Beyond Cost-Efficiency

Spring 2022

Background

The International Maritime Organization (IMO) has set goals to achieve low carbon shipping by 2050. The decarbonization strategy is certain to provoke regulations to reduce greenhouse gas emissions. The uncertainty of to which degree and in which form presents a considerable risk for the shipping stakeholders, mainly shipowners. To set the global maritime industry on a climate-aligned course and meet the goals of the Paris Agreement, zero-emission vessels must be the dominant and competitive choice by the end of this decade. With a fuel transition characterized by a wide range of fuel options and unknown future regulations, the shipowners face a complex and uncertain decision process regarding fuel selection.

Main goal and focus area

The aim of the thesis is to develop a decision support method for shipowners selecting among a wide range of fuel options on the road to decarbonize shipping. The method shall be able to move beyond cost-efficiency and take technical, environmental, and social factors into consideration.

Main activities

The candidate should presumably cover the following main points:

1. A literature review of ship fuel options
2. Develop a multi-criteria optimization model and a belonging decision support method for ship fuel selection
3. Map the decision basis for fuel selection and the preferences of different stakeholders
4. Compare and evaluate different fuel options for deep-sea shipping
5. Apply the decision support method to a case study concerning shipowner fuel selection for operation at deep sea
6. Discuss and conclude the thesis work

Modus operandi

At NTNU, Professor Stein Ove Erikstad will be the responsible advisor. Øyvind Endresen from DNV and Martin Wattum from Klaveness will be co-supervisors. Klaveness will provide data and information to the case study.

The work shall follow the guidelines given by NTNU for the MSc Project work.

Stein Ove Erikstad
Professor/Responsible Advisor

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SUMMARY

Around 80% of global trade by volume and over 70% by value is carried by sea. Global shipping over deep seas ensures the most cost-effective transport of import and export of food and manufactured goods and has a significant impact on the world economy. At the same time, maritime transport is responsible for about 3% of global greenhouse gas (GHG) emissions. The United Nations' International Maritime Organization (IMO) has set goals to achieve low carbon shipping by 2050. The decarbonization strategy is certain to provoke regulations to reduce greenhouse gas emissions. The uncertainty of to which degree and in which form presents a considerable risk for the shipping stakeholders, mainly shipowners. The aim of decarbonization has provoked a new fuel transition, characterized by a wide range of fuel options and unknown future regulations. Shipowners face a complex and uncertain decision process regarding future proof fuel selection.

To support the process, a multi-criteria optimization model and a belonging decision support method for ship fuel selection are developed. The model is open to including a wide range of technical, economic, environmental, and social decision criteria and numerous fuel options. The criteria are selected and weighed by the decision-maker. The fuel performance are quantified and evaluated based on defined performance levels. The method combines the stakeholder's subjective preferences of criteria with an objective evaluation of the fuel performance. Criteria, barriers, and fuel performance were evaluated in three different approaches;

1. Comparison-based screening of fuel options for deep-sea shipping based on six key performance indicators (KPIs)
2. Survey among stakeholders
3. Case study considering shipowner fuel selection for operation at deep sea.

In the comparison-based screening of fuel options for deep-sea shipping, twelve fuel options were evaluated based on their performance on six KPIs covering technical, economic, environmental, and social aspects. Within each criterion, five performance levels were defined, referred to as the performance level system. The screening process took the energy source for production (fossil, bio, or green) into account. The results showed no clear choice among the alternative fuels. LNG will probably continue to be an important fuel for deep-sea in the transition to more carbon-neutral fuels. Another possible transition solution might be the fossil version of potential carbon-neutral fuels, combined with CCS technology (so-called blue fuels). This will contribute to increasing the technology maturity level and the available bunkering facilities and facilitate a future transition to the greener version of the fuel.

The subjective preferences of decision-makers were mapped through a questionnaire survey among stakeholders in the industry and a focus interview with a shipowner. VLSFO/HFO and battery-electric propulsion gained the overall highest score on the average of all 12 criteria included in the survey. Green/blue methanol, renewable biofuels, and green/blue ammonia were, on the other hand, stated as the top three preferred fuels. All criteria, both technical, economic, environmental, and social criteria, were ranked as 'fairly important' or more important, which confirms a complex decision problem. Even if all barriers were stated as significant, the results showed a will to act. Among the participants in the survey, which mainly were forward-leaning Norwegian stakeholders, 79% believed that the first move toward green fuels will be within ten years for their own fleet and operation. Governmental and international regulators were ranked as the top driver in shipping decarbonization, followed by a group of cargo owners, market and customers, and ship owners.

Finally, the decision support method was applied to a case study concerning shipowner fuel selection for operation at deep sea. The case study shows that if business continues as usual, LNG will continue to be the preferred fuel until 2050. However, with sustainable development, green methanol and renewable biodiesel can obtain a competitive performance and be the preferred fuel for shipowners. Notice that the results for such a case study will depend on the decision context, the selected criteria, and the fuel options included.

Both the screening of fuels, the survey results, and the case study show that there still exists large barriers to implementing low carbon emission fuels. The greener fuel alternatives face several challenges, but common main barriers are low technology maturity levels, low energy densities, poorly developed infrastructure, deficient safety regulations, and high costs. A crucial decision for the industry is where the stakeholders should invest time, research, and money to bring the decarbonization of shipping forward and reach the goal of reducing 50% of GHG emissions by 2050.

The thesis argues that better mapping of the fuel selection process is required in order to accelerate the decarbonization of shipping. The decision support method for ship fuel selection provides clearer objectives, greater robustness, and traceability to the choices made during the decision process. The decision support method can assess a wide range of criteria and perspectives of the decision-maker and pay attention to the changing performance of the different fuel alternatives, which will improve the communication of factors influencing the fuel selection process. The identification of criteria and barriers can be used to map where support and development is needed to increase the fuel performance on key criteria. Better insight into the stakeholder preferences can provide knowledge of decision criteria and identify current showstoppers for green action. Dialog and cooperation between stakeholders will improve policies and accelerate the establishment of decarbonization incentives. As proposed in this thesis, better mapping and structuring can be achieved through a more systematic decision-making method.

SAMMENDRAG

Rundt 80% av verdenshandelen etter volum og over 70% av verdi fraktes til sjøs. Global skipsfart over dype hav sikrer den mest kostnadseffektive transporten av import og eksport av mat og produserte varer og har en betydelig innvirkning på verdensøkonomien. Samtidig er sjøtransport ansvarlig for om lag 3% av globale klimagassutslipp (GHG). FNs internasjonale sjøfartsorganisasjon (IMO) har satt seg mål om å oppnå lavkarbon skipsfart innen 2050. Avkarboniseringsstrategien vil med sikkerhet fremprovosere reguleringer for å redusere klimagassutslipp. I hvilken grad og i hvilken form er enda usikkert, noe som utgjør en betydelig risiko for aktører i skipsfarten, i hovedsak rederier. Målet med avkarbonisering har skapt en ny drivstofftransisjon, preget av et bredt spekter av drivstoffalternativer og ukjente fremtidige reguleringer. Redere står overfor en kompleks og usikker beslutningsprosess for et fremtidssikkert og robust valg av drivstoff.

For å støtte prosessen utvikles en multi-kriterie optimaliseringsmodell og en tilhørende beslutningsstøttemetode for valg av drivstoff. Modellen er åpen for å inkludere et bredt spekter av tekniske, økonomiske, miljømessige og sosiale beslutningskriterier og en rekke drivstoffalternativer. Kriteriene velges og vektlegges av beslutningstaker. Drivstoffytelsen blir kvantifisert og evaluert basert på definerte ytelsesnivåer. Metoden kombinerer beslutningstakerens subjektive preferanser av kriterier med en objektiv evaluering av drivstoffytelsen. Kriterier, barrierer og til hvilken grad ulike drivstoff oppnår ulike kriterier ble evaluert i tre ulike tilnærminger;

1. Sammenligningsbasert screening av drivstoffalternativer for dyphavsfart basert på seks nøkkelindikatorer (KPIs)
2. Spørreundersøkelse blant aktører i skipsfart
3. Casestudie om reders valg av drivstoff for operasjon på dypt hav

I den sammenligningsbaserte screeningen av drivstoffalternativer for dyphavsfart, ble tolv drivstoffalternativer evaluert basert på deres ytelse på seks nøkkelindikatorer som dekker både tekniske, økonomiske, miljømessige og sosiale aspekter. Innenfor hvert kriterium ble det definert fem ytelsesnivåer, referert til som ‘performance level system’. Screeningsprosessen tok hensyn til energikilden for produksjon (fossil, bio eller grønn). Resultatene viste ikke noe klart valg blant de alternative drivstoffene. LNG vil trolig fortsatt være et viktig drivstoff for dypvann i overgangen til mer karbonnøytrale drivstoff. En annen mulig overgangsløsning kan være den fossile versjonen av potensielle karbonnøytrale drivstoff, kombinert med CCS-teknologi (såkalte blå drivstoff). Dette

vil bidra til å øke teknologimodningsnivået og tilgjengelige bunkringsfasiliteter og legge til rette for en fremtidig overgang til den grønnere versjonen av drivstoffet.

Beslutningstakernes subjektive preferanser ble kartlagt gjennom en spørreskjemaundersøkelse blant aktører i næringen og et fokusintervju med en reder. VLSFO/HFO og batterielektrisk fremdrift fikk den samlede høyeste poengsummen på gjennomsnittet av alle 12 kriteriene som var inkludert i undersøkelsen. Grønn/blå metanol, fornybart biodrivstoff og grønn/blå ammoniakk ble likevel oppgitt som de tre foretrukne drivstoffene. Alle kriterier, både tekniske, økonomiske, miljømessige og sosiale kriterier, ble rangert som ”ganske viktige” eller viktigere, noe som bekrefter et komplekst beslutningsproblem. Selv om alle barrierer ble oppgitt som betydelige, viste resultatene en vilje til å handle. Blant deltakerne i undersøkelsen, som hovedsakelig var fremoverlente norske skipsfartsaktører, mente 79% at det første grepet mot grønne drivstoff vil være innen ti år for egen flåte og drift. Statlige og internasjonale regulatorer ble rangert som den største driveren for avkarbonisering, etterfulgt av en gruppe med lasteeiere, marked og kunder, og redere.

Avslutningsvis ble beslutningsstøttemetoden brukt på en casestudie om reders valg av drivstoff for operasjon på dypt hav. Case studien viser at dersom driften av skipsfart fortsetter som vanlig, vil LNG fortsette å være det foretrukne drivstoffet frem til 2050. Med bærekraftig utvikling kan grønn metanol og fornybar biodiesel oppnå en konkurransedyktig ytelse og være det foretrukne drivstoffet for redere. Merk at resultatene for en slik casestudie vil avhenge av beslutningskonteksten, de valgte kriteriene og drivstoffalternativene som er inkludert. Både screening av drivstoff, resultatene fra spørreundersøkelsen og casestudien viser at det fortsatt eksisterer store barrierer for å implementere drivstoff med lavt karbonutslipp. De grønnere drivstoffalternativene står overfor flere utfordringer, men lav modenhet av teknologi, dårlig utviklet infrastruktur, mangelfulle sikkerhetsforskrifter og høye kostnader ble konstatert som betydelige barrierer. En avgjørende beslutning for skipsfart er hvor aktørene skal investere tid, forskning og penger for å bringe avkarboniseringen av skipsfart fremover og nå målet om å redusere 50% av klimagassutslippene innen 2050.

Masteroppgaven argumenterer for at bedre kartlegging av drivstoffutvelgelsesprosessen er nødvendig for å akselerere avkarboniseringen av skipsfart. Beslutningsstøttemetoden for valg av skipsdrivstoff gir klarere mål, større robusthet og sporbarhet til valgene som blir tatt under beslutningsprosessen. Beslutningsstøttemetoden kan vurdere et bredt spekter av kriterier og perspektiver til beslutningstakeren og ta hensyn til den endrede ytelsen av ulike drivstoffalternativ, noe som vil forbedre kommunikasjonen av faktorer som påvirker drivstoffvalgsprosessen. Identifikasjon av kriterier og barrierer kan brukes til å kartlegge hvor støtte og utvikling er nødvendig for å øke drivstoffytelsen på sentrale kriterier. Bedre innsikt i aktørenes preferanser kan gi kunnskap om beslutningskriterier og identifisere aktuelle showstoppere for grønn handling. Dialog og samarbeid mellom aktører vil forbedre politikken og fremskynde insentiver for avkarbonisering. Bedre kartlegging og strukturering kan oppnås ved en mer systematisert beslutningsmetode, slik som metoden foreslått i denne oppgaven.

PREFACE

This thesis is the work of a Master of Science degree at the Department of Marine Technology at the Norwegian University of Science and Technology (NTNU). The thesis is written during the spring semester 2022 and is the the final work of the five-years master's degree program with specialization in Marine System Design. The workload corresponds to 30 credits. Parts of the work is based on a pre-project from the fall of 2021. This mainly concern a literature review of ship fuel pathways. The report is written in its entirety by Dorthe Alida Arntzen Slotvik.

The motivation of the work is to gain knowledge about the current status of zero-emission fuel for vessels operating at deep sea, and how this insight can be used to accelerate the uptake of alternative fuels and contribute to the decarbonization of shipping.

This master thesis has allowed me to expand my knowledge in a self-chosen direction, a challenging but enjoyable part of my education.

DAASlotvik

Dorthe Alida Arntzen Slotvik

Trondheim, June 10, 2022

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ACKNOWLEDGEMENT

I would like to thank my two supervisors, Professor Stein Ove Erikstad (NTNU) and Øyvind Endresen (DNV), for sharing knowledge, providing good references, and guiding me throughout the semester. I would also like to thank Klaveness and especially Martin Wattum for valuable insight into the shipowner's perspective and contribution to the case study. In addition, I would like to thank Ph.D. candidate Benjamin Lagemann for discussion and frequent support.

Lastly, I would like to thank Lucia, Maiten, Marit, Sofie, Thea, Tiril, and Hjørdis. I am grateful for a fun and motivating working environment.

Thank you,

Dorthe Alida Arntzen Slotvik

ABBREVIATIONS

GHG	Greenhouse Gas
IMO	International Maritime Organization
HFO	Heavy Fuel Oil
VLSFO	Very Low Sulphur Fuel Oil
MGO	Marine Gas Oil
NG	Natural Gas
LNG	Liquefied Natural Gas
LPG	Liquified Petroleum Gas
HVO	Hydrotreated Vegetable Oil
KPI	Key Performance Index
CCS	Carbon capture and storage
ICE	Internal Combustion Engine
FC	Fuel Cell
DF	Dual Fuel
TRL	Technology Readiness Level
CAPEX	Capital Expenses
OPEX	Operational Expenses
VOYEX	Voyage Related Expenses
GWP	Global Warming Potential
IGC Code	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF Code	International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels
MCDA	Multi Criteria Decision Analysis
MCDM	Multi Criteria Decision Making
AHP	Analytical Hierarchy Process

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CHAPTER 1

INTRODUCTION

This chapter introduces the problem assessed, presenting the background and objective of the study, including scope and limitations. The chapter also gives an overview of the report structure, including a short description of each chapter.

1.1 Background

Around 80% of global trade by volume and over 70% by value is carried by sea. Global shipping over deep seas ensures the most cost-effective transport of import and export of food and manufactured goods and has a significant impact on the world economy. At the same time, maritime transport is responsible for about 3% of global greenhouse gas (GHG) emissions [1]. These emissions are projected to increase significantly if mitigation measures are not put in place swiftly. The International Maritime Organization (IMO) has set decarbonization strategies that follow sustainable development goals. Alternative marine fuels play an essential role in the road to achieving low carbon shipping by 2050. The wide range of ship fuel options makes the situation messy and challenging to handle for stakeholders involved.

IMO has established a GHG strategy to reduce the total annual GHG emissions from international shipping by at least 50% by 2050 compared to 2008 levels. The world seaborne trade are expected to grow further, a factor that pulls in the opposite direction of IMOs ambitions. According to the 4th IMO GHG study, shipping emissions could, under a business-as-usual scenario, increase up to 130% of 2008 emissions by 2050. At the same time, technical innovations and tactical operations present an untapped potential for cost-effective reductions of the emissions [2]. To set the global maritime industry on a climate-aligned course and meet the goals of the Paris Agreement, zero-emission vessels must be the dominant and competitive choice by the end of this decade. With a fuel transition characterized by a wide range of fuel options, the ship owners face a complex and uncertain decision regarding fuel selection.

Current methodologies for comparing alternative fuels are mainly based on economic and environmental performance. However, there is limited work on the numerous additional factors influencing the selection process. These factors must be included better to understand the overall performance of the different fuel options and handle the complexity of the problem, including technical and social considerations. For other research studies assessing multiple criteria in the evaluation of ship fuels (e.g., [3], [4], [5], [6], [7] and [8]), there are large variations in which decision criteria that are assessed. There are also limited studies that include the subjective preferences of stakeholders, which is a central element in the final decision. Stakeholders have thoughts about which criteria are important and their relative importance, but they also have considerations about the fuel performance. A feasible fuel option should meet multiple technical, economic, environmental, and social criteria. However, the performance stated by the shipowner is not necessarily consistent with the real performance of the fuel option.

Therefore, this thesis has attempted to combine the subjective preferences of the decision-maker regarding criteria selection and weighting with the objective performance of a wide range of fuel options stated from literature research. The thesis wish to draw out hidden and unconscious factors influencing the fuel decision process and identify main barriers to the uptake of alternative fuels. The insight of criteria and barriers for the ship fuel selection problem shall serve as guidance in an important but uncertain decision for the future.

1.2 Objectives

Finding the most suited fuel option for global shipping is a challenging task dependent on numerous technical, economic, environmental, and social factors. The thesis seeks to map the current decision basis for fuel selection, to identify decision criteria and barriers of action. The thesis aim to use the insights to systematize a decision support method for shipowners selecting among a wide range of fuel options.

A multi-criteria optimization model that can include a wide range of criteria and perspectives of the decision-maker and pay attention to the changing performance of the different fuel alternatives will improve the communication of factors influencing the fuel selection process. The thesis collects information, from a general, qualitative description to processed and adapted quantitative data that will serve as input to the decision model. A case study for deep-sea shipping is prepared to illustrate the decision support method and highlight the subjectivity of the fuel decision. However, the method is open to include a wide range of criteria and numerous fuel options, making it able to support all shipping stakeholders.

1.3 Scope and limitations

The study assesses the prospects for eight energy carriers by applying a multi-criteria decision analysis approach, mainly considering the stakeholders' preferences. Figure 1.1 shows the graphical abstract of the thesis problem and fuel options in scope. The study includes an assessment of technical, environmental, economic, and social factors influencing the selection of ship fuels. Questionnaires and focus interviews are applied to elicit key criteria and their relative importance from different stakeholders, explicitly focusing on shipowners.

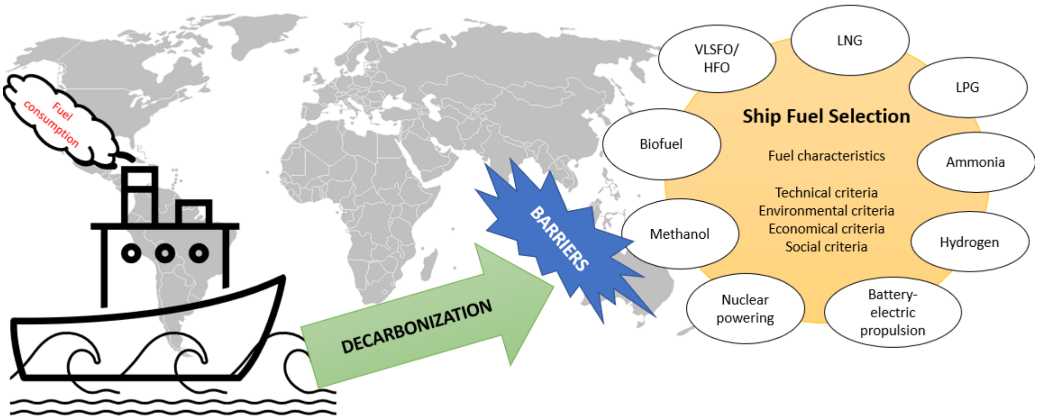


Figure 1.1: Ship Fuel Transition Challenge (inspired by 'Graphical abstract' figure in [9])

The thesis focuses on the benefits and challenges of different alternative fuels and how stakeholders compare them in fuel selection. The collection of subjective preference information concentrates on Norwegian stakeholders. Therefore, the findings must be evaluated and handled cautiously before drawing lines to other geographical regions or cases. The scope of this thesis is deep-sea shipping due to its large impact on global emissions. Still, general considerations and contrasts to short sea shipping are included to understand the overall picture of ship fuels better.

In this thesis, alternative fuels referrers to all fuels that are not designated as conventional fuels (fuel oil, etc.). Green fuels are used as a common destination for low- and zero-carbon emission fuels.

The study results depend on the included fuel types and the opinions of the individuals included in the stakeholder preference study. Only mono-fuelled options are assessed, but other possibilities are discussed. Assumptions regarding fuel production pathways and current fuel performance will also affect the outcome. A high-level approach is used for modeling due to the extensiveness of the thesis objective. Only a selection of technical, economic, environmental, and social criteria are addressed. Due to the target to decarbonize shipping, the main environmental focus will be on CO_2 emissions.

1.4 Report structure

This section presents the structure of the thesis. As shown in Figure 1.2, the first four chapters form the literature background of the thesis. The methodology is presented in chapter 5. Further, the fuel selection optimization modelling is presented chapter 6. In chapter 7, a selection of fuels is evaluated using a comparison-based approach that combines KPIs and performance in a performance level system. Subjective information from stakeholders is collected in chapter 8. The developed decision support method is applied to a case study in chapter 9.

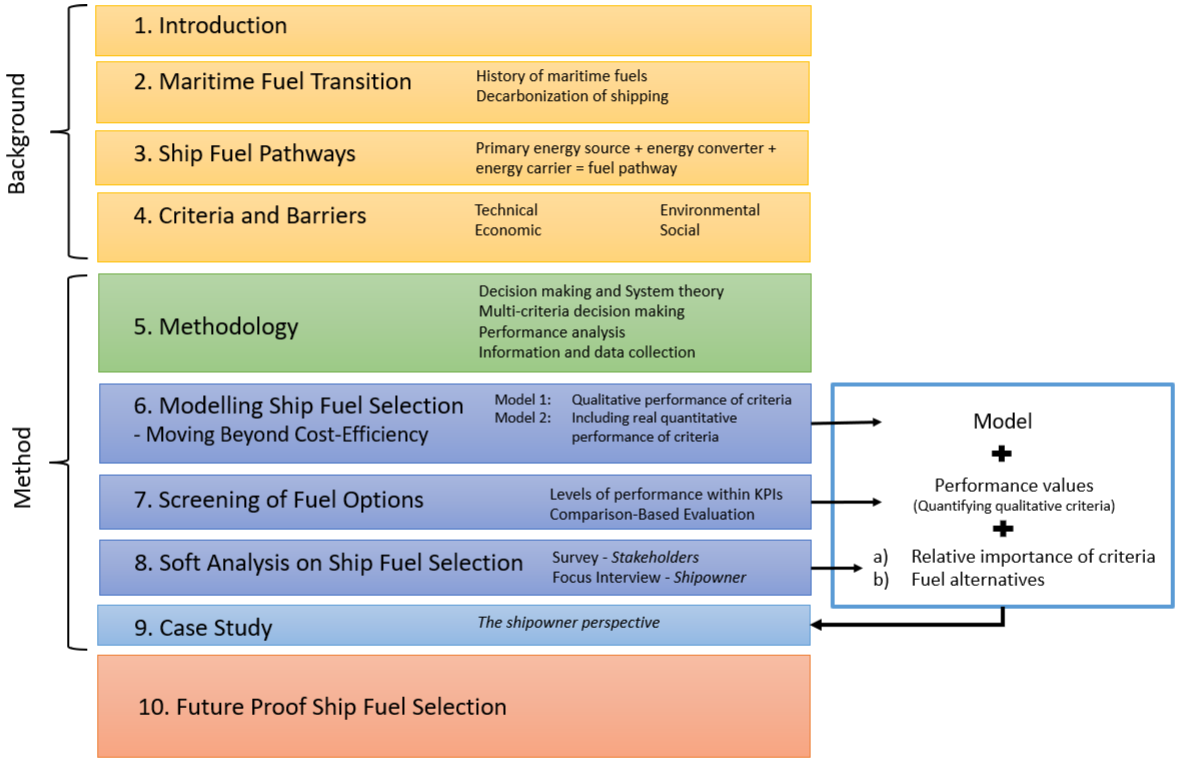


Figure 1.2: Overview of the thesis structure

The following list includes a more detailed description of the content in each chapter:

- chapter 2 presents a literature background for maritime fuels and addresses the fuel transition provoked by the decarbonization of shipping.
- chapter 3 introduces different ship fuel pathways. The chapter includes *fuel families* based on primary energy sources, main energy converters, and a selection of fuel options for shipping.
- Based on a literature review, chapter 4 presents key criteria and barriers to the uptake of zero- and low-carbon emission fuels in shipping. The chapter also presents the decision context and expectations for ship fuels in terms of design for operation. The chapter introduces a range of factors influencing the fuel type decision.
- chapter 5 introduces the methodology for the project work, including relevant theory and methods for modelling and information collection. System perspectives, multi-criteria decision making and soft analysis in terms of survey and focus interview are central components.
- chapter 6 presents two mathematical multi-criteria optimization models which take the relative importance (weighting) of the criteria into account. Both models are based on the weighted sum method (presented in subsection 5.2.3). The first model is simple and handles all criteria as qualitative. The second model opens up to include real quantitative performance of specific criteria. Model 1 will be applied to the case study.
- chapter 7 presents a specific performance level system that quantifies qualitative performance within a selection of criteria. The level system is defined for six key performance indicators (KPIs) and used to perform a comparison-based screening and evaluation of the fuels for operation at deep sea. All KPIs have been allocated the same relative importance (weighting) in this screening process.

- chapter 8 presents a soft analysis of the ship fuel selection. The chapter includes the collecting of information on criteria and barriers in a survey among stakeholders and a focus interview with a shipowner, Klaveness. The interview section includes a shipowner selection and weighting of criteria. A selection of fuel types is further pairwise compared by the shipowner using the analytic hierarchy process (AHP). The AHP is described in subsection 5.2.1.
- In chapter 9, a case study is performed to gain insight into how the relative importance of criteria influences the decision outcome. This case study aims to combine the subjective criteria selected and weighted by the shipowner with the objective performance values for the different fuel options. Two case scenarios are studied: 1) 'business as usual' and 2) 'sustainable development'.
- chapter 10 discuss future proof fuel selection, both in general and from a shipowner perspective. The chapter also discusses how the knowledge of barriers and fuel flexibility can be used to increase the willingness to select greener fuels among shipowners and where the stakeholders should invest resources to accelerate the fuel transition.
- chapter 11 concludes the project work and presents further recommendations.

CHAPTER 2

MARITIME FUEL TRANSITION

This chapter presents the history of maritime fuels and key drivers on the road toward the decarbonization of shipping. The chapter also addresses the operational difference between short-sea and deep-sea shipping.

2.1 History of maritime fuels

Since the beginning of time, humanity has used the sea to transport cargo. Starting with minor trading routes with ships propelled by human and wind power, continuous development and higher demand have inspired faster, more cost-efficient, and effective transport at sea. The power systems of ships have been through several global and innovative revolutions, shown in Figure 2.1. The three first revolutions of shipping propulsion, from wind to coal, coal to steam, and steam to oil, were all characterized by every vessel making the same transition. The fourth revolution appears to be different, as the transition includes a wide range of fuel alternatives.

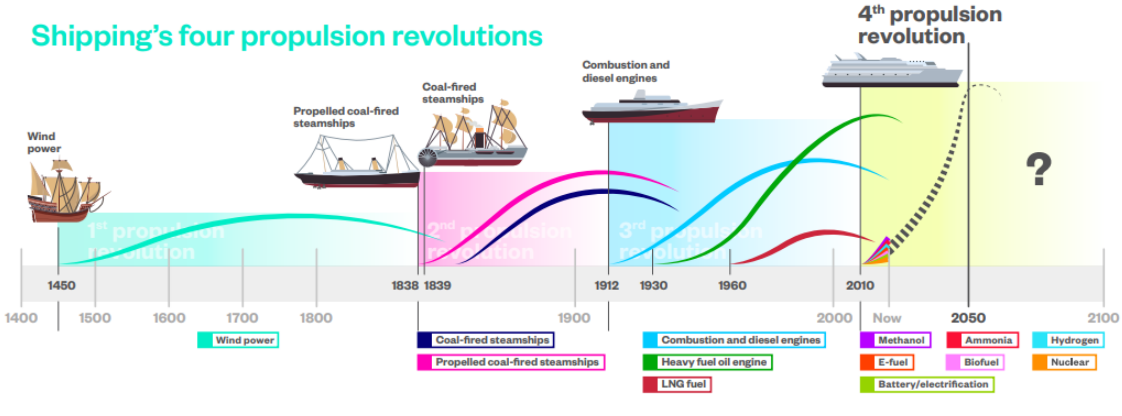


Figure 2.1: Shipping's four propulsion revolutions [10]

To date, fossil fuels have dominated the energy supply for maritime transport. The primary "bunker" fuel in shipping is fuel oil, including both heavy fuel oil (HFO), used in combination with exhaust treatment technologies, and Low Sulfur Heavy Fuel Oil (LSHFO) or Very Low Sulphur

Fuel Oil (VLSFO). HFO has a high content of carbon and air pollutants such as sulfur (SOx) and nitrogen (NOx) and is a very viscous residual fuel. Therefore, regulations on marine emissions (including GHG emissions and other emissions to air) have been gradually tightened, mainly led by IMO.

In Figure 2.2, DNV predicts the energy mix development in maritime sector until 2050. Until 2020, when 'IMO 2020' entered into force, over 79% of the energy fuel mix was covered by HFO, with the remaining parts mainly covered by other fossil fuels (e.g., marine diesel oil (MGO) and liquified natural gas (LNG)) [11]. 'IMO 2020' is known as the rule that limits the sulfur content in fuel oil used on board ships operating outside designated emission control areas to 0.50% m/m (mass by mass) [12]. The effect of 'IMO 2020' is shown in Figure 2.3, where a change in the fuel mix already can be spotted. A trend is that marine fuel demand is changing from 'cheaper and powerful' to 'eco-friendly and sustainable'.

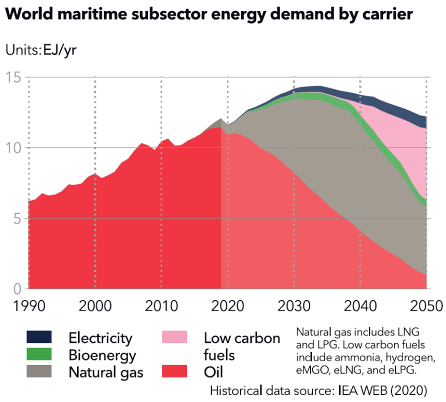


Figure 2.2: Energy mix development in maritime sector (adopted from [13])

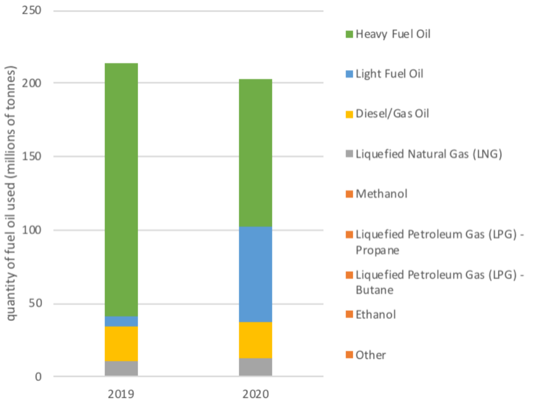


Figure 2.3: Aggregated annual amount of fuel type consumed by all ships above 5,000 GT (figure 2 in [14])

Never before have there been so many options for shipping fuel. Today's available fuel mix ranges from the fossil HFO, MDO and LNG, methane and methanol to greener mineral oil, bio-fuels, hydrogen, ammonia, and battery power. Notice that the illustration in Figure 2.1 has a negative forecast for LNG (red line), decreasing already from the year 2000. This may be discussed, but in this project, the evaluation of LNG is based on the development and increased number of vessels built and on order with LNG-fuelled propulsion systems.

Several trends in the industry indicate that environmental regulations at some point will favor low- and zero-emission fuels over traditional fossil fuels. So far, this is not the case, and fossil fuels with a few additional equipments (e.g., scrubber) to meet the current requirements for emissions are still the most straightforward and cheapest choice for a shipowner.

Figure 2.4 shows the current uptake of alternative fuels and technologies in shipping, including hybrids. The large number of scrubbers are mainly covered by bulk carriers, container ships, crude oil tankers, and oil/chemical tankers. These vessels typically operate at deep sea. New fuel alternatives and greener technology are primarily implemented on vessels operating at short sea, such as ferries and fishing vessels. Even if the initiative is positive, it has little impact on shipping's significant emissions as they primarily come from large cargo vessels operating at deep sea.

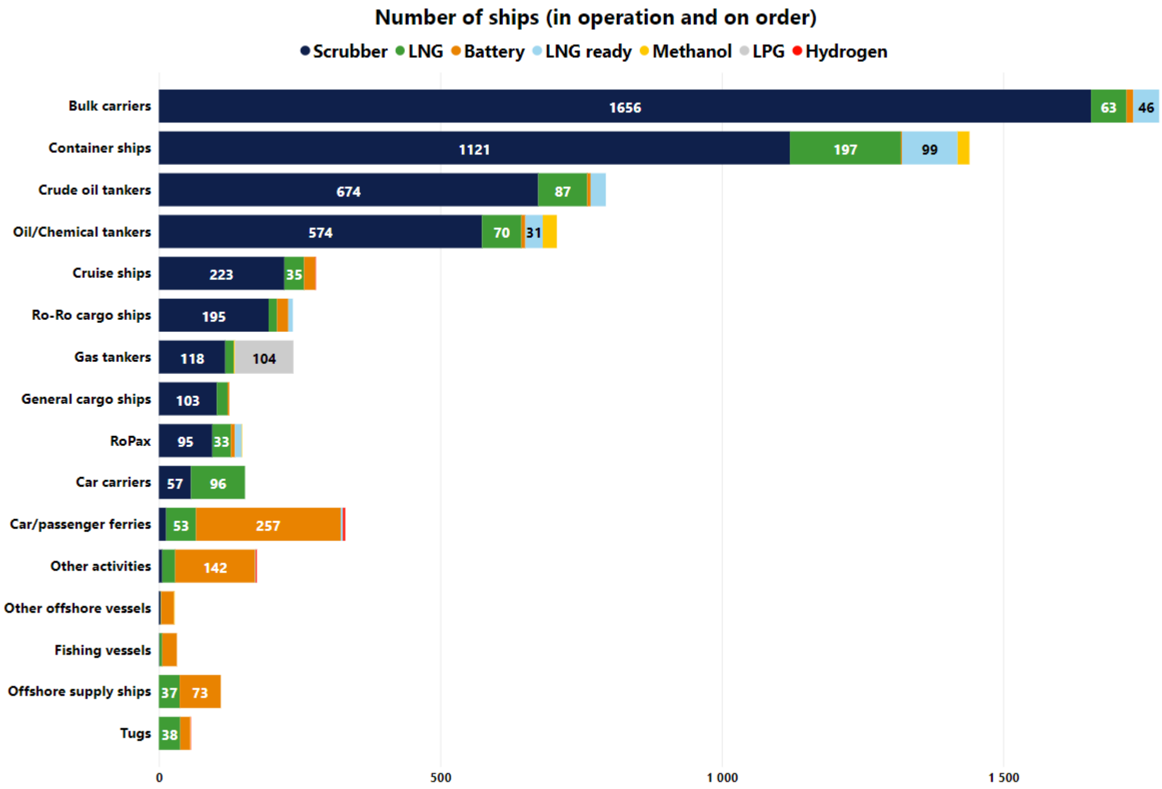


Figure 2.4: Number of ships with alternative fuels and technology, in operation and on order (accessed through DNVs AFI platform, May 2022 [15])

2.2 Decarbonization of shipping

The maritime industry faces a 'chicken-or-egg' scenario, where both fuel supplies and ship owners are waiting for new, alternative low and zero carbon emission fuels to enter the market. The ship owners do not dare to build new vessels with zero-emissions fuel systems, as they do not know if the fuel will be globally available. At the same time, the ports and fuel suppliers do not see an existing demand for green fuel and, therefore, are concerned about the return on investment. The variety in the numerous alternative fuels makes it even harder for both actors to know what type of fuel to commit. The question is who should lead the venture.

The limited customer demand and lack of global regulations for zero-emission shipping are essential barriers to initiating investments from both sides of the industry. Most potential alternative fuels have limited infrastructure, lower energy density, extensive storage and safety requirements, and hence significantly higher costs than today's dominant fossil fuels [16]. However, one thing is clear: to meet IMOs ambitions for shipping's decarbonization within 2050, the industry must perform a fuel transition led by 'net' zero carbon fuels. The fuel alternatives require mature international regulations and economic competitiveness for the transition to be successful.

With 2008 as a baseline year, IMO's strategy is to reduce at least 50% of total GHG emissions from shipping by 2050. At the same time, the average carbon intensity (CO_2 per tonne-mile) shall be reduced by at least 40% by 2030, and 70% before 2050. The ambitions are illustrated in Figure 2.5. This put increased pressure for accelerated decarbonization and reduction of shipping's emissions to air. Policies and regulations, demands from cargo owners and consumers, and access to capital are three fundamental factors that will drive the sector toward lower emissions.

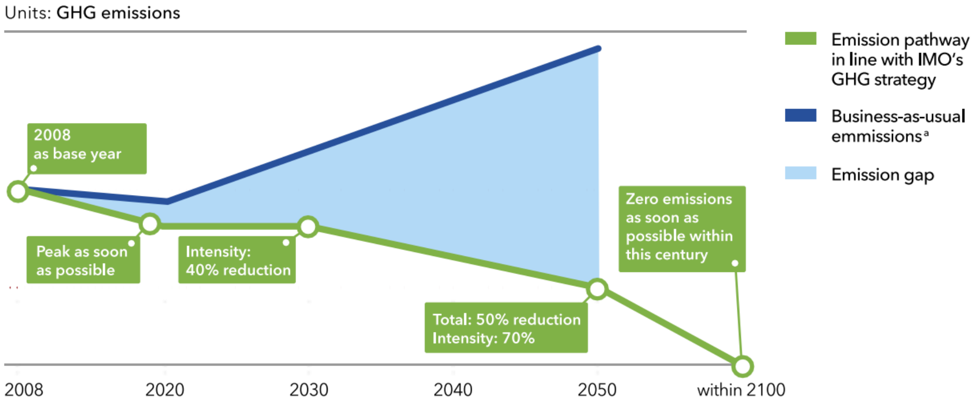


Figure 2.5: IMO's GHG reduction ambitions for shipping towards 2050 (adopted from DNV [17])

To achieve IMO's ambitions, new technology must be implemented, and system boundaries must be re-evaluated. New and promising technology is under development, but it must be scaled up and made available to have acceptable costs. The revolution must be driven by both operators (ship owners, cargo owners, and charterers), suppliers (designers, shipbuilders, engine manufacturers, fuel suppliers), investors (banks, insurance), and regulators (policymakers). The many stakeholders in the industry must take incentives and drive sustainable development.

2.2.1 Regulations and policies

Regulations and governmental policies are key drivers for shipping decarbonization, strongly led by IMO. To achieve the ambitions of reduced GHG emissions, IMO divides decarbonization measures into two; (i) a limited set of short-term measures, and (ii) more comprehensive medium- and long-term measures. IMO introduces a combination of technical and operational measures, and several short-term measures shall be set into force by 2023. An overview of IMOs GHG measures is presented in Table 2.1. Note that IMO also regulates other emissions, such as SOx and NOx emissions, but this will not be addressed in detail in this thesis.

Measure	**Into force**	**Description**
Energy Efficiency Design Index (EEDI)	Jan. 2013	For newbuilds mandating up to 30% or more improvement in design performance depending on ship type and size. It aims at promoting the use of more energy-efficient (less polluting) equipment and engines. The EEDI requires a minimum energy efficiency level per capacity mile (e.g., tonne mile) for different ship types and size segments.
Ship Energy Efficiency Management Plan (SEEMP)	Active	For all ships above 400 GT in operation – although it contains no explicit and mandatory requirements for content and implementation. SEEMP is an operational measure that establishes a mechanism to improve the energy efficiency of a ship cost-effectively. The SEEMP also provides an approach for shipping companies to manage ship and fleet efficiency performance over time using, for example, the Energy Efficiency Operational Indicator (EEOI) as a monitoring tool.
Fuel Oil Consumption Data Collection System (DCS)	Active	Mandating annual reporting of CO_2 emissions for all ships above 5,000 GT.
Energy Efficiency Design Index for Existing Ships (EEXI)	By 2023	A retroactive application of the EEDI to all existing cargo and cruise ships above a specific size. This will impose a requirement equivalent to EEDI Phase 2 or 3 (with some adjustments) to all existing ships regardless of the year of build and is intended as a one-off certification. EEXI is a technical measure, just looking at the design of the ship comparably as the EEDI does for newbuildings.
Carbon Intensity Indicator (CII)	By 2023	E.g. Annual Efficiency Ratio [AER – grams of CO_2 per dwt-mile]) - and rating scheme where all cargo and cruise ships above 5,000 GT are given a rating of A to E every year. For ships that achieve a D rating for three consecutive years or an E rating, a corrective action plan needs to be developed as part of the SEEMP and approved. CII is an operational measure considering the actual consumption and distance travelled for each individual ship in service[18].
Strengthening of the SEEMP (Enhanced SEEMP)	By 2023	To include mandatory content, such as an implementation plan on how to achieve the CII targets, and making it subject to approval. Verification and audit requirements for the SEEMP will only apply to ships above 5,000 GT subject to the CII requirements.
Energy-efficient operation index (EEOI)	Voluntary	A voluntary monitoring tool provided by the IMO to measure and monitor the actual CO_2 emission per ton-mile of transport work done by the ship. The EEOI enables operators to measure the fuel efficiency of a ship in operation and to gauge the effect of any changes in operation, e.g., improved voyage planning or more frequent propeller cleaning, or introduction of technical measures such as waste heat recovery systems or a new propeller.

Table 2.1: IMOs key decarbonization measures [19]

IMO regulations are currently only considering tank-to-propeller emissions. The whole lifecycle (well-to-wake) of CO_2 and other GHG emissions must be considered in order to fulfill the decarbonization of shipping and evaluate possible zero-emission concepts, as the new fuel alternatives can be produced from both fossil and renewable energy sources. IMO are working on GHG lifecycle guidelines [20].

In addition to IMO setting global guidelines, the EU has taken responsibility and aims to take the lead on the decarbonization through the European Green Deal strategy [21]. The European Commission aims to make Europe the first climate-neutral continent by 2050. The "Fit for 55" strategy has the goal of reducing emissions by at least 55% by 2030 compared to 1990 levels [22].

The development and implementation of new technology are influenced by shipping policies entering into force, both over short-, medium- and long term. In addition to the global regulations, regions, nations, and ports establish their own regulations and policies, all affecting decisions for the design and operation of ships. All these regulations and incentives indicate that shipping intends to reduce environmental impact and GHG emissions, forcing the ship owners and suppliers to act if they wish for investors and to be competitive in the future. This push can be included in the term "carbon risk".

2.2.2 Carbon risk

Carbon risk refers to the negative impact of unexpected changes due to carbon costs and regulations, embracing financial, regulatory, and cargo risks. Regulatory carbon risk primarily covers the risk of not satisfying future emissions regulations, leading to either denied operation of the vessel or costly retrofitting. Cargo risk is the risk of charterers and cargo owners, including carbon footprint and tracking of emissions as a central part of negotiating contracts. Cargo owners are already taking action and aiming for carbon-neutral transport within 2040 [23]. The combination of not being within regulations and neither being an attractive operator for charterers affects the financial risk, which covers loss of investors and capital, as well as risk of losing contracts and hence revenue. Figure 2.6 illustrates the increasing carbon risk as the decarbonization of shipping develops.

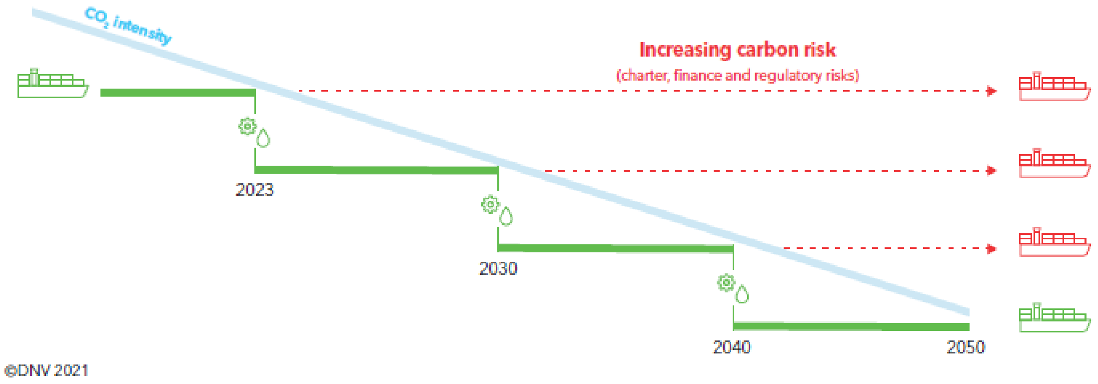


Figure 2.6: The decarbonization stairway and potential exposure to carbon risk (figure 4.1 in [13])

2.3 Deep-sea versus short-sea shipping

Shipping can be divided into two main categories: Short-sea and deep-sea shipping. Short-sea shipping embraces vessels operating in limited geographical areas with frequent port calls on short routes. The ships have a relatively low energy demand per round-trip and are often picked as candidates for pilot projects of new fuels. Norway has utilized this opportunity and is electrifying and developing hybrid-powered solutions for the ferry sector [24]. Deep-sea shipping covers large, oceangoing vessels operating at long routes, often without a regular schedule. This requires global fuel availability and infrastructure. In addition, the ship owners will maximize the cargo space, requiring high energy density fuels [25]. Zero-emission for deep-sea vessels is generally more complicated and challenging than for vessels operating short-sea. At the same time, these deep-sea vessels are the major cause of emissions from shipping. Hence, this is where we need to act.

As the current battery technology makes it impractical as a primary propulsion energy source for vessels operating at deep sea, other alternatives must be considered. Options such as LNG, biofuels, methanol, and LPG are discussed, providing a globally adequate bunkering infrastructure and quantities that satisfy the demand. Nuclear propulsion is another option that is technically feasible for large vessels. However, this option presents numerous political and societal barriers. Wind-assisted propulsion and weather routing can also decrease the costs of reduced emissions for large tankers and bulk carriers. However, a case study done by TU Delft showed that the fuel savings depends largely on the specific routes and travelling month (stronger wind conditions in the winter months) [26]. In this report, wind-assisted propulsion will not be further investigated.

A number of options and combinations are under development to decarbonize the maritime industry. The 'correct' fuel alternative for a small ferry sailing across a fjord might not be optimal for a large tanker sailing across the Atlantic ocean. The solutions will vary based on ship type and size, location, and operational factors. The large variety makes the process of decarbonization even harder, as there today does not exist a straightforward solution for the stakeholders.

CHAPTER 3

SHIP FUEL PATHWAYS

This chapter focus on primary sources of energy, energy conversion, and ship fuel types. First, the fuel energy sources will be presented in terms of ”fuel families”. Thereafter, the chapter presents relevant types of energy converters and a selection of fuel types. The chapter summarizes possible ship fuel pathways (energy source - fuel type - converter). This will serve as a knowledge basis for the further mapping and evaluation of ship fuel options.

In the mission to decarbonize shipping, fuels and energy are the measures with the highest potential for reducing emissions (see Figure 3.1). The combination of energy source, converter, and fuel alternative opens up a wide range of opportunities than include several factors of uncertainty. As the industry starts to look at the whole value chain, future regulations and the whole decarbonization of shipping require a clean fuel pathway.

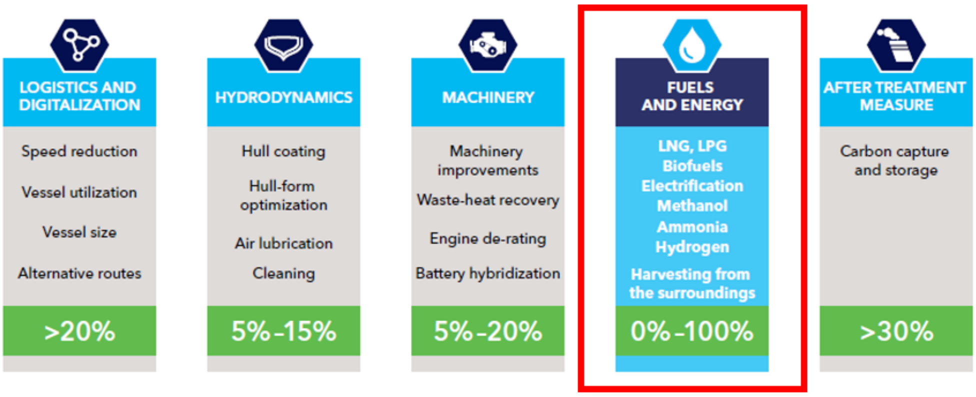


Figure 3.1: Available technologies to decarbonize shipping and their GHG emission reduction potential, highlighting fuels and energy as the focus area of this paper (figure 3 in [13])

3.1 Fuel ”families” - based on primary energy source

Fuel options in type of same energy carrier can originate from different energy sources, giving significant variations in life cycle cost and emission. Deciding whether a fuel can be referred to as green mainly depends on the primary energy source and how the fuel is produced. The different fuel alternatives can be categorized into ”fuel families”, depending on the primary energy source of the fuel. This section will give a short introduction to the four fuel families;

- **Fossil fuels** - from the decomposition of buried carbon-based organisms that died millions of years ago (fossil sources)
- **’Blue’ fuels** - from reformed natural gas with CCS
- **Biofuels** - from sustainable biomass sources
- **Electrofuels** - from renewable electricity, and nitrogen or non-fossil carbon

’Blue’ fuels, biofuels, and electrofuels present possible solutions that will challenge the conventional fossil fuel family in the green shift. An important notice is that even these families must be produced in a sustainable way. This includes using renewable electricity only, limiting the amount of water used during biomass production or only using biomass that can not be used for food, and ensuring that the carbon capture and storage (CCS) process is safe and secured.

3.1.1 Fossil fuels (grey)

Fossil fuels are formed by natural geological processes. Fossil fuels utilize the energy of organic sources that have been going through a geological process of millions of years, transforming the organisms into fossil sources. The process transforms the minerals into several high-carbon minerals, such as coal, oil, and natural gas. These transformed minerals are extracted through mining and drilling and further exploited as energy through combustion.

Fossil fuels are the dominant global energy source. In shipping, fossil fuels such as HFO and MGO play an essential role in the dependability of global fuel supply. However, the high dependability comes with significant negative consequences. When burning fossil fuels, carbon dioxide (CO_2) is produced. CO_2 is the largest driver of global GHG emissions and a major contributor to local air pollution.

3.1.2 ’Blue’ fuels (fossil sources + CCS)

Blue fuels use carbon capture and storage (CCS) technology to meet zero-emission demand. CCS is an additional solution to reduce CO_2 emissions from ships. In general, CCS takes the CO_2 emissions and stores them underground. For two decades, the Norwegian Oil Industry has stored CO_2 from facilities such as the Sleipner and Snøhvit field [27][28]. Now, Norway is moving to the forefront of CCS technology with the Longship CCS Project. This is the first industrial CCS project developing significant CO_2 store capacity and belonging infrastructure, storing CO_2 emissions from the European continent [29]. CCS is primarily developed for large, stationary emissions points such as power generation plants or factories. The maritime industry has also taken an interest in using carbon capture and temporary storage technology onboard vessels to contribute to the decarbonization of shipping. Figure 3.2 shows the concept of post-combustion capture onboard vessels. Liquid absorption technology, with or without membranes, is interesting for CCS system concepts onboard vessels. However, system complexity, costs, space requirements, and lack of regulations are challenges for onboard CCS systems. In addition, the concept still needs a large-scale demonstration with persuasive results. Another major barrier is the lack of infrastructure for the total CCS value chain, which is necessary for easy-accessible systems where the captured CO_2 can be stored (Ch. 3 in [13]).

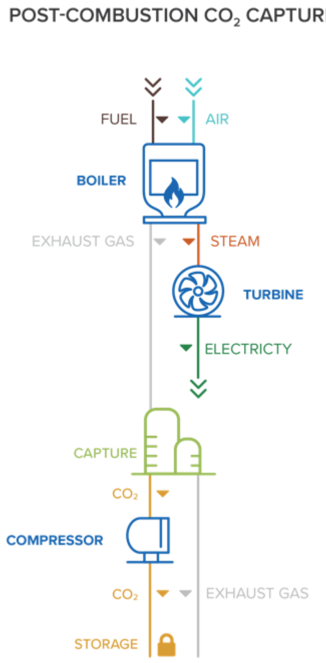


Figure 3.2: Conceptual illustration of post combustion capture onboard vessels (adopted from [30])

A maritime CCS system does also have important requirements for land-based infrastructure. There must be reception facilities and ways to transport the CO_2. Possible solutions could be dedicated CO_2 carriers, underground storage, or utilizing the CO_2 for other purposes. The low maturity of onboard CCS technology and support infrastructure are main challenges that need further development. However, embedded CCS systems can play an important role in meeting emissions targets before carbon-free fuels become viable due to the high maturity of onshore applications. Ship-based CCS will probably also be a long-term measure given the long life of existing and planned hydrocarbon-powered ships.

3.1.3 Biofuels

Biofuels are derived from primary biomass or biomass residues, both vegetable, animal, or a combination, that are converted into liquid or gaseous fuels. The fuels are obtained from a variety of feedstocks and conversions. Figure 3.3 shows a simplified life cycle of biofuels; CO_2 absorption for biomass biosynthesis, generation of renewable raw materials, biofuel processing and production, and fuels burning and gas emissions.

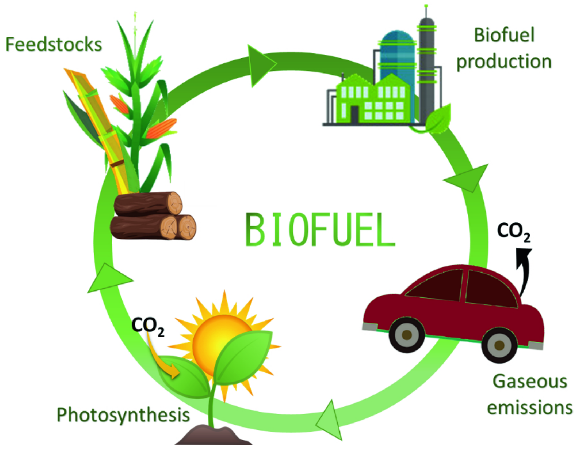


Figure 3.3: Simplified life cycle of biofuels (adopted from [31])

Biodiesel and liquid biogas (LBG) are the most promising biofuels for ships. Common types of biodiesel are fatty acid methyl ester (FAME), biomass-to-liquids (BTL), and hydrotreated vegetable oil (HVO), suitable for replacing MDO and MGO. LBG can replace fossil LNG, while straight vegetable oil (SVO) is suitable for replacing HFO [25]. To produce a more stable fuel, biodiesel is often added in small quantities to mineral diesel. The possibility for direct replacement of the traditional fossil fuels is favorable for both bunkering infrastructure and the fuel system onboard the vessel.

Biofuels contain no sulfur and reduce CO_2 emissions compared to fossil fuels. However, a commercial challenge is a high price and that it may not be available in suitable quantities for shipping. Biofuels compete with other sectors such as food production. Utilizing waste products for fuel is still a possibility, but with a growing world population, area for food crops will, in all cases, be prioritized over fuel production. Renewable biofuels from sustainable biomass sources are required for sustainable well-to-wake production.

3.1.4 Electrofuels

Electrofuels, also called e-fuels or green fuels, are fuels produced through water electrolysis with hydrogen (H_2) as the building block. Water and electricity are needed to produce electrofuels. During the electrolysis, electricity splits water into oxygen and hydrogen. It is critical to use renewable electricity to ensure a fully sustainable fuel. Hydrogen is either used alone or combined with nitrogen or carbon dioxide to form liquid or gaseous energy resources through synthesis processes. Depending on the desired fuel product, these synthesis processes use different catalysts to produce fuels, such as ammonia, methane, or methanol. In most cases, electrofuels only require small modifications to fuel and engine systems to replace or blend with traditional fuels used in internal combustion engines (ICE). They are therefore often referred to as drop-in fuels [32]. Figure 3.4 and Figure 3.5 shows the production pathway of carbon-based and nitrogen-based electrofuels, respectively.

Renewable energy can be variable. Electrofuels can utilize or store the surplus energy of times with high energy production and add stability to the grid. Another advantage of electrofuels is that it limits the required expansion of the electricity network, as it can be used on islanded systems where delivery of fossil fuels has high costs. Unfortunately, electrofuels currently have relatively high prices due to high conversion losses and high costs for transportation and distribution. The

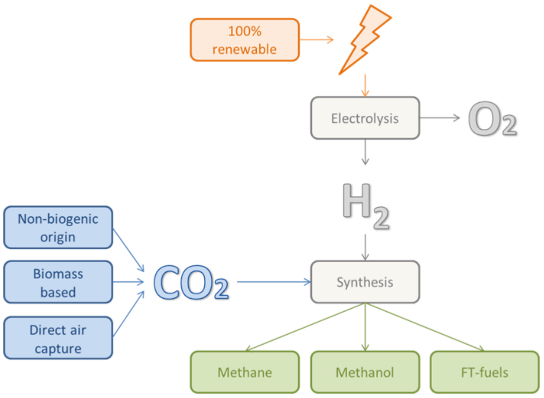


Figure 3.4: Production pathway of carbon based electrofuels (adopted from [33])

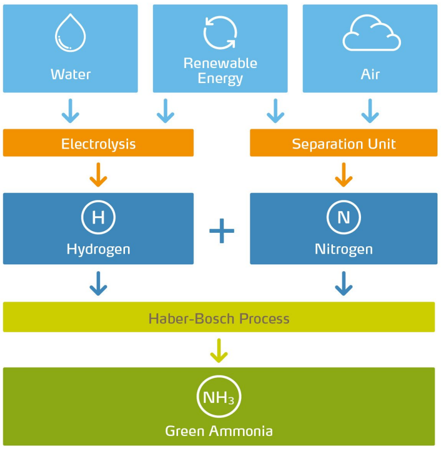


Figure 3.5: Production pathway of nitrogen based electrofuels (adopted from [34])

low overall efficiency of electrofuels (compared to, e.g., battery electric vehicles) is another disadvantage. Up-scaling and more knowledge will decrease these costs, but the price of renewable electricity will remain a key factor. The high availability and low price of renewable electricity can make electrofuels dominant in shipping. Hydrogen and ammonia produced through electrolysis are stated as promising fuel alternatives still under development.

Carbon-based synthetic fuels such as methanol and ammonia have similar properties to conventional fossil fuels. These chemical syncretization processes can be known as power-to-gas (PtoG) and power-to-liquid (PtoL), or 'power-to-fuel' (PtoF) processes [25]. Figure 3.6 shows the principal production pathway of power-to-fuel.

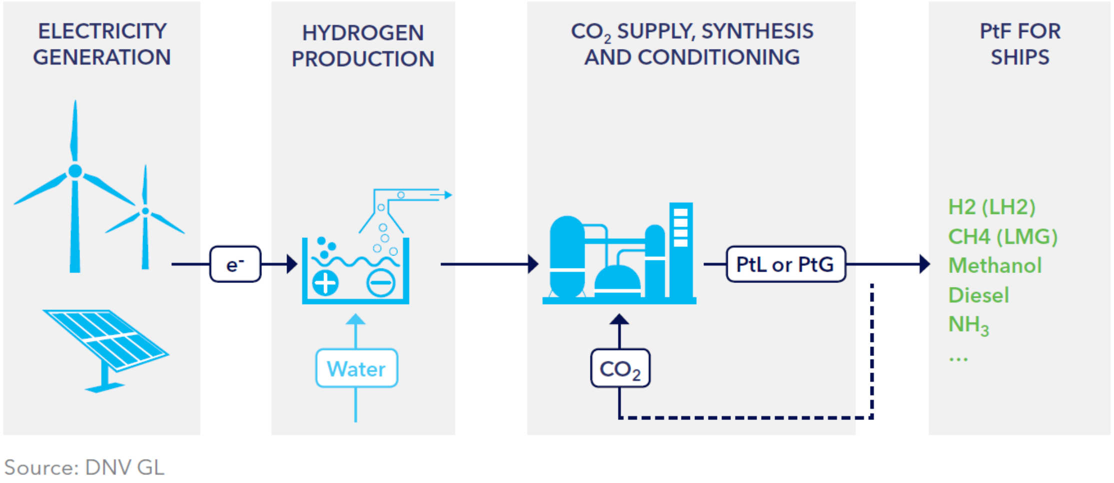


Figure 3.6: Principal production pathway for power-to-fuel *(power to liquid (PtL), power to gas (PtG) = power to fuel (PtoF))* (figure 14 in [25])

3.2 Energy conversion

Energy conversion is the process of changing energy from one form to another; in this case, the transformation of energy from the form of primary energy sources provided by nature to forms that can be utilized as fuel on a ship. A conversion process transforms chemical energy into thermal energy. Combustion is the chemical conversion of fuel and air (reactants) to combustion products, where the combustion releases the chemical bond energy of the fuel.

For vessels, energy conversion is a central part of the powering system. The overall purpose is to convert the fuel's energy into thrust and propulsion, matching the ship's resistance for a given speed. A conceptual sketch of energy conversion in ship propulsion is shown in Figure 3.7. A given energy converter may apply many alternative fuels.

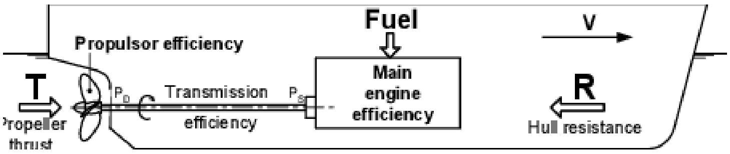


Figure 3.7: Overall concept of energy conversion in ship propulsion (adopted from [35])

Figure 3.8 illustrates an overview of possible prime movers for ship propulsion. Only a selection of energy converters will be presented, including internal combustion engines (ICEs), gas turbines, batteries, and fuel cells (FCs). In addition, the section will present hybrid solutions and summarize the main characteristic of prime movers.

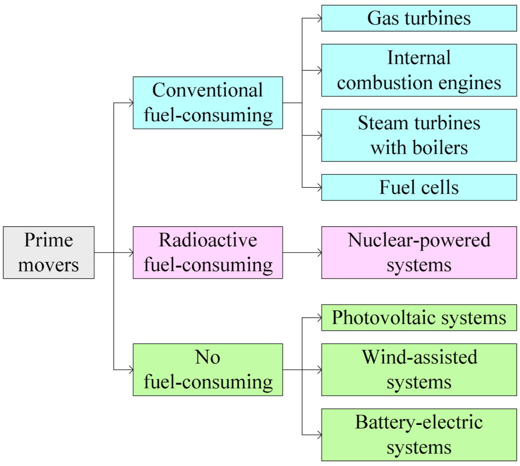


Figure 3.8: Possible power sources for ship propulsion (adopted from [8])

3.2.1 Internal combustion engine

An internal Combustion Engine (ICE) is the most common device for converting fuel energy to mechanical energy. The ICE uses thermal power to transform the energy through internal combustion. ICEs are available in a broad power and speed range and can be designed to use a large variety of fuels. The ICE has comparatively high energy utilization. Large, two-stroke engines are most commonly used for vessels operating at deep sea.

Figure 3.9 shows the basic mechanisms of how an ICE works. The reciprocating engine consists of a cylinder, piston, and a crank mechanism — the cylinder volume changes due to piston motion. The crank mechanism transfers linear piston motion to the rotation of the crankshaft. Fuel and air are transferred into the cylinder. It is an intermittent process where compression, combustion, and expansion happen in the closed volume. The gas exchange consists of exhaust and induction.

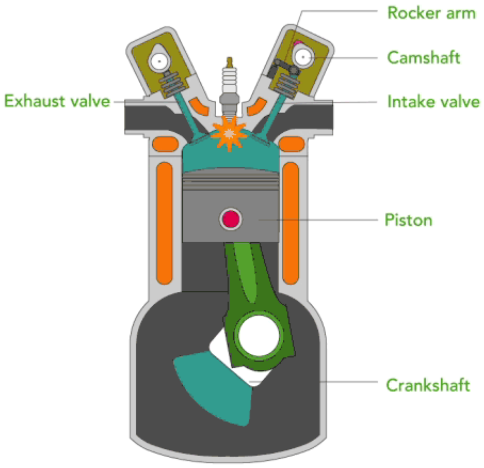


Figure 3.9: The basic mechanics of how an internal combustion engine works, one cylinder (adopted from [36])

ICEs are the most common application for energy conversion, both at sea and on land. It is compatible with several different fuels, ranging from the conventional HFO and MGO to newer fuel alternatives such as hydrogen and ammonia. The reciprocating engine and rotary engine are basic designs. Spark (SI) or compression (CI) ignition is used for ignition. For the gas exchange, both four-stroke and two-stroke engines are used. Naturally, aspiration, supercharging, or turbocharging is used for air supply. The engine can be designed for low-speed (<300 rpm), medium-speed (300-1000 rpm), and high-speed (>1000 rpm).

3.2.2 Gas turbines

Gas turbines are a type of continuous internal combustion (IC) engine. The gas turbine burns an air-fuel mixture and produces hot gases that spin a turbine to produce power. In contrast to other IC engines, which combustion occurs intermittently, the combustion of gas turbines occurs continuously [37]. Figure 3.10 illustrates the working concept of gas turbines, with the three primary sections mounted on the same shaft: the compressor, the combustion chamber, and the turbine. Gas tubines have been used on ships for more than fifty years. It was commercially developed to operate warships and merchant fleets. Gas turbines have a excellent power to weight ratio (PWR, or specific power), which is the main advantage compared to ICEs.

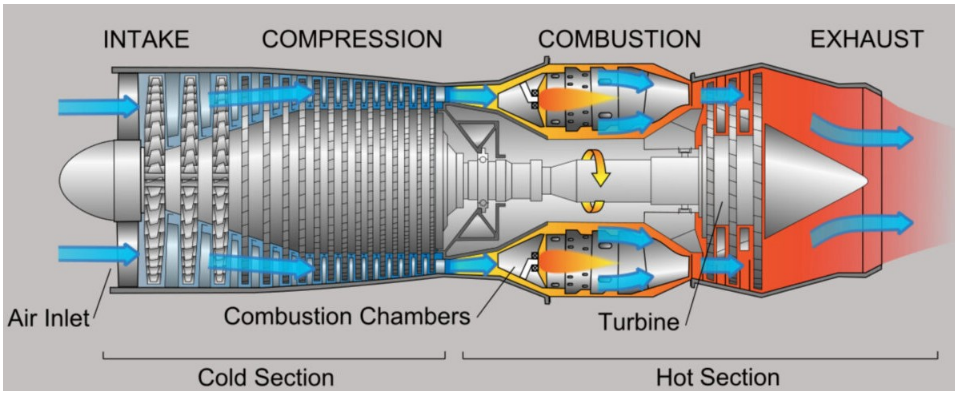


Figure 3.10: Working of gas turbines (adopted from [38])

3.2.3 Batteries

A battery is an electrochemical energy conversion device for storing electricity using chemicals. The stored energy will eventually go empty, and the battery will "go dead". By providing the ability to directly store electrical energy for propulsion, batteries give opportunities to optimize power systems. The electrification of the Norwegian ferry industry is a good example of this. The global interest and demand for batteries accelerate technology development and decrease costs. However, battery volume and weight, implying reduced cargo capacity, still limit the pure battery-electric propulsion to short-sea shipping. By installing batteries on board vessels, the dependency on producing the exact amount of energy required by the vessel at any given time can be modified [39]. This includes peak shaving when a battery discharges on high loads and charges on low loads while the engine remains on a stable load level. Peak shaving can potentially reduce the overall energy consumption, especially for very dynamic loads (e.g., during thruster or crane operations). The characteristics of batteries depend on factors such as the chemical composition and charging rates [40]. Today, lithium-ion batteries dominated the field of batteries. The Maritime Battery Forum has concluded that "The potential of batteries on board large ocean-going vessels (deep-sea shipping), with the currently available technology, lies in hybridization" [41]. Hybridization is further explained in subsection 3.2.5

3.2.4 Fuel cell

A fuel cell is an electrochemical energy conversion device (similar to batteries), but the chemicals constantly flow into the cell (it never “goes dead”, as the battery). Fuel cells convert the chemical energy in a fuel directly into electrical and thermal energy through electrochemical oxidation. Depending on the fuel cell and fuel type, the direct conversion can give an electrical efficiency of up to 60%. This way of conversion also minimizes vibration and noise, which is a challenge in conventional ICEs. Most fuel cells use hydrogen & oxygen, producing water & electricity.

Figure 3.11 shows the functional principle of a fuel cell. There exist several types of fuel cells capable of operating with various fuels for various applications. Common to all fuel cell types is that they consist of an anode, an electrolyte, and a cathode. Proton Exchange Membrane (PEM) and Solid Oxide Fuel Cells are the most relevant fuel cell technologies available for maritime applications.

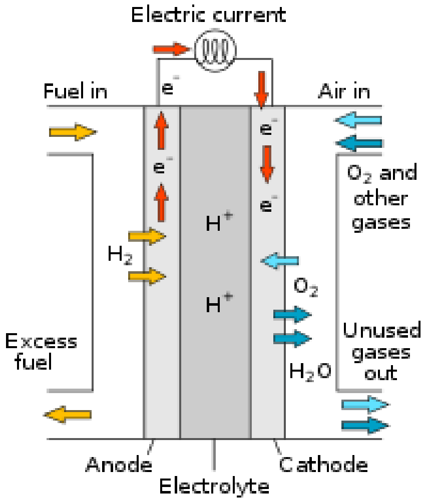


Figure 3.11: Functional principle of a fuel cell, in this case a Proton Exchange Membrane (PEM) Fuel Cell (adopted from [42])

Fuel cells differ by low temperature ($< 100°C$) and high temperature ($600 - 1100°C$). Low-temperature fuel cells, such as the Proton-Exchange Membrane (PEM) fuel cell, have a rapid start-up and low efficiency and require hydrogen or methanol as fuel. This type is most suitable for compact or portable devices with frequent on/off cycles, typically in short sea shipping. High-temperature fuel cells, such as solid oxide fuel cells (SOFC), require a long start-up but provide high efficiency and flexibility. This can be an advantage in deep-sea shipping, where a high share of the energy consumption is related to ship propulsion over long distances at steady speed [13]. There is a more extensive selection of fuel cell technology than PEMFC and SOFC, but not all are suited for vessel power generation.

Fuel cells have several advantages, such as improved air quality (by reducing pollutants such as NOx and SOx), reduced CO_2 emissions, minimal vibration and noise, reduced maintenance, and provided economic viability by being independent of fossil resources. The modular and flexible design is also highly favorable for an industry in constant transformation. The system also has low weight, low energy consumption, a high level of redundancy, and fast "charging", which are essential aspects of the vessel's operation. In addition, the technology can be utilized for load management by peak load shaving, as for batteries. However, barriers such as low durability, high costs, regulatory uncertainties, and lack of infrastructure for hydrogen as fuel puts the widespread implementation on hold [13].

3.2.5 Prime movers and hybrid solutions

The propulsion system's efficiency depends on the engine converter system (converting the fuel energy into useful transmittable power), the efficiency of the propulsor converter (converting the power into useful thrust), fuel type properties, and quality. An engine, also called a prime mover, converts one or more forms of energy (chemical, electrical, fluid pressure/flow, etc.) into mechanical force. For the propulsion of commercial ships, diesel engines (low, medium, or high speed), gas turbines, electric motors, and steam turbines are the most common types of ship engines. Diesel engines have typically had a 95% market share, and gas turbines and steam plant the remaining 5%. In the later years, electric engines and batteries have had a significant increase, in addition to the fuel cells that have caught the interest of the maritime industry. Table 3.1 presents the main characteristics of common prime movers in the maritime industry.

Engine	Power range MW	Spec. power kW/ton	Spec power kW/m^3]	Fuel type	Efficiency %	Spec Cost EUR/kW
Diesel engine	0.5-90	17-440	18-350	MGO, MDO, HFO, NG	38-52	140-450
Gas turbine	1-40	550-1000	220-400	JF, NG, MGO	20-42	320-500
Steam plant	20-45			HFO, NG	28-33	550-620
Fuel cell (SOFC)	0.005-10	50	50	NG, MGO	45-60	4-14[43]

Table 3.1: Comparison of prime movers, with common fuel types; Marine Gas Oil (MGO), Marine Diesel Oil (MDO), Heavy Fuel Oil (HFO), Natural Gas (NG), Jet Fuel (JF) [44]

Table 3.1 and Figure 3.12 presents main characteristics of common prime movers in maritime industry, in addition to some specific new developments. Potential for reduced emissions, fuel flexibility, and when the technology reaches the market are other characteristics of high importance. Several new concepts are under development, such as two-stage turbocharging, hybrid electric turbochargers, and advanced combustion engines. One such advanced combustion concept is the reactivity-controlled compression ignition (RCCI).

	Diesel engine	**DF engine**	**GD engine**	**RCCI**	**SOFC**	**LT-PEMFC**
Emission reduction potential (NOX & PM)	Low (after treatment required)	High	Medium (after treatment required)	High	>99%	>99%
Fuel flexibility	Only diesel (incl. bio- & synthetic) & DME	Medium (high Octane number)	High	High	Sulphur-free fuels	Only pure hydrogen
Efficiency	<>	45-50%	<>	45-55%	50-60%	45-55%
Time to market (MW scale)	Now	Now	± 5 years	> 10 years	5-10 years	<1-3>
Modularity prime mover	Low	Medium	Medium	Medium	High	High
Power density	High	Medium	Medium	Medium	Low (future: medium)	High

Figure 3.12: Overview of prime mover options (adopted from [45])

The use of dual-fuel (DF) engines on vessels is rapidly increasing. A DF engine is an ICE where the primary fuel, usually natural gas, is mixed with air in the cylinder, as in a SI engine. When the engine operates in gas mode, the NO_x emissions reduce significantly. The engine runs at liquid fuel (e.g., MDO, HFO, or liquid biofuels) in situations with a lack of gas fuel supply. The DF technology takes advantage of the environmental benefits and low costs offered by gas and provides fuel flexibility that is highly valuable in a transition phase. DF engines have supported LNG to take a larger market share in maritime fuels. In addition, the flexible power generation solution is capable of adapting to several new types of fuels, such as hydrogen or methane.

However, the existing DF engines are limited to fuels with high Octane numbers (e.g., hydrogen and methane). The combustion of other fuels (e.g., ammonia and methanol) requires new developments or solutions. The gas-diesel (GD) engine is a solution capable of combusting fuels in a diesel-like process. A GD engine must apply additional measures such as exhaust gas after-treatment (e.g., water injection) to combat the NO_x emissions. This engine system is still under development, and the manufacturers are looking for ways of retrofitting diesel or DF engines with low effort [45].

Hybrids

Hybrid propulsion systems are obtained by combining different converter types. Combustion engines and battery power are the most common hybrid solution. The combination aims to optimize engine operation while reducing emissions, a suitable option for ships with flexible operation profiles and varying power demands. Hybrid solutions provide several benefits such as flexibility and optimum efficiency, lower NOx, SOx, and CO_2 emissions, and give the opportunity of both silent and zero-emission operation [46]. Depending on the ship type and the operational profile of the engine, hybrids have a CO_2 emission reduction potential of 10-30%[47]. The peak shaving effect presented in subsection 3.2.3 is another benefit of hybrid solutions. In this case, the battery equalizes the engine loads, reducing pressure on the machinery and thus lower maintenance demand. For vessels using dynamic position (DP), a hybrid solution with batteries can provide backup power that reduces the energy consumption from reserve engines [48]. A fully electrical solution with high efficiency can be obtained by combining batteries (with up to 80% efficiency) and fuel cells (up to 60% efficiency). Understanding the operational profile and finding the best efficiency is necessary for optimal operation. There is a potential to increase efficiency by using hybrid solutions and combinations.

3.3 Energy carriers

Today's maritime fuel market is broad and without any clear winner, but a trending focus is alternative fuels with low or zero emissions. In this section, a selection of fuel alternatives will be presented. The selected fuels are listed below:

1. Conventional fuels
    (a) Marine Diesel Oil (MGO)
    (b) Heavy Fuel Oil (HFO)
    (c) Very Low Sulphur Fuel Oil (VLSFO)
2. Liquefied Natural Gas (LNG) and Methane
3. Liquefied Petroleum Gas (LPG)
4. Methanol
5. Advanced Biodiesel
6. Hydrogen
7. Ammonia
8. Battery-electric propulsion
9. Nuclear powering

3.3.1 Conventional fuels: MGO, HFO and VLSFO

Marine gas oil (MGO) and Heavy fuel oil (HFO) are the dominant fuels in the shipping industry today. These conventional fuels and their combinations are the main reason for shipping being responsible for approximately 3% of global CO_2 emissions. Low Sulphur Fuel Oil (LSFO) and Very Low Sulphur Fuel Oil (VLSFO) are variants of fuel oil that contain less sulfur and therefore complies with the IMO 2020 regulations.

MGO is a blend component of light cycle (gas) oil (LCGO), containing approximately 60% aromatics. The high aromatic nature gives a higher density than gas oil from an atmospheric distillation refinery. The MGO is considered as a low sulphur fuel oil (LSFO) due to a sulphur content from 0.10-1.50 m/m% [49]. Another traditional marine fuel is the marine diesel oil (MDO), covering marine fuels composed of various blends of distillates (e.i. MGO) and HFO. MGO and MDO are expensive fuels for commercial shipping compared to HFO.

HFO is the remnant from petroleum's distillation and cracking process and has a viscous and sticky consistency. HFO is highly concentrated in sulfur (maximum sulfur limit of 3.5%(mass)) and nitrogen, giving a highly polluting combustion process. Other environmental concerns such as oil spills and emissions of toxic compounds and particulates are also introduced by the use of HFO on board vessels. However, HFO is approximately 30% cheaper than other alternatives. The low cost and high availability make HFO highly attractive despite its negative environmental impact [50]. HFO combined with scrubber technology (exhaust gas treatment) is commonly used on board vessels, keeping the SO_x emissions within regulated limits.

From 2020, IMO implemented a global sulfur limit of 0.50% (mass/mass). This implies that SO_x scrubbers or equivalent technology are mandatory on vessels still consuming HFO, reducing the global demand for HFO [51]. For the same regulatory reason, the demand for MGO is expected to rise, and so is the MGO fuel price. As seen in the DNVs fuel mix presentation (Figure 2.3), the share of vessels operating on HFO was predicted to decrease drastically in 2020 (from approx. 8 EJ/year to 1 EJ/year), with MGO and LSFO taking a more dominant market position before alternative fuels fully enters the market. A challenge in this transition is still to monitor emissions and ensure that vessels follow these standards.

Summary of HFO, VLSFO and MGO:
Conventional fuels have high energy density and fully developed technology, making them the preferred fuel system on board ocean-going vessels. The high availability, fully developed infrastructure, and mature safety regulations make it the safest choice for a shipowner regarding low cost and reliable operation. However, the sulfur limits forcing a transition from HFO to MGO will affect the low cost. High MGO prices may force the ship owners to consider alternative fuels. In addition, the significant adverse environmental impact gives high carbon risk and is facing uncertainties regarding future regulations of emissions and demands from stakeholders.

3.3.2 LNG and methane

LNG is a colorless and non-toxic liquid formed when natural gas is cooled down to -163°C (at 1 bar of absolute pressure). LNG has a similar composition as the natural gas used for households and power generation in the industry. With the cooling process compromising the gas volume about 600 times and the fact that LNG will not ignite, the fuel becomes both safer and more efficient to store and transport on vessels. LNG must be stored in insulated tanks for cryogenic application due to its low boiling point. LNG has a growing position as a maritime fuel, both for LNG carriers but also for other ocean-going vessels. Methane (CH_4) is the main component of LNG, which is the hydrocarbon fuel with the lowest carbon content and hence the highest potential to reduce CO_2 emissions. However, methane is a GHG, and the methane slip must be controlled to reduce GHG emissions when using LNG. LNG does not produce any SO_x emissions. LNG is expected to be the most important transition fuel before the decarbonization of shipping reaches zero-emission vessels.

The LNG technology is commercially available today. Since the 1950s, LNG has fuelled LNG carriers. The current global LNG fleet has 294 vessels in operation and 502 vessels on order, with 2028 as the expected year of delivery. In addition, 229 vessels are prepared for conversion to LNG as fuel, so-called "LNG ready" (information accessed through afi.dnvgl.com [15]). The concept of being "fuel-ready" will be further discussed in chapter 10.

LNG's volumetric density [MJ/l] is approximately 40% lower than diesel, but the gravimetric energy density [MJ/kg] is around 18% higher. LNG has a volumetric density equal to 1/3 of diesel by including the storage system, which implies more than twice the volume to store the fuel. This is potentially a loss of valuable storage capacity for cargo. The required technology for using LNG as ship fuel, including piston engines, gas turbines, and storage and processing systems, are commercially available [25].

The production capacity of LNG has no problem with serving the maritime fuel market. The dedicated LNG ship bunkering infrastructure is still limited but improving rapidly due to the significant interest. The industry is investing in LNG infrastructure. Several bunkering vessels are ordered and expected to be delivered for operation in parallel with the many LNG-fuelled deep-sea ships ordered for the next years. LNG bunker vessels are already operating in key locations in Europe (e.g., Amsterdam, Rotterdam, the North Sea, and the Baltic Sea) and on the Florida coast. Local bunkering depots and bunkering by trucks are also expected to have a central role in a fuel market with increased demand for LNG. While waiting for the LNG bunkering network to develop for operation at deep sea, dual-fuel engines can be a risk-limiting choice that offers flexibility and redundancy.

As mentioned, LNG has no SO_x emissions. In addition, particle emissions are low, and NO_x emissions are lower than for traditional fossil fuels. Today, LNG is the cleanest fossil fuel commercially available. A main challenge is the GHG emissions during production (well-to-tank) and methane slip. Depending on the engine cycle (diesel cycle or Otto cycle), LNG fuelled engines has a potential of 10-20% CO_2 reduction compared to similar engines fuelled by fuel oil. The DF engine technology is also tested with a fuel mix of natural gas and hydrogen, providing reduced GHG emissions [25].

Since 2017, IMO has regulated LNG through the International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code, further explained in subsection 4.2.6). Regulation of LNG bunkering is still only covered by national regulations, and only a few ports have local rules for LNG bunkering. Well-developed, standardized regulations are an advantage for the further market development of LNG fuel, but its lack is not considered a barrier.

LNG is moving towards fully developed technology with various suppliers in the market. The effect of scaling and increasing competition positively affects the CAPEX for such a fuel system. Compared to a combined HFO-scrubber system, LNG systems' costs are still higher. LNG must be stored in insulated tanks, which provides additional capital cost, both for the vessel and the bunkering infrastructure. However, a gas engine system provides about the same efficiency as continual engine systems, providing roughly the same energy consumption. The costs of operating a vessel are approximately the same for an LNG-fuelled and an HFO-fuelled vessel (without scrubber). The maintenance cost does also have the potential of being lower for cleaner fuels, but this will develop with increased knowledge and experience. The fuel price of LNG is currently competitive with MGO and has the potential to challenge both low-sulphur HFO and high-sulphur HFO with scrubbers. An additional bonus for selecting LNG as a fuel is that some ports offer discounts to LNG-fuelled ships [52].

Summary of LNG:
The LNG fuel system technology is developed and in operation, but the storage requires more volume than HFO. Global bunkering infrastructure is under development, and the production capacity has no limit for maritime fuel applications. There are frequent variations in the fuel price, but in general, LNG's economic aspect competes with MGO. LNG is the cleanest fossil fuel on the market but still has high emissions. LNG is currently regulated through the international IGF Code.

3.3.3 LPG

LPG is any mixture of propane and butane in liquid form. An oil and gas production or a byproduct of an oil refinery are the two main types of LPG sources. LPG from renewable energy sources can be produced if the byproduct comes from renewable diesel production. Propane has a boiling point of $-42°C$ and is gaseous under ambient conditions. Butane is found in two types of forms; iso-butane and n-butane, which have a boiling point of $-12°C$ and $-0.5°C$, respectively. Propane and both types of butane can be liquefied at moderate pressure (lower than 8.5 bar at $20°C$) [32].

LPG can be used in a two-stroke diesel-cycle engine, a four-stroke lean-burn Otto-cycle engine, or a gas turbine for ship fuel. However, the MAN ME-LGI series, a single two-stroke diesel engine, is currently the only commercial engine available for LPG [53]. By mixing LPG and steam with CO_2 and hydrogen, it can be turned into methane, which can be used in a regular gas or dual-fuel engine.

LPG has low energy density than traditional fuel oil and requires larger fuel tanks. Storing of LPG is done either under pressurized or refrigerated conditions. Specialized bunkering equipment (e.g., an LPG fuel tank) is required for keeping the correct pressure and temperature.

The global production of LPG is approximately the same as HFO and MGO and is enough to cover the global demand for marine fuel. Currently, there is no fully developed infrastructure for LPG ship bunkering, but it can be developed by adding distribution installations to existing LPG storage locations and terminals. For distributing the fuel to ships, dedicated facilities or special bunker vessels can be used.

The fuel production and combustion of LPG have approximately 17% lower CO_2 emissions than HFO. However, LPG slip is a threat as propane and butane are significant contributors to GHG emissions, with a global warming potential (GWP) that is three to four times higher than CO_2. On another side, LPG has no sulfur emissions and significantly reduces particulate matter (PM) emissions. The applied technology decides the reduction potential of NO_x emissions [25].

LPG is not included in IMO's IGF Code, and there is no planned implementation of the international regulation of LPG. Each LPG case must follow the alternative design approach to prove that its level of safety is in line.

Regarding capital costs, the installation of an LPG system (including ICE, fuel tanks, and process system) on board a vessel is half the price of an LNG system (assumed pressurized type C tanks in both cases), because LPG do not need any special materials to handle cryogenic temperatures. The costs of operating an LPG system are considered similar to an oil-fuelled vessel without scrubbers, even if they still are limited practical experience [25]. As for all fuels, the fuel price fluctuates but is in the range of LNG and fuel oil.

Summary of LPG:
The LPG fuel technology is commercially available but not yet common in operation. LPG has a lower energy density than diesel and requires specialized storage tanks. There is no developed bunkering infrastructure, but it can easily be expanded by the use of distribution installations. The CAPEX of LPG is approximately halved compared to LNG, while the fuel price is in the same range. LPG includes propane and propane, which contributes to GHG emissions. Even if some concepts of LPG are approved, safe regulation still requires an alternative design approach.

3.3.4 Methanol

Methanol (CH_3OH) is the alcohol with the lowest carbon content and highest hydrogen content of any liquid fuel. On a commercial scale, methanol is commonly produced from natural gas. It can also be produced from other feedstock resources, such as coal or renewable sources (e.g., biomass or recycled CO_2). The renewable pathway of methanol complies with IMO's 2050 carbon emissions targets [54]. With a flashpoint of 11-12$°C$, methanol is considered a low-flashpoint fuel. By converting methanol to dimethyl ether (DME), it can be used as fuel for diesel engines.

Wärtsila and MAN offer methanol-fuelled engines, where the engine systems are adopted from the high-pressure diesel combustion process [55]. Methanol has powered ships by use of diesel engines modified to operate at both marine diesel and methanol, showing an equivalent or higher performance level than diesel engines [56]. Another option is to use methanol as a hydrogen carrier using fuel cells. The Viking Line ferry MS Mariella has test operated with such a fuel cell system since 2017, but the concept is not yet commercially available [32].

As a liquid fuel, methanol can be stored in conventional liquid fuel tanks as long as modifications regarding its low-flashpoint properties and requirements from IMOs IGF Code are fulfilled [55]. Methanol has a liquid form between -93$°C$ and +65$°C$ at atmospheric pressure. Its density and lower heating value (19.5 MJ/kg) make storage more manageable and less costly than LNG, hydrogen, and ammonia. However, methanol still requires fuel tanks that are more than double as large as the conventional oil (e.g., MGO) tanks. Compared to LNG, the required size of methanol fuel tanks is similar, or smaller [32].

There is an increasing demand for methanol (doubled from 2006 to approx. 80 million tonnes in 2016), mainly due to the high consumption in Asia (more than 60%). The production capacity of methanol is not enough to cover the whole fuel demand in shipping [25]. Methanol production capacity must increase if the methanol fuel suppliers aim to cover 25-30% of the marine market. The increased capacity is not necessarily a problem but will require large investments. Renewable feedstocks or electrofuels could also partly serve the demand.

The bunkering infrastructure of methanol as a marine fuel is poorly developed and a challenge for widespread adoption. Currently, methanol-powered ships are mainly receiving fuel by trucks or, in some cases, bunkering vessels [55]. Due to its application to diesel engines and storing tanks, only minor modifications to terminal infrastructure are required for developing a bunkering network for methanol. Even so, there already exist available bunkering options for methanol in over 88 of the world's top 100 ports [54].

Methanol combined with an ICE will give around 10% reduction of CO_2 emissions (tank-to-propeller) compared to conventional fuel oil. In a well-to-tank perspective of methanol from natural gas, the CO_2 emissions are equal to or around 5% higher than fuel oils. If methanol is produced from renewable biomass sources, the emissions are significantly lower [25]. Methanol is a clean-burned fuel and has lower emissions of both NOx and PM than conventional fuels. The NOx emissions depend on the technology applied but are 30-60% lower than for HFO. The NOx emissions are still not below Tier III NOx limits for operating in Emission Control Areas (ECA), and exhaust gas reticulation (EGR) or selective catalytic reduction (SCR) systems must be applied in order to satisfy the standards [57]. Methanol produces close to zero SOx emissions and is within IMOs sulfur emission limits.

Methanol has a history of safe handling at sea, as it has been shipped globally for over 100 years [54]. For methanol as a marine fuel, the regulations of the IGF Code are the main applicable guideline. An alternative design approach is still needed for methanol fuel systems, but more specific regulations are under development by IMO. Class societies such as DNV can also provide rules and guidelines directly for methanol, which may shorten the process.

Methanol is a cost-competitive fuel alternative compared to other non-conventional options. Maersk presented dual-fuel engine, complex fuel supply system, and tank size as the key drivers of additional CAPEX cost of methanol compared to VLSFO [58]. Compared to LNG systems, the installing cost onboard a vessel is around 60% lower for methanol fuelled system [25]. The cost of retrofitting a ship to run on methanol is also lower than for alternative fuels, which is mainly due to the compatibility with existing storage and bunkering infrastructure [54]. The practical experience of operating with methanol systems is still limited, but the operational costs are expected to be similar to oil-fulled systems without scrubbers.

The price of fossil methanol has earlier been in the range of HGO and MGO prices, with an increased price in the later years. Methanol prices show regional variation and usually follow the price of natural gas. Lower oil prices will easily make methanol more expensive than distillate fuels. Carbon-neutral methanol and methanol from renewable resources bring the fuel price further up. An advantage of the dual-fuel methanol engines is that when the methanol price is high, the vessel can still operate on marine diesel [56].

Summary of Methanol:
The methanol fuel system technology is commercially available but not commonly used. The fuel is more manageable than LNG but has a low energy density compared to conventional fuels. The bunkering infrastructure is poorly developed, and the production capacity is relatively low. However, only minor modifications are required to already established infrastructure. The costs of methanol are competitive with fossil production. Methanol has only 10% reduction of CO_2 emissions for fossil methanol compared to fuel oil, but the reductions are potentially better with renewable production. An alternative design approach is still required for safety regulation, but regulations are under development.

3.3.5 Hydrogen

Hydrogen (H_2) is an energy carrier that can be produced from various energy sources. Almost all hydrogen is produced by reforming natural gas, but another option is to produce it by electrolysis of renewables. By using renewable energy sources or adding carbon capture and storage (CCS) to natural gas production, carbon neutral production can be achieved. The large energy required for producing H_2 as fuel must also be renewable for this to be complete. Hydrogen can be converted in adapted combustion engines or fuel cells, where fuel cells provide the highest efficiency of 50-60% or higher. Producing hydrogen by electrolysis can be used to transport and store renewable energy and hence stabilize the energy output of renewable resources such as wind power plants [15]. The hydrogen production from electrolysis has no strict requirements to location as long as the electrical power supply is adequate, which gives more flexibility to the distribution infrastructure.

Hydrogen can either be stored as compressed gas, a cryogenic liquid or chemically bound for use on vessels. The main barrier to hydrogen is transportation and storage as hydrogen requires specially-designed storage tanks and bunkering systems. Hydrogen has approximately three times larger energy density per mass than HFO. At the same time, liquified H_2 has a volumetric density of 71 kg/m^3, implying that it needs five times more volume to store the same energy amount as HFO. Liquified hydrogen also requires cryogenic storage due to its low boiling point (–253°C at 1 bar), increasing the cost of storage. Chemically bound hydrogen would also give a volumetric energy density lower than both ammonia and carbon-based synthetic fuels. In addition to requiring large space for storage, hydrogen is highly flammable and requires costly storage systems due to safety issues [59]. Depending on the pressure, hydrogen stored as compressed gas takes approximately 10-15 times more volume than HFO for the same energy amount [25].

The yearly production of hydrogen, mainly from natural gas, corresponds to 150 million tonnes of ship fuel. The production capacity has no principal limitations due to the many energy sources to produce hydrogen from, and shipping could be served by hydrogen fuel without problem [15]. Currently, the chemicals sector (mainly ammonia synthesis) covers 65% of the hydrogen demand, while the refining sector for hydrocracking and desulphurization of fuels covers 25%. Technology for land-based hydrogen storage is available, but as for now there is limited experience with the storage of hydrogen onboard vessels. Hydrogen is new to the maritime fuel market and bunkering infrastructure are under development, but technical and safety of storage remain as challenges. Today, there is one prototype of a hydrogen bunker vessel under testing [60]. Liquefied storage tanks are under development and the first tank for marine applications was recently installed [61].

The combination of hydrogen and fuel cells produces zero CO_2 emissions tank-to-wake and removes all NOx, SOx, and particular matter (PM) emissions from vessels. Using an ICE as an energy converter will produce NOx emissions while GHG emissions still could be kept to a minimum.

Hydrogen produced by electrolysis with renewable energy and converted by fuel cells is close to the definition of zero-emission fuel.

Hydrogen is not transported as marine cargo such as LNG and methanol. There is neither any large-scale experience with hydrogen as a marine fuel, mainly due to the safety aspects of storing hydrogen onboard ships. Hydrogen-powered propulsion systems are new to shipping and are under testing for ferries and cruise ships. Regulations of hydrogen (as a low-flashpoint fuel) in fuel cells are under development to be included in the IGF Code. Still, there are no existing international regulations or class rules covering hydrogen as fuel. However, through the Joint Industry Project MarHySafe, DNV has developed a Handbook for hydrogen-fuelled vessels, giving guidelines for the application [62]. There are several ongoing projects focusing on hydrogen, with the aim to gain more knowledge and understand the related risks and hazards.

The main capital cost of hydrogen as a marine fuel is the storage tanks for liquefied hydrogen, which, compared to LNG tanks, requires higher insulation quality, lower storage temperatures, and currently has limited marine applications. Costs of combustion engines and the additional fuel system and the operation of these are estimated to be similar to engines using LNG [25]. Fuel cells have a shorter lifetime than conventional piston engines and turbines, depending on fuel quality and system management operation. This gives an extra expense for more frequent replacement. Green hydrogen, produced by electrolysis powered by renewable electricity, is a one-step production process. This makes the production less energy-demanding and gives a cost advantage compared to ammonia, and synthetic fuels [63]. A reduction in the price of electrolyzers will also affect the CAPEX and hydrogen production costs.

Hydrogen produced from electrolysis has an average cost of 1770 USD/t crude oil equivalent, while production from natural gas gives an average price of 1370 USD/t crude oil equivalent (including production, compression, storage, and transport) [15]. This is more than double the conventional fuel price. The hydrogen fuel price depends on the production and distribution of the energy. The cost of green hydrogen, produced by electrolysis, highly depends on the price of electricity, while hydrogen produced from natural gas depends on the gas price. Locally produced hydrogen will minimize the cost of distribution. Hydrogen production that uses surplus intermittent renewable energy might lower hydrogen prices. The cost of liquid hydrogen is around 30% more costly than compressed hydrogen [32].

Summary of Hydrogen:
There is limited technological experience with hydrogen as a marine fuel, but the technology is of high interest and under development. Hydrogen has a very low energy density, requires large storage space, and has safety challenges due to characteristics such as high flammability. Hydrogen production capacity is potentially high and flexible, as its only requirement is an adequate electrical power supply. There is currently no established bunkering infrastructure for hydrogen as a marine fuel. Hydrogen is costly, and the economic aspects depend on the cost of electricity and natural gas. Hydrogen as a fuel option is potentially zero-emission if produced with renewable energy. Safe regulation can be obtained by an alternative design approach, but standard regulations are under development.

3.3.6 Ammonia

Ammonia (NH_3) is a chemical energy carrier and a potential fuel for shipping. The energy is released by breaking chemical bonds. Ammonia can either be obtained from fossil feedstocks (such as natural gas) or from renewable energy sources. Green ammonia is obtained by producing hydrogen through the electrolysis of water powered by renewable energy sources and collecting nitrogen from the air using an air separation unit. The Haber-Bosch process is currently the only commercially available method for directly synthesizing ammonia from hydrogen and nitrogen. The technique has been used in large-scale applications on land [64].

Combustion of ammonia is challenging due to its high auto-ignition temperature, narrow flammability limits, high heat of vaporization, and toxicity. Ammonia also has some requirements regarding which materials can be used in the engine due to corrosion. Fuel cells can also be used to convert the energy of ammonia. However, this technology is still limited to qualitative studies and is not mature at a large scale. Ammonia weighs twice as much as HFO and requires triple the volume to deliver the same energy amount.

Ammonia has a yearly production volume of 170-180 million tonnes, most of it from natural gas. Agriculture is responsible for 80% of the ammonia demand, mainly for fertilizer and some industrial products [34]. The annual production corresponds to approximately 76 million tonnes of fuel oil. The widespread demand for ammonia in the land-based industry has given a well-developed distribution network on land. The production of ammonia from hydrogen and nitrogen is a mature and commercially available technology, well-suited for local production as long as adequate electricity is available. This may be an advantage for the development of bunkering infrastructure in ports. Ammonia has more than 50% higher energy density per unit volume than liquid hydrogen, which makes the storage and distribution more manageable and increases the feasibility for deep sea shipping [32].

Currently, there are no ammonia-fuelled ships and no bunkering infrastructure for vessels. However, the shipping industry is increasingly interested in this carbon-free, potential fuel. The demonstration of effective onboard converters and bunkering infrastructure development remain as barriers. As ammonia has similar characteristics to LPG, this technical advantage can be used to store and transport ammonia as fuel. In addition, the toxicity must be taken into account.

Ammonia releases no CO_2 emissions and can be close to zero-emission if renewable energy is used for the production [34]. However, with the current production mainly from fossil energy sources, the carbon emissions are high without CCS technology. Nitrous oxide (N_2O) is another GHG that will have increased importance if ammonia becomes a common option for maritime fuel.

Ammonia is a low-flashpoint fuel and subject to IGF Code. There is currently no initiated development of specific international regulations of ammonia as a fuel, and the alternative design approach by SOLAS must be followed to prove safety. However, DNV has recently established class rules for ammonia, included in the ”Fuel Ready” class notation [65]. Höegh Autoliners has already got this class notation for a vessel, making it the first vessel ready to be operated with ammonia. At the end of 2019, the Green Shipping Program and Color Line started a pilot project on ammonia as a maritime fuel [66]. The pilot is currently under development, and a safety handbook for ammonia has been developed as a part of the project [67]. Both the handbook and the class rules are valuable guidelines for stakeholders that consider the implementation of ammonia as fuel.

The cost of renewable ammonia production depends highly on electricity and the electrolyzer load factor (number of running hours per year), similar to hydrogen. A lower load factor will increase the price drastically. The transportation costs of ammonia are similar to LPG costs, as long as the lower energy density of ammonia is accounted for [32]. The fuel price of ammonia is estimated to be in the range of methane gas. Assuming a mature and available ammonia fuel technology in 2030, the price is estimated to be between 1800 and 2300 USD/t of fuel oil equivalent [25]. IRENA do also predict ammonia to have high fuel costs in the future, see Figure 3.13. From Maersk estimations, the additional capital costs of ammonia compared to VLSFO are the dual-fuel engine, the complex fuel supply system, and the need for larger and cryogenic tanks [58].

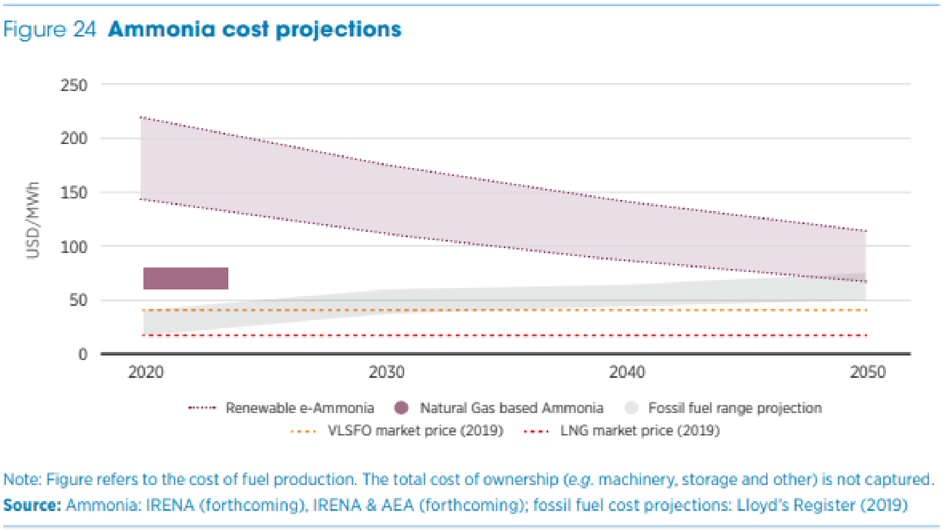


Figure 24 **Ammonia cost projections**

Note: Figure refers to the cost of fuel production. The total cost of ownership (*e.g.* machinery, storage and other) is not captured.
Source: Ammonia: IRENA (forthcoming), IRENA & AEA (forthcoming); fossil fuel cost projections: Lloyd's Register (2019)

Figure 3.13: Ammonia cost projections (figure 24 in [68])

Summary of Ammonia:
Ammonia as a maritime fuel has low technology maturity level but is under research and development. Ammonia has a low energy density, but it is higher than hydrogen, making it more feasible for deep sea operation. The global production capacity is high and can be compatible with LPG infrastructure. Ammonia has high costs, and it is even higher if produced from renewable energy sources to obtain zero carbon emissions. There are no international regulations for ammonia, but handbooks and class rules are established.

3.3.7 Advanced biodiesel

Biodiesel is the most promising biofuel for ships and is suitable for replacing or blending with MDO/MGO. Biodiesel covers biofuels such as hydrotreated vegetable oil (HVO), biomass-to-liquids (BTL), and fatty acid methyl ester (FAME) [25]. Advanced biofuels are the second and third-generation biofuels derived from sources such as woody crops, wastes/residues, and aquatic autotrophic organisms (e.g., algae). Advanced biofuels do not compete with food production and are hence considered more sustainable than first-generation biofuels [15]. In this thesis, advanced HVO will be the main biofuel assessed. In HVO, the oxygen has been removed using hydrogen, making it a high-quality fuel with long-term stability.

As a possible drop-in fuel, biofuels are in general compatible with existing engine systems and infrastructure of conventional fuel oils. In addition, biodiesel matches the energy density of diesel, eliminating the barrier of fuel storage onboard the vessel. There is still limited commercial experience with biofuels in shipping. In Norway, several ferries are fitted with biodiesel systems and have operated without reported problems [69]. However, some of these ferries are operating at regular diesel due to high prices and uncertainties in the fuel supply of biodiesel [70].

Regarding the production capacity, 81 million tonnes of conventional transport fuel were produced globally in 2017. This includes oil crop biodiesel, sugar, and starch-based ethanol and HVO [25]. Even if the fuel is compatible with current infrastructure, there is still a lack of available biodiesel. Only a few ports offer biofuels (e.i. in Norway and the Netherlands), but the future development of algae-based fuel production may provide better supply [15].

The potential reduction of emissions for biofuels depends highly on feedstock, biofuel generation, and engine type. For HVO, the GHG emissions from well-to-wake are halved compared to diesel. The PM and NOx emissions are also lower, and there are no SOx emissions. Note that other biofuels, such as FAME, have higher NOx emissions. The overall sustainability of biofuels is debated; some doubt the GHG reductions while others claim biofuels to be a decisive fuel for deep sea shipping if aiming for the $2°C$ climate goal [25].

Regulation of biofuels is covered by several standards, both regarding technical and sustainable aspects. ISO 8217:2017 is an essential standard for marine fuels used in marine diesel engines and boilers [71]. In addition, both the EU Renewable Energy Directive and the Routable on Sustainable Biofuels (RSB) address sustainability criteria for biofuels [15].

The modification of ship engines and infrastructure to comply with biofuels is around 5% of the engine costs. Operating on advanced HVO does not bring any additional costs. There is limited experience with biofuel systems operation, which needs further investigation, but the operational costs are currently expected to be similar to oil-fuelled systems without scrubbers. In general, advanced biofuels are more expensive than fossil fuels. The high price and currently low production volume challenge the large-scale use of biofuels in shipping. The development of second- and third-generation biofuels may lower costs, but this is hard to predict.

Summary of Advanced Biodiesel:
Advanced biodiesel is compatible with conventional diesel engines and can easily be used as a drop-in fuel. It has a similar energy density as conventional fuel, making it suitable for deep-sea operation without loss of cargo-carrying capacity. The production capacity is low, and the infrastructure is poorly developed. Biodiesel has high costs, and the related emissions are discussed. The fuel is regulated by standards that cover both technical and sustainable aspects.

3.3.8 Battery-electric propulsion

Fully electric powering is another ”fuel” alternative on the road toward decarbonization of shipping. This power system consists of batteries connected to onshore chargers and an electric grid when in port. Plug-in hybrid vessels are more common, combining battery operation with a conventional fuelled engine. The batteries are mainly used for hybrid ships to optimize the power system and reduce fuel consumption. Currently, there are 439 ships with batteries in operation, where 20% of them are fully-electric [15]. More than half of the fully-electric vessels are located in Norway, primarily thanks to the electrification of the Norwegian ferry industry. The shore-based infrastructure of charging vessels is globally limited and density-located in areas of initiative.

The high weight and large volume of batteries combined with short-range capacity remain a main barrier to fully-electric deep-sea vessels. Currently, fully-electric systems are only suitable for specific vessel types with short sailing distances. Fully-electric powering systems can be zero-emission by using electricity from renewable sources. Another feasible alternative is to use CCS technology during electricity production.

Installing battery systems is very costly compared to diesel engines and has a long pay-back period on the investment. The interval of power system replacement also increases, and a battery must typically be replaced after approximately ten years [72]. The implementation also requires charging stations and land-based infrastructure providing electricity. The price of operating a fully-electric power system is subject to large regional and seasonal variations and depends heavily on the price of electricity.

Summary of Battery-electric Propulsion:
The technology of battery-electric propulsion is mature and in common operation for short sea vessels, but the high energy density makes it unfeasible for deep-sea vessels. A widespread and global bunkering infrastructure does not exist, and bunkering is mainly customized for local supply. Battery and electricity costs are high, the latter with large regional and seasonal variations. Battery-electric propulsion has zero emissions if produced from renewable electricity or with CCS technology.

3.3.9 Nuclear powering

Nuclear powering covers the propulsion of ships (or submarines) with heat provided by a nuclear reactor. The power plant heats water to produce steam for a turbine to move the ship’s propeller. Nuclear powering is mainly suitable for ships that require long-range without refueling or powerful propulsion, such as submarines. Over 160 ships, mostly naval warships such as submarines, are powered by nuclear reactors. Some civil nuclear ships also exist, such as icebreakers or aircraft carriers [73].

Nuclear powering is a possible technology that can provide zero-emission propulsion for ships operating at deep sea. The propulsion power generation has the potential of emitting zero CO_2, CH_4, NOx, SOx and PM emissions [74]. In addition to this, nuclear power is much more energy-dense than conventional fuels. In [75], Schøyen and Steger-Jensen investigate ”Nuclear propulsion in ocean merchant shipping: The role of historical experiments to gain insight into possible future applications”. The paper provides a list of insights about merchant nuclear propulsion: it may be technically feasible, nuclear-powered ships may meet restricted access in ports or canals, the costs are vast and uncertain compared to conventional ships, and a regulatory framework is a prerequisite for operation. In general, nuclear power energy can produce zero carbon emission fuels, for example, with hydrogen or ammonia as energy carrier [76].

There is extensive experience with nuclear propulsion in naval vessels. The technology is not commercially feasible and brings safety and security risks. Public opinion also affects nuclear power, mainly due to nuclear accidents such as Hiroshima, Nagasaki, Fukushima, and Chernobyl. Other barriers are radioactive waste disposal, and accidental release of radioactivity [77].

Nuclear powering is only presented in this section because it is included in the survey presented in section 8.1. Except for this, it will not be further evaluated in this thesis.

Summary of Nuclear Powering:
Nuclear power has a very high energy density and can provide zero-emission for all vessels at sea. The technology is used for naval vessels but is not commercially available. Nuclear power is a highly debated topic that meets opposition in the population due to radioactivity and related accidents.

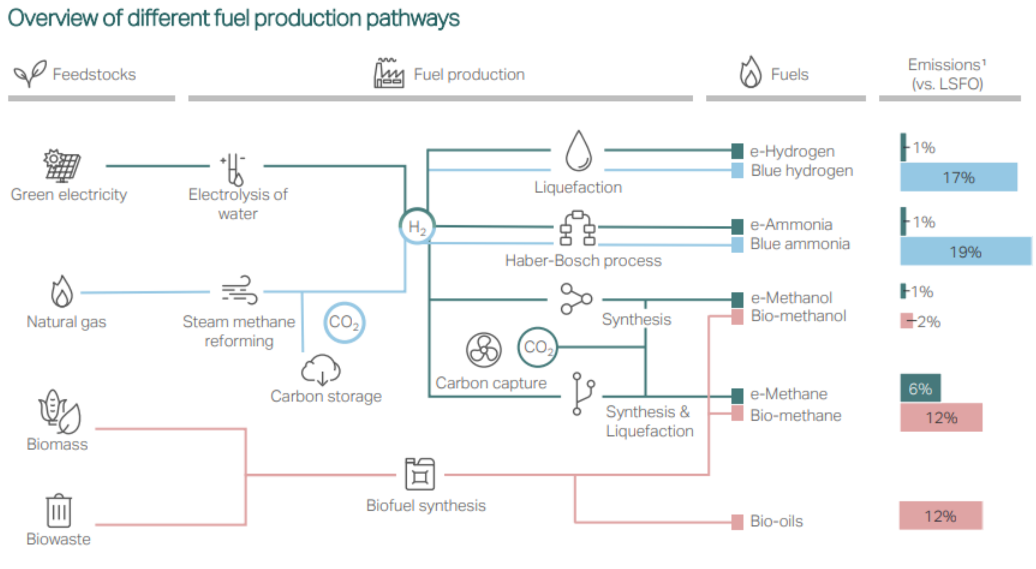
3.4 Summary of ship fuel pathways

The insight into fuel pathways is essential to understanding the well-to-wake perspective of fuel production. Table 3.2 summarize the possible pathways (energy source - energy carrier - converter) for the discussed fuel alternatives. In addition to the green pathways, CCS technology can be added to fossil production to create blue, low-to-zero-carbon emission pathways.

Fuel Alternative	**Fuel family**	**Pathway**
HFO/MGO	Fossil	Fossil - HFO/MGO - ICE
LNG	Fossil Fossil	NG - LNG - ICE NG - LNG - FC
LPG	Fossil	Fossil - LPG - ICE
Methanol	Fossil Bio	NG - Methanol - ICE Biomass - Methanol - ICE
Advanced Biodiesel	Bio	Biomass - Advanced biodiesel - ICE
Hydrogen	Fossil Fossil Green Green	NG - H_2 - ICE NG - H_2 - FC Renewable - H_2 - ICE Renewable - H_2 - FC
Ammonia	Fossil Fossil Green Green	NG - NH_3 - ICE NG - NH_3 - FC Renewable - NH_3 - ICE Renewable - NH_3 - FC
Fully electric	Green	Energy mix - Electricity - Battery-electric system

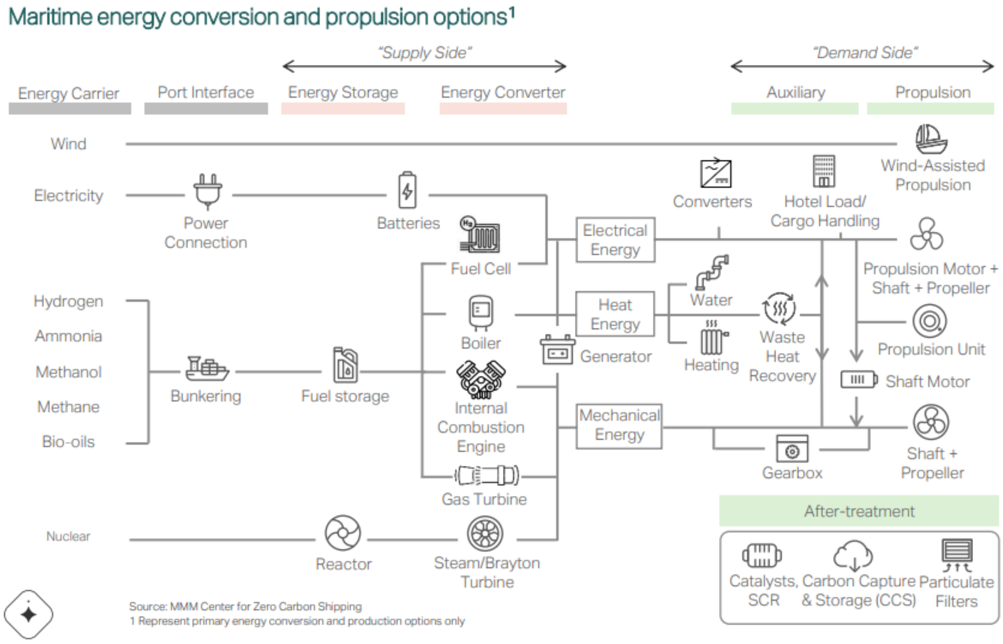
Table 3.2: Summary of pathways (inspired by section 5.9 in [32])

Figure 3.14 presents an overview of alternative fuel pathways, while Figure 3.15 summarizes maritime energy conversion and propulsion options. The first figure also illustrates how some fuels are produced from synthesis. These are often referred to as ”synthetic fuels”, which are liquid or gaseous fuels that are produced artificially but still have the same properties as fossil fuels. Synthetic fuel production uses renewable resources and mimics the properties obtained from the natural fossil fuel process [78].



Source: MMM Center for Zero Carbon Shipping
Note: Only key processes are included; For bio-methane, methane slip emissions from the choice of engine technology and upstream production is considered based on technology readiness in 2030.
1 Relative comparisons to LSFO emissions of 96 gCO2-eq /MJ (direct emissions well-to-wake) by 2030

Figure 3.14: Overview of different fuel production pathways (adopted from [79])



Source: MMM Center for Zero Carbon Shipping
1 Represent primary energy conversion and production options only

Figure 3.15: Maritime energy conversion and propulsion options (adopted from [79])

CHAPTER 4

CRITERIA FOR FUEL SELECTION AND BARRIERS OF ACTION

Several factors will influence the decision of a decision-maker (e.g., a shipowner or a set of stakeholders) to select a fuel option. The decision basis is formed by design preferences and operational requirements, and guidelines. Whether conscious or not, these preferences and requirements state the criteria. As the criteria are decisive for the final selection, they also establish barriers of action if not fulfilled at a sufficient level.

This chapter will define expectations for design and operation and present criteria for selecting alternative ship fuels and barriers to the uptake of alternative fuels. Most criteria are based on fuel characteristics, which will be the foundation of how well a fuel alternative performs within specific criteria.

4.1 Decision context: Design for operation

The shipping industry is a traditional industry with a high level of experience, leading to high expectations. However, this solid foundation is put out of play in the green shift of shipping. With low or no experience, common incentives, knowledge sharing, and being open to change expectations are essential to reach the desired goal of decarbonizing the industry.

Expectations from shipping are mainly based on the vessels' design and operation, which is further based on the market demand. Operational requirements must be established already in the preliminary design phase, where main ship specifications such as capacity, speed, range, and stability are defined. For a shipowner building a fleet, a set of design variables (e.g., number of ships and individual ship size and speed) must be stated and evaluated according to related technical, economic, environmental, and legal restrictions. When several combinations of design options satisfy the requirements, the ideal solution could be found based on optimizing some measure of merits. However, expectations of design and operation set the terms for deciding which ship system to build and which fuel option to adapt.

4.1.1 Design

Ship design is an iterative process that is commonly described by the spiral model shown in Figure 4.1. However, as the design spiral focus on the improvement of an initial concept rather than the generation of new designs, it has limitations for innovative solutions. By using *the mission* of the ship as the starting point for the design process, the number of loops to find a feasible solution can be reduced. The mission defines tasks, capacity, and performance expected by the owner or operator. The method uses a system engineering approach and defines systems and functions initially. Further, dimensions are selected based on estimated requirements for capacity stated by the mission. Eventually, the performance is evaluated, and adjustments are made.

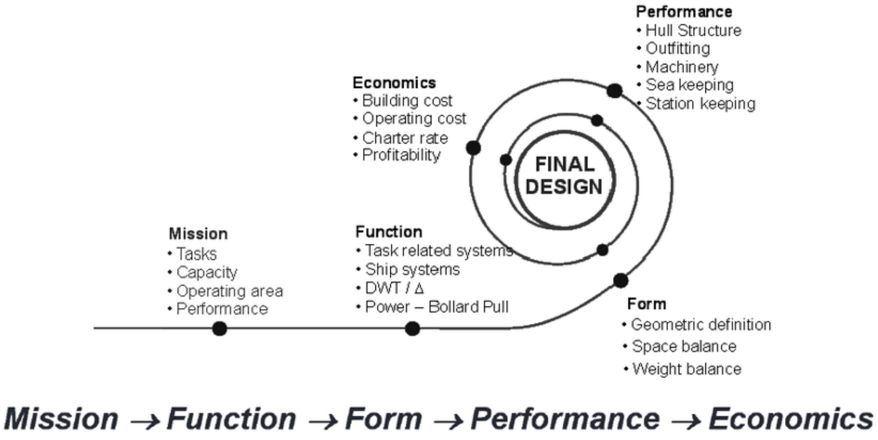


Figure 4.1: System-Based Ship Design Process (adopted from [80])

The expectations for design can be generalized in the System Based Design (SBD) process, which can be summarized as shown in Table 4.1.

System Based Design Process		
Customer requirements	Mission statement	i. Task, capacity, performance demands, range and endurance ii. Rules, regulations and preferences iii. Operating conditions (e.g wind, waves, currents, ice)
Functional requirements	Initial sizing of the ship	i. Based on capacity, where the areas and volumes needed for cargo spaces and task related ii. Based on weight, where the cargo weight, the weight of task related equipment and weight of the ship itself defines the size of the vessel
Form	Parametric exploration	i. Variation of main dimensions, hull form and lay out of spaces on board to satisfy the demands for both capacity and weight
Engineering synthesis		i. Calculating and optimizing ship performance, speed, endurance and safety
Evaluation of the design		i. Calculating building costs and operation economics

Table 4.1: System Based Design Process [80]

The objective of design can be within various categories such as *design for functionality, design for economic efficiency* or *design for production* (including constructional cost savings etc.). With a growing focus on the environment, *design for the environment* and *design for disposal/scrap* are objectives with increasing importance. The shipowner must define the main objective and evaluate the relative importance of the different aspects and criteria. An optimal design will balance the different objectives based on the shipowner preference [81].

The mission statement is influenced by the interaction and expectations of different stakeholders, for example, by demand from cargo owners or international regulations to follow. As these expectations gradually move towards more environmental perspectives, the objective of mission and design will change.

4.1.2 Operation

The mission is stated by tasks performed by the vessel or fleet, the required capacity, and the area of operation. Operational requirements related to future demand for range and necessary energy capacity are essential in selecting a fuel system for the ship design.

A wide range of ship types and sizes serve both local and global routes. However, most ships can be categorized within three different modes of operation:

- Liner shipping: (High-capacity ocean-going) vessels, typically container, ro-ro, and general cargo vessels, transport goods on regular routes on fixed schedules. The ships follow a published schedule, similar to a bus line.
- Industrial shipping: The shipper (cargo owner) controls the fleet of vessels (owned or on time-charter) and must transport the total demand while minimizing costs.
- Tramp shipping: Mix of mandatory contract cargoes and optional spot cargoes, with several daily requests for spot cargoes. The ship operator must negotiate spot cargoes and schedule the fleet. Ships follow the available cargoes, similar to a taxi service. This is a continuous and interwoven process with the objective of maximizing profit.

The expectations and demand for operation form the design decision. Design decisions must be made even with an uncertain future and lack of knowledge. The wide range of fuel options and uncertain development and supply of fuel increases the complexity of both design and operation. Development of infrastructure and possible green corridors may influence the sailing pattern of green vessels, influencing aspects of both operation and design. It will be important to connect decisions of design to operational strategies. As mentioned in chapter 3, the low- and zero-carbon fuel options have higher energy densities and therefore require more space on board the vessel. One must balance the scheduling of routes with high utilization of the vessel capacity. An example is weight-critical vessels with extra volumetric capacity, which implies free capacity up to a certain value where the capacity begins to eat of the cargo capacity. The shipowner must constantly try to optimize the operation with regard to design. This process involves many crossroads and decisions will be made based on the current level of knowledge and high-weighted decision criteria.

4.2 Decision criteria

For evaluating and selecting ship fuels for the future, different criteria are set by the stakeholders. A criterion is "a standard by which you judge, decide about, or deal with something" [82]. Key criteria are used as a baseline for decision-making, whether conscious or not. This section will present and discuss a selection of technical, economic, environmental and social criteria. The criteria will always be subjective and depend on both the situation and the preference of the decision-maker. A selection of criteria is collected based on a comprehensive literature review of the topic.

4.2.1 Technology maturity of fuel system

The technology must be fully developed and mature to be commercially attractive. The technology maturity level relates to factors such as system complexity, storage solutions, handling of low flashpoints, autonomy level, and safety. Mapping current and future technology are essential to evaluate different fuel options. In this thesis, only the maturity of the fuel system on board ships (fuel type and compatible energy converter) will be considered.

The technology readiness level (TRL) is a method for estimating the maturity of technologies. The concept originates from the NASA space program. TRLs are based on a scale from 1 to 9, where 9 is the most mature technology. Figure 4.2 shows the NASA definition of the TRL.

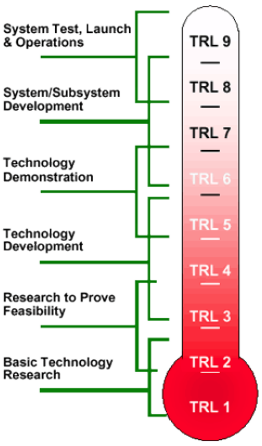


Figure 4.2: NASAs Technology Maturity Levels (adopted from [83])

Figure 4.3 shows Maersk's grading of the maturity levels of alternative fuels from their Industry Transition Strategy 2021 [58]. The grading includes production capacity, onboard fuel system, safety, and regulation. Ammonia and hydrogen stand out with a low level of maturity for the onboard fuel system. In contrast, the feedstock availability and fuel production for methanol and biofuels still need to be developed. The figure presents the characteristics of the fuel types in an easy, quantitative way. These characteristics can and will be used to evaluate fuel performance in chapter 7.

🟩 Mature and proven
🟨 Solutions identified
🟥 Major challenges remain

Alternative fuels for decarbonization

Energy Carrier	Feedstock availability	Fuel production	Fuel storage, logistics, bunkering	Onboard fuel conversion[1]	Onboard safety and fuel management[2]	Regulation[3]
Fossil fuels	🟩	🟩	🟩	🟩	🟩	🟩
e-hydrogen	🟩	🟨	🟥	🟥	🟥	🟥
Blue hydrogen	🟩	🟩	🟥	🟥	🟥	🟥
e-ammonia	🟩	🟨	🟥	🟥	🟥	🟥
Blue ammonia	🟩	🟩	🟥	🟥	🟥	🟥
e-methanol	🟨	🟨	🟩	🟩	🟨	🟨
Bio-methanol	🟨	🟨	🟩	🟩	🟨	🟨
e-methane	🟨	🟨	🟩	🟩	🟨	🟥
Bio-methane	🟨	🟩	🟩	🟩	🟨	🟥
Bio-oils	🟨	🟥	🟩	🟨	🟩	🟨

Figure 4.3: Varying maturity levels and challenges of decarbonization options using alternative fuels, early years of transition (adopted from [58])

4.2.2 Applicability: Onboard storage and fuel management

Applicability of the fuel is an essential consideration regarding new fuels. Even if the fuel exists and is fully working in other sections such as land transport, it must still be suitable for use at sea. Operation at sea adds another level of requirements for safety aspects such as stability, limited safety zones, and uncertain travel to shore due to, for example, bad weather. The applicability parameter covers the adaptability to ships, mainly regarding size and space requirements. This is categorized into two sub-parameters, onboard storage, and fuel management. Other critical characteristics for the applicability of fuels are also discussed.

Energy density and required onboard storage capacity of fuel

The energy density and the belonging storage demand of fuel are determining factors for the fuel's applicability for certain ship types and sea operations. For deep-sea applications, the storage capacity is a key barrier to many alternative fuels.

The energy density of fuels can be divided into volumetric energy density (energy content per volumetric unit) and gravimetric energy density (energy content per mass unit). Low gravimetric and volumetric densities imply a fuel with higher mass that requires more space, which is disadvantageous for fuel storage on board a vessel. Increased volume- and mass displacement used for the fuel will decrease the available space for cargo, which implies reduced revenue and increased cost per transported cargo unit.

Figure 4.4 illustrates the energy densities for different fuel alternatives. Note that the figure only shows fuel properties and does consider aspects such as the need for specialized storage tanks or additional systems. This is important to have in mind, especially for fuels that require refrigerated/cryogenic or pressurized storage.

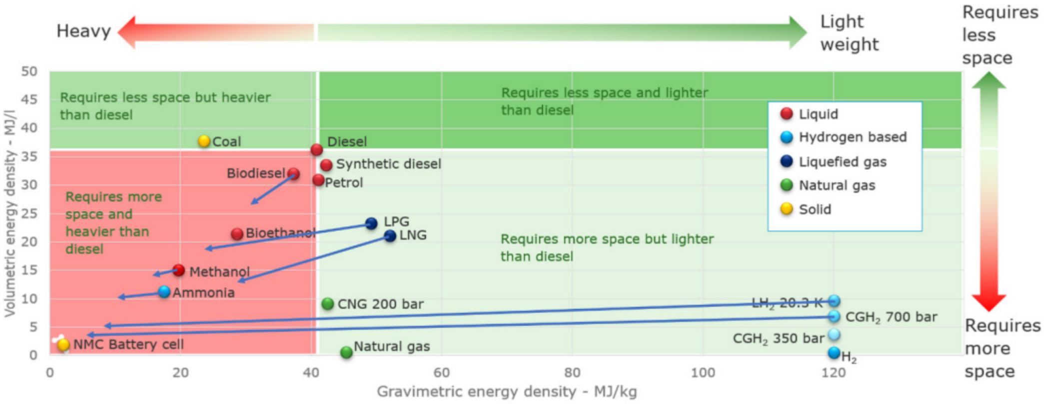


Figure 4.4: Volumetric and gravimetric energy densities for various fuels. The arrows represent the impact on density when taking into account the storage systems for the different types of fuel (indicative values only) (figure 6-1 in [32])

The fuel storage capacity of a vessel varies and does depend on the time the owner needs the ship to operate between bunkering. Fuels with lower energy density and bunkering intervals of hours or days will be challenging to make applicable for operation at deep sea if the aim is to have the same cargo capacity. Table 4.2 shows the vessel endurance range for different fuel types, which indicates the bunkering interval of a vessel (general, irrespective of tank size).

Fuel	HFO	MGO	LNG	LPG	Methanol	Hydrogen	Ammonia	Adv. biofuel	Fully-electric
Vessel endurance range	Months	Months	Weeks - months	Weeks	Weeks	Hours - days	Weeks - months	Months	Hours

Table 4.2: Typical bunkering intervals for vessels using different alternative fuels (inspired by table 6-1 in [32])

Onboard fuel management

Alternative fuel options also bring new aspects to onboard fuel management, such as safety, the demand for maintenance and trained crew. These aspects and how difficult they are to handle will vary from fuel type to fuel type.

Flammability and toxicity are two critical characteristics of fuels. The kindling point and the flash point are two temperatures that one must be aware of. The kindling point, or the autoignition temperature, is the lowest temperature for a substance to spontaneously ignite in the air without an external source of ignition, such as a spark or flame. This temperature is required to supply the activation energy needed for combustion. The flash point indicates how easy a chemical may burn and is the lowest temperature at which a fluid generates a sufficient amount of vapor to form a mixture that can be ignited. A material or fuel with lower flash points is more flammable and hazardous than those with higher flash points. Low-flashpoint fuels come with higher risks and require more safety measures, and are regulated by IMOs IGF Code (see subsection 4.2.6). Advanced biodiesel (HVO) has a relatively low autoignition temperature (204°C compared to 316°C for diesel). LNG and LPG are examples of fuels with low flash points (-188°C and -104°C, respectively).

The flammability limits show the range of conditions where fuel is flammable, given a temperature of 25 °C and atmospheric pressure. A wide flammability range may indicate higher risk and require additional safety measures. HFO is flammable, with flammability limits of 6.2-12.3 volume % in air (23°C). LNG is in the same range with limits of 4-15 vol % in air. Hydrogen has a wide flammability range, from 4-74.2 vol % in air, which indicates that hydrogen is flammable under several conditions. Ammonia also has high flammability with 15-28 vol %, at the same level as methanol with a range of 6.7-36 vol %. LPG is in the lower layer with a range of 1.8-10.1 vol %, but the fuel with the lowest flammability is advanced biodiesel (HVO) with approx. 0.6-7.5 vol % in air [32].

In addition to temperature and flammability, toxicity may set boundaries for crew and cargo. This is an issue for ammonia, which is highly toxic. Methanol does also have low acute toxicity and is dangerous for humans. The toxicity and required safety zones are main barriers to implementing ammonia in short-sea shipping.

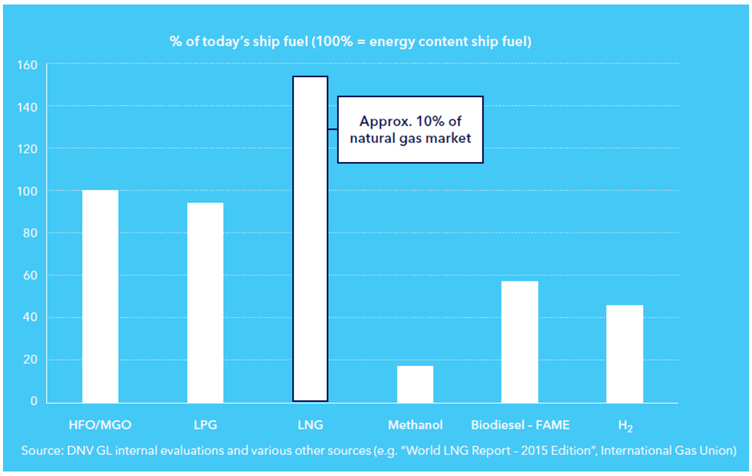
4.2.3 Availability: Production capacity & bunkering infrastructure

A widespread and steady supply is needed to convince ship owners to change towards greener fuels. The uncertainty of global production capacity and bunkering infrastructure are barriers to realizing full-scale ship concepts with zero-emission fuel systems. The availability parameter seeks to map the availability of the supply of alternative fuels, the current bunker situation, and how compatible it can be with existing infrastructure.

Global fuel production capacity

Since the maritime fuel market is currently dominated by a large variety of alternative fuels and not a specific "best" alternative, all fuels could meet the current quantity demand without significant production growth. However, the supply can get problems if one fuel alternative rapidly increases its development and a large number of operators adopt it for their vessels within a short period of time.

In *Alternative Fuel Guidance Complete 2019*, DNV addresses the production of possible ship fuels per year relative energy content, rendered in Figure 4.5. The figure shows the shipping industry's energy needs versus the worldwide energy production of selected alternative fuels. The energy consumption of the global fleet, per now supplied by HFO and MGO, serves as the 100 percent baseline. The comparisons state that LNG and LPG are the only "new" fuels with the current production to supply the global fleet, where LNG still could serve other sectors, unlike LPG, which would have to give all its production to shipping. Massive investments in production capacity are required to tackle a possible rapid rise in demand for all other fuel alternatives [25]. An issue regarding availability is using the same fuel in other sectors (i.e., road transport and aviation), which will reduce the availability of fuel for shipping.



Source: DNV GL internal evaluations and various other sources (e.g. "World LNG Report - 2015 Edition", International Gas Union)

Figure 4.5: Annual production capacity of possible marine fuels (relative energy content) (figure 7 in [25])

The production capacity of alternative fuels highly depends on the fuel families (or energy sources). As the different fuels can be produced from various energy sources, the up-scaling potential of worldwide production is large. Regardless of the outcome of the future fuel type mixture, renewability in the form of electrofuels and batteries charging at ports will have a significant role. This will continue to increase the demand for electricity production on land.

The different pathways and well-to-tank production do not affect the vessel's tank-to-wake system. A possibility is to start the production of the fuel alternatives from fossil energy sources before gradually increasing the renewable energy production. Another promising option is to build fuel-ready vessels with the flexibility to change fuel type during the vessel's lifetime.

Bunkering availability

The lack of bunkering infrastructure is a main barrier to adopting alternative fuels in shipping. Table 4.2 clearly illustrates the need for innovation and new solutions for fuel infrastructure to fill the endurance gap created by the low energy densities of the fuel alternatives.

The traditional maritime fuels, HFO and MGO, have the only well-developed worldwide supply infrastructure. The bunker stations are mainly based in ports, and vessels often refuel during cargo loading. During the last 20 years, the LNG value chain has been under development. This has been one of the shipping industry's first major joint steps for facilitating greener fuels at large scale. The significant investments have developed production centers and global distribution networks, making LNG more available. It is likely that the preparation of alternative fuels for global distribution will begin with the infrastructure, just as the development of LNG started by expanding on existing terminals. The establishment of the natural gas infrastructure lays the groundwork for the pathway to developing similar infrastructure for zero-emission fuel alternatives.

Marine stakeholders must collaborate to quickly scale up storage, bunkering, and fuel transfer infrastructure across major shipping routes to keep pace with the demand for decarbonized fuels. The storage facilities are usually located at port and must comply with port authorities and other safety regulations for storing potentially dangerous substances (e.g., ammonia). A future option may be establishing offshore bunkering stations to make low energy density fuels more available for deep-sea routes.

4.2.4 Costs: Capital costs, operational costs and fuel costs

For a ship owner, costs may be the most important decision criteria for selecting a fuel. If the costs are too high, the owner will not be competitive in the market. Zero-emission fuels have a major impact on the total cost of ownership (TCO) of vessels. The cost gap between fossil fuels and new alternatives is wide. Maersk states that the production price of alternative fuels is 2-8 times more costly than fossil fuels [58]. The cost parameter seeks to map the current cost situation of the alternative fuels and discuss if and how technological progress, scaling, and other industry measures can make the green transformation manageable.

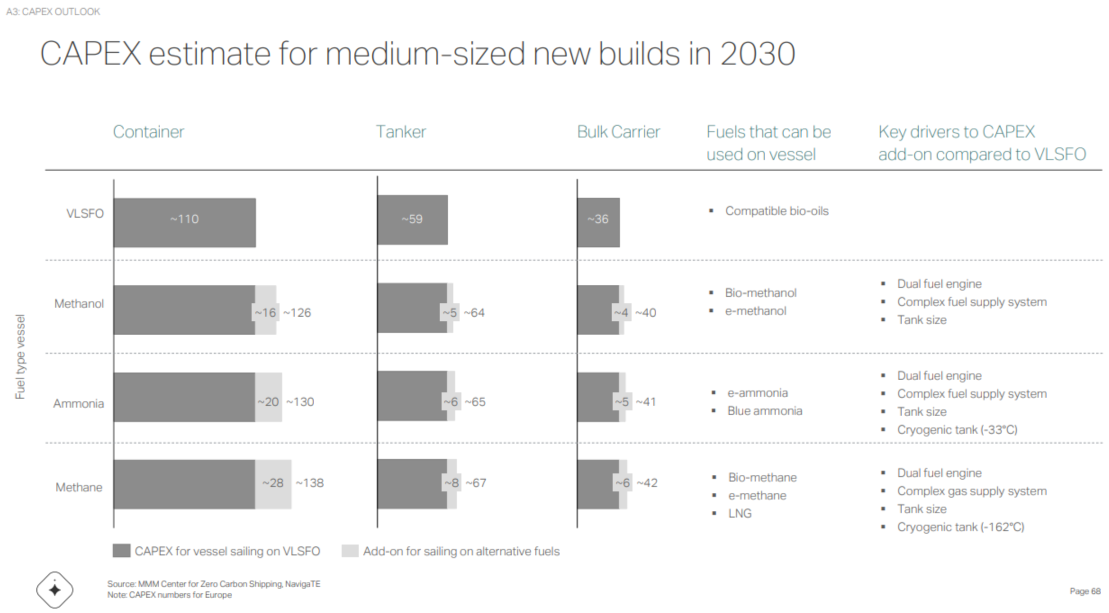
In this project, the costs will be divided into capital costs (CAPEX) and operating costs (OPEX). The voyage-related costs (VOYEX), such as fuel price, will be included in the OPEX. For a fuel transformation, the initial investment cost of technology, system, and equipment is a highly relevant factor. Being one of the first movers for new, innovative technology tends to be very costly and includes uncertainty regarding operation and maintenance. On the other hand, this might be profitable in the long run. As the whole well-to-wake production process of the fuel will affect the fuel price, the goal must be to lower the overall life cycle expenses.

Capital cost (CAPEX)

Capital costs, or capital expenses (CAPEX), are the money a company spends to buy, maintain or upgrade its fixed assets, such as property, technology, or equipment. IFor a company, the capital spending is used to increase the capacity or efficiency for more than one accounting period. These costs are essential to maintain existing systems and invest in other assets or new technology to facilitate company growth. New vessels, retrofits, and fleet maintenance will, in most cases, be the largest investment for a ship owner.

The capital expenses of engines, storage, processing, and retrofitting are important factors regarding alternative fuels and the belonging fuel system. Even though the investment of a new vessel or a new engine system is a major cost, it tends not to be the dominant factor for a business case. A relevant factor is often the desired return of the investment over a given period or the price of fuel over the ship's lifetime.

In 'Industry Transition Strategy 2021'. Maersk' presented estimates for CAPEX of medium-sized newbuilds in 2030 (Figure 4.6). Methane stands out as the fuel with the highest CAPEX costs for all vessel types, with methanol and ammonia right behind. Dual fuel engines, complex fuel or gas supply systems, tank size, and the need for cryogenic tanks are key drives for the increased cost.



Fuel type vessel	Fuels that can be used on vessel	Key drivers to CAPEX add-on compared to VLSFO
VLSFO	Compatible bio-oils	
Methanol	Bio-methanol e-methanol	Dual fuel engine Complex fuel supply system Tank size
Ammonia	e-ammonia Blue ammonia	Dual fuel engine Complex fuel supply system Tank size Cryogenic tank (-33°C)
Methane	Bio-methane e-methane LNG	Dual fuel engine Complex gas supply system Tank size Cryogenic tank (-162°C)

Source: MMM Center for Zero Carbon Shipping, NavigaTE
Note: CAPEX numbers for Europe

Figure 4.6: CAPEX estimate for medium-sized newbuilds in 2030 (adopted from [58])

An additional cost for new, alternative fuels is often due to different physical characteristics influencing the handling and storing. Lower energy density fuels require larger volumes for storing on board the vessels. An increased space demand can also be expected for converter systems (e.i. fuel cells) for generating power for alternative fuels. In addition to more costly storage and propulsion technology, will a fuel system that takes up more of the space on board a vessel also influences the cargo capacity. This will further affect the operational costs. Understanding and finding a way around these challenges will be crucial for making alternative fuels competitive.

Cost of converter and storage systems

The cost of the converter and storage system is investigated by DNV, excluding the processing system. LNG with an ICE-converter is estimated to be in the range of 500-2000 USD/kW, and hydrogen with ICE was estimated down to 1000 USD/kW. By combining LNG with a fuel cell converter, the costs may range from 2500-20000 USD/kW. Similar prices were found for hydrogen and fuel cell converter. Prices for ammonia and LPG combined with an ICE-converter were not available, neither the prices for a battery-electric system. Fuel cell costs have large variations but are, in general, much more expensive than internal combustion engines. The large cost variations indicate uncertainty due to low maturity levels and poor market interest. An important notice is that the fuel cells have a shorter life expectancy, leading to replacement approximately every 10th-year [32].

The storage tanks may also be a large part of the capital costs. The cost of tanks for LNG with an ICE ranges typically from 3-7 USD/kg LNG equivalent. Hydrogen requires large storage tanks due to its low energy density, and the cost of the storage tanks is estimated to range from 7-19 USD/kg LNG equivalent when using fuel cells. When using an ICE, the range decreases to 8-16 USD/kg LNG equivalent, which still is relatively high. The price for the storage of ammonia and LPG is not available. Methanol and advanced biofuels with an ICE have a storage price down to 2 UDS/kg LNG equivalent (data collected from figure 6-6 in [32]).

Operational cost (OPEX) and fuel costs

Operating expenses (OPEX) are the costs a company incurs for running its day-to-day operations. OPEX includes costs such as supplies, maintenance, and repairs, property taxes, insurance, salary, and wages. An additional cost will occur for ships to reduce emissions, such as scrubbers, exhaust cleaning, or more extensive interventions such as fuel change. Even if several alternative fuel types have no emissions from tank-to-wake, the fuel solutions, including CCS systems, might have added operational costs.

Several voyage-related expenses occur during operation since the vessels travel from port to port. There are costs related to bunkering, port and canal dues, cargo handling, pilotage, and towage. It covers all charges and taxes that occur when planning or operating a ship under a normal voyage charter, mainly related to the costs incurred to earn the freight or other voyage revenue. The voyage expenses depend on the length of the voyage and the number of port calls. The fuel costs are often considered the largest voyage expense for deep-sea shipping.

In addition to being a large source of emissions, the fuel tends to dominate the expenses for operating a vessel. The fuel price is a complex function, depending on the cost of the primary energy source (raw material), production, and distribution, and is highly influenced by the market's supply and demand balance (or unbalance). The market conditions are difficult or impossible to predict even for traditional fuels, making it even worse for new fuel alternatives.

Figure 4.7 shows the fuel price for various fuels. Figure 4.8 presents specific fuel prices applied by DNV in a new case study. The prices are based on a future scenario where "low-cost renewable electricity is available for the production of electrofuels at a lower cost than biofuels". The fuel price table does not include considerations of carbon taxes [13].

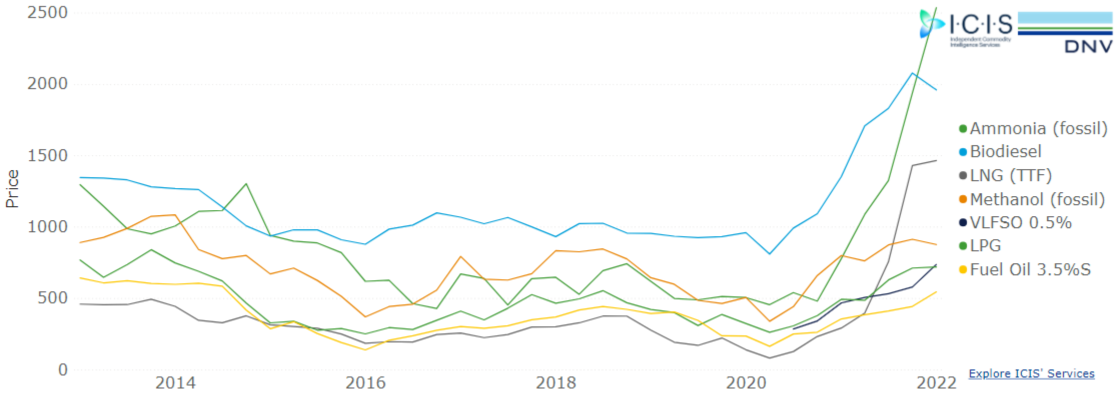


Figure 4.7: Fuel price [USD/ton MGO equivalent] for various fuels (accessed from DNVs Alternative Fuels Insigth Platform, June 2022 [15])

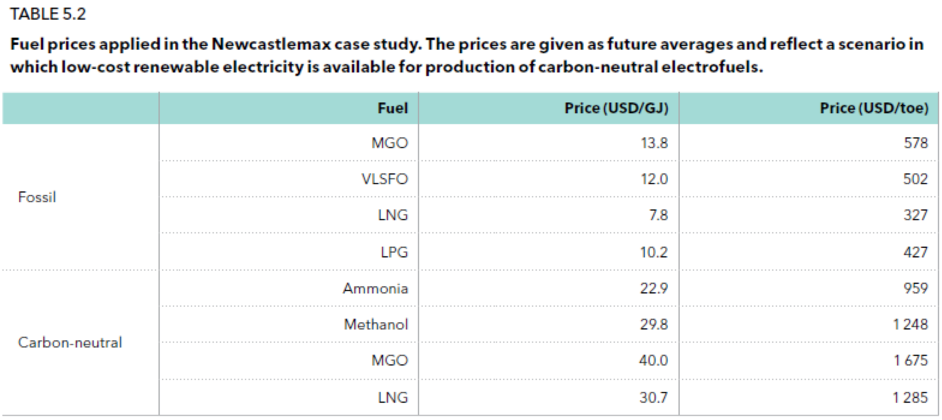


TABLE 5.2

Fuel prices applied in the Newcastlemax case study. The prices are given as future averages and reflect a scenario in which low-cost renewable electricity is available for production of carbon-neutral electrofuels.

	Fuel	Price (USD/GJ)	Price (USD/toe)
Fossil	MGO	13.8	578
	VLSFO	12.0	502
	LNG	7.8	327
	LPG	10.2	427
Carbon-neutral	Ammonia	22.9	959
	Methanol	29.8	1 248
	MGO	40.0	1 675
	LNG	30.7	1 285

Figure 4.8: Fuel price applied in DNV case study 2021 (table 5.2 in [13])

Possible cost reductions

In general, alternative fuels provide higher costs for a shipowner. However, the development of regulations indicates profit from investing in sustainable technology, possible reductions for zero-emission incentives, and penalties or banning from operating the vessel if emissions are too high.

With the "Fit for 55" strategy, as mentioned in subsection 2.2.1, the EU has begun the mission to reduce emissions from the shipping sector, firstly by monitoring, reporting, and verifying the CO_2 emissions. The part of the further plan is to tax almost 70% of emissions from voyages to the European Economic Area [84]. Suppose a carbon tax is set high enough. In that case, it can be used as a powerful incentive to motivate the switch to clean energy sources and emission-free fuels simply by making it more rewarding economically. Norway introduced a carbon tax already in 1991 as one of the first countries to do so. Some ports and fjords, such as the World Heritage fjords in Norway, have already begun to set high requirements for low emissions to allow vessels access [85]. This can be seen as an indirect cost reduction for zero-emission fuels.

4.2.5 Environmental impacts

The environmental impact of fossil fuels is the reason for the global focus on the decarbonization of shipping. The shipping industry strives for better environmental performance and lower emissions to comply with the current and future environmental goals and regulations. As stated in the introduction, the fuels and belonging sources of energy have the largest emission reduction potential. The environmental impact is a self-written parameter for evaluating the fuels.

Environmental impact is the effect that humanity's actions have on the environment, including both adverse and beneficial changes. Emissions can roughly be divided into emissions to air and emissions to sea. Sea emissions include bunker spills, ballast, etc., while air emissions cover SO_x, NO_x, particulate matter (PM), and greenhouse gas (GHG) emissions. Many of the emissions to air and sea are locally or globally regulated through design and operation, for example, through IMOs Ballast Water Management Convention [86]. A categorization of environmental impacts is shown in table Table 4.3

Environmental impact category	**Main emissions**	**Description**
Acidification	SOx, NOx, NH_3	Acid depositions exceed critical loads over areas of sensitive ecosystems, influencing ecosystem, recreation and biodiversity. The recovery is slow. The three primary gases contributing to the acidification phenomenon are sulphur dioxide (SO_2), nitrogen oxide (NO_X) and ammonia (NH_3) [87].
Eutrophication	NOx	Nitrogen depositions exceed critical loads over areas of sensitive ecosystems. This causes nutrient imbalance, algea bloom, oxygen depletion and influences the biodiversity [88].
Health impact	PM, SOx	PM emissions have an impact on the respiratory system (affecting respiratory diseases such as asthma and bronchitis), and may cause serious health problems or even death [89].
Climate change, GHG emissions	CO_2, CH_4, N_2O	GHG is easily explained ”gases that trap heat in the atmosphere”. Carbon dioxide (CO_2) is stated as the main GHG emission, but methane (CH_4), nitrous oxide (N_2O) and flourianted gases also play a major role in global warming. CO_2 is also a major source of ocean acidificaiton, since it dissolves in water to form carbonic acid (weak acid) [90].

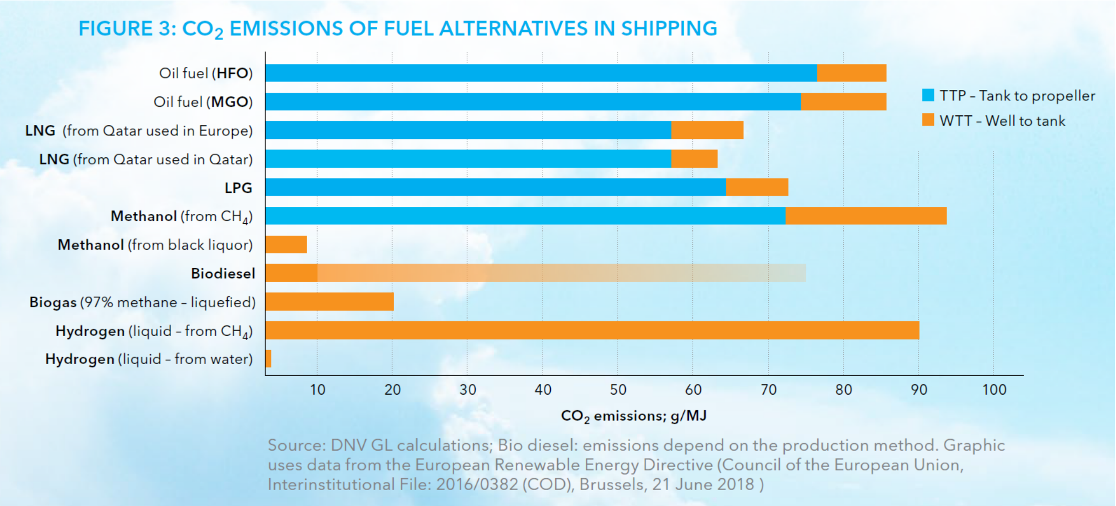
Table 4.3: Categorization of environmental impact

Health impact and climate change will be discussed further. In the decarbonization of shipping, the focus will be on GHG emissions in terms of carbon emissions, and this will also be the main environmental focus in this thesis.

Greenhouse gas emissions

GHG emissions can easily be explained as ”gases that trap heat in the atmosphere” [90]. Carbon dioxide (CO_2) is stated as the main GHG emission, but methane (CH_4), nitrous oxide (N_2O), and fluorinated gases also play a major role in global warming. As mentioned in subsection 2.2.1, the regulatory framework currently only consider emissions from tank-to-propeller. To truly understand the greenhouse gas impact of the fuels, the emissions produced in the generation and transmission of the energy, and the well-to-tank emissions, must be included. The total calculation of emissions should be well-to-wake, including emissions from production, transport, storage, and conversion to mechanical energy onboard the vessels.

Figure 4.9 presents the CO_2 emissions from well-to-tank and tank-to-propeller of different fuels in shipping. Even if some fuels have no GHG emissions from the conversion onboard the vessel, the source of energy is a highly important factor in considering the fuels as carbon neutral. An important remark is that methanol and hydrogen produced from natural gas have higher carbon footprints than HFO and MGO. This is important to consider when considering building vessels before a renewable production capacity is in place. Hydrogen produced from renewable energy is the cleanest fuel well-to-wake. Carbon capture and storage (CCS) technology could also potentially be used to reduce emissions, well-to-tank and tank-to-wake, and make various fossil fuels or productions more attractive in light of the environment. However, as stated in subsection 3.1.3, this technology still needs some development both for the energy procession and application onboard vessels.



Source: DNV GL calculations; Bio diesel: emissions depend on the production method. Graphic uses data from the European Renewable Energy Directive (Council of the European Union, Interinstitutional File: 2016/0382 (COD), Brussels, 21 June 2018)

Figure 4.9: CO_2 emissions of fuel alternatives in shipping (figure 3 in [25]).

Public health impact

Air pollution from fossil fuels is not only harmful to the environment, but it can also cause public health issues such as asthma, heart disease, lung cancer, and premature death [91]. A new study from Harvard University and University College London has quantified the health consequence of fossil fuel combustion and linked it to over 8 million premature deaths in 2018 [92]. The study findings show that fossil fuels' public health impact is significantly more damaging than previously thought. Public health is important for the Government, policymakers, and other stakeholders.

4.2.6 Maturity of safety regulations

Safety is a primary concern when developing and implementing new fuel types, bringing several new safety-related risks. Once again, we are talking about maturity, the maturity of safety regulations. Several of the alternative fuels have no rules or regulations that are applicable for storage and machinery systems. To successfully adopt a new alternative fuel, the development of safety regulations and stakeholders' handling of the belonging safety-related risks will be crucial. The safety regulation parameter covers the existing regulations and the expected development of these for the different fuels.

The UN's IMO develops the international environmental and safety standards for shipping. IMO has two highly relevant codes for regulating fuels, the International Code of Safety for Ships using Gases or other Low-Flashpoint Fuels (IGF Code) and the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) [93][94]. The IGC Code presents risk reduction measures for the design and construction of transporting liquefied gases by sea. The IGF Code regulates vessels operating with gaseous or low-flash-point liquid fuels that the IGC Code does not cover. The IGF Code has detailed provisions for natural gas in liquid or compressed form, which well regulates fuels such as LNG. Regulations for low-flashpoint diesel fuels, methanol, and the use of maritime fuel cells are under development.

An alternative design approach according to IMO MSC.1/Circ.1455 (guidelines for the approval of alternatives and equivalence as provided for in various IMO instruments) can be used to demonstrate an equivalent level of safety for fuels not covered by these codes [95]. This may be a time-demanding, uncertain, complex, and costly process for individual cases, where the specific flag administration must approve. Classification companies may simplify the process by providing rules and guidelines.

In the Maritime Forecast 2021, DNV lists various conditions to why the level of safety requirements increases when applying land-based technology to ships, making the safety regulation process onboard ships more costly and time-consuming. The list is as follows, reproduced in its entirety [13]:

- A ship operating out in the open seas is self-reliant and can in most instances not rely on help from outside.
- Crew and passengers cannot escape to safety in the same way as from a car or within a building on shore.
- Due to space constraint, the safety distances are much smaller on ship than a comparable installation on shore.
- The environmental conditions are challenging on board ships with humidity, sea spray, vibrations and inclinations.
- The power demand for a ship is in a different order of magnitude compared to other applications (for instance automotive) considering similar fuel technology.
- Low temperature materials are a necessity for many fuels. As opposed to supporting structures for onshore facilities, ship steel is not resistant to low temperatures.

There is a lack of international standardization regarding regulations and guidelines for bunkering. The infrastructure is currently only covered by local and national regulations.

4.2.7 Social acceptability and public opinion

Public opinion is the aggregate of individual views or attitudes about a specific topic or issue held by a significant proportion of a population [96]. Public opinions influence social acceptability. Social acceptability can be defined as the collective judgement or opinion of a project, plan, or policy. The opinion can be both positive and negative and may vary for different areas (e.g., nations or regions). In local regions, social acceptability has shown to be a showstopper for a wide range of projects, for example, wind farms, tourism projects, and hydrocarbon exploration activities [97].

Social acceptability is necessary to implement new concepts or technology. For shipping, there must be a global social acceptance of how to operate the global fleet. Public opinion sets high requirements for safety for crew and cargo, and there is an increasing demand for environmental protection and reducing the environmental footprint. Nuclear power has a history of meeting social resistance. Even if it has the potential to play a significant role as a clean energy source, public opinion will always affect how governments choose to produce energy.

4.3 Barriers to the uptake of alternative fuels

A barrier can be defined as ”something that prevents something else from happening or makes it more difficult”, or ”anything used or acting to block someone from going somewhere or from doing something, or to block something from happening” [98]. In this thesis, barriers refer to factors and challenges preventing a company from investing in and implementing greener fuel alternatives.

The alternative fuels for shipping all have challenges and barriers before being globally implemented. These barriers may vary from fuel to fuel. How mature the fuel technology is, how easily it can be adapted to existing vessels and operations, and how available the fuel is in terms of bunkering and infrastructure are all factors that will influence the decision. All fuel alternatives will also have a different environmental impact. In addition, new fuel alternatives will have other safety aspects to consider, which can lead to challenges regarding the maturity of existing regulations. Even though all other aspects are within acceptable frames, the cost is still likely to be the factor determining the main decision. Both capital, operational, and voyage expenses, including the fuel price, must be within sustainable limits for a ship owner.

4.3.1 Regulatory, commercial, technical, and cultural barriers

In [99], where LNG as a path to enabling clean marine transport is investigated, barriers are put into four categories: regulatory, commercial, technical, and cultural, as shown in Figure 4.10.

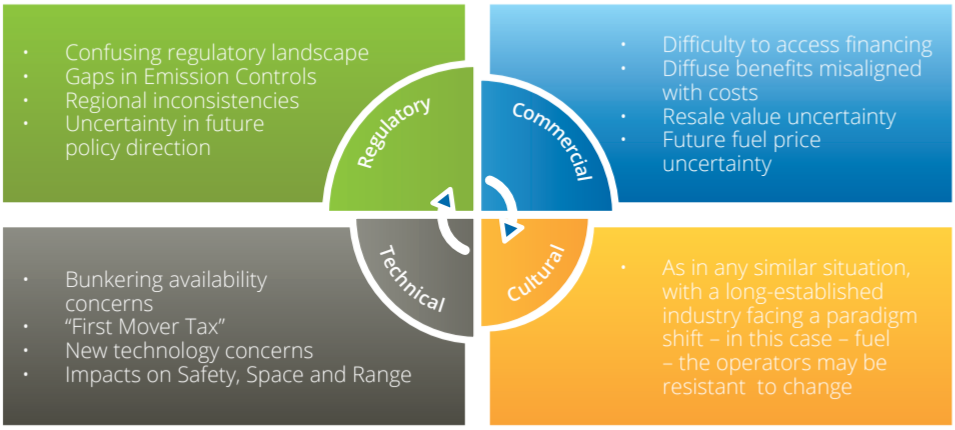


Figure 4.10: Categorization of barriers (adopted from [99])

Here, regulatory barriers cover confusing regulatory landscapes, gaps in emission control, regional inconsistency, and uncertainty in future policy direction. The regulatory landscape includes several levels, ranging from international to national and regional levels. A vessel often operates in waters with different regulations, which can be confusing for the ship operator. Emission control is a main driver for choosing alternative fuels, and the lack of it will strongly affect the green business case. With a ship lifetime of 25 years, will future policy directions influence today’s fuel selection. However, the future is uncertain, and governments are being obscure about which regulations will come into force.

Commercial barriers cover the access to capital, diffuse benefits, resale value uncertainty, and future fuel price uncertainty. Limited experience and uncertainty make financiers hesitate to invest in alternative fuels. As the capital expenses of most alternative fuels are much higher than for conventional fuels, this is a possible showstopper. Governmental incentives that can ease access to credit or reduce the risk of bank financing can lower this barrier. The way to operate ships is also diffuse; for instance, the shipowner is not necessary the one that operates the vessel and pays for the fuel costs, leading to diffuse benefits of fuel savings. Uncertainty regarding a vessel's resale value is general and does not only apply to ships operating with alternative fuels. However, a clear statement of increased emission regulations in the future will help improve the resale value of ships able to operate with green fuels. The uncertainty regarding future fuel prices is a barrier and general challenge for all fuel types.

Technical barriers involve concerns of bunkering availability, ”First Mover Tax”, concerns of new technology, and impacts on safety, space, and range. Here, ”first tax mover” refers to a financial penalty that strikes the first movers due to lack of experience and mistakes that occurs with new concepts. Being the first mover often requires higher investments, higher patience, and higher risk, which has shown to be a barrier for many shipowners. Many alternative fuels have lower energy density and new safety concerns compared to conventional fuels. This can affect the required space onboard the vessel and the possible range, which will influence both cargo-carrying capacity and how and where the vessel can sail. New technology and new safety concerns may also increase the complexity and add workload to the crew, which can be seen as an unwanted burden. The lack of international safety standards and codes can be viewed as both a technical and a social barrier.

Cultural barriers refer to the fact that operators might resist change, which is typical for ”a long-established industry facing a paradigm shift”. Decisions are often based on experience, and there can be skepticism related to less familiar technology and fuel. The barrier can be lowered by increasing the quality and awareness of information pertaining new fuels. The level of knowledge must be increased, and communication about the advantages of alternative fuels must be improved. The cultural barriers will probably fade out as time passes and the first movers have overcome decisive challenges.

4.3.2 Offshore, onshore and market driven barriers

DNV, on the other hand, divides barriers to the fuel transition into three categories: offshore barriers, onshore barriers, and marked driven barriers [76]. This is illustrated in Figure 4.11. Most of the same barriers mentioned above are covered, but the supply of zero-carbon fuels from the overall energy market is highlighted in terms of the availability of fuels. The cooperation between stakeholders, such as fuel suppliers and ship operators, is highlighted. In addition, 'market' is included as its own category. The marked driven barriers cover the lack of demand for green transport and the end-costumer not paying for the additional cost of zero-emission transport. Several factors could drive green incentives, for example, long-term 'green' contracts, long-term financing to green ships, supportive green procurement policies, and risk-sharing mechanisms to reduce the risk for first movers [100].

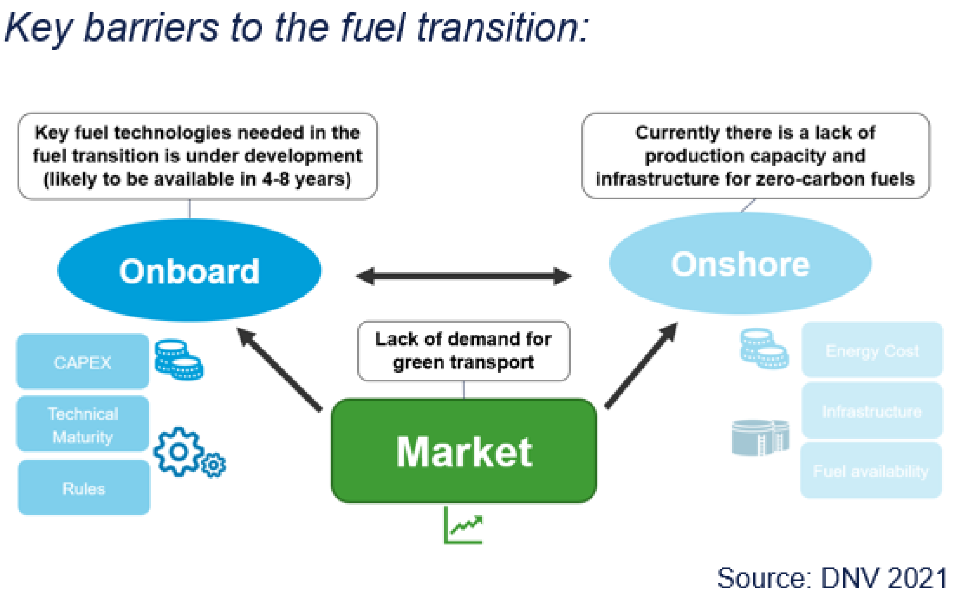


Figure 4.11: Key barriers to the fuel transition (from DNV [101][100])

4.3.3 Summary of barriers

Barriers could also be divided into supply-side- and demand-side barriers, where the demand side refers to the shipowners' willingness to invest in alternative fuels. However, even with different categorizations, the same barriers are covered. In general, the current status of knowledge cannot provide a clear scenario for the future fuel outlook. The existing fuel alternatives have several common challenges, limiting their competitiveness with conventional fuels. The following list summarizes the barriers to the uptake of alternative fuels identified through the literature review:

- **Low technology maturity level**
  Fuel system technology not commercial available. System complexity and safety issues limits the TRL. There must be a demand and willingness to invest in the technology in order to provide fast development. An important consideration is where the stakeholders should put their capacity and investments, in the concepts where only basic research is prepared or in the higher levels where solutions are identified, and demonstration is proven.

- **Low operational experience and being the first mover**
  Low operational experience and knowledge. High risk related to unknown operational aspects. Challenging and costly to be the first mover.

- **Onboard storage of fuels**
  Impact on safety, space, and range. Low energy density fuels require large space for storing. Available space on board ship. Loss of cargo space and probably loss of income. Low-flashpoint fuels need specialized storage tanks, which are more costly. Adaptability to existing vessels and operation.

- **Bunkering availability concerns**
  Bunkering network and port infrastructure are poorly developed for low-emission fuel alternatives and not globally available for vessels operating at deep sea. Demand for alternative fuel has to be supported by a reliable infrastructure.

- **Production capacity and supply of fuel**
  Uncertain demand and unknown required supply from renewable production. Even if the global production capacity exists, large investments are required to tackle a possible rapid rise in fuel demand for all new fuel alternatives. Investing in fuel alternatives that are not able to serve the whole maritime fuel market may meet challenges if several shipowners decide to implement this concept. Many alternative fuels also rely on access to renewable electricity. Reliable supply and delivery of energy produced with net zero-emission is a requirement.

- **Renewable energy supply and cost**
  Access to renewable electricity, reliable supply, and delivery of energy produced with net zero-emission. Renewable electricity is a highly important factor in producing most zero carbon emission fuel alternatives. Renewable energy supply must be certain, and the cost of electricity must be within acceptable limits.

- **Currently too high investment cost/cost of retrofit**
  Difficulty in accessing financing. Diffuse benefits are misaligned with costs - the one paying for the fuel system is not necessarily the one paying for the fuel, leading to a lack of motivation to invest in the alternative fuel systems. Resale value uncertainty.

- **High fuel price**
  Currently non-competitive fuel costs. Fuel costs represent a major expense in deep-sea shipping. There is high uncertainty in the expected price for the low- and zero-carbon emission fuel alternatives.

- **Reliability of fuel system**
  A reliable fuel system is crucial for the operation and for keeping contract agreements. Reliability is dependent on high availability and quality over time. One needs to know the probability that the fuel system will perform adequately on its intended function for a sufficient duration without failure. Reliability refers to the risk that the installed fuel system could affect the ability of the ship to sail.

- **Monitoring of emissions**
  Lack of monitored emissions and hence not being able to follow up on whether emissions regulations are followed will make sure that high-emissions fuels are still the cheapest alternative on the market, making it impossible for zero carbon emissions fuels to be competitive. Carbon risk can be an essential tool.

- **Low maturity of safety regulations**
  New fuel options introduce new safety concerns. Lack of safety standards and regulations. Confusing regulatory landscape and regional inconsistencies. Alternative design processes are time-requiring. Guidelines and class rules may soften the process.

- **Lack of information on the fuel characteristics**
  Lack of information about the characteristics of the fuels (prediction of fuel price, fuel consumption, the off-hire time needed for retrofitting, etc.)

- **Lack of market and customer demand for green fuels**
  Lack of incentives and demand for green transport. The end-customer not paying for the additional cost of zero-carbon transport.

- **Organizational, behavioral and cultural barriers**
  Organizational and behavioral barriers refer to resistance provoked by internal aspects or the people involved in the decision, for example, personal opinions, organizational setup, or managerial practices. Organizational barriers also cover the hindrance of the flow of information among employees, resulting in commercial failure. There can also be a lack of access to information. Cultural resistance, formed by the fact that a ”long-established industry facing shift of fuels and technologies may be resistant to change” is also included [99].

CHAPTER 5

METHODOLOGY

In this thesis, the approach to providing decision support for fuel selection is mainly based on the knowledge of criteria and the performance of alternatives. Decision-making theory, especially multi-criteria decision analysis (MCDA), is used to compare and evaluate different fuel alternatives with respect to decision criteria set by the stakeholders. This chapter presents the methodology used in this project, including relevant theories and methods. The theory of system engineering and multi-criteria decision making (MCDM) is presented and discussed in relation to illustrate its contribution to the decision-making process. Figure 5.1 shows a graphical description of components included in the developed decision support method.

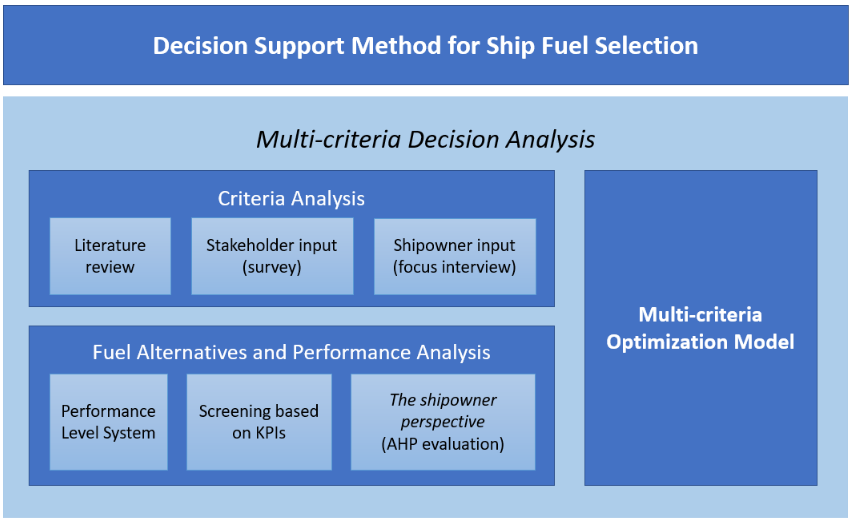


Figure 5.1: Graphical description of components included in the developed decision support method

The analytical hierarchy process (AHP), the weighted sum method (WSM), and multi-criteria optimization are applied to gain insight into the fuel selection problem and understand important trade-offs. A performance level system is presented to quantify qualitative criteria. Criteria weighted by shipowners are included in a multi-criteria optimization model to move beyond cost-efficiency and consider other important performances. This model is presented in chapter 6. In chapter 9, the model is applied to a case study of *the shipowner perspective*.

5.1 Decision and system theory

The decisions that engineers make are often of high consequence, whether to the company's income, the safety of people in the workspace, or the environment. This also applies to decision-makers in the shipping industry. Engineering decision-making often includes multiple, potentially conflicting requirements that must be balanced. In classical optimization, such decision problems are solved by selecting one desired requirement as the objective function and handling the rest as constraints. However, complex decisions often involve several criteria of high importance. Multiple criteria problems include "a range of processes that clarify the consequences of the underlying trade-offs between criteria in configuring alternative solutions" [102].

5.1.1 Decision making

A decision-making process is the steps taken and choices made to select the best alternative or action to meet a desired result. The main components of the process are defining the problem, gathering information, identifying possible alternatives, setting evaluation parameters, and eventually making a decision. A step-by-step decision-making approach is showed in Figure 5.2. A more specific description of the steps is collected in Table 5.1.

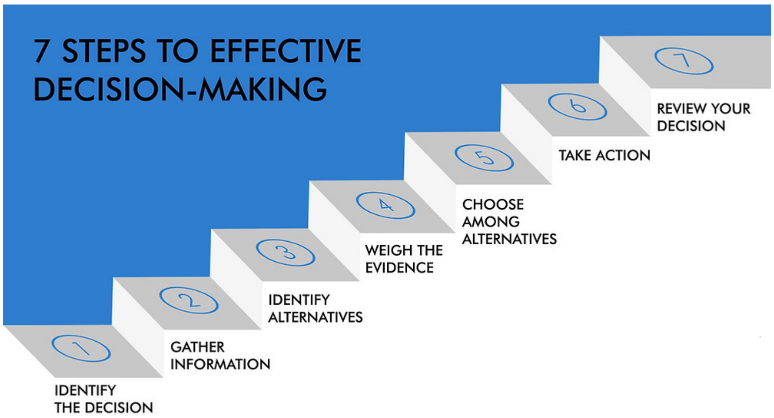


Figure 5.2: 7 steps to effective decision-making (adopted from [103])

i	Step	Description
1	Assessing the problem: Identify the decision	Identify needs. Why make the decision? Clearly define the decision.
2	Gather information	Get relevant information and insights about your decision: What's relevant and what's not? Verify the information.
3	Identify alternatives	Identify both alternatives and paths of actions. Establish new alternatives? List all possible and desirable alternatives.
4	Weight the evidence	Based on the intel you have, list the pros and cons of each alternative and imagine its final outcome. Then, order the alternatives according to your own specific value system. Discuss consequences of decisions.
5	Choose among alternatives	Select an option/a combination of options using logical judgement based on available information.
6	Take action	Begin to implement the chosen alternative.
7	Review and evaluate the decision	Evaluate whether or not the alternative has satisfied the need identified in Step 1. Is there a need to gather more detailed or somewhat different information or explore additional alternatives.

Table 5.1: Description of 7 steps to decision-making (inspired by [103])

The decision-making process involves several risks created by different uncertainties. Risk involves two aspects: (i) the probability that something goes wrong and (ii) the consequence of the worst outcome scenario. When making decisions, identifying risk and how it can be increased is crucial. Possible risk or *threats* can be identified through several brainstorming tools, such as the SWOT analysis ([104][105]), Porter's Five Forces analysis ([106][107]) or the VRIO analysis ([104][108]).

A rational approach should be used to evaluate and analyze the possible options in terms of cost and benefits, to maximize earnings and minimize losses. However, the decision process may be affected by subjective opinions that will affect the quality of logic. An overall tendency is that decision-makers tend to choose the alternative closest to their starting condition (status quo). This is common for a conventional industry such as shipping. Three common psychological aspects that affect decision-making are listed below [109]:

- **Framing effect** - The influence of past experience and surrounding context.
- **Loss aversion** - The phenomenon that people are more motivated to avoid a loss than to realize a profit (e.g., "it's easier to give up on a discount than accepting a price increment, even if there is no difference between the starting and final price"). Related to fuel selection, low-emission fuels are more likely to give a future discount, while conventional fuels with high emissions are likely to experience price increments.
- **Isolation effect** - Humans isolate consecutive probabilities. How the problem is formulated affects the decision made. It is important to see the whole picture.

5.1.2 System perspectives

System engineering is a multidisciplinary approach that describes the system in interrelation with its surroundings, with the system as a subject and its surroundings as a whole. The approach divides the components into subsystems and elements and describes how these interact. The system perspectives can describe development and changes over time, for example, a system in a life cycle perspective. System thinking handles complexity by "looking at connected wholes rather than separate parts" [110]. The approach emphasizes the interactions in the systems and is essential in complex problems and decisions that include several stakeholders and a large range of possible solutions.

Figure 5.3 illustrate the general setup of a model in system theory. System boundaries must be allocated in order to separate the system from its surroundings. The boundaries are important to concentrate interactions inside the system while allowing exchange with external systems. System boundaries are also important to simplify the problem and focus on essential characteristics. System theory describes a system as a composition of components and the connections in-between them. These components and connections form a *whole*. System boundaries are defined to separate the system from the rest of the world, where the parts outside the boundaries form the *surroundings*. The input and outputs, for example, information or energy, create interactions with the surroundings. A system model is often created to simplify and understand a real-life system [111].

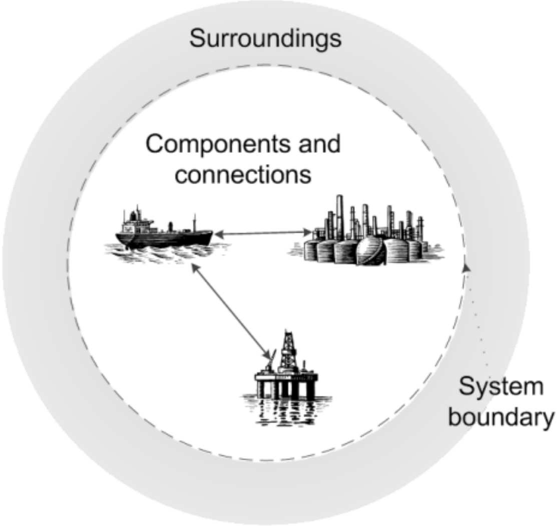


Figure 5.3: General setup of system theory models (adopted from [111])

Stakeholders do have a central role in system engineering. They establish goals and criteria and define needs and required functionality early in the process. Life cycle modelling is often applied, where levels of complexity and uncertainty are considered, and changes and variations are included. Different life cycle phases usually require different types of solution architecture and model constraints. The system engineering approach also involves the generation and evaluation of alternative solutions and verification and validation of the system model. The main focus is to identify relations and interactions of factors with respect to the overall behavior and performance of the system. Balancing factors to achieve a satisfactory outcome is important [112].

Another perspective of system engineering is the 'system thinking paradox': *"One can only truly understand a system by considering all of its possible relationships and interactions, inside and outside of its boundary and in all possible future situations (of both system creation and life), but this makes it apparently impossible for people to understand a system or to predict all of the consequences of changes to it" [113].* However, the approach is commonly used to simplify complex systems and problems. By dividing complex problems into parts and understanding each individual part and how they interact, the problem becomes more manageable and easier to understand. System thinking provides flexibility that is crucial in changing situations and is a convenient approach to making decisions even in uncertain and incomplete situations. An essential part of the method is to map information and identify so-called *known* knowns and *unknown* unknowns.

The fuel selection problem can be modelled in several different ways. One option is to consider the marine engine, or the onboard fuel and propulsion system, as a system that interacts with the rest of the ship. Another option is to define the ship as the main system, with the propulsion system as a sub-system. Then the ship can be a part of a fleet, which then is a sub-part of a larger transport system. Various system boundaries, extended both in time and space, can be used to study the environmental impact of marine transportation problems [114].

The fuel selection problem includes interactions between technology, nature, and society. The problem is modelled as an open and dynamic system, as the system is highly affected by impacts and development of performance levels within key criteria and the overcoming of barriers. With the interaction of nature and society, the system is also a combination of natural and man-made.

5.1.3 Multi-criteria decision making

Multi-criteria decision-making (MCDM) involves a range of possible actions. Each action is characterized by a set of consequences, where some are beneficial and others less so, and where the decision-maker must weigh the pros and cons, often through a range of decision rules or criteria, before selecting a preferred action [102]. Alternatives can be defined as the actions, choices, or options that are a possible solution to the decision problem. The criteria are the attributes, objectives, or values relevant to the alternatives. For multi-criteria decision problems, the alternatives are evaluated and compared according to the different criteria [115]. The decision-maker will decide on criteria and dedicate weights representing their relative importance. In this project, fuel options are the alternatives that will be evaluated according to specific criteria set by the stakeholders.

MCDM originates back to Benjamin Franklin's letter to his friend Joseph Priestly in 1772, where he describes the method 'moral or prudential algebra' [116]. Franklin describes an approach of 'pros' and 'cons' of two (and only two) alternatives being compared. The approach identifies the most suitable alternative by discovering tradeoffs by use of weighting. In the letter, Franklin states the importance of individual preferences in decision-making and, at the same time, emphasizes the value of structured decision-making methods.

As mentioned, Franklin's approach only includes two alternatives. In the book Decision with Multiple Objectives: Preferences and Value Tradeoffs', Ralph Keeney and Howard Raiffa introduce methods for having several alternatives and multiple decision-makers [117]. MCDM history was summarized in 2011 by Köksalan, Wallenius & Zionts in the book 'Multiple Criteria Decision Making: From Early History To The 21st Century' [118]. MCDM has, throughout history, grown as a part of operations research and involves numerous designing computational and mathematical tools for supporting decision-makers to make a subjective evaluation of performance criteria.

In [115], Belton and Stewart present the MCDA process in three main steps: (1) problem structuring, (2) model building, and (3) challenging thinking leading to an action plan. The process is illustrated in Figure 5.4. In the first phase, the problem is identified and structured according to the stakeholders' preferences and values. In the next phase, the model is built by defining criteria and specifying alternatives. This phase also includes the selection of model type and method, as discussed in section 5.2. In the last phase, the input to the model is implemented in the action plan. Evaluation and analysis of the results have a central role, and the phase seeks to challenge intuition. MCDM is an iterative process. New alternatives, adjustments to criteria and weighting, or crucial gaps in the model might be discovered throughout the process.

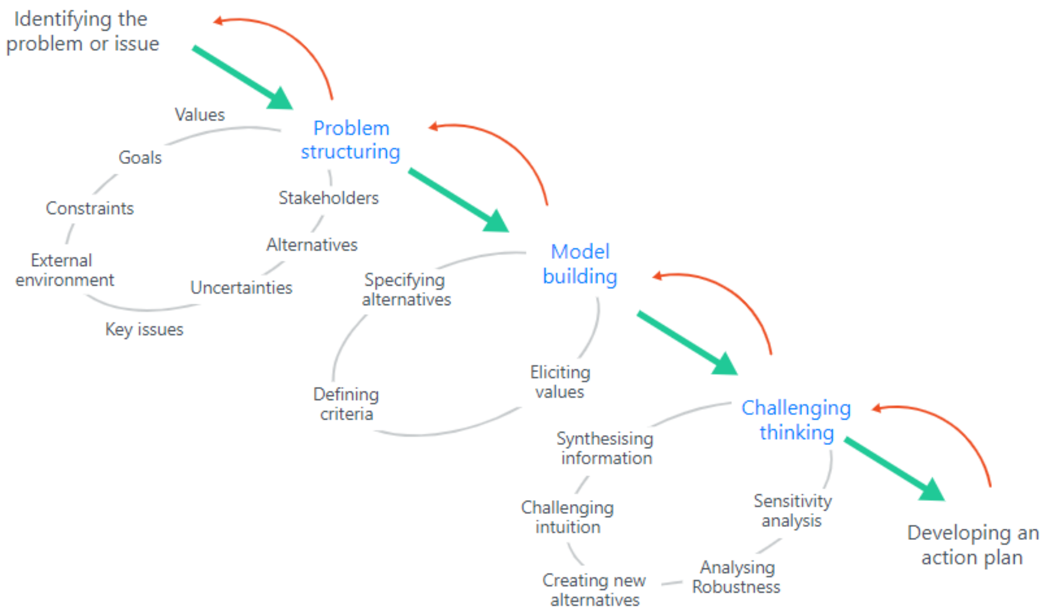


Figure 5.4: Overview of the MCDA/MCDM process (from [115], reproduced in [119])

The MCDM process can be summarized by the following steps, which also will be the steps to follow in this thesis [119]:

1. Structuring the decision problem
2. Specifying criteria
3. Weighting the criteria
4. Measuring alternatives' performance
5. Scoring alternatives on the criteria
6. Applying scores and weights to rank alternatives
7. Supporting decision-making

Modelling considerations

An important aspect of MCDM problems is defining and grouping decision criteria. The same considerations as in general modelling also applies for MDCM, and in [120] they summarize important considerations presented in literature ([42][121]). The summation is reproduced below:

1. **Understandability:** The problem and included aspects must be analyzed and fully understood to avoid conflicts and undesired results.
2. **Completeness:** All aspects relevant to the selection are included. The level of detail (sub-criteria) should, however, be kept at a minimum, still capturing all the key aspects of the problem.

3. **Size (simple/complex):** Balance the size of the problem and avoid over-complications, including the number of criteria and alternatives. A complex problem formulation that involves a high level of specifications will require great effort to collect necessary information and data.
4. **Value relevance:** The selected criteria must be important (have value) for the decision-maker to meet the overall goal.
5. **Operationality:** The model should be practical and easy to apply to real-life problems. Define criteria that can be used to make a reasonable judgement of the alternatives.
6. **Measurability:** The criteria must be measurable. Performance levels must be defined in order to evaluate and compare the alternatives.
7. **Redundancy:** Criteria should not be redundant. A factor or a measure should be covered by one criterion and one criterion only. Avoid duplicates or irrelevant criteria for the desired goal.
8. **Mutual independence of preferences:** Independent evaluation of alternatives is possible. The performance of an alternative can be stated for one single criterion without knowing the performance of the remaining criteria.

5.1.4 The system perspectives of a decision process

A decision process can, in general, be presented from system perspectives. In this case, the decision problem is the system that further can be divided into three sub-systems (or elements); the problem, the criteria, and the alternatives. The criteria define which system information is needed for the decision process, while the alternatives have a performance that seeks to fulfill the criteria. The decision context can be viewed as the system surroundings. The system boundaries are defined by simplifications, assumptions, and limitations of the decision modelling. The problem, criteria, and alternatives interact with each other and receive input and produce output to the decision context. Figure 5.5 illustrates the system perspectives of a decision process. In this project, it is important to identify how the alternatives, the ship fuel options, can influence the level of performance of the key criteria and thus provide knowledge and support for fuel selection.

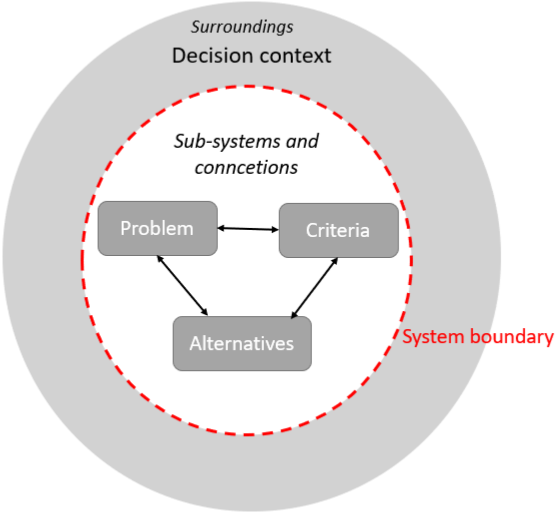


Figure 5.5: The system perspectives of a decision process.

In general, systems engineering and MCDM follow the same three main phases:

- **Problem description and structuring:** Overall understanding of the problem. Identify decision-maker (stakeholder), needs, requirements, and options/alternatives
- **Model building and specification of necessary input:** Model selection and design. Collecting data, specify performance of criteria.
- **Implementation and testing of model:** Verification and validation of system and evaluation of results.

In business, costs are often set as the main criteria and evaluated against other criteria such as environment, safety, or public opinion. Managers often seek to get a high return on investments, but the highest return comes typically at the cost of a high risk of losing money. MCDA is used to gain high returns while keeping the risk at an acceptable level. In this project, we seek to move beyond cost-efficiency and include key criteria set by the stakeholders, and evaluate the risk provoked by uncertainty in the future development of the different fuel alternatives.

5.2 Multi-criteria decision analysis methods

Multi-criteria decision analysis (MCDA) is a set of decision methods or approaches used to structure and evaluate decision problems, helping the decision-maker(s) select an alternative while considering multiple criteria. The approach combines the subjectivity of the decision-maker and the objectivity of measurements. MCDA supports the decision-makers by structuring the problem and collecting information to identify trade-offs and select a preferred option [115].

There exist a large range of MCDM methods, and different authors have presented different forms of classification. Which method to select mainly depends on the available information. One type of classification is presented by Sen and Yang in [102], where they present a decision tree for selecting an appropriate MCDM method, see Figure 5.6.

Most MCDA applications are based on 'weighted-sum' methods (WSMs), based on the decision-makers weighing the decision criteria and rating the alternatives on each criterion. The WSM is described in more detail in subsection 5.2.3. Even if this method is most common, other approaches for MCDM exist, such as performance matrix and outranking methods. The performance matrix is a simple table that presents the alternative's performance on the criteria. This approach works well when one alternative performs much better on all criteria. This is, however, a seldom situation in MCDM, which often involves complex situations and trade-offs between criteria. Outranking methods do involve pairwise ranking of alternatives according to each criterion without using weights. The approach is based on dominance and requires preference independence, meaning that one alternative's performance in one criterion shall not influence the performance of other criteria. Value function methods, a sub-type of WSMs, assign a numeric value to determine the level of performance among the alternatives and often includes a weight, the relative importance, of each criterion. A simple value function method is the additive model, which can be described by the following equation [115]:

$$V(a) = \sum_{i=1}^{m} w_i v_i(a) \tag{5.1}$$

Here, $V(a)$ is the overall value of an alternative, determined by the sum of the alternatives assigned performance value $v_i(a)$ of a criterion i and the relative importance (weight) w_i of a criterion i.

Another possible method is reference level models, which seek optimization by considering the best performance of the most important criteria. The reference levels are defined as goals, and the method requires that the decision-maker prioritize or rank the criteria according to importance. The method is considered "goal programming", as the most crucial criterion is evaluated for each alternative until it satisfies the desired level of performance. The method eliminates alternatives not within the limit, moves to the second most important criterion, and repeats the process until all criteria are evaluated.

As MCDA problems can include either or both qualitative and quantitative data, the methods are mainly distinguished by which information that is required. The decision tree in Figure 5.6 is applied to select an appropriate MCDM method for the fuel selection problem. The decision tree serves as a guideline for which MCDA method to apply based on the available information. Even if the decision tree brings you to one specific method, combining methods to structure the problem and obtain a solution is also possible. This thesis applies a combination of the Analytical Hierarchy Process (AHP), and the WSM implemented in multi-objective optimization. The WSM combines the range of criteria into a single objective function.

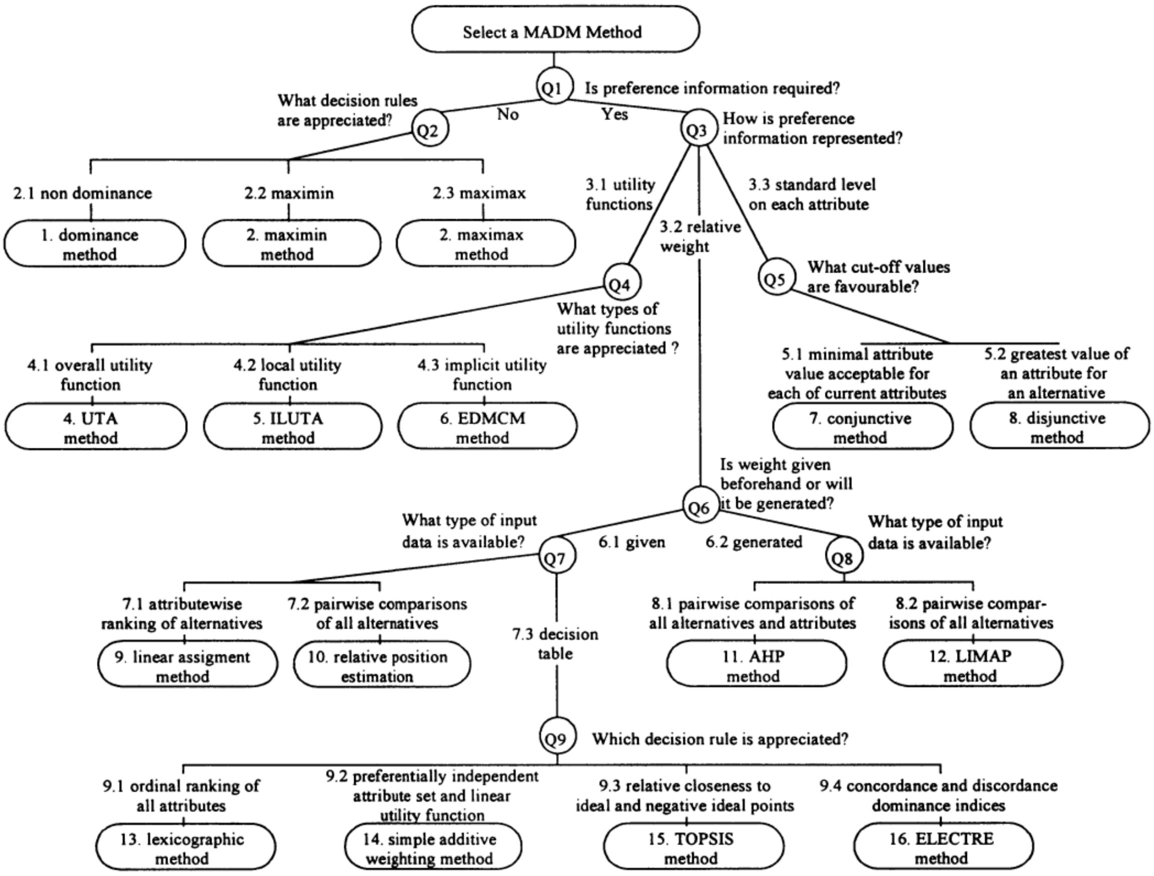


Figure 5.6: Decision tree for selecting a MCDM method (figure 3.4 in [102])

5.2.1 Analytic hierarchy process (AHP)

The Analytic Hierarchy Process (AHP) is based on pairwise comparison and is a widely used method for MCDA. The essence of the method is to construct a matrix expressing the relative values of a set of criteria or attributes. The stakeholders must decide the importance of one criterion compared to another (e.g., the importance of cost compared to safety). The intensities of importance from Table 5.2 are used to value the criteria. Such pairwise comparison is carried out for all factors considered in the problem. The AHP method gives the ability to quantify qualitative information as it converts the evaluations of criteria into numbers. This is very useful in MCDM problems that often involve criteria and alternatives that are difficult to measure with numbers.

Intensity of importance	**Definition**	**Explanation**
1	Equal importance	Two factors contribute equally to the objective.
3	Somewhat more important	Experience and judgement slightly favor one over the other.
5	Much more important	Experience and judgement strongly favour one over the other.
7	Very much more important	Experience and judgement very strongly favour one over the other. Its importance is demonstrated in practice.
9	Absolutely more important	The evidence favouring one over the other is of the highest possible validity.
2,4,6,8	Intermediate values	When compromise is needed.

Table 5.2: The Saaty Rating Scale, AHP method

The next step is to calculate a list (the eigenvector) of the relative weights of the relevant factors to the desired outcome. The final step is to calculate the consistency of the judgements. This is done with a Consistency Ratio (CR). If the CR is much larger than 0.1, the judgements can not be trusted. The judgements are too close to randomness, and the process must be repeated. The CR is calculated by comparing the Consistency Index (CI) to a corresponding value from a large sample of matrices of purely random judgements. The Consistency Index is defined as:

$$CI = \frac{(\lambda_{max} - n)}{(n-1)} \tag{5.2}$$

Where λ_{max} is the principal eigenvalue, which is obtained from the summation of products between the sum of columns of the reciprocal matrix and each element of the eigen vector.

n	3	4	5	6	7	8	9	10	11	12	13	14	15
RCI	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

Table 5.3: Random consistency index (RI) for matrix size n (adapted from [122])

As described in [102] and [122], the AHP method can be summarized by the following steps:

1. Identify the hierarchical structure of the MCDA problem
2. Formulate the comparison matrix (pairwise comparisons)
3. Generate the normalized eigenvector, also called the relative weight vector (RVV)

4. Score the alternatives
5. Rank the elements based on the relative weight vector

Consistency must be checked for all comparisons done in the process.

5.2.2 Multi-criteria Optimization

Mathematical optimization is a tool used to maximize or minimize an objective function by finding the *optimal* value in a set of inputs. With regard to some criteria, the method detects the best available solution from a set of alternatives. Multi-objective optimization is a sub-field of multi-criteria decision-making that concerns mathematical optimization problems that involve simultaneous optimization of more than one objective function. The problem usually involves tradeoffs between conflicting objectives, adding complexity to the problem. For example, to optimize the operational performance of a ship, one would desire a ship that is both cost-efficient and environmental-friendly. Such objectives are often in conflict, which leads to tradeoffs. The set of tradeoffs that improve one criterion at the expense of another is called the Pareto set. A solution is "Pareto optimal" if no change leads to improved satisfaction for one objective without worsening another. The Pareto front is the set of Pareto optimal solutions. It is up to the decision-maker to select a preferred solution from the "Pareto optimal" solutions in the Pareto sets. The optimization model detects a range of feasible Pareto solutions, but which tradeoffs to accept must still be evaluated by the decision-maker [123][124].

The method can be used to identify the set of Pareto optimal solutions, quantify the tradeoffs, or find the single solution that satisfies the subjective preference of a specific decision-maker. This thesis combines the multiple objectives (defined in terms of criteria) into one objective function using the Weighted-Sum Method.

5.2.3 The weighted sum method

The WSM involves the weighting of criteria to reflect their relative importance, where the sum of the weights equals 1. Each alternative is scored according to its performance on each criterion. For each alternative, the individual performance value of each criterion is linearly combined into a total score. The alternatives are then evaluated based on the total performance score. The performance value is usually 0-100, giving a total score in the same range. The method allows combining several criteria into a single objective function. The criteria considered will be weighted in accordance with their relative importance set by the decision-maker [125]. The total score is combined by the use of the same principle as for value functions, described in the section 5.2.

Assume a given MCDM problem with n decision criteria m alternatives. All criteria are assumed to be benefit criteria, which implies that the higher value is the better value. Let w_i be the relative weight of importance of criterion C_i and a_{ij} be the performance value of alternative A_j for criterion C_i. Then the weighted-sum score, or total importance, of alternative A_j can then be defined as:

$$A_j = \sum_{i=1}^{n} W_i a_{ij}, for j = 1, 2, 3, ..., n. \tag{5.3}$$

For a maximization objective, the alternative with maximum total performance value implies the best alternative and the opposite for a minimizing objective. An important note is that this method only applies to data and performance values that are expressed with the same unit, implying that the values must be normalized.

5.3 Performance analysis

Performance analysis is the process of observing or evaluating the performance of a particular scenario or option in comparison to the objective. A performance analysis must be prepared in order to identify how the fuel alternatives perform within each criterion. In this thesis, the evaluation of fuels is based on defined performance levels within each criterion. This will be referred to as the "performance level system".

The approach is based on establishing simplified but representative evaluation indicators (criteria) and defining levels of performance for each indicator. The simplified performance system enables a quantitative comparison of alternatives based on qualitative criteria. The stepwise approach is listed below:

1. Select criteria and define them as key performance indicators (KPIs)
2. Quantification of qualitative criteria
   (a) Define the number of performance levels
   (b) Define the qualitative performance that satisfies the different levels
3. Identify the quantitative fuel performance within the KPIs based on the defined performance level system
4. Compare the fuel alternatives

In chapter 7, a specific performance level system is defined based on six selected KPIs. The system is used to compare and evaluate a selection of fuel options for deep-sea shipping.

5.4 Information and data collection

Multi-criteria decision-making requires information and data on selection criteria and alternatives. Which type of information and data that needs to be collected will vary from case to case and are based on the decision-makers criteria selection. Information and data on fuel alternatives can be found in a large range of sources. In this thesis, a summary of fuel information and performance is presented in chapter 3. Necessary information is quantified by the use of the described performance level system. Information about the decision-makers' preferences in the fuel selection problem is collected through a soft analysis using a survey and focus interview. The methods collect both qualitative information and quantitative data.

Information can be gathered in different forms (quantitative or qualitative) through different sources (primary or secondary sources). A combination of research approaches can be applied to obtain a broad insight into the problem, and a satisfactory result [126].

Primary and secondary research refers to the way of collecting information and data. Survey and focus interviews are both primary research methods where the original information is collected directly connected to the project's purpose. Secondary research gathers information through published sources and literature reviews. Secondary research was applied in chapter 3 and chapter 4 to get an initial understanding of the wide range of ship fuel types and criteria. The secondary research prepared in these two chapters forms the basis for the defined performance levels and the evaluation of fuels in chapter 7.

The gathered information can be either quantitative or qualitative. The collection of numerical data is categorized as quantitative research. The method helps produce statistics and get an overview of the situation. The quantitative information is often presented in terms of averages and must be evaluated carefully. Extremes can highly influence an average value. On the other hand, qualitative research collects non-numerical information, often in terms of views and perspectives. Focus groups and interviews can be used to identify habits and understand stakeholders' needs and requirements and how they evaluate a situation or a problem. As this thesis aims to map the ship fuel selection process in the decarbonization of shipping, a combination of primary, secondary, quantitative, and qualitative research is performed.

5.4.1 Survey

A survey is a series of questions sent to a set of research participants that provides self-reported data. Questions in a survey can be qualitative and quantitative, but the method is often used to collect quantifiable information. The questions are usually in the form of true/false or yes/no, multiple-choice, rankings, or ratings. Open questions can be included to let the participants add information the questions fail to cover [127]. Several commercial software options provide a wide range of survey design and analysis tools. In this thesis, the tool 'Survio' is used.

5.4.2 Focus groups and interviews

A focus group is a group of people assembled to respond and discuss something. The group is studied to gather information and knowledge of what to expect from a larger population. Interviews with a focus group are an effective qualitative research method that provides opinions and attitudes. The interview is normally based on a set of questions or discussion points. The interview should be open-ended and make it easy for the participants to include additional inputs. Selecting participants for the focus group is an essential part of the method. In this thesis, a focus interview with one shipowner is conducted as a follow-up to the survey on ship fuel selection.

CHAPTER 6

MODELLING SHIP FUEL SELECTION - MOVING BEYOND COST-EFFICIENCY

This chapter presents two mathematical multi-criteria optimization models for selecting ship fuel types. The first model is a simple Weighted-Sum Model that combines different qualitative criteria, taking the criteria's relative importance (weighting) and how the different fuel alternatives perform on each criterion into account. Model number 1 will be further tested in the case study in chapter 9. The second model includes the real quantitative performance of specific criteria such as costs and emissions. Model 2 is based on a combination of the model presented in 'Optimal ship lifetime fuel and power system selection' by Lagemann et al. ([128]) and the model presented in 'Optimized selection of vessel air emission controls—moving beyond cost-efficiency' by Balland et al. ([129]).

6.1 Problem description

Fuel type selection for the future is a difficult challenge. Not only do there exist a wide range of fuel alternatives, but they all come with an uncertain future development of aspects such as fuel system technology and bunkering infrastructure. In addition, numerous exogenous conditions will affect ships under operation, such as future emission regulations and carbon tax. With the ship's long lifetime, risks and benefits are hiding on the planning horizon. The fuel selection problem is modelled by the use of assumed fuel performance development within discrete periods. This is done to understand the decision context and how the decision-maker evaluates different factors and prioritizes the many criteria. The problem addressed in this thesis is: "Given a known fuel criteria performance scenario, what is the best fuel choice through the ship's lifetime with respect to criteria selected and weighed by the decision-maker?". The model requires an evaluation of the performance value of each fuel option for all the included criteria. These values can be time-period dependent, e.g., with reduced risk over time or increased technology maturity of the fuel system.

The model applied to evaluate ship fuel types based on the decision-makers criteria, and belonging relative importance is described in Figure 6.1. The model is open and can include a wide range of criteria and alternatives. Some input parameters may be scenario-specific and vary depending on the boundary conditions. The model processes the input parameters and presents the weighted total performance for each given fuel option and scenario.

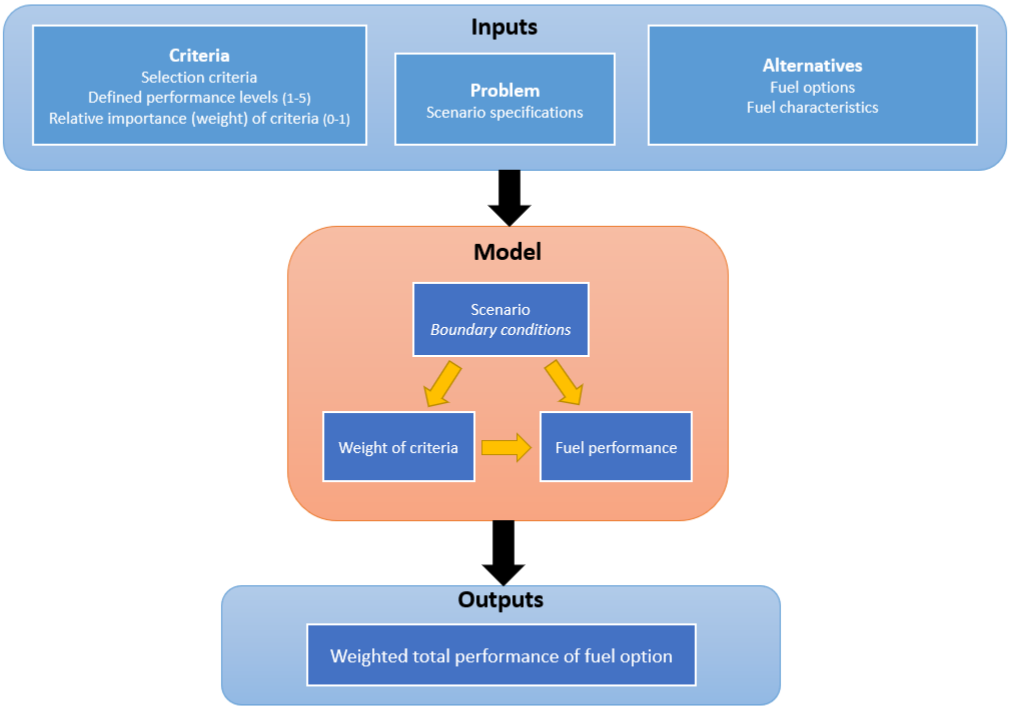


Figure 6.1: Simplified schematic description of model applied to evaluate ship fuel types

6.2 Multi-criteria optimization model 1: Qualitative performance

The first model determines which fuel type to select with respect to the decision-makers preference, regardless of ship type or operational trade. The weighted sum method (described in subsection 5.2.3) is used to combine several criteria into a single objective function. As an input to the model, the decision-maker must weigh the relative importance of each criterion. The weighting will give a subjective, objective function based on the stakeholder's preference(s).

The model needs four inputs; The set of qualitative criteria, the set of fuel alternatives, the relative importance (weighting) of the different criteria, and an evaluation of how the different fuel alternatives perform within each criterion. This performance value can be determined in many ways, but a main requirement for the model is that all values are on the same scale to be combined. Scaling and normalization of scores is an essential process in multi-criteria optimization, and several scaling techniques are presented in [125]. A scaling in terms of defining levels of performance is suggested in section 5.3 and further applied in chapter 7.

The model output will depend on how the user chooses to weigh the different criteria. The model needs to be open enough to let each decision-maker include his own selected criteria. The criteria to consider will be dependent on each case and should be specifically defined for each decision-maker.

6.2.1 Model notation

The notation applied in model 1 is presented in Table 6.1

Sets	**Description**
A	Set of qualitative criteria a
F	Set of fuel options f
T	Set of discrete time periods t
Parameters	
W^a	Relative importance (weight) of criterion a
V_{fta}	Performance value of fuel type f at period t for criteria a
Variables	
x_{ft}	Binary variable, 1 if fuel option f is chosen at time t, 0 otherwise

Table 6.1: Notation in Model 1

6.2.2 Mathematical model formulation

In this model, the fuel selection problem is modelled as a maximizing problem, as the aim is to identify the fuel option with the overall highest performance taking the weighting of criteria into account.

Objective function:

The objective is to identify preferred fuel options by maximizing the total weighted performance value of the fuels over all periods of time.

$$\max Z = \sum_{a\in A}\sum_{t\in T}\sum_{f\in F} W^a \cdot V_{fta} \cdot x_{ft} \tag{6.1}$$

Subject to:

Equation 6.2 ensures that precisely one fuel option is selected in each time period:

$$\sum_{f\in F} x_{ft} = 1, \forall t \in T \tag{6.2}$$

Equation 6.3 represents the binary constraints:

$$x_{ft} \in \{0,1\}, \forall f \in F \tag{6.3}$$

6.3 Multi-criteria optimization model 2: Including real quantitative performance of criteria

As the first model is relatively simple, model 2 is an extension trying to include several aspects of the fuel selection problem. It is possible to quantify the performance value of some fuel selection criteria. Among the criteria discussed in chapter 4, do costs and emissions have real quantitative performance values. There should also be possible to identify real values for the required onboard storage capacity of fuel and global fuel production capacity. However, the other criteria are qualitative, making it difficult to compare the different fuel options. Model 2 allows the combination of quantitative criteria and qualitative criteria. The qualitative criteria must still be quantified as described in section 6.2. For the criteria with real quantitative performance values, these values can be normalized into the same scale as applied for the qualitative criteria. When all values are on the same scale, they can be combined into one single objective function using the Weighted-Sum Method.

Model 2 includes emissions (both well-to-tank and tank-to-wake), cost of investment, and potentially cost of retrofit, while the user selects additional criteria to include in the decision. The additional criteria will be added to the objective to influence the optimal solution. In this model, economic and environmental criteria will always be included in the decision. Notice that this model is limited to real performance values of economic and environmental criteria. Still, it is also possible to add several terms presenting other criteria with real performance values.

6.3.1 Background models

As mentioned, model 2 is inspired by on a combination of two already established models. Model 2 is a multi-criteria optimization model for fuel selection, where included components are inspired by the ones presented in [128] and summarization of objective criteria is based on the Weighted-Sum Method similar to the presentation in [129].

In [128], the aim was to identify the best power system and fuel choices throughout the ship's lifetime. The model is multiple objective functions that take costs and GHG emissions into account, and a solution is found based on a fixed fuel price scenario. The problem was approached as a compromise selection between emissions and cost over time, modelled by using two objectives: (1) Minimizing the total cost of ownership and (2) Minimizing the global warming potential. The model evaluated possible switch of fuels throughout the lifetime, either between two compatible fuels (no additional cost) or switching where retrofit of power system is needed (retrofit cost added). A lost opportunity cost based on the potentially additional fuel and power system weight compared to the baseline fuel system was also included.

In [129], a multiple criteria optimization model for the selection of air emission controls is presented. The model is an extension of the single criterion model described in [130]. The objective of the model is "to create an implementation plan determining which controls to install at which time period". There is a given planning horizon, where an emission reduction plan is created (either based on emission regulations or the shipowner's motivation) for the vessel to comply with at every time period.

6.3.2 Model notation

To avoid confusion, the model notation will mostly be similar to the two preliminary models. The sets, parameters and variables used in the model are presented in Table 6.2, Table 6.3 and Table 6.4, respectively.

Sets	Description
A	Set of qualitative criteria a
F	Set of fuel types f
S	Set of pre-generated ship power system options s for energy storage and power conversion
T	Set of discrete time periods t

Table 6.2: Sets in Model 2

Parameters	Description
C_s^{NB}	Newbuild cost of a ship with power system option s
$C_{s's}^{R}$	Retrofit cost from option s' to option s
C_{ft}^{F}	Fuel cost of fuel type f in time period t
C_{st}^{LO}	Lost opportunity costs of a ship with power system s per time period t
B	Energy consumption per time period t
E_f^{WTT}	Well-to-tank emissions of fuel f per time unit
E_f^{TTW}	Tank-to-well emissions of fuel f per time unit
K_{fs}	1 if fuel and power system s are compatible, 0 otherwise
W^{CAPEX}	Relative importance (weight) of the investment/retrofit cost criterion
$W^{fuelprice}$	Relative importance (weight) of the fuel price criterion
$W^{emission}$	Relative importance (weight) of the emission criterion
W^a	Relative importance (weight) of criterion a
V_{fta}	Performance value of fuel type f at period t for criteria a

Table 6.3: Parameters in Model 2

Variables	Description
x_{ft}	Binary variable, 1 if fuel f is chosen at time t, 0 otherwise
y_{st}	Binary variable , 1 if power system s is chosen at time t, 0 otherwise
$r_{s'st}$	(Auxiliary variable, required for linearization) Binary variable, 1 if retrofit is to be made from power system option s' to power system option s after period t, 0 otherwise

Table 6.4: Variables in Model 2

6.3.3 Mathematical model formulation

In contrast to Model 1, this model presents a minimizing problem, as the aim is to have low costs and low emissions. This must be taken into account when defining the performance levels of the qualitative criteria.

Objective function:

The objective is still to identify the preferred fuel option, now by minimizing the total performance value of the fuels over all periods of time. The 'best' performance must hence be the lowest performance value.

$$\min Z = W^{CAPEX} \sum_{s \in S} \left(C_s^{NB} \cdot y_{s0} + \sum_{t \in T} \left(C_s^{LO} \cdot y_{st} + \sum_{s' \in S} C_{s's}^{R} \cdot r_{s'st} \right) \right) \tag{6.4}$$

$$+ W^{fuelprice} \sum_{t \in T} \sum_{f \in F} B \cdot C_{ft}^{F} \cdot x_{ft} \tag{6.1a}$$

$$+ W^{emissions} \sum_{t \in T} \sum_{f \in F} B \cdot (E_f^{WTT} + E_f^{TTW}) \cdot x_{ft} \tag{6.1b}$$

$$+ \sum_{a \in A} \sum_{t \in T} \sum_{f \in F} W^{a} \cdot V_{fta} \cdot x_{ft} \tag{6.1c}$$

Subject to:

Equation 6.5 and Equation 6.6 ensures that precisely one fuel and one ship power system option are selected:

$$\sum_{f \in F} x_{ft} = 1, \forall t \in T \tag{6.5}$$

$$\sum_{s \in S} y_{st} = 1, \forall t \in T \tag{6.6}$$

Equation 6.7 presents the compatibility constraint, to make sure that fuel f and power system s can only be selected if they are compatible with each other:

$$x_{ft} + y_{st} \leq 1 + K_{fs}, \forall f \in F, \forall s \in S \tag{6.7}$$

Equation 6.8. Equation 6.9 and Equation 6.10 represents the retrofit constraints: ”Switching from a power system s’ to another power system s in consecutive periods”.

$$y_{s'(t-1)} + y_{st} - 1 \leq r_{s'st} \qquad \forall s', s \in S, t \in T \setminus \{0\} \tag{6.8}$$

$$y_{s'(t-1)} + y_{st} \geq 2r_{s'st} \qquad \forall s', s \in S, t \in T \setminus \{0\} \tag{6.9}$$

$$r_{s'st} = 0 \qquad \forall s', s \in S, t = 0 \tag{6.10}$$

Equation 6.11 and Equation 6.12 presents the binary constraints:

$$x_{ft} \in \{0, 1\}, \forall f \in F \tag{6.11}$$

$$y_{st} \in \{0, 1\}, \forall s \in S \tag{6.12}$$

6.4 Possible extension

The models are open to a large range of extensions. As mentioned, real quantified performance values can be obtained and added as objectives for the criteria that allow it. Another possible extension is to add a restriction for 'minimum carrying capacity' related to the lost opportunity cost, like a requirement for how much cargo the ship must be able to transport. Some vessels also have extra volume or weight capacity, meaning that there will be no cargo capacity loss up to a certain volume or mass value. Another possible extension is to consider emission control regulations, for example, by adding constraints on maximum allowed emission.

EU's 'Fit for 55 package' presents different penalties, such as the "FuelEU GHG limit penalty" and "FuelEU shore power penalty", which could be introduced as input to the optimization problem if the vessels are operating in the EU [131]. Carbon pricing could be applied through EU Emissions Trading System (ETS) [132]. However, for FuelEU Maritime, other types of input data are needed (e.g., "Time in EU port", installed power, GHG target (well-to-wake), actual GHG emissions, etc.) to calculate the potential penalty costs.

CHAPTER 7

SCREENING OF FUEL OPTIONS FOR OPERATION AT DEEP SEA

This chapter presents a specific performance level system that quantifies qualitative performance within a selection of criteria. The level system is defined for six specific KPIs and used to perform a comparison-based screening and evaluation of fuels for operation at deep sea. All KPIs have been allocated the same relative importance (weighting) in this screening process. The screening is prepared mainly to demonstrate the level performance system, but the comparison is still a representative evaluation of the fuels.

7.1 Selection of KPIs

The screening is based on overall performance of the following key performance indicators (KPIs):

1. Technology maturity level of fuel system (TRL)
2. Required onboard storage capacity (based on the energy density of fuel)
3. Availability in terms of bunkering availability and global production capacity
4. GHG emissions (well-to-wake)
5. Maturity of safety regulations
6. Costs in terms of investment cost and fuel price

The six KPIs are defined to assess and rank the different fuel alternatives in a comparable manner. Not all aspects are included, but a selection of performance indicators is simplified and based on the ability to do a quantification in the evaluation. The screening is done by the author only and is based on the literature review of fuel pathways and characteristics (chapter 3) and criteria (chapter 4).

7.2 Defined performance levels

A level performance system quantifies qualitative criteria and compares the fuel alternatives. Performance levels are defined for each KPI, where 5 is the top level (highest performance), and 1 is the bottom level. The performance value of the fuels is defined based on how well they perform within each criterion, and in general, the scoring evaluates the performance from 1 (very poor) to 5 (very good). The performance levels of the KPIs are defined in Table 7.1-Table 7.6. Further, each fuel alternative is scored according to the specific KPI levels.

The technology maturity levels applied in this paper are presented in Table 7.1.

Level	**Description**
5	Fully mature technology, commonly used on new ships and operation
4	Commercially available, but not common in operation
3	Under piloting and/or with only a few commercial applications
2	Under development, small scale testing/ planned piloting or full-scale testing
1	Not tested in full scale and no piloting or full-scale testing underway

Table 7.1: Performance levels of technology maturity (TRL) of fuel systems and technology

The levels of applicability are presented in Table 7.2. The levelling is primarily based on the energy density, as safety issues also can be covered by the TRL.

Level	**Description**
5	High energy density, no cargo loss. Minimum safety related risks
4	Relative high energy density, some cargo loss may occur
3	Medium energy density, some cargo loss is expected
2	Low energy density, barrier for deep sea shipping
1	Low energy density, both regarding mass and volume. Significant safety issues.

Table 7.2: Performance levels of applicability of fuel systems and technology

The levels of availability are presented in Table 7.3. The total evaluation score will be based on an average score of production capacity and bunkering infrastructure.

Level	**Production Capacity**	**Bunkering Infrastructure**
5	Able to cover all maritime fuel demand	Fully developed, worldwide
4	Able to cover all current maritime fuel demand, some interaction challenges	Infrastructure in place, some development still remains directly applicable to current infrastructure
3	Medium-small capacity, not able to cover all fuel demand	Local infrastructure in place, global expansion under development
2	Small capacity, only relevant as drop-in fuel	Local infrastructure under development
1	Low capacity, not an option	No infrastructure in place or planned

Table 7.3: Performance levels of availability of fuels, including production capacity and bunkering infrastructure

The levels of environmental impact of GHG emissions are presented in Table 7.4. Both well-to-tank and tank-to-well emissions will be taken into account for the scoring of the fuels.

Level	Description
5	(Potentially) carbon neutral well-to-wake
4	Low GHG emissions, well-to-tank and/or tank-to-wake
3	Some GHG emissions, potential for reduction
2	Large GHG emissions, but not the worst
1	Significantly GHG emissions, no reduction possible

Table 7.4: Performance levels of GHG emissions

The levels of safety regulation maturity are presented in Table 7.5.

Level	Description
5	Fully regulated and directly applicable
4	Well regulated. Subject to international regulations, specific regulations under development
3	Alternative design approach, individual demonstration required. Some concepts approved.
2	Alternative design approach, individual demonstration required. No concepts approved yet.
1	No guidelines for approaching safety regulation

Table 7.5: Performance levels of safety regulation

The levels of expenses are presented in Table 7.6. The total evaluation score will be based on an average score of capital costs and fuel price.

Level	CAPEX	Fuel Price
5	Cheaper than conventional engines	Lower than MGO, competitive
4	Equal to conventional diesel/gas engines	Equal to current fuel price of MGO, competitive
3	Slightly more expensive than conventional engines	Higher than current MGO price, almost competitive
2	Much higher expenses than conventional options	Higher than current MGO price, not competitive. Depends on development of infrastructure
1	Significantly higher expenses than conventional options	Much higher than current MGO price, will not be competitive

Table 7.6: Performance levels of costs

7.3 Comparison-based evaluation of fuel alternatives for deep-sea shipping

In this section, the selected fuel alternatives will be compared and evaluated based on their current suitability for operation at deep sea. The six KPIs and the defined score levels are the foundation for the comparison-based evaluation. Conventional HFO and MGO are used as benchmark fuels. The performance scores given in this section will also be used as a basis for the scores applied as ”status quo” in the case study in chapter 9.

7.3.1 Results of evaluation

An overall assessment of the fuels is prepared based on best judgement from the literature review. Figure 7.1 presents the full result of 12 different fuel alternatives, whereas some of them are included with both fossil and renewable energy sources. The total result chart is not very readable but included to show the diversity and range of the fuel situation. The result will be presented in more detail further down. Note that the scoring of the alternatives is based on energy source (fuel family) and fuel type. The energy converters for the different fuel types are only discussed and not directly considered when scoring the fuels.

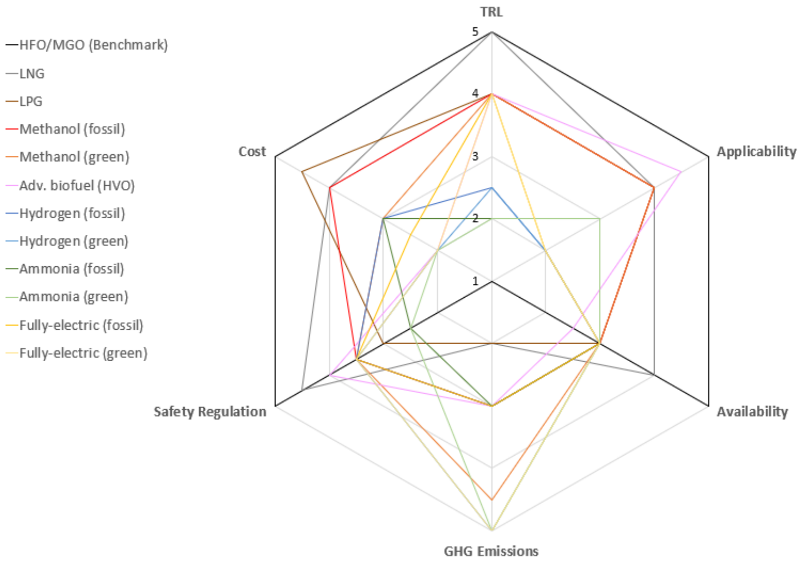
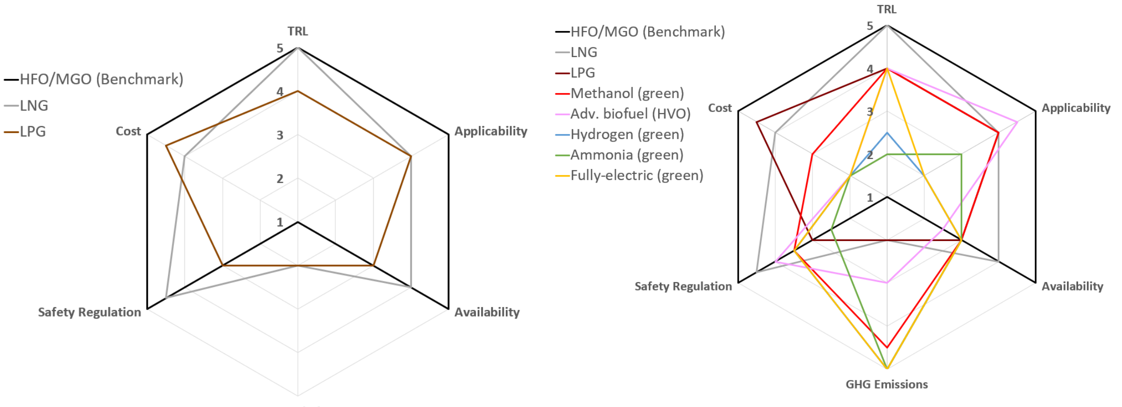


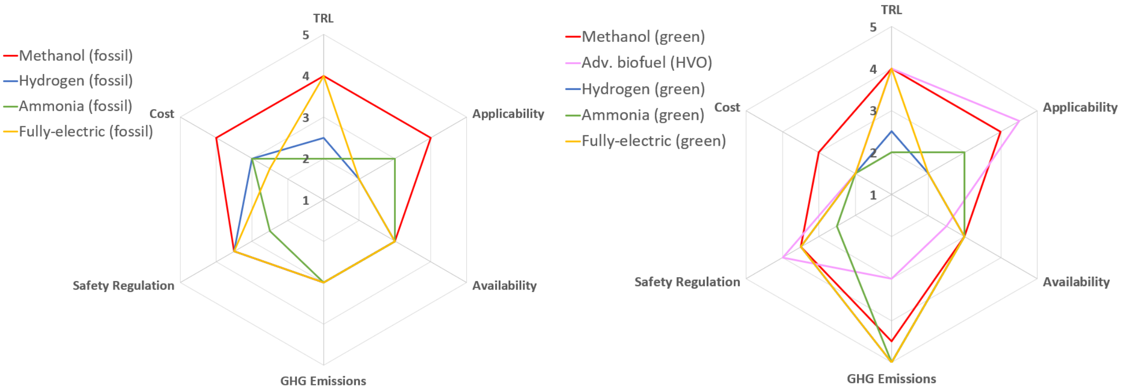
Figure 7.1: Full result chart of screening results. Presenting 12 different fuel versions, including both fossil and green energy production.

Figure 7.2 split up the results and shows the individual scores in more detail. Figure 7.2a shows the conventional fuels and fossil LNG and LPG. The benchmark fuels (HFO/MGO) got top score for all KPIs except GHG emissions, the most crucial parameter for the goal of decarbonizing shipping. The investment and development of LNG in the past years have led to high scores, but also here, the main challenge is emissions. LNG is, however, stated as an important transition fuel towards a zero-emission shipping industry.



(a) HFO/MGO, LNG and LPG

(b) The 'greenest' version of the eight different fuel types



(c) Fossil version of possible low-carbon fuels

(d) Low-carbon emission fuel alternatives

Figure 7.2: Extraction of screening results

Figure 7.2b presents the eight different fuel alternatives addressed in this project but includes only the 'greenest' alternative of each fuel. This is done better to compare the potential carbon-neutral fuels and the conventional fuels. Based on this presentation, it looks like methanol is a feasible fuel alternative. However, this alternative has high TRL but is still not competitive on costs and cannot serve the whole maritime fuel market due to low production capacity.

Figure 7.2c presents the fossil alternative of each 'new' fuel alternative, where methanol comes out best and stands out for the cost and applicability parameter. Fully-electric falls through due to high costs and low applicability for deep sea, while ammonia shows good potential but still has low TRL. All these fuels score poorly at GHG emissions. However, by adding CCS technology to the production and combustion of these fuels, low-carbon emissions can be obtained.

Figure 7.2d presents the fuel families 'green' and 'biofuels', which are the families with the best score on GHG emissions. These fuels have gained a score of 2.5-3 for availability. It is crucial to have in mind that this includes both infrastructure and production capacity. In contrast, some fuels are pulled down mainly due to low production capacity (advanced biodiesel and methanol), while others are due to poorly developed infrastructure (e.g., hydrogen, fully-electric). Ammonia scores well on GHG emissions and applicability but still remains the development of technology and safety regulations

7.3.2 Detailed justification of scoring

LNG fuel technology is well developed and common in operation. The production capacity has no limit, and global infrastructure is under development. However, the storing of LNG tanks requires a larger volume than conventional fuel, which pulls down the score on applicability. LNG is the cleanest fossil fuel but still has high emissions and therefore scores poorly for the GHG emission parameter. International safety regulations cover LNG, and the costs are competitive with MGO.

LPG scores equal to LNG for applicability but has a lower score for technology maturity level, availability, and safety regulation. All these factors can be explained by an industry that has not invested in the fuel alternative. The technology is commercially available but not yet common in operation. There is neither a developed infrastructure, but this can easily be expanded. Since the fuel is not well established in the industry, neither are its regulations set. Ship owners that want to apply LPG as fuel on their vessels must go through the alternative design approach. However, this might not be a complicated process as several LPG power system concepts are already approved. The low score of emissions is given because of propane and butane's high contribution to GHG emissions. With a similar fuel price and CAPEX costs approximately halved compared to LNG, LPG scores in the top range of the cost parameter.

Methanol fuel technology is mature and commercially available but not commonly used in shipping. The fuel is more manageable than LNG, but the lower energy density than conventional fuels results in a score of 4 on applicability. The global production capacity is relatively low and cannot serve the whole maritime fuel market. The infrastructure is currently poorly developed, but only minor modifications to already established diesel infrastructure is required to increase the availability. The application of methanol as fuel still requires an alternative design approach, but regulations are under development. Fossil methanol has only a 10% reduction of CO_2 emissions compared to conventional fuel oil, potentially lower if it is produced from renewable sources. The costs of fossil-produced methanol are competitive, but renewable produces methanol will probably give a higher price.

Advanced biodiesel (HVO) is compatible with current diesel engines, giving it a high score for both technology maturity level and applicability. Its similarity also makes the fuel well regulated and covered by several general standards and own sustainability guidelines. However, it has a low production capacity and poorly developed infrastructure, resulting in one of the worst availability scores. The low availability also results in high fuel costs. The environmental impact of using biodiesel is debated, but the use of HVO gives around a 50% reduction in GHG emissions. Advanced biodiesel may be an essential tool in shipping decarbonization, primarily because it can be used as a drop-in fuel for vessels operating at conventional fuel oils.

Hydrogen has a low maturity level, and the operational experience is limited to short-sea, mainly due to its low energy density and challenging safety issues. However, the potential for zero carbon emission production (well-to-wake) has made the industry start research and investigate the possibility of development for both technology, regulations, and infrastructure, resulting in a score of 3-4 on safety regulation. Hydrogen has a high production capacity and can be produced both from natural gas and renewable resources. This makes the implementation of hydrogen-fuelled power systems less risky as fossil hydrogen can be used while waiting for adequate renewable production. The poorly developed infrastructure does, however, pull down the score on availability. Hydrogen is a costly fuel and highly depends on the cost of electricity or natural gas.

Ammonia has the lowest technology maturity level and is currently not tested on board ship, but the opportunity is under research and development. The higher energy density of ammonia compared to hydrogen has sparked interest in its use in deep-sea vessels. Other advantages are the high production capacity and its compatibility with LPG infrastructure. Ammonia can be a zero-emission fuel through green production or applying CCS technology to fossil production. The fuel alternative has no international regulations and no concepts approved through the alternative design approach. However, handbooks and class rules are established due to the increased interest in the industry, and the fuel option has therefore gained a score of 3 for safety regulation. Ammonia has high costs, and the costs are expected to continue to be high in the years to come.

Fully-electric power systems (batteries) have an overall high technology maturity level. However, the technology is still not ready for deep-sea operation mainly due to its high energy density. Electricity has no limit for production capacity but is highly dependent on well-developed infrastructure. This infrastructure is currently not adequate for the shipping industry. Fully-electric vessel operation can be zero-emission if the electricity is produced from renewable electricity or with CCS technology. The costs are high and have large regional and seasonal variations.

7.4 Discussion of screening

The presented results are a qualitative evaluation based on 'best judgement' obtained from described literature review and knowledge. The scores include high uncertainty and are not directly based on quantitative data. Several parameters, such as fuel availability and fuel price, are hard to predict for undefined specific fuel demand and fuel alternatives not being scaled and commercially available.

Two of the parameters, availability, and costs, are divided into two sub-parameters. As the given score within this parameter is based on a qualitative average, one of the sub-parameters could have a significant impact and pull the score either up or down. An option had been to evaluate based on several KPIs (e.g., as in the table in Appendix D). However, this would have been a more comprehensive study not able to finish within the given timeline and course credit.

Another critical aspect of the evaluation is that it is difficult to evaluate the technology maturity level for deep-sea operations. In general, the fuel technology can have a top score for TRL, but applicability aspects can make it not feasible for operation at deep sea. An important decision for stakeholders is if one should continue to develop deep-sea technology for alternatives that has showed good results on short-sea operation but currently is limited due to low energy density, or if one should change the path and invest in other, new fuel alternatives.

The evaluation is based on a literature review, including studies that have prepared similar assessments. How other studies have evaluated the different fuels within various parameters may have a large impact on the score given in this project. Much of the data used is based on a range from minimum to maximum (e.g., the data for flammability and fuel price). This implies high uncertainty, which will be reflected in the given scores. The uncertainty is primarily for low-developed fuel concepts with low scaling and a lack of operational experience. Increased technology development and commercial scaling will probably provide more complete and certain data.

This evaluation is also based on a selection of fuels. The selection of fuels was random based on first-impression knowledge. Several other fuel alternatives have good future prospects as maritime fuels, such as Liquefied biogas (LBG, or bio-LNG) or liquefied synthetic methane. A complete picture of the fuel availability for deep-sea shipping could be provided by making a more comprehensive study and including several fuel alternatives.

Carbon-neutral fuels can be produced from various energy sources or energy systems with net-zero carbon emissions, including the use of CCS technology both in production and for the power system on board the vessel. It must be noted that carbon neutrality is often confused with “zero emissions”.

CHAPTER 8

SOFT ANALYSIS OF SHIP FUEL SELECTION

This chapter presents a soft analysis of the ship fuel selection. The chapter includes collecting information on criteria and barriers in a survey among stakeholders and a focused interview with a shipowner, Klaveness. The shipowner identifies and prioritizes key criteria for ship fuels. A selection of fuel types is further pairwise compared by the shipowner using the analytic hierarchy process (AHP). The AHP is described in subsection 5.2.1.

8.1 Survey: *'Ship fuel selection - criteria and barriers'*

A survey on "Ship Fuel Selection - Criteria and Barriers" was developed to include stakeholder perspectives and gain insight to the decision context of ship fuel selection. The survey was sent out through the SFI Smart Maritime network (the Norwegian Centre for improved energy efficiency and reduced harmful emissions from the maritime sector [133]) and to a sustainability focus group within the Norwegian Shipowners' Association network [134]. The survey focuses on expectations for future ship fuels, criteria for selection, and barriers of action. The full survey report can be found in Appendix E

A similar survey was organized in [135], with the aim to gain insight into the energy efficiency gap in shipping. In [5], another similar study was conducted for Swedish stakeholders, where the contributors were asked to pairwise compare criteria and fuel options. The survey in this thesis is, however, more general, and a detailed comparison is only performed by one shipowner in the focus interview in section 8.2. The main reason for this was to reduce the required time to respond to the survey and hence gain a wider range of insight.

8.1.1 Survey methodology

The questionnaire survey was developed to identify key criteria for fuel selection and barriers of action among stakeholders in the shipping industry. The survey also asked questions about the stakeholder's impressions of different fuel alternatives and aimed to evaluate if criteria ranked with high importance were in line with the performance of the preferred fuels.

The questionnaire was divided into five parts and consisted of 31 questions. Its overall structure is listed below.

1. Respondent/company characteristics
2. Criteria for selection
3. Evaluation of ship fuel options according to criteria
4. Barriers for alternative ship fuel options
5. Overall evaluation of ship fuel options

The first questions aimed to map general information about the company and the respondent conducting the survey. The questions collected information such as area of operation or expertise, type of trade, years of experience in shipping, and stakeholder group. This was essential to separate the data and identify trends in criteria and barriers based on different backgrounds and roles in shipping. Further, the survey asked two strategic questions related to the planned time horizon for use (first move) of zero-carbon emission (tank-to-wake) fuels and key drivers in shipping decarbonization. In the next part, the responders were asked to rate the importance of different criteria for alternative fuel selection on a 1-5 Likert scale, from 1 (not important) to 5 (extremely important). After the importance of the criteria were stated, the responders evaluated the fuel options according to the criteria. The performance of nine fuel options was evaluated according to the 12 criteria on a 1-5 Likert scale, from 1 (very poor) to 5 (very good). In the fourth part, the barriers presented in Table 8.2 were rated from 1 (causes no problem) to 5 (showstopper). The responders had the ability to answer ”don't know” on questions of evaluation of fuels and rating of barriers. They were also encouraged to add comments on missing criteria and barriers. In the final part of the survey, the nine fuel options were rated from 1 to 8 (where 8 represents the top score) according to the overall preference of the responders, using a 5-10 years perspective.

Table 8.1 and Table 8.2 present the criteria and barriers included in the survey, respectively. Nine ship fuel alternatives - VLSFO/HFO, LNG/methane, LPG, methanol, hydrogen, ammonia, biofuels, battery-electric propulsion, and nuclear powering - were included and ranked by the 12 performance criteria.

Criteria	Index	Sub-criteria
Technical	T.1	Technology maturity of fuel system
	T.2	Onboard fuel management (related to safety aspects, maintenance demand, trained crew, etc.)
	T.3	Required onboard storage capacity of fuel
	T.4	Global fuel production capacity
	T.5	Bunkering availability
Economical	E.1	Investment cost/cost of retrofit
	E.2	Fuel price
Environmental	M.1	Greenhouse gas (GHG) emissions (well-to-tank)
	M.2	Greenhouse gas (GHG) emissions (tank-to-wake)
Social	S.1	Public health impact
	S.2	Maturity of safety regulation
	S.3	Social acceptability, public opinion

Table 8.1: Criteria included in survey.

Barrier	Sub-barrier
Technical	Fuel system technology not commercial available
	Available space onboard ship
	Current bunkering infrastructure and fuel availability
	Lack of safety standards and regulations
	Low operational experience and knowledge
	Reliability (risk of affecting the ability to sail)
Economical	Currently too high investment cost/cost of retrofit
	Currently non-competitive fuel costs
Environmental	Lack of regulations and incentives for decarboniztion
Social	Organizational and behavioural barriers (personal opinions, information flow/access, organizational setup, managerial practices, cultural resistance, etc.)
Commercial	Lack of market and customer demand for green fuels

Table 8.2: Barriers included in survey.

8.1.2 Survey results and analysis

Responders

A total of 31 persons responded to the survey, of which 13 represented the group of shipowners, and 6 had a background in research/academia. Other stakeholder groups represented were ship management, system/equipment supplier, shipyard, trading house, engine manufacturer, ship designer, and governmental authority. 28 out of 31 responders were based in Norway and came from a medium to large organization. The main share had more than ten years of experience in shipping. The results show a varied group of stakeholders, representing both shipowners, researchers/academia, ship managements, and system/equipment suppliers. Representants for the deep-sea operation cover 47% of the results, while short sea (including coastal vessels/ferries) covers 33%. Cargo transport is the most represented trade, mainly with bulk and tanker vessels in the fleet.

Key drivers in the decarbonization of shipping

The responders were asked to prioritize a list of 11 potential drivers from top to bottom, where the top represented the most important driver. The overall results are presented in Figure 8.1. The results show that governmental and international regulators are the top driver, followed by a group of cargo owners, market and customers, and ship owners. Shipbuilders got the overall lowest score.

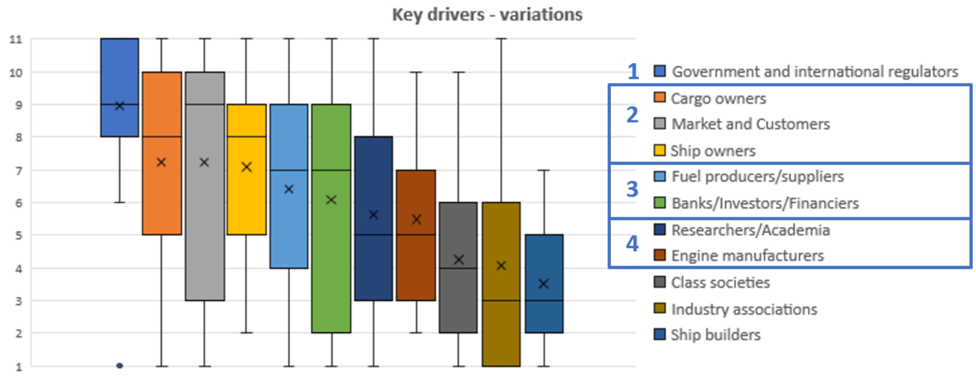


Figure 8.1: Survey results: Key drivers in the decarbonization of shipping (variations)

All group (shipowners, researchers/academia, others) ranks cargo owners as the top three key drivers. All groups except researchers/academia put regulators as the leading driver. All groups also agree that shipbuilders and industry associations are in the bottom 3. For shipowners, class societies and shipbuilders are a solid bottom. Market/customers and banks/investors/financiers have been prioritized higher for shipowners and 'others', the two groups representing the industry. Researchers/academia was placed in the middle by 'others' and in the lower half by shipowners but ranked as the number three driver by researchers/academia themself.

Planned time horizon of implementation of fuels

The participants were asked to estimate the adoption of green fuels and the planned/expected time horizon for using green fuels, referring to the first move/implementation in their vessels/fleet. In this survey, green fuels referred to fuels with zero carbon emissions tank-to-wake. The result can be found in Figure 8.2

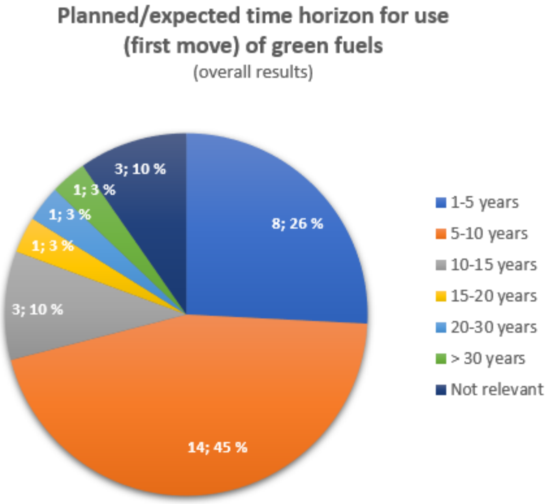


Figure 8.2: Survey results: Planned time horizon for uptake of green fuels

79% answered that the first move for green fuels would be within ten years, compared to the 10% who believe it will take 15 years or more, implying no decarbonization before 2040. Shipowners and others represent the 'early'-drivers, while the researchers/academia had split opinions. According to a survey prepared by the Norwegian Shipowners' Association, over 90% of the shipping companies say that they believe they will be climate neutral by 2050, in line with the Norwegian Shipowners' Association's climate strategy [136].

Criteria for selection

The variance of criteria importance can be found in Figure 8.3. Generally, all criteria are stated with relatively high importance, with an average evaluation as "fairly important" or higher. Even if there are some variations, the average states that onboard fuel management, bunkering availability, and global production capacity gained the highest importance. In addition, did all responders agree that the technology maturity of the fuel system and the fuel price are in the top range, ranking these two criteria as very important or extremely important. Even if all criteria are rated with high importance, required onboard storage capacity of fuel, maturity of safety regulations, public health impact, and social acceptability/public opinion covers the lower range. Public health impact had larger variations among the responders.

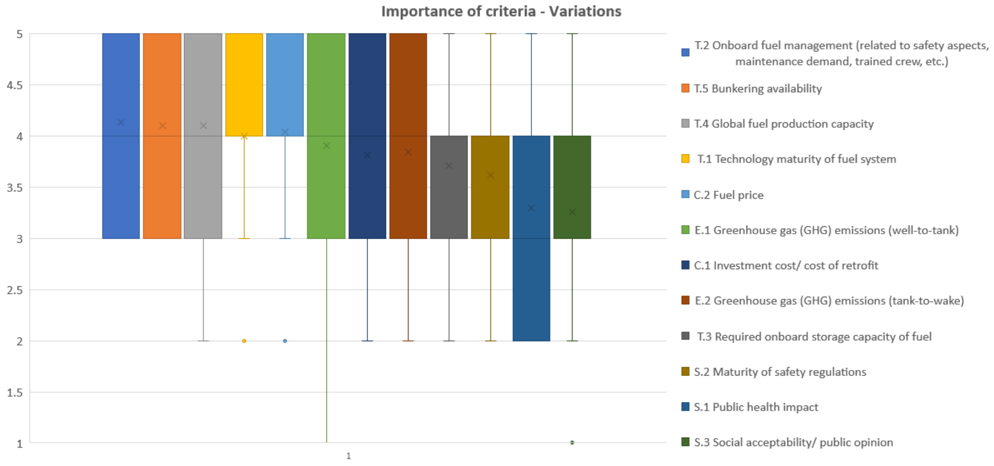


Figure 8.3: Survey results: Importance of criteria (variations)

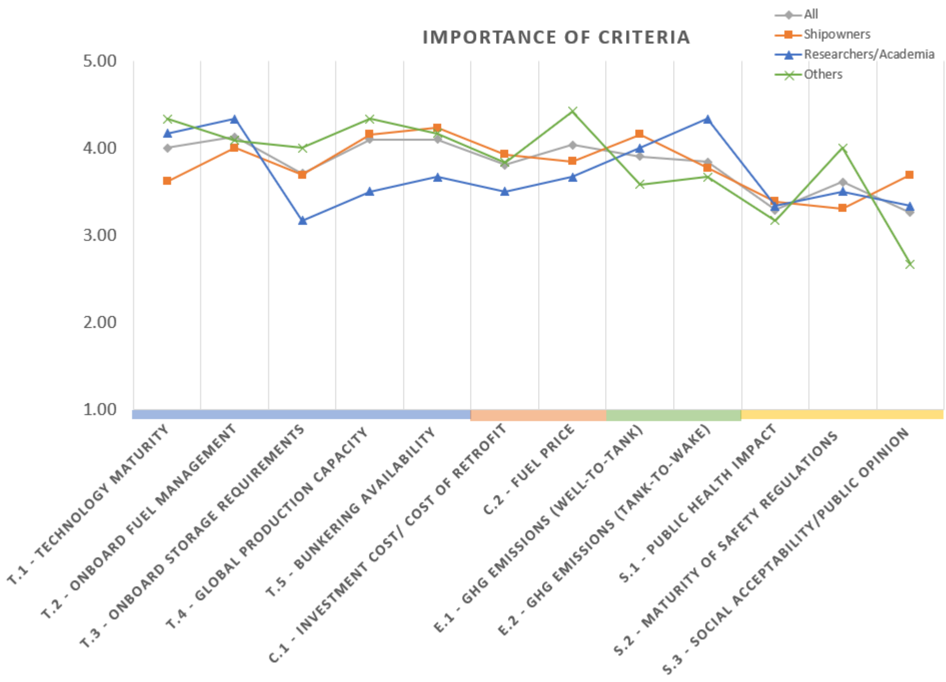


Figure 8.4: Survey results: Importance of criteria (stakeholder groups)

Figure 8.4 show how the different groups rated the importance of the criteria. Shipowners rate bunkering availability as the top criteria, closely followed by global production capacity and GHG emissions (well-to-tank). Researchers/academia place onboard fuel management and GHG emissions (tank-to-wake) on top, followed by technology maturity of the fuel system. The group of 'others' identifies fuel price as the top criteria, with technology maturity of the fuel system and global production capacity in a split second place.

Rating of ship fuel options according to criteria

After stating the importance of the criteria, the participants were asked to rate nine fuel alternatives according to the criteria. The fuel performance on each criterion on a 1-5 Likert scale, where 1 represents that the fuel performs ‘very poor’ on the criterion, and 5 represents that the fuel performs ‘very good’. The participants also had the ability to answer “Don’t know”.

For the presentation of the results, the different categories of criteria are clustered. The results show the average results of the fuel options within the different criteria categories. Figure 8.5 and Figure 8.6 shows how the different fuel options are rated within the criteria categories. VLSFO/HFO and battery-electric propulsion gained the overall highest performance score on the average of all criteria. VLSFO/HFO is a clear winner for technical criteria but scores lowest for environmental criteria. Green/blue ammonia and hydrogen score low for technical and economic criteria. However, ammonia and hydrogen are rated in the top range, along with battery-electric propulsion and nuclear powering for environmental criteria. Renewable biofuels, green/blue methanol LPG, and LNG are all in the middle range for all categories. The environmental performance is the main difference separating biofuels and methanol from LPG and LNG. Based on this overall figure, the results substantiate that “there is no silver bullet” in the wide range of ship fuels. Please read these results carefully, as the figures show manipulated results where the average response is combined.

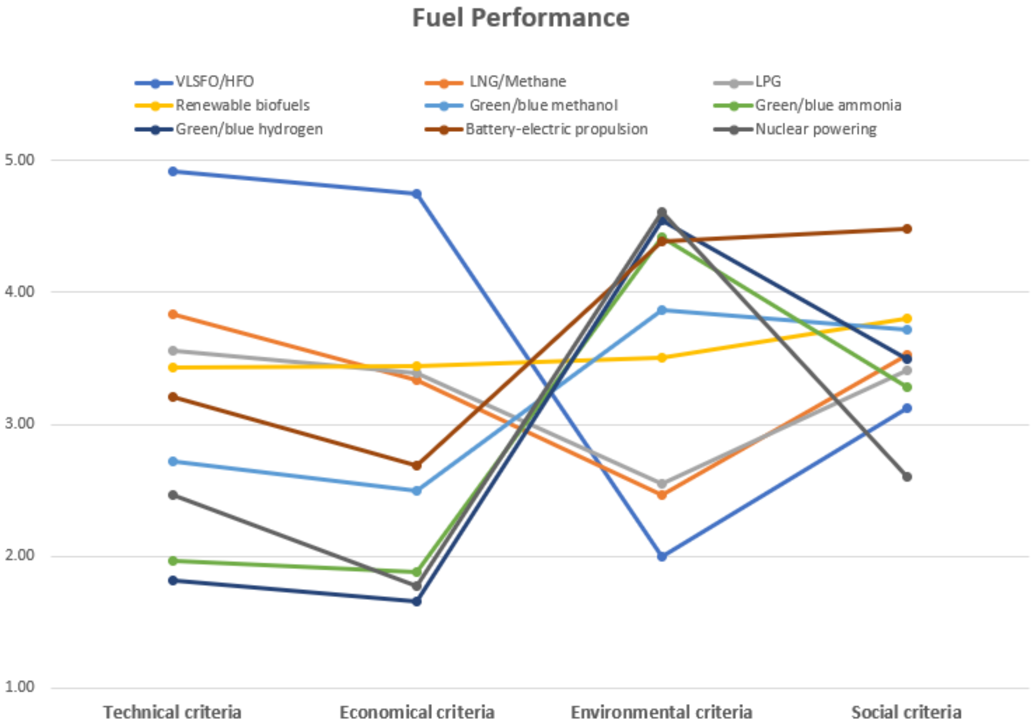


Figure 8.5: Survey results: Fuel performance within criteria categories

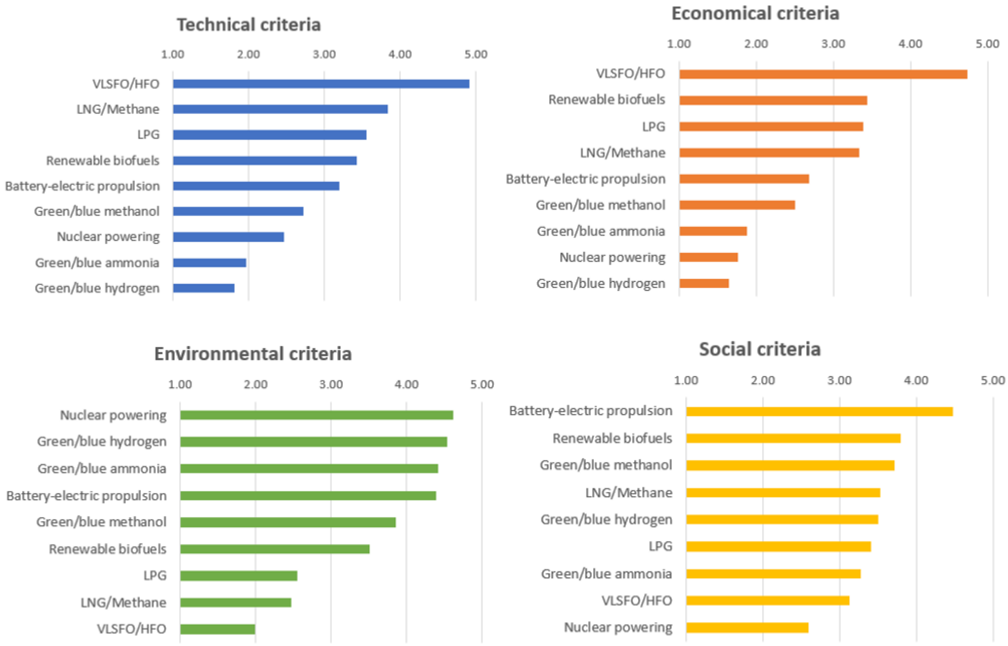


Figure 8.6: Survey results: Fuel performance within criteria categories (2)

Preferred fuel option

The participants were asked to rate their overall performance of the different fuel options from 1 to 8 (where 8 represents the top score), using a 5-10 year perspective. Figure 8.7 shows the variations in the scoring of the fuel alternatives. There are large variations, and all fuel options have received both top and bottom scores. Green/blue methanol, renewable biofuels, and green/blue ammonia are rated as average top-three fuel options. LPG, nuclear powering, and VLSFO/HFO form the bottom, even though VLSFO/HFO was ranked with the overall highest score within all criteria and ammonia in the bottom range. Also, notice that methanol was rated as bottom-four on the criteria performance. Battery-electric propulsion gained the highest score for the overall ranking of criteria but rated in the mid-range in the case of overall fuel preference. This might be explained by the relatively large share of deep-sea actors participating in the survey. In the survey prepared in [136], ammonia was stated as the preferred energy carrier when the shipping companies are to adopt which solutions they will use to achieve the emission targets within 2050.

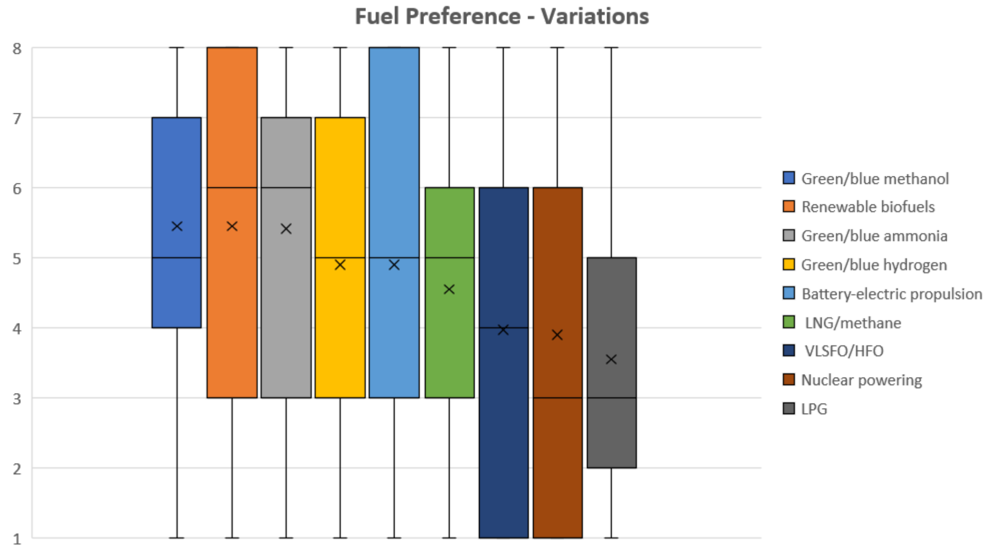


Figure 8.7: Survey results: Overall fuel preference (variations)

Barriers of action

The participants were asked to rate the list of barriers on a 1-5 Likert scale, where 1 represents a factor that ‘causes no problem’ and 5 represents a possible ‘showstopper’.

The overall results in Figure 8.8 show that bunkering infrastructure and fuel availability is the top barrier, followed by non-competitive fuel costs, the fuel system technology not being commercially available, and too high investment cost/cost of retrofit. Lack of market and customer demand for green fuels is also rated in the upper range. In the mid-range, we find a lack of regulations and incentives for decarbonization, the available space on board the vessel, and a lack of safety standards and regulations. Low operational experience and knowledge and organizational and behavioral barriers are rated in the lower range, implying low resistance in the case of action. Also, notice that few barriers are considered not to cause any problem. The survey results align with the results from the survey in [136], where the industry points to high investment costs, lack of technology, and availability of alternative fuels as today’s largest barriers.

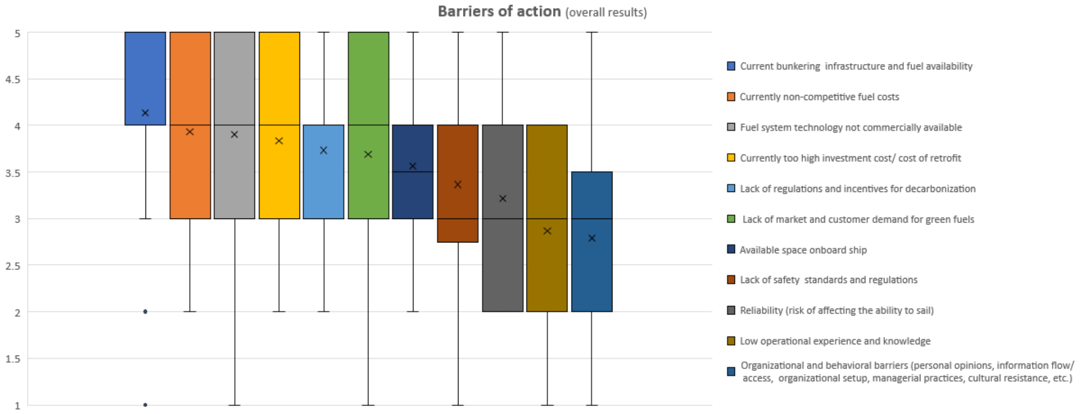


Figure 8.8: Survey results: Barriers of action (variations)

There are, in general, small variations among the stakeholder groups, but researchers/academia rates ‘low operational experience’ higher than the shipowners. In addition, shipowners and ’others’ tend to see economic, environmental, and commercial factors as a greater barrier compared to researchers/academia.

Please notice that low operational experience and knowledge is rated as a bottom barrier among several groups, especially the shipowners. Onboard fuel management was, however, rated as a criterion of high importance. It is possible that the definition of this barrier was vaguely defined and therefore has been misunderstood.

The fuel mix in 2050

Finally, the participants were asked to evaluate which fuels they believed to be a part of the fuel mix in 2050 by assigning %-share to the different fuels options (total 100%).

Figure 8.9 shows the overall average of the future fuel mix. The results allow two conclusions; Either it will be many different fuel types in 2050, or the participants strongly disagree.

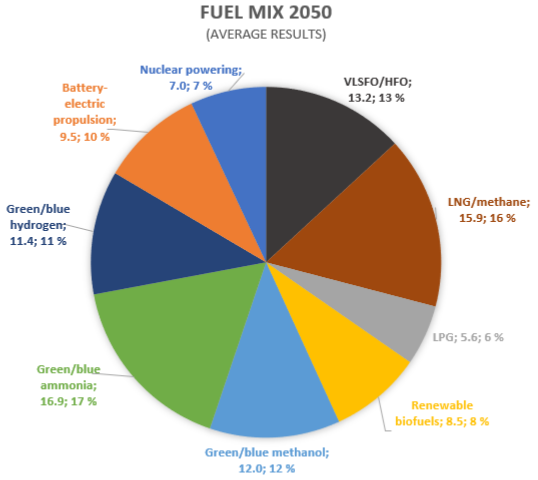


Figure 8.9: Survey results: Fuel mix in 2050

The variations shown in Figure 8.10 indicate that ammonia and LNG have received a relatively high share of the fuel mix and that the participants strongly disagree on the share of VLSFO/HFO, hydrogen, and batteries.

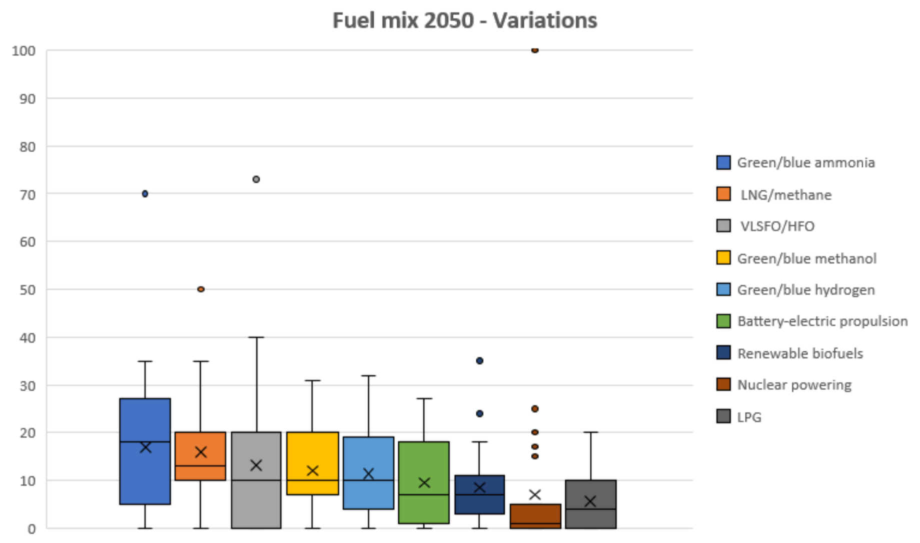


Figure 8.10: Survey results: Fuel mix in 2050 (variations)

8.1.3 Key findings from survey

Key findings from the survey are listed below:

- 79% believes that the first move for adoption of green fuels in their vessels/fleet will be within ten years
- All criteria are of high importance. Technical and economic criteria do, however, dominate the top ranking.
- Battery-electric propulsion gained the overall highest performance score, combining the average score of all criteria
- Green/blue methanol, renewable biofuels, and green/blue ammonia are rated top-three preferred fuel options
- Current bunkering infrastructure is the largest barrier, followed by barriers of costs, low technology maturity level, and lack of regulations and incentives for decarbonization

8.1.4 Discussion, limitations and comments to survey

As the responders were asked to give the criteria a score from 1 (not important) to 5 (very important) independent of other criteria, all criteria obtained an overall high score, an average score of 3 or higher. It is likely to believe that a comparison-based method of scoring the criteria would have given another result, as such a method will force trad-offs. This is well illustrated in the case study, where the shipowner was asked to rank the criteria from top to bottom, and pairwise compare the top criteria. However, such a comparative method would have required more resources and would have been more time-demanding for the participants. A suggestion for further evaluation of the criteria and trade-offs is to facilitate a workshop with individuals and stakeholder groups to prepare such pairwise comparison, similar as done in [5].

Several important aspects in the fuel transition were excluded from the survey. This includes onboard CCS and the circular economy of building a vessel capable of sailing on the green fuels. Another essential aspect is the concept of fuel flexibility, with ”fuel-ready” options and ”lock-in-risk”, that is, the ability to switch between fuels at low cost.

General feedback from the participants mentioned the difficulties of answering questions since the coastal and deep-sea shipping markets are so different that there will probably be large discrepancies in fuel types utilized in short sea, regional and deep-sea shipping. As this survey included a wide range of shipowners and stakeholders, a further suggestion is to prepare a more specific survey focusing on either short-sea or deep-sea shipping. Another comment was the difference between ’preferred fuel’ and ’realistic fuel’, especially in a 5-10 years perspective, highlighting battery and nuclear as good examples of such dilemmas.

The limited number of participants is a main limitation of the survey results. The participants are also limited to a network of actors that aims to “improve the energy efficiency and reduce harmful emissions from the maritime sector”. Researchers/academia ranked shipowners on top as a key driver for shipping decarbonization. This might be because they, on a day-to-day basis, are working with a group of forward-leaning shipowners. The overall forward-leaning network may also have resulted in an optimistic response. Also, notice that 28 out of 31 responders are based in Norway. The results might have differed if this was a global questionnaire/study. It can only represent a narrow Norwegian result, so please keep this in mind when using it to evaluate a global shipping industry.

8.2 Focus interview: *The shipowner perspective*

This chapter presents a focus interview with a shipowner, Klaveness. The focus interview aims to gain insight into the shipowner's perspective and the real-life decision process of fuel selection. The chapter starts with a general sense of the shipowner's strategic background and the fuel selection process. Further, an evaluation of criteria and fuel alternatives is performed. The interview is a qualitative study, and besides the evaluation prepared using the AHP, all results are gained from questions and discussion.

The interview aims to identify the most important criteria and their relative importance for a specific shipowner. The interview has a global, deep-sea perspective, as this is where the shipowner operates. This is also the segment of shipping with the largest carbon emission reduction potential. Interview and discussion with the shipowner are used to identify key criteria and relevant fuel types. The AHP is used to obtain the criteria's weighting (relative importance) and compare the selected fuel options according to the criteria. The focus interview addressing *the shipowner perspective* can be summarized as follows:

1. The shipowner strategy and general considerations for the fuel selection process
2. Identification of key criteria
    (a) Order a selection of criteria from top to bottom, where top represents highest importance. For this ranking, the same criteria as used in the survey in section 8.1 are included.
    (b) Identify top five criteria
    (c) Perform a pairwise comparison of the top five criteria to obtain weighting/relative importance (AHP)
3. Identify relevant fuel alternatives and performance values
    (a) Shipowner screening of fuel options suitable for deep sea operation
    (b) Pairwise comparison of fuel options according to top five criteria (AHP)

8.2.1 Background

To understand the evaluation performed by the shipowner, the strategic background and the shipowners' position in the shipping industry must be stated. Klaveness is a shipowner who operates at deep sea and transports cargo using combination carriers for bulk and tank. The company has 65 years of experience and is currently operating a fleet of 16 vessels: eight CABU (72 500-80 500 DWT) and eight CLEANBU (82 500 DWT) vessels, both combination carriers [137][138].

Klaveness highlights their main strategy to 'decarbonize shipping' when asked about strategy. They reflect on how the deep-sea segment involves energy optimization and energy carriers that are more demanding to changes. A main focus within the company is to reduce energy consumption both during sailing and in port. The company has large retrofit projects that aim to make more energy-efficient ships. They look at both newbuilds and retrofits, but mainly energy efficient measures on retrofits. This includes zero-emission solutions and measures such as improved management of ship performance, more frequent recoating and cleaning, lower sailing speed, timing the arrival to port, and weather-routing, to mention some. The company has invested in expensive antifouling measures and trained the crew for energy efficiency. The measures are individually tailored to each vessel, but a trend is that the newer vessels are equipped with more measures due to their remaining lifetime. Some of the vessels have had the measures installed from delivery from the shipyard.

Klaveness has already operated some of its vessels on biofuel. Despite this, they say that it is difficult to state when to expect the first move of zero-emission fuels since they have global trade and a global lack of green electricity. The shipowner mentions that it might be a possibility if green fuels are established on a specific trade where they operate, a so-called *green corridor*. Special contracts are discussed as possible ways for the shipowner to influence such development in their trades.

Fuel selection - the process, criteria and barriers

Further, the interview addresses the fuel selection process. Klaveness emphasizes that numerous factors come into play. An important aspect is to evaluate the well-to-wake energy efficiency of fuels and that a low factor of effort is an advantage. Other aspects are operating costs with the specific fuel type and safety for crew, which varies from ship type to ship type. The competition with other fuels and whether other actors are interested in the same fuel type is also considered.

When asked about fuel type requirements for their vessels, the primary condition is safe operation at deep sea. Klaveness states that they have few absolute requirements but that the ships must have fuel and an engine that can maintain the speed set by the cargo owner. The hurry of the cargo owners depends on their current feedstock. It can also be expensive cargo which makes it costly to keep it on board a vessel without being able to resell it. The ship also has a demanded range to serve the specific trades.

When discussing criteria for fuel selection, Klaveness emphasizes that there are many criteria of high importance. It must be safe and manageable for the crew, and it must be possible to get hold of when bunkering is needed. The shipowner does also put high requirements of how green the fuel *really* is, not allowing any slip or any greenhouse gas emissions. The shipowner has not stated a concrete list of criteria, but an overall requirement is that it must be at least as safe as today's solution.

The shipowner says that they put more into the process of fuel selection now than before and that the more they learn about the fuel, the more questions arise and the more things are being emphasized. In general, more knowledge adds several aspects. The shipowner started the focus on fuels in 2019, probably as a consequence of the IMO 2050 goal and the zero-emission policy. When building a vessel with a lifetime of 30 years, the zero-emission goal of 2050 in practice begins now. A lot has happened in a short period of time. The perspective has changed from "which green fuels can one imagine?" two years ago to today's fuel evaluation in detail-level.

Technology maturity and fuel availability are mentioned when discussing barriers to zero-emission fuels. Another important aspect is the financial part of global trading - some must be responsible for covering the additional cost of green fuel. The cargo owners must convince their consumers of the worth of this cost increase. The main challenge is whether or not the consumer is willing to pay for a lower environmental footprint. A trend is that cargo owners are starting to document their scope 3 emissions, which are linked to shipping. The fact that cargo owners care about emissions from shipping is a game-changer that potentially can accelerate the process of decarbonization.

8.2.2 Identification and weighting of top criteria (AHP)

Klaveness was asked to rank the 12 criteria from the survey, with the criteria of the highest importance on the top. The prioritized list is as follows:

1. Fuel price
2. Bunkering availability
3. Investment cost/ cost of retrofit
4. Technology maturity of fuel system
5. Maturity of safety regulations
6. Onboard fuel management (related to safety aspects, maintenance demand, trained crew, etc.)
7. Required onboard storage capacity of fuel
8. Greenhouse gas (GHG) emissions (well-to-tank)
9. Greenhouse gas (GHG) emissions (tank-to-wake)
10. Public health impact
11. Global fuel production capacity
12. Social acceptability/ public opinion

The ranking was stated as tricky. It was discussed how the thoughts about how the prioritized list would change over time based on how the company thinks and which challenges they are facing at the moment. The fact that "all" criteria are important for the deep sea was also discussed. GHG emissions might not be that important in the starting process when the focus is to achieve a transition of fuels, but in the long run, will well-to-wake GHG emissions be essential for sustainable fuel types.

Further, Klaveness was asked to set the relative importance (weighting) of the criteria by pairwise comparing the top five criteria using the AHP method (presented in subsection 5.2.1). The comparison is shown in table Table 8.3. The result shows that fuel price is somewhat more important than bunkering availability and investment costs but has equal importance at the technology maturity of the fuel system and almost the same importance as the maturity of safety regulations. Technology maturity of the fuel system and safety regulations are, on the other hand, much more important than bunkering availability.

	Fuel price	Bunkering availability	Investment cost/cost of retrofit	Technology maturity of fuel system	Maturity of safety regulations	Relative importance (RVV)
Fuel price	1	3	3	1	2	0.2132
Bunkering availability	1/3	1	3	1/5	1/5	0.1835
Investment cost/cost of retrofit	1/3	1/3	1	3	1/2	0.1868
Technology maturity of fuel system	1	5	1/3	1	1	0.2055
Maturity of safety regulations	1/2	5	2	1	1	0.2110
Totals						*1.0000*

Table 8.3: Pairwise comparison of shipowners' top criteria

The pairwise comparison rates fuel price and maturity of safety regulations as top relative importance, while bunkering availability is ranked at the bottom of these five criteria. However, all criteria were prioritized in the range of 20% importance. The pairwise comparison shows that even if they were prioritized in a list, larger variations exist in the evaluation of importance when the criteria are pairwise compared. This substantiates the shipowner's perspective that all criteria are important for deep sea, leading to challenging tradeoffs. However, the ranking is consistent, with a consistency ratio of 0.040.

8.2.3 Shipowner screening of fuel options

Klaveness was further asked to identify which fuel options are relevant for their fleet operating at deep sea. The shipowner screening of fuels was based on the same fuels that were included in the survey. The screening was done quickly and straight to the point, and the results are presented in Table 8.4. Regarding the fossil fuels, Klaveness mentioned that they might be relevant for a shipowner that selects fuel technology today, but that they also have a "best before" date on the future horizon.

Fuel option	**Relevant for deep sea? YES/NO**	**Prerequisites**	**Justification**
VLSFO/HFO	YES	CCS technology	Carbon capture and lack of green renewable energy can make fossil fuel live longer
LNG/methane	YES	CCS technology	Carbon capture and lack of green renewable energy can make fossil fuel live longer
LPG	YES	CCS technology	Carbon capture and lack of green renewable energy can make fossil fuel live longer
Methanol	YES	Sustainable production	
Hydrogen	YES	Depending on tank (onboard storage costs), type of ship and NOx slip	With lower costs for fuel tanks and more energy efficient ships, it may be suitable for some type for segment. Ex. tank ships with wind.
Ammonia	YES	Depending on tank (onboard storage costs), type of ship and NOx slip	
Biofuels	YES	Sustainable production, scaling	
Battery-electric propulsion	NO		Weight, charge and energy amount (battery capacity)
Nuclear powering	NO		Technologically challenging, acceptance in port, safety

Table 8.4: Shipowner first-evaluation of fuel options

8.2.4 Pairwise comparison of fuel options (AHP)

The fuels evaluated as relevant for deep-sea were then compared pairwise to the top five criteria. The structure hierarchy of the selection problem is illustrated in Figure 8.11 and the result is presented in Table 8.5.

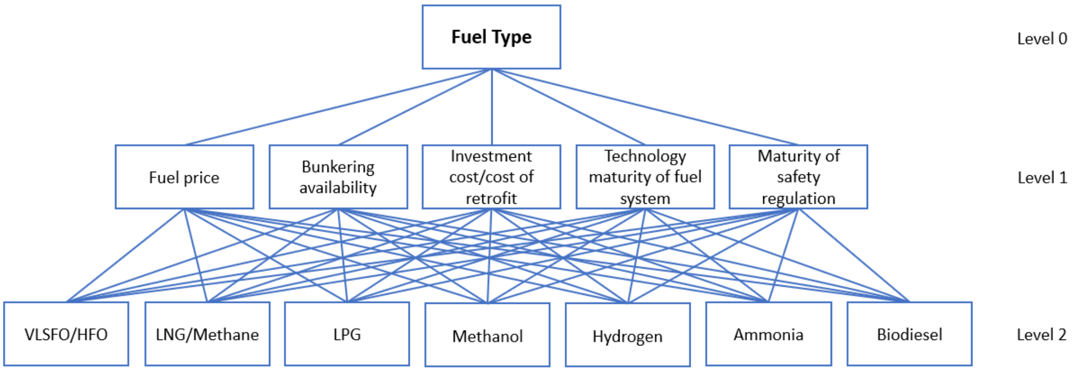


Figure 8.11: Structure of hierarchy

	Relative performance (RPM) on criteria					
	Fuel price	**Bunkering availability**	**Investment cost/cost of retrofit**	**Technology maturity of fuel system**	**Maturity of safety regulations**	**Totals**
VLSFO/HFO	0.1602	0.1737	0.1568	0.1607	0.1609	0.1623
LNG/methane	0.1500	0.1540	0.1528	0.1495	0.1466	0.1504
LPG	0.1531	0.1519	0.1349	0.1530	0.1556	0.1500
Methanol	0.1393	0.1269	0.1347	0.1416	0.1445	0.1378
Hydrogen	0.1282	0.1243	0.1449	0.1191	0.1197	0.1270
Ammonia	0.1282	0.1243	0.1435	0.1213	0.1202	0.1272
Biofuels	0.1411	0.1448	0.1322	0.1548	0.1525	0.1454
Consistency ratio (CR)	*0.2976*	*0.7423*	*0.6564*	*0.6171*	*0.6022*	1.0000

Table 8.5: Fuel Options Performance Matrix

Notice that all the consistency ratios are too high (> 0.1) for the pairwise comparison of the fuels. This simply means that the shipowner's subjective evaluation of fuel preference is inconsistent, that the evaluation is too random and that the judgement cannot be trusted. A suggestion is to use the consistency ratio to give feedback to the shipowner regarding their consistency and get them to reconsider their answers. Due to a limited time frame, such feedback was not given in this case. However, an inconsistent comparison and evaluation of the fuel performance mirrors the complex and challenging decision of fuel selection.

CHAPTER 9

CASE STUDY

This case study aims to combine the subjective criteria selected and weighted by the shipowner with the objective performance values for the different fuel options. The uncertainty of the performance values will be investigated by use of suggested scenarios for future improvement or worsening of the fuel's performance. Model 1 presented in section 6.2 will be tested for two case scenarios; i) 'business as usual' and ii) 'sustainable development'. The general case approach is as follows:

1. Identification and weighting of key criteria
2. Identification of fuel alternatives to include in the study
3. Set *status quo* criteria performance value/score of fuel alternatives within each criterion based on collected data and information
4. Create scenarios of the alternative's performance value in three time periods until 2050

9.1 Case description

A shipowner seeks to widen their perspectives and gain insight to decide which fuel alternative to prepare for implementation to their fleet and select for their newbuilds for the coming years. The shipowner has identified key criteria and possible fuel options, where some of the criteria have higher relative importance.

The criteria considered are the ones selected in cooperation with Klaveness in section 8.2: Fuel price, bunkering availability, investment cost/cost of retrofit, technology maturity of the fuel system, and maturity of safety regulation. In addition, the well-to-wake GHG emissions are included to assess the energy source of the fuel and include aspects of the entire fuel pathway. Their relative importance (weights) are presented in Table 9.1, where GHG emissions are given equal importance as the total importance of the other criteria. The performance value of the fuel options for the qualitative criteria is based on a quantification of the fuel characteristics presented in chapter 3, similar to the screening in chapter 7.

Criteria	Relative importance
Fuel price	0.2132
Bunkering availability	0.1835
Investment cost/cost of retrofit	0.1868
Technology maturity of fuel system	0.2055
Maturity of safety regulations	0.2110
Totals of "other criteria"	1.0000
GHG emissions (well-to-wake)	1.0000
Totals of all criteria	2.0000

Table 9.1: Weighted importance of criteria

As described in chapter 6, the criteria performance values of the fuel alternatives must be at the same scale to combine them in a common objective function. A local scale of 1-5 is chosen in this case study. Since Model 1 represents a maximizing problem, a score of 5 represents the best performance, and 1 represents the worst performance. The scale (performance level system) follows the same principles as presented in section 5.3 and illustrated in chapter 7. Specific levels are not reproduced here due to similarity to the performance levels presented in the screening.

A planning horizon of 3 time periods is chosen for the case study, each period corresponding to 10 years. The planning horizon represents years from 2020 to 2050, which is the 'deadline' for the 50% reduction target of the decarbonization discussed in section 1.1 and section 2.2.

9.1.1 System boundaries and limitations

Model 1 is rather simple in its form but has a wide range of application possibilities. This is a very simplified case of the fuel selection process. The limitations of the case study are listed below:

1. *'Green' and renewable fuel alternatives:* The case study includes both the fossil and 'green' fuel alternatives. Green fuel alternatives are produced from carbon-neutral energy resources, such as electricity from renewables (e.g., solar or wind power) or nuclear energy. Only renewable biofuel is included in the study, meaning biofuel from sustainable biomass sources. The case study does not include blue fuel alternatives (fossil fuels combined with CCS technology). 'Alternative fuels' is a collective designation for the green and renewable fuel options considered zero-carbon emission fuels.
2. *Only GHG emissions:* For simplicity, and since the thesis focus on decarbonization, only GHG emissions, mainly in terms of CO_2 emissions, are considered.
3. *Constant fuel conversion efficiency:* The fuel conversion efficiencies are assumed to not change over time, and the energy consumption is assumed to be constant for all time periods. The energy conversion system will not be evaluated in detail.
4. *Fixed scenarios:* The assumed scenarios imply a certain future of fuel performance.
5. *Constant importance of criteria:* The relative importance of the criteria is assumed to be constant for all time periods.
6. *Constant performance values:* The performance values of the fuels can change from time period to time period. Several of the criteria are time-dependent and are facing an uncertain

future. In this case study, fuel price, bunkering availability, investment cost/cost of retrofit, safety regulation, and TRL are assessed as time-dependent criteria. The well-to-wake GHG emissions will be constant for all three time periods.

7. *Criteria independent of primary energy source:* The set of fuel alternatives includes both fossil and green/renewable alternatives of different energy carriers. The bunkering availability, investment costs/cost of retrofit, the technology maturity of the fuel system, and the maturity of safety regulations are assumed to be independent of the primary energy source for the fuel options. However, fuel prices and GHG emissions will vary based on the primary energy source. Notice that since the bunkering availability is considered independent of energy source, the green production capacity and supply to bunkering stations are assumed to be sufficient in line with the development of the bunkering network.

9.2 Case scenarios

As mentioned, uncertainty is modelled by using a set of fixed scenarios. In this case study, two main scenarios (based on those presented in [139] and [140]) are studied. The first scenario presents a 'business as usual' situation, where fossil fuel is cheap, clean fuels are expensive, and emission taxes are absent. In addition, there is slow or no development of fuel system technology and bunkering infrastructure of alternative fuels. The second scenario presents a 'sustainable development' situation, where fossil fuel costs are increased, and emission taxes have entered into force. There is rapid maturation of fuel system technology, and the bunkering network is expanded in line with the increased demand for green fuels. The scenarios are used to simulate the phase-in of new technology and the development of regulations and bunkering infrastructure.

Notice that the cost criteria will fluctuate from time period to time period based on the market situation. In contrast, the performance value for the other criteria can only increase until "top" performance. For example, when the technology of the fuel system is fully mature, referring to top performance, it cannot gain a lower maturity level as the development is assumed to not be reversed. The same applies to the maturity of safety regulations and the development of bunkering infrastructure and availability.

The status quo fuel performance values are presented in Table 9.2. In the current fuel situation, only the conventional fuels (MGO/HFO/VLSFO) and LNG has fully developed technology and safety regulation. LNG, methanol, and biodiesel have commercially available technology for ships but are not common in operation. Conventional fuels have globally available bunkering, and the availability of LNG is also rapidly increasing. Biodiesel is competitive on investment and in the case of retrofit, but has high fuel price and low bunkering availability. Hydrogen and ammonia are costly and have low or no possibilities for bunkering and low maturity of both technology and safety regulation. Green methanol, renewable biodiesel, green hydrogen, and green ammonia are considered zero-carbon emission fuels, giving a top performance score for GHG emissions. LNG is the cleanest fossil fuel option and scores better than the two other fossil options. The status quo values will be used as the performance values in the first time period for both case scenarios. In contrast, the two remaining time periods will have different performance values for the two scenarios. The emission performance is constant for all time periods in both case scenarios.

Fuel option	**Criteria**					
	Fuel price	Bunkering availability	Investment cost/ cost of retrofit	Technology maturity	Safety regulation	GHG Emissions
MGO/HFO/VLSFO	5	5	5	5	5	1
LNG	5	4	4	5	5	2
LPG	4	3	5	4	3	1
Methanol (green)	3	3	4	4	4	5
Renewable biodiesel	2	2	5	4	4	5
Hydrogen (green)	2	1	2	2	2	5
Ammonia (green)	2	1	2	1	3	5

Table 9.2: Status quo performance value of fuel options

9.2.1 Case 1: Business as usual

Case scenario 1 presents a 'business as usual' situation, where the alternative fuels continue to have high fuel prices and slow development of both technology maturity and bunkering availability. Fossil fuels continue to be cheap, and there is no carbon tax or green incentives that are put into action in the foreseeable future. Methanol and biodiesel, which both have fossil options and have already been tested for deep sea, are set to have a higher development level for this situation than ammonia and hydrogen, which both are new to the fuel market. The performance values for the three time periods of case scenario 1 are shown in Table 9.3.

Time period 1: 2020-2030	Fuel price	Bunkering availability	Investment cost/ cost of retrofit	Technology maturity	Safety regulation	GHG Emissions
MGO/HFO/VLSFO	5	5	5	5	5	1
LNG	5	4	5	5	5	2
LPG	4	3	5	4	3	1
Methanol (green)	3	3	4	4	4	5
Renewable biodiesel	2	2	5	4	5	5
Hydrogen (green)	2	1	2	2	2	5
Ammonia (green)	2	1	2	1	3	5

Time period 2: 2030-2040	Fuel price	Bunkering availability	Investment cost/ cost of retrofit	Technology maturity	Safety regulation	GHG Emissions
MGO/HFO/VLSFO	5	5	5	5	5	1
LNG	5	5	4	5	5	2
LPG	4	3	5	4	3	1
Methanol (green)	3	3	4	4	4	5
Renewable biodiesel	2	3	5	5	5	5
Hydrogen (green)	2	2	2	2	3	5
Ammonia (green)	2	2	2	2	3	5

Time period 3: 2040-2050	Fuel price	Bunkering availability	Investment cost/ cost of retrofit	Technology maturity	Safety regulation	GHG Emissions
MGO/HFO/VLSFO	5	5	5	5	5	1
LNG	5	5	4	5	5	2
LPG	5	3	5	4	4	1
Methanol (green)	3	3	4	4	4	5
Renewable biodiesel	2	4	5	5	5	5
Hydrogen (green)	2	2	3	3	4	5
Ammonia (green)	2	3	3	3	4	5

Table 9.3: Scenario 1: 'Business as usual'-development of fuel performance

9.2.2 Case 2: Sustainable development

Case scenario 2 presents a 'sustainable development' scenario, where the alternative fuels gradually get a higher maturity level of both technology and safety regulation. They also gain a more competitive fuel price, as carbon tax restricts fossil fuel options. Bunkering availability follows the development and is expanded in line with the increased demand for green fuels. The performance values for the three time periods of case scenario 2 are shown in Table 9.4.

Time period 1: 2020-2030	Fuel price	Bunkering availability	Investment cost/ cost of retrofit	Technology maturity	Safety regulation	GHG Emissions
MGO/HFO/VLSFO	5	5	5	5	5	1
LNG	5	4	4	5	5	2
LPG	4	3	5	4	3	1
Methanol (green)	3	3	4	4	4	5
Renewable biodiesel	2	2	5	4	5	5
Hydrogen (green)	2	1	2	2	2	5
Ammonia (green)	2	1	2	1	3	5
Time period 2: 2030-2040	Fuel price	Bunkering availability	Investment cost/ cost of retrofit	Technology maturity	Safety regulation	GHG Emissions
MGO/HFO/VLSFO	4	5	5	5	5	1
LNG	4	5	5	5	5	2
LPG	4	3	5	4	3	1
Methanol (green)	4	4	4	5	5	5
Renewable biodiesel	4	3	5	5	5	5
Hydrogen (green)	4	3	3	3	3	5
Ammonia (green)	4	4	3	4	4	5
Time period 3: 2040-2050	Fuel price	Bunkering availability	Investment cost/ cost of retrofit	Technology maturity	Safety regulation	GHG Emissions
MGO/HFO/VLSFO	3	5	4	5	5	1
LNG	3	5	4	5	5	2
LPG	3	3	4	4	4	1
Methanol (green)	3	4	4	5	5	5
Renewable biodiesel	4	3	5	5	5	5
Hydrogen (green)	5	5	4	4	5	5
Ammonia (green)	5	5	4	5	5	5

Table 9.4: Scenario 2: 'Sustainable development' of fuel performance

9.3 Case results and analysis

As both cases scenarios have the same performance values in time period 1 (status quo), the results are similar. Conventional fuels (MGO/HFO/VLSFO) are the option with the overall highest performance of the selected criteria and weighting.

For scenario 1, LNG is the preferred fuel in time period 2 (2030-2040), due to the stated development of bunkering infrastructure and LNG being the fossil fuel with the lowest emissions. This is the only thing that separates LNG from VLSFO in the given performance values for this time period. LNG is still the preferred fuel in the third time period (2040-2050), followed by VLSFO and renewable biodiesel. LNG is also the fuel option with the highest total performance of all time periods.

For scenario 2, green methanol and renewable biodiesel are the two options with the highest overall performance in time period 2. This is mainly due to the increased maturity level, both for fuel system technology and safety regulations. The improved performance of fuel price that at the same time is reduced for the fossil options do also influence the result. In time period 3, green ammonia is the preferred fuel option, followed by green hydrogen. This is due to the fully developed bunkering network, technology, and safety regulations, in addition to competitive fuel costs. Methanol is the option with the highest score if the performance of all periods is summarized.

CHAPTER 10

DISCUSSION: FUTURE PROOF SHIP FUEL SELECTION

Fuel selection is a complex decision that involves factors hard to quantify. The future is uncertain, and it is difficult or impossible to point out the ”correct” answer for today’s situation. However, gathering a large amount of information and discussing potential outcomes is important to support the decision to be made.

This chapter discusses different aspects of future proof ship fuel selection on the road to decarbonizing shipping. The section also discusses how the knowledge of barriers and fuel flexibility can be used to increase the willingness to select greener fuel alternatives among shipowners and where the stakeholders should invest (both time, money, and resources) to accelerate the fuel transition.

10.1 Complex and uncertain decision making, multiple criteria and tradeoffs

In normal day-to-day life, when facing decisions without significant consequences, people unconsciously weigh multiple criteria and make decisions based on only intuition [141]. However, when making decisions with high risk or unknown consequences, the decision-maker often avoids structuring the problem and evaluating the weighting of the multiple criteria. Good structure and well-thought-out criteria weighting are fundamental in complex situations that affect various stakeholders. This characterizes a fuel selection problem that includes numerous important criteria and a wide range of fuel options. In such complex problems, there is typically hard to state an optimal solution, and MCDA can be used as decision support to differentiate between solutions. The method provides an early decision tradeoff among different performance indicators and identifies areas of conflict. As presented in chapter 5 are tradeoffs common in complex situational decision making. Criteria and objectives are often in conflict, and it can be difficult to gain high performance of one criterion without compromising another criterion. A well-considered tradeoff comes from a tactical or strategic choice made with complete comprehension of both advantages and disadvantages of the decision.

Including sustainability factors in the decision process can be challenging as sustainability deals with a wide range of criteria from different areas, increasing the complexity and uncertainty of the decision-making process. However, MCDA can be applied to reach the desired goal, the management and prioritizing of tradeoffs are still in the hands of the decision-maker. Within the different dimensions of the decision, the decision-makers have some aspects that can be negotiable and some aspects where they can not make compromises. The acceptable and negotiable aspects of tradeoff management are shown in Figure 10.1.

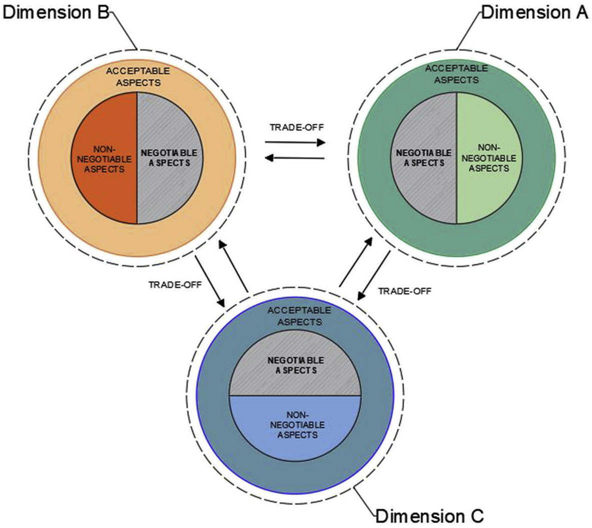


Figure 10.1: Acceptable and negotiable aspects in trade-offs management (adapted from [142])

In complex decisions, a threshold for criteria should be made to not move on with choices and tradeoffs that are not acceptable. Early considerations of tradeoffs are needed when selecting a fuel type that should be able to stand out the time and be within IMO's 2050-limits. Thresholds are essential to delimit acceptable from unacceptable impacts, and this can, for instance, be done by establishing a minimum level of performance within all criteria. Tradeoff rules (similar to tradeoff rules in sustainability assessment, e.g., Gibson's tradeoff rules ([143][144])) could be established for ship fuel assessment and used to define acceptability performance levels and rules for the decision process.

The screening in chapter 7 covers both technical, economic, environmental, and social criteria. It might be representative and can serve as a first-evaluation or *screening*. However, to make a well-weighed decision, the fuels must be evaluated and compared in detail-level. This can be done by adding several criteria and sub-criteria which are more representative of specific fuel characteristics. The selection of decision criteria will affect the ranking of fuels. In the fuel selection problem, one should strive to include a wide range of criteria that can cover most of the characteristics of the different fuel types. By including a wide range of characteristics, the risk of misleading ranking of fuels can be reduced. However, adding several criteria to the comparison will also increase the complexity of the decision. Which and how many criteria to include will depend on the decision-maker and the purpose of the analysis. Ideally, all aspects of the fuel types and the decision context. However, identifying all these aspects remains a challenge that includes many uncertainties.

10.1.1 Handle uncertainty

Uncertainty is related to epistemic situations that involve imperfect or unknown information. A high amount of uncertainty applies to predicting future situations, for example, for something that is not known or not certain.

In [145], uncertainty is divided into three dimensions: location of uncertainty, level of uncertainty, and nature of uncertainty. It is important for all actors involved in the decision process to agree on the dimensions of uncertainty and how to handle them. By understanding the different dimensions, crucial uncertainties can be identified, described, and prioritized. This is a vital step towards an adequate recognition and treatment of uncertainty in decision support efforts, enabling more focused research on complex and uncertain issues.

It is certain that the marine fuel market will be going through momentous changes in the upcoming decades, but how to best implement and manage this change is still uncertain. A holistic approach is elementary to support shipowners, operators, and other actors in the decision processes involved in the fuel transition. Identifying the main criteria and stating the performance of different fuel types is necessary to highlight where the alternative fuels lack to comply with requirements. This can further be used to identify barriers of action and invest resources to fill the gaps to drive the uptake of alternative fuels among shipowners and operators.

Decision problems involve uncertainties that will typically increase in parallel with the decision's complexity. Ideally, decision-makers would have had complete certainty regarding the outcomes of their actions. However, most problems include decisions that must be taken in an uncertain context. This mainly applies to complex systems and decisions where some factors of uncertainty cannot be avoided or eliminated [146][147]. To include a wide range of decision criteria and numerous fuel alternatives in the decision problem would increase both the complexity and the uncertainty.

There is also a significant uncertainty related to changing fuel performance levels and changing the importance of criteria. This change may occur due to new regulations or policies, potentially improving the conditions of alternative fuels. Lack of data will also make predicting or estimating future fuel characteristics difficult. Another uncertainty is how the different stakeholders and decision-makers evaluate the fuel performance. In the shipowner pairwise comparison of fuels and their performance on selected criteria, the evaluation was stated as inconsistent. As the number of comparisons increases (due to added criteria or added alternatives), the risk of inconsistency is likely to increase. In a complex decision problem with a wide range of options, inconsistency is difficult to avoid, especially when the performance of the options is uncertain. The AHP method highly relies on the consistency of the decision-maker and sets expectations to a high level of knowledge to make a decision that can be trusted. The method requires a good explanation of the rating scale and close follow-up to avoid errors or inconsistency. Therefore, the method might be both challenging and time-demanding to apply to a wide range of stakeholders in an international industry. As the decision support method facilitated in this thesis, the combination of subjective preference of criteria and objective, fact-based evaluation of fuel performance might be a more suitable approach.

A key theme is developing suitable models that describe future uncertainty in fuel characteristics and performance. The focus should be on exogenous uncertainties, such as market rates, fuel prices, new regulations, and accidents, and how they influence decision-making. Such models are the foundation for decision-making tools for shipowners and operators that can assist in short-term optimization of the fleet and operations and strategic choices for geographical allocation of the fleet. An accelerated environmental operation profile can be obtained by modelling both local and global fuel decision problems, taking uncertainty into account in the best possible way. A method that can support and enable the decision-makers to better account for the consequence of changes and uncertainties on a ship's lifecycle performance is essential.

10.2 The shipowner perspective

Ship owners are now facing large decisions in the time of decarbonization of shipping. Today's fuel transition is more complex and includes several aspects of uncertainties and carbon risk. The decision process will include a larger number of alternatives than earlier fuel selection processes, which will increase the work of gathering data. In addition, the identification of feasible alternatives and the prioritization of these will be challenging due to barriers as currently low technology maturity level, lack of operational experience and poorly developed fuel infrastructure.

A shipowner must make decisions and handle uncertainty, forming robust solutions. With lack of knowledge and uncertain future of the development of different fuel options, one must avoid to putt all eggs in one basket. The needs and expectations for a shipowner will change throughout the ship life, but must still be within acceptable levels of performance over its entire lifetime. The strategy to decarbonize shipping may however influence the way stakeholders think and requirements that are set. The fuel range, which currently is a main requirement for operation at deep sea, might be adjusted if bunkering infrastructure are developed or new concepts (e.g. "battery swapping") are introduced, giving the vessel a "good enough" coverage.

The 'shipowner' profile is an important aspect of the final decision. The shipowner must select a risk profile and an environmental profile. For risk, the shipowner may want to invest in high risk waiting for a high reward, but can also have a 'wait-and-see'-strategy, or be proactive in the decision making. For the environmental profile, the shipowner could select an emission target that comply with current regulations, or be leaning forward and already now comply with regulations expected within a certain time horizon.

The fuel strategy will have impact on ship design and future operation. The cargo carrying capacity of a vessel is a main source of income for shipowners. Therefore, the required tank volume and locations and its impact on cargo capacity and range are crucial. Ships ordered in 2022 and the next few years will most likely sail towards 2050 when shipping emissions according to IMO's targets are to be halved from the 2008 baseline. This means that shipowners must guess or "gamble" on which technology or fuel "wins". Most depends on how far to sail and operating area. In any case, it is important to use as little energy as possible and to be as efficiently as possible.

For a business case, the area of opportunity must be investigated. Will the consumers be willing to pay for lower environmental impact? Tradeoff between costs, environment, infrastructure and availability, and risk must be evaluated. For a shipowner ordering a newbuild, several considerations must be made. The shipowner must understand which factors that are of significant importance. Crucial dimensions of fuel, such as fuel price, infrastructure (both upstream and downstream), regulations and technology progress, must be considered. Framework conditions must be set for the decision process and connected to the main purpose, the different scenarios and relevant stakeholders.

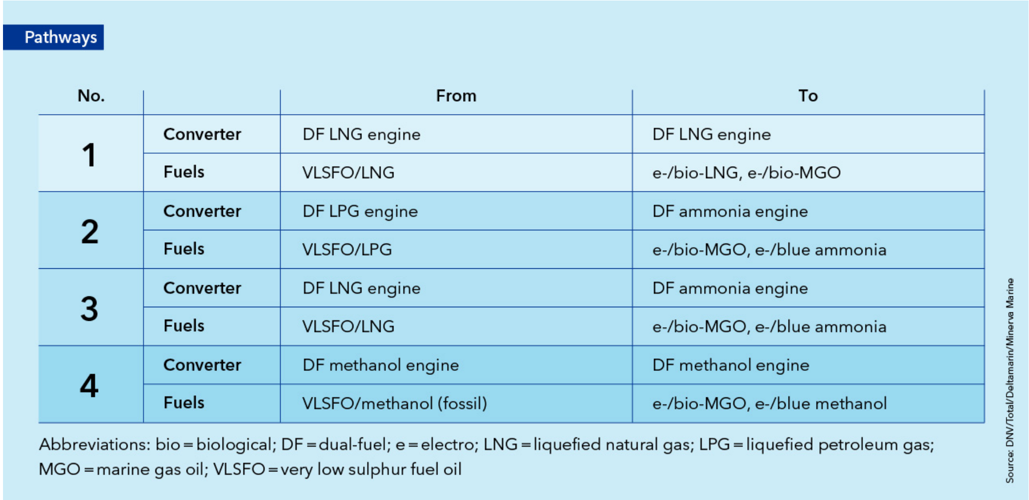
Regarding carbon risk, it will be critical for ship owners to manage carbon risk throughout the lifetime of the vessel and take GHG target trajectories into account in design, making a carefully and detailed assessment of fuel selection. For a ship owner to fully understand the risks and costs related to the decarbonization of shipping will be crucial for the fleet survival.

As for now, energy-efficiency measures and emission after treatment systems (e.g. scrubbers) may be sufficient to follow regulations and manage carbon risk. However, as the technology develops and decarbonization accelerate, long-term measures such as the fuel strategy will be decisive to meet the GHG limits. This will not necessary mean that the ship owners must build zero-emission vessels now, but facilitating for later retrofitting or change of fuel in the vessels lifetime will lower the risk of making the wrong fuel decision. This facilitation can be included in the term 'fuel-flexibility'.

10.3 Fuel flexibility

This thesis only assesses and compares mono-fuels. However, dual-fuelled vessels and fuel flexibility are frequently mentioned as possible solutions in the fuel transition. Wärtsila has defined fuel flexibility as "the ability to burn a variety of fuels and immediately switch fuels during operation without reducing load or sacrificing power plant availability" [148]. Fuel flexibility can also be associated with "lock-in-risk", meaning the ability to switch to other fuels at a low cost. Fuel flexibility can also be in terms of 'bridging', which refers to vessels being able to convert from one fuel to another during the transition. This facilitates an easy and less costly retrofitting of the onboard fuel system. Flexibility can ease the transition from conventional fuels, via low-carbon fuels, to carbon-natural (or zero-emission) vessels. If the ship owners take early action and establish a thorough fuel strategy for the decarbonization pathway, investments and modifications can be minimized along the way.

Dual-fuel engines are a good example of flexible fuel technology and are increasingly entering commercial operation at deep sea. Examples of flexible fuel pathways are gathered in Figure 10.2. An important notice is that some fuel changes require system modifications, for example, moving from LPG to ammonia. The fuel transition pathways may also involve drop-in fuels. Fully developed fuel flexibility must comply with the whole fuel system, including energy converters, onboard power system, storage tanks, and the shore-side fuel infrastructure. The industry is working on technology and guidelines for fuel flexibility, such as DNVs new class notation, 'Fuel-Ready', which indicates that a conversion to an alternative fuel has been accommodated and verified already in the newbuild design [149].



Pathways

No.		From	To
1	Converter	DF LNG engine	DF LNG engine
	Fuels	VLSFO/LNG	e-/bio-LNG, e-/bio-MGO
2	Converter	DF LPG engine	DF ammonia engine
	Fuels	VLSFO/LPG	e-/bio-MGO, e-/blue ammonia
3	Converter	DF LNG engine	DF ammonia engine
	Fuels	VLSFO/LNG	e-/bio-MGO, e-/blue ammonia
4	Converter	DF methanol engine	DF methanol engine
	Fuels	VLSFO/methanol (fossil)	e-/bio-MGO, e-/blue methanol

Abbreviations: bio = biological; DF = dual-fuel; e = electro; LNG = liquefied natural gas; LPG = liquefied petroleum gas; MGO = marine gas oil; VLSFO = very low sulphur fuel oil

Source: DNV/Total/Deltamarin/Minerva Marine

Figure 10.2: Some realistic bridging-technology pathways (from DNV JIP project [150])

Fuel flexibility and the 'fuel-ready' concept are feasible options for newbuilds. However, at what cost are the shipowner willing to gain flexibility for vessels already built and in operation? Is it relevant to consider retrofitting several times during the ship's lifetime, or is this too expensive? This will be an essential consideration for a shipowner selecting fuel for the future.

10.4 Transition fuels and key drivers in the decarbonization of shipping

As presented in chapter 2, the current status of the fuel transition is a more diverse fuel mix. It is a continued strong interest in LNG, experimentation with LPG, methanol, biofuels, and early developments of hydrogen and ammonia. A solution in a transitional period is to use flexible ship concepts that can be rebuilt or where space has been set aside for retrofitting new equipment and fuel systems. Onboard CCS can also serve as an important solution to conventional fossil fuels (e.g., HFO, VLSFO, and MGO).

Fuel and technology costs are the main deciding factors influencing the fuel mix and the availability of the fuel. In the fuel transition, shipowners depend on cooperation with stakeholders and other actors. The supply of sustainable energy and well-developed infrastructure is a requirement for a greener fuel mix. It is also important that the cargo owners and customers are willing to pay for the green shift and more sustainable transport of goods.

Developments in technology and the future fuel mix will likely be driven by international regulations. Still, other drivers, for instance, charter requirements or other market mechanisms, may also have a significant impact [76]. As presented in the result of the survey among stakeholders (subsection 8.1.2), many actors influence the decarbonization of shipping and which roadway to follow to reach the goal. Cargo owners, market and customers, and ship owners are the group with the second-highest ranking on the key drivers, after Government and international regulators as the top driver. Fuel producers and suppliers were also stated as important drivers, probably due to the industry's dependence on supply fuel from sustainable energy. Banks, investors, and financiers can also influence which fuels and technologies to drive forward based on green funding, better loan terms, and higher willingness to invest in sustainable solutions.

The ship technology industry is characterized by different market mechanisms. There exist standard regulations for technology, but at the same time, the actors can buy emission permits that are priced based on market-based considerations. The shipowner can evaluate if one shall invest in technology or purchase emission permits. With the tightening of requirements from the market and customers, these market mechanisms can be adjusted.

Both shipping companies, cargo owners, and consumers are concerned about the total climate footprint of goods. This means that energy consumption must be calculated entirely from the source of the propeller (”well to wake”). When the well-to-wake footprint is documented, stakeholder insight can increase. As mentioned regarding carbon risk in subsection 2.2.2, a trend is that some cargo owners choose to pay more for transport with lower climate footprints. The Sea Cargo Charter has recently established a global framework for ”aligning chartering activities with responsible environmental behaviour to promote international shipping’s decarbonization” [151]. There is increased pressure from people and politicians. With higher CO_2 taxes and more requirements for shipping, the EU’s taxonomy, and a tighter quota market, the calculation is more and more in favor of zero-emission technologies.

10.5 Knowledge of barriers

In section 4.3, the main barriers to the uptake of zero-emission fuels based on the prepared evaluation were presented. The identification of barriers provides crucial knowledge in the fuel selection process. The uncertain future development of the different fuels, technologies, and regulations gives shipowners a complex carbon risk outlook. The shipowners cannot combat these barriers alone, and these challenges require cooperation between stakeholders. However, by knowing the different risks and uncertainties of the fuel alternatives, measures can be made to increase the level of information and reduce risk.

The adoption of alternative fuels depends on how to combat the barriers, demand from charterers, technical incentives, and international cooperation and requires proactive regulations. Fuel infrastructure is a main issue for several alternative fuels. Widespread and certain supply is needed to convince shipowners to select greener fuel alternatives. An interesting consideration is the effect of increased availability, both in terms of technology (high TRL) and bunkering.

Securing supply from sufficient production and adequate bunkering infrastructure is crucial for a new fuel alternative to become competitive in the marine fuel market. In the case of planning for fuel flexibility, the lower energy densities and hence required onboard modifications must be taken into account. The retrofitting will be complex and costly without planning. Selecting a fuel strategy that maintains flexibility in fuel choice may be decisive for further survival in the shipping market.

Another possible approach is to think long-term and select a fuel technology system that first can combine fossil fuels that are commercially available now with CCS technology, then go over to the green version of the same fuel when this enters the market. The performance of the two production pathways of the same fuel (e.g. fossil ammonia and green ammonia) can be used to evaluate the future competitiveness of the fuel option.

Several ship owners will likely select the same option even if many fuel alternatives characterize this fuel transition. If many operators adopt the same fuel alternative for their ships within a short time, this will probably have a large impact on the development.

To make the fuel decision, the shipowner does, however, have other aspects and barriers to consider than those mentioned in this evaluation. This includes such as ship specifications (ship type, main dimensions, loading capacity, the lifetime of a vessel, implemented energy-efficiency measures) and trade (operational demands, cargo type, minimum cruising range), GHG target trajectories (for a newbuild), and design options (alternative fuels, retrofits). Combining these with the fuel price (and its variation) can give an estimated total cost of ownership [13].

10.5.1 Secure supply of renewable energy

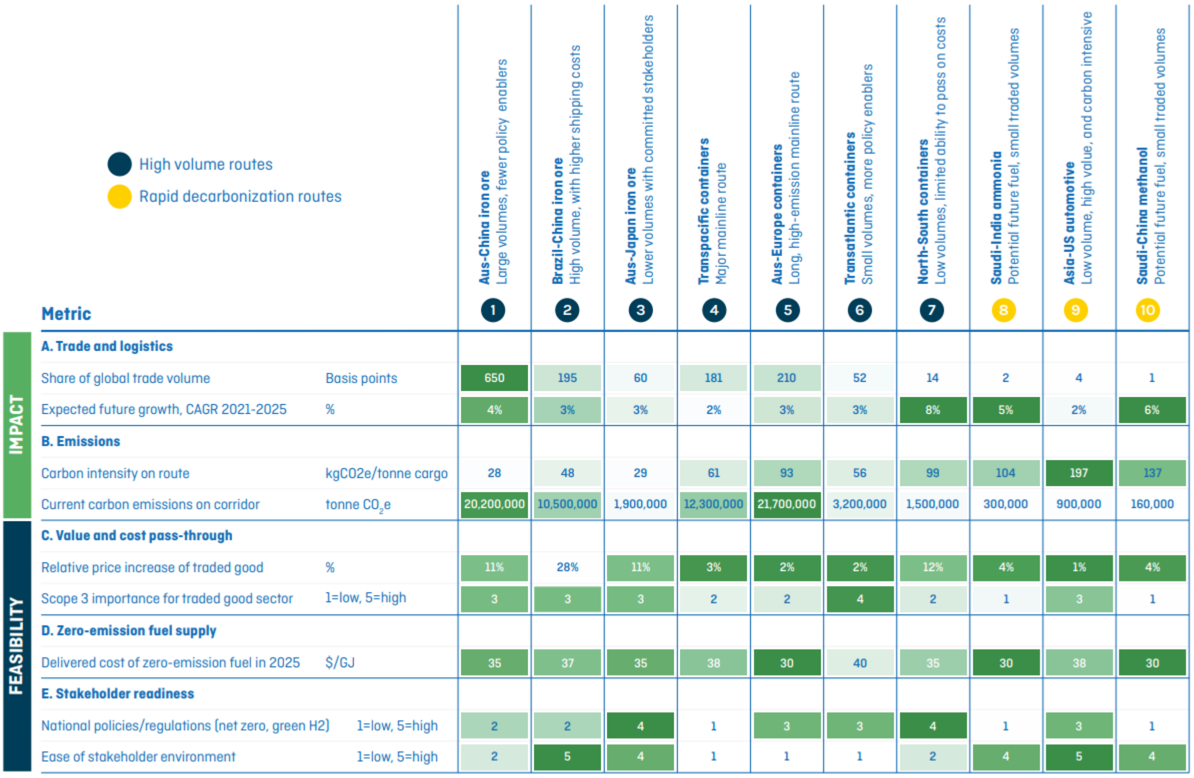
Fossil energy sources have been a vital resource to provide secure energy supplies all over the globe. The IEA defines energy security as "the uninterrupted availability of energy sources at an affordable price" by the IEA. Long-term energy security focuses on larger investments based on energy strategy related to economic and environmental developments. Short-term energy security deals with sudden changes in the energy supply-demand balance and how to handle these [152]. The world needs energy, but fossil sources have unbearable negative consequences for the environment. The world desires more sustainable energy security, indicating a need to develop and secure supply from renewable energy sources. Sustainable energy "meets the needs of the present without compromising the ability of future generations to meet their own needs" [153]. Renewable energy sources and sustainable energy supply are requirements to secure sustainable energy for the world and produce zero-emission fuels. Green energy hubs and green corridors can be the starting point for securing a worldwide renewable energy supply for shipping fuels.

10.5.2 Green corridors

The KPIs scoreboard in chapter 7 is a general consideration and does not include geographical aspects. Specific ship routes may be more suitable for implementing some of the new fuel alternatives, given high availability along the route or at both ports ends. The "Getting to Zero coalition" has started the work with 'green corridors', providing the opportunity to establish available low-emission fuels along specific deep-sea routes [154].

In this case, a corridor refers to a shipping route from harbor to harbor. A green corridor is a route where coordinated investment in infrastructure and bunkering facilities can serve the fuel demand between the two harbors. Green corridors can establish an initial market for green transport and reduce the risk for shipowners to invest in selected fuels as bunkering is available and fuel supply is secured. Initially, this might be suitable for liner shipping, which mainly sails between fixed ports (as a "large-scaling" of the short sea ferry routes, easily said).

In COP26, several countries have already signed the "Clydebank Declaration for green shipping corridors" [155][156]. To establish a green corridor, the stakeholders must cooperate to identify a suitable route (e.g., using AIS data to investigate ship traffic) and select which fuel to offer in the belonging port hubs. The 'Getting to Zero Coalition' presents four critical building blocks to establish a green corridor [154]: i) cross-value-chain collaboration and commitment across stakeholders, ii) a viable fuel pathway (well-to-wake perspective), iii) Customer demand for green transport, and iv) policy incentives and regulations (e.g., safety standards) to narrow cost gaps and accelerate adaption. The building block builds on the same principles as the identified barriers to the uptake of alternative fuels. The coalition has shortlisted ten corridors based on impact and feasibility criteria, shown in Figure 10.3.



● High volume routes
● Rapid decarbonization routes

	Metric		① **Aus-China iron ore** Large volumes, fewer policy enablers	② **Brazil-China iron ore** High volume, with higher shipping costs	③ **Aus-Japan iron ore** Lower volumes with committed stakeholders	④ **Transpacific containers** Major mainline route	⑤ **Aus-Europe containers** Long, high-emission mainline route	⑥ **Transatlantic containers** Small volumes, more policy enablers	⑦ **North-South containers** Low volumes, limited ability to pass on costs	⑧ **Saudi-India ammonia** Potential future fuel, small traded volumes	⑨ **Asia-US automotive** Low volume, high value, and carbon intensive	⑩ **Saudi-China methanol** Potential future fuel, small traded volumes
IMPACT	**A. Trade and logistics**											
	Share of global trade volume	Basis points	650	195	60	181	210	52	14	2	4	1
	Expected future growth, CAGR 2021-2025	%	4%	3%	3%	2%	3%	3%	8%	5%	2%	6%
	B. Emissions											
	Carbon intensity on route	kgCO2e/tonne cargo	28	48	29	61	93	56	99	104	197	137
	Current carbon emissions on corridor	tonne CO_2e	20,200,000	10,500,000	1,900,000	12,300,000	21,700,000	3,200,000	1,500,000	300,000	900,000	160,000
FEASIBILITY	**C. Value and cost pass-through**											
	Relative price increase of traded good	%	11%	28%	11%	3%	2%	2%	12%	4%	1%	4%
	Scope 3 importance for traded good sector	1=low, 5=high	3	3	3	2	2	4	2	1	3	1
	D. Zero-emission fuel supply											
	Delivered cost of zero-emission fuel in 2025	$/GJ	35	37	35	38	30	40	35	30	38	30
	E. Stakeholder readiness											
	National policies/regulations (net zero, green H2)	1=low, 5=high	2	2	4	1	3	3	4	1	3	1
	Ease of stakeholder environment	1=low, 5=high	2	5	4	1	1	1	2	4	5	4

Figure 10.3: Analysis of 10 shortlisted corridors against impact and feasibility criteria (adopted from [154])

The first green shipping corridor is announced to be at one of the world's busiest container ship routes, between Los Angeles and Shanghai, where cities, ports, shipping companies, and cargo owners are committed as partners [157]. Green corridors can be used to lower the barrier of low bunkering availability and lack of incentives for green transport, as they can be used to up-scale and accelerate the uptake of alternative fuels.

10.6 Robust decision support

All different aspects of future fuel selection must be considered to provide decision support. The approach must be flexible and adaptable to different vessel types. The fuel selection problem is modelled to support the decision-maker, making it easier to make a choice. The decision problem requires both insight and structuring. For instance, when the ship fuel pathways shall be evaluated, this can be modelled by looking at the ship's operational profile throughout its lifetime. Another aspect that can be modelled is the space issues onboard a vessel and where to allocate space for fuel and cargo. Modelling real-life challenges can support the industry to make better decisions.

Results from studies that evaluate and compare ship fuel options depend on the included fuels, the assumptions made regarding the fuel production pathway, and the current fuel performance. When modelling for future scenarios, the result will also depend on the assumed future performance of the fuels and other external factors that will affect the fuel picture. Fuel selection is a subjective decision; it will also depend on the group of experts or stakeholders included in the study. Selecting crucial criteria, including many fuels, and addressing how stakeholders view the issue is crucial to cover the whole decision process.

The soft analysis of the fuel selection shows that the decision is taken based on floating information and that there is a lack of structure in the decision process. This thesis helps to shed light on the factors that influence the final decision. In a decision-making process, the process itself is just as important - contributing to insight and understanding.

The survey gave insight into perspectives and thoughts from the industry. Collecting and structuring information from different stakeholders will provide broader views of the fuel selection process. By quantifying qualitative information, loose thought and undefined decision factors can be structured. The structured information could more easily be evaluated and compared and used as input in decision support models. A suggestion is to prepare a similar case study like the one presented in chapter 9 for other actors than a shipowner, for example, by researchers or the government. This could be used to identify deviation in both input (prioritizing of criteria) and output (results) among stakeholders and either confirm or disapprove of a shipowner's perspective. A wide range of stakeholder input could be used to validate the current status of knowledge and identify disagreements and common barriers in the decision context. Specific cases could also be prepared for different focus areas, such as deep-sea or short-sea, or in terms of ship types. By testing the model for different stakeholders' perspectives, the sensitivity of the decision-maker can be identified, and one might be able to quantify how subjective the fuel decision in reality is. Additional sensitivity analysis for varying importance of criteria and how this affects the weighted performance of the fuel options could also be interesting.

System engineering can be used to structure the decision problem. By defining system boundaries and establishing which factors to include in the modelling of the problem and which external factors can affect the system (the problem statement) and simulate future changes, better insight and knowledge can be obtained. A well-considered, robust, and future-proof solution lies in the ability to structure and model the problem. The decision support method and the belonging multi-criteria optimization model presented in this study might be the first step to such an approach.

CHAPTER 11

CONCLUSION

This thesis assesses the decision basis for ship fuel selection, including criteria for selection and barriers to the uptake of alternative fuels. A multi-criteria optimization model and a belonging decision support method for ship fuel selection are developed. The decision support method is open and able to include a wide range of criteria and perspectives of the decision-maker and pay attention to the changing performance of the different fuel alternatives, improving the communication of factors influencing the fuel selection process.

Criteria, barriers, and fuel performance were evaluated in three different approaches; 1) A comparison-based screening of fuel options for deep-sea shipping based on six KPIs, 2) a survey among stakeholders, and 3) a case study considering shipowner fuel selection for operation at deep sea. In general, technical, economic, environmental, and social criteria were considered highly important, and no clear fuel choice was stated, confirming a challenging, uncertain, and complex decision. All approaches illustrate that there exists considerable barriers to the uptake of alternative fuels. Low technology maturity levels, poorly developed bunkering infrastructure, low maturity of safety regulations, and high costs were stated as main barriers.

The thesis argues that better mapping and structuring of the fuel selection process is required to accelerate the decarbonization of shipping. The decision support method for ship fuel selection provides clearer objectives, greater robustness, and traceability to the choices made during the decision process. Identification of criteria and barriers can be used to map where support is needed to increase the fuel performance on key criteria. Better insight into the stakeholder preferences can provide knowledge of decision criteria and identify current showstoppers for green action. It took 20 years to develop an LNG infrastructure that now seems competitive in the shipping industry. To reach the IMO targets, the fuel system and infrastructure of carbon-neutral fuel options must mature faster. Dialog and cooperation between stakeholders will improve policies and accelerate green incentives. As proposed in this thesis, better mapping and structuring can be achieved through a more systematic decision-making method.

11.1 Further work

Suggestions for further work is listed below:

- A possible extension of the thesis work is to digitalize the scoreboard and the performance level system, for example by making a dashboard and visualize the results in PowerBI. This extension may open up for several or other KPIs and fuel alternatives, and easy adjustment of the levelling and scoring.
- Extend the model to include a more detailed level of the fuel system, for example by including dual-fuel solutions, specifying converters and assess the efficiency.
- The model could be extended to include the "profile" of the decision maker, regarding such as risk profile (e.g., high risk) or environmental strategy (e.g., forward leaning emission target setting)
- Perform a sensitivity analysis, both for criteria included, weighting of criteria and the sensitivity of the decision-maker. This can improve the robustness and asses uncertainties in the ranking of fuels.
- Perform a more comprehensive study on the stakeholders perspectives. Shipping is global and hence a global and more representative assessment should be performed. A study could also be prepared for a more narrow market segment or specific ship types.
- As the evaluation in this thesis are general, further work and investigation of a specific trade, shipping route or vessel type could give an extra level of understanding of the complexity of the transition to greener fuels. This could, for example, be applied to a specific 'green corridor', where the fuel performance probably could be stated more specific.
- Continue to investigate what remains to remove barriers and close gaps between conventional and alternative fuels. One suggestion is to examine how increased availability will effect value and fuel selection for ship owners (e.g. by use of a optimization or simulation model). This will also include a further look at the current port and bunkering infrastructure.

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APPENDIX A

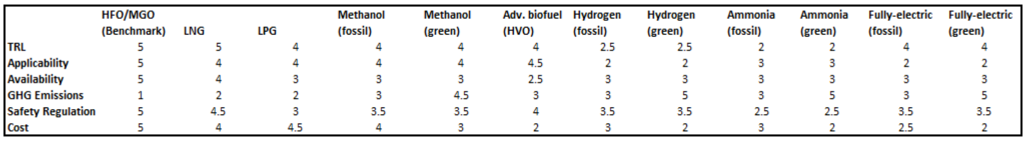
SCREENING DATA

A.1 KPI Score-levels and Performance Score of Fuels applied in Screening

Fuel type	Fuel family	TRL	Applicability	Availability	GHG Emissions	Safety Reg.	Cost
HFO/MGO	fossil	5	5	5	1	5	5
LNG	fossil	5	4	4	2	4-5	4
LPG	fossil	4	4	3	2	3	4-5
Methanol	fossil	4	4	3	3	3-4	4
Methanol	green	4	4	3	4-5	3-4	3
Adv. biofuel (HVO)	bio	4	4-5	2-3	3	4	2
Hydrogen	fossil	2-3	2	3	3	3-4	3
Hydrogen	green	2-3	2	3	5	3-4	2
Ammonia	fossil	2	3	3	3	2-3	3
Ammonia	green	2	3	3	5	2-3	2
Fully-electric	fossil	4	2	3	3	3-4	2-3
Fully-electric	green	4	2	3	5	3-4	2

Table A.1: Appendix: Score of fuel according to the five selected parameters.

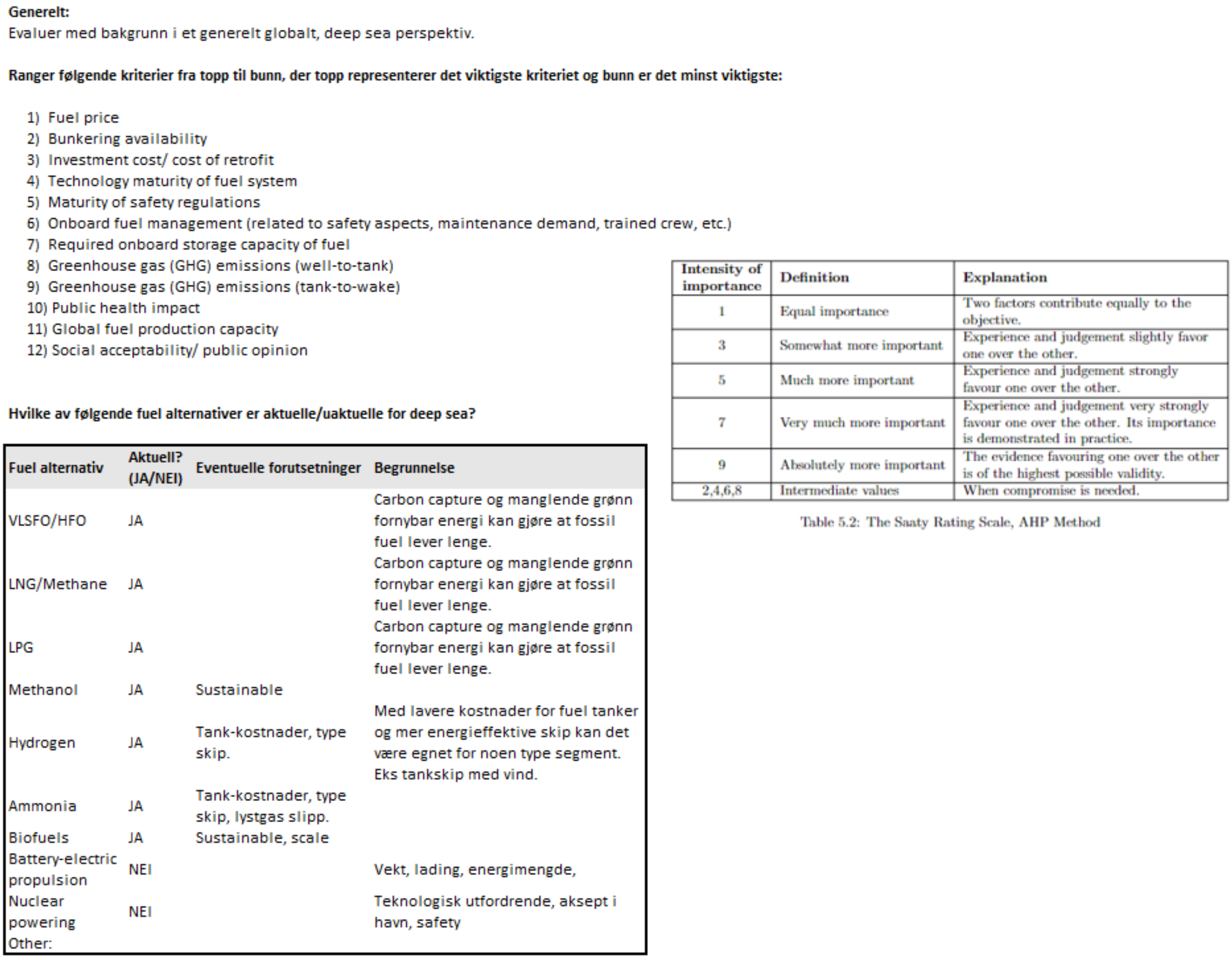
A.2 Excel sheet: Screening values



	HFO/MGO (Benchmark)	LNG	LPG	Methanol (fossil)	Methanol (green)	Adv. biofuel (HVO)	Hydrogen (fossil)	Hydrogen (green)	Ammonia (fossil)	Ammonia (green)	Fully-electric (fossil)	Fully-electric (green)
TRL	5	5	4	4	4	4	2.5	2.5	2	2	4	4
Applicability	5	4	4	4	4	4.5	2	2	3	3	2	2
Availability	5	4	3	3	3	2.5	3	3	3	3	3	3
GHG Emissions	1	2	2	3	4.5	3	3	5	3	5	3	5
Safety Regulation	5	4.5	3	3.5	3.5	4	3.5	3.5	2.5	2.5	3.5	3.5
Cost	5	4	4.5	4	3	2	3	2	3	2	2.5	2

APPENDIX B

EXCEL SHEET: WEIGHTING OF CRITERIA AND FUELS - THE SHIPOWNER PERSPECTIVE (THE AHP METHOD)



Generelt:
Evaluer med bakgrunn i et generelt globalt, deep sea perspektiv.

Ranger følgende kriterier fra topp til bunn, der topp representerer det viktigste kriteriet og bunn er det minst viktigste:

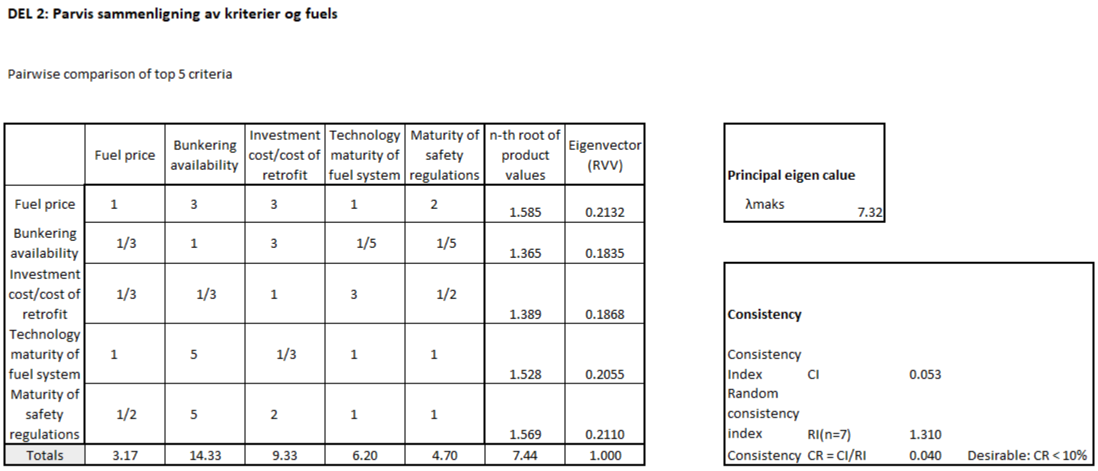
1) Fuel price
2) Bunkering availability
3) Investment cost/ cost of retrofit
4) Technology maturity of fuel system
5) Maturity of safety regulations
6) Onboard fuel management (related to safety aspects, maintenance demand, trained crew, etc.)
7) Required onboard storage capacity of fuel
8) Greenhouse gas (GHG) emissions (well-to-tank)
9) Greenhouse gas (GHG) emissions (tank-to-wake)
10) Public health impact
11) Global fuel production capacity
12) Social acceptability/ public opinion

Intensity of importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective.
3	Somewhat more important	Experience and judgement slightly favor one over the other.
5	Much more important	Experience and judgement strongly favour one over the other.
7	Very much more important	Experience and judgement very strongly favour one over the other. Its importance is demonstrated in practice.
9	Absolutely more important	The evidence favouring one over the other is of the highest possible validity.
2,4,6,8	Intermediate values	When compromise is needed.

Table 5.2: The Saaty Rating Scale, AHP Method

Hvilke av følgende fuel alternativer er aktuelle/uaktuelle for deep sea?

Fuel alternativ	**Aktuell? (JA/NEI)**	**Eventuelle forutsetninger**	**Begrunnelse**
VLSFO/HFO	JA		Carbon capture og manglende grønn fornybar energi kan gjøre at fossil fuel lever lenge.
LNG/Methane	JA		Carbon capture og manglende grønn fornybar energi kan gjøre at fossil fuel lever lenge.
LPG	JA		Carbon capture og manglende grønn fornybar energi kan gjøre at fossil fuel lever lenge.
Methanol	JA	Sustainable	
Hydrogen	JA	Tank-kostnader, type skip.	Med lavere kostnader for fuel tanker og mer energieffektive skip kan det være egnet for noen type segment. Eks tankskip med vind.
Ammonia	JA	Tank-kostnader, type skip, lystgas slipp.	
Biofuels	JA	Sustainable, scale	
Battery-electric propulsion	NEI		Vekt, lading, energimengde,
Nuclear powering	NEI		Teknologisk utfordrende, aksept i havn, safety
Other:			



DEL 2: Parvis sammenligning av kriterier og fuels

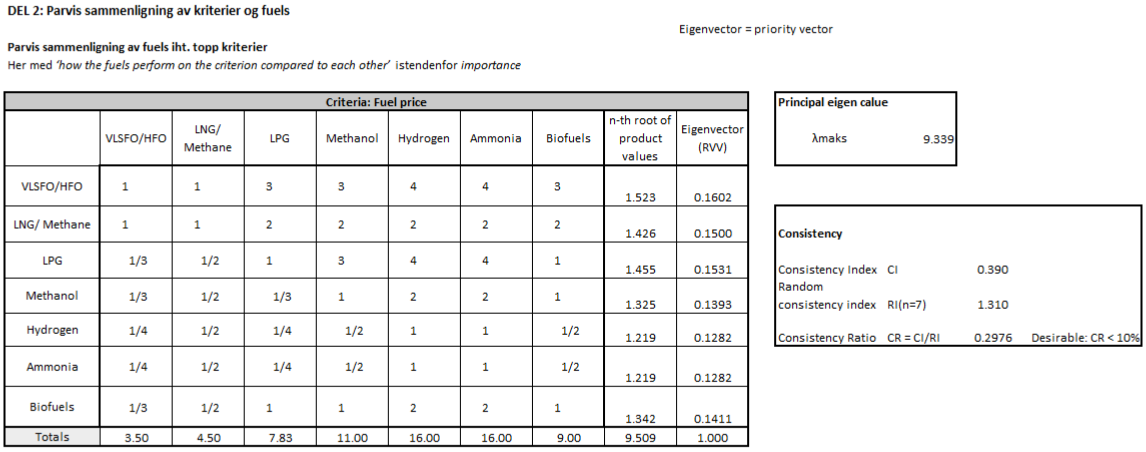
Pairwise comparison of top 5 criteria

	Fuel price	Bunkering availability	Investment cost/cost of retrofit	Technology maturity of fuel system	Maturity of safety regulations	n-th root of product values	Eigenvector (RVV)
Fuel price	1	3	3	1	2	1.585	0.2132
Bunkering availability	1/3	1	3	1/5	1/5	1.365	0.1835
Investment cost/cost of retrofit	1/3	1/3	1	3	1/2	1.389	0.1868
Technology maturity of fuel system	1	5	1/3	1	1	1.528	0.2055
Maturity of safety regulations	1/2	5	2	1	1	1.569	0.2110
Totals	3.17	14.33	9.33	6.20	4.70	7.44	1.000

Principal eigen calue
λmaks 7.32

Consistency

Consistency Index CI 0.053
Random consistency index RI(n=7) 1.310
Consistency CR = CI/RI 0.040 Desirable: CR < 10%



DEL 2: Parvis sammenligning av kriterier og fuels

Eigenvector = priority vector

Parvis sammenligning av fuels iht. topp kriterier

Her med *'how the fuels perform on the criterion compared to each other'* istendenfor *importance*

Criteria: Fuel price

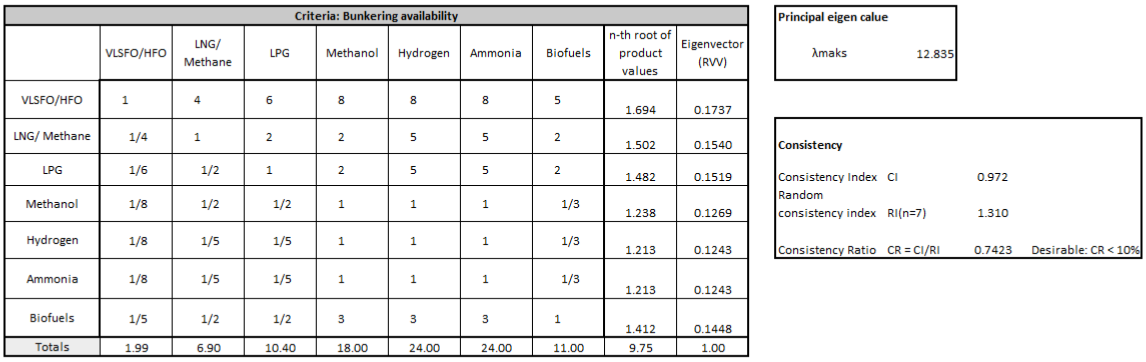
	VLSFO/HFO	LNG/ Methane	LPG	Methanol	Hydrogen	Ammonia	Biofuels	n-th root of product values	Eigenvector (RVV)
VLSFO/HFO	1	1	3	3	4	4	3	1.523	0.1602
LNG/ Methane	1	1	2	2	2	2	2	1.426	0.1500
LPG	1/3	1/2	1	3	4	4	1	1.455	0.1531
Methanol	1/3	1/2	1/3	1	2	2	1	1.325	0.1393
Hydrogen	1/4	1/2	1/4	1/2	1	1	1/2	1.219	0.1282
Ammonia	1/4	1/2	1/4	1/2	1	1	1/2	1.219	0.1282
Biofuels	1/3	1/2	1	1	2	2	1	1.342	0.1411
Totals	3.50	4.50	7.83	11.00	16.00	16.00	9.00	9.509	1.000

Principal eigen calue
λmaks 9.339

Consistency

Consistency Index CI 0.390
Random consistency index RI(n=7) 1.310

Consistency Ratio CR = CI/RI 0.2976 Desirable: CR < 10%



Criteria: Bunkering availability

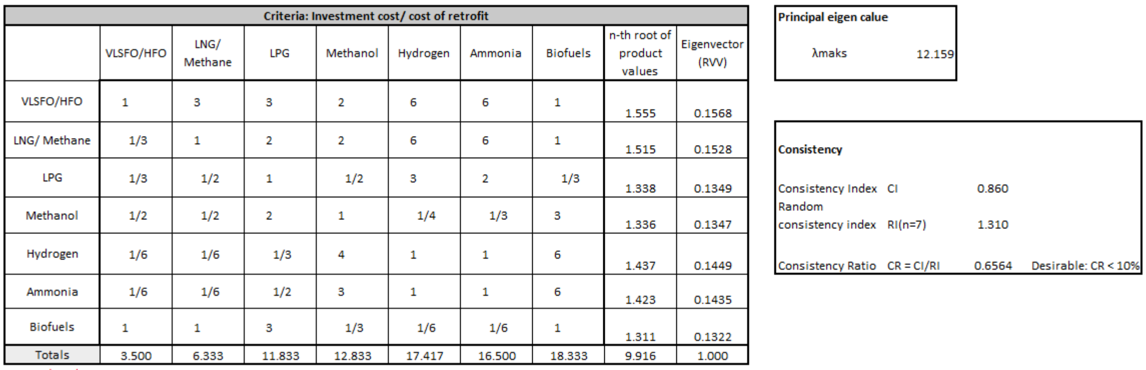
	VLSFO/HFO	LNG/ Methane	LPG	Methanol	Hydrogen	Ammonia	Biofuels	n-th root of product values	Eigenvector (RVV)
VLSFO/HFO	1	4	6	8	8	8	5	1.694	0.1737
LNG/ Methane	1/4	1	2	2	5	5	2	1.502	0.1540
LPG	1/6	1/2	1	2	5	5	2	1.482	0.1519
Methanol	1/8	1/2	1/2	1	1	1	1/3	1.238	0.1269
Hydrogen	1/8	1/5	1/5	1	1	1	1/3	1.213	0.1243
Ammonia	1/8	1/5	1/5	1	1	1	1/3	1.213	0.1243
Biofuels	1/5	1/2	1/2	3	3	3	1	1.412	0.1448
Totals	1.99	6.90	10.40	18.00	24.00	24.00	11.00	9.75	1.00

Principal eigen calue
λmaks 12.835

Consistency

Consistency Index CI 0.972
Random consistency index RI(n=7) 1.310

Consistency Ratio CR = CI/RI 0.7423 Desirable: CR < 10%



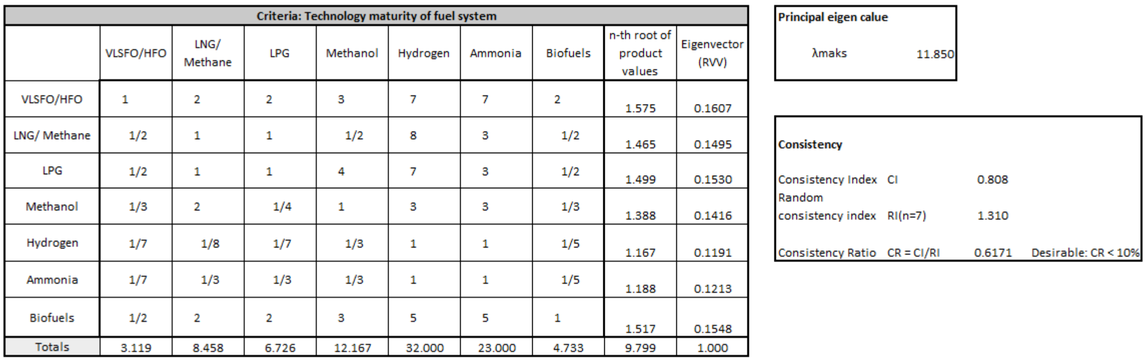
Criteria: Investment cost/ cost of retrofit									
	VLSFO/HFO	LNG/ Methane	LPG	Methanol	Hydrogen	Ammonia	Biofuels	n-th root of product values	Eigenvector (RVV)
VLSFO/HFO	1	3	3	2	6	6	1	1.555	0.1568
LNG/ Methane	1/3	1	2	2	6	6	1	1.515	0.1528
LPG	1/3	1/2	1	1/2	3	2	1/3	1.338	0.1349
Methanol	1/2	1/2	2	1	1/4	1/3	3	1.336	0.1347
Hydrogen	1/6	1/6	1/3	4	1	1	6	1.437	0.1449
Ammonia	1/6	1/6	1/2	3	1	1	6	1.423	0.1435
Biofuels	1	1	3	1/3	1/6	1/6	1	1.311	0.1322
Totals	3.500	6.333	11.833	12.833	17.417	16.500	18.333	9.916	1.000

Principal eigen calue

λmaks 12.159

Consistency

Consistency Index	CI	0.860	
Random consistency index	RI(n=7)	1.310	
Consistency Ratio	CR = CI/RI	0.6564	Desirable: CR < 10%



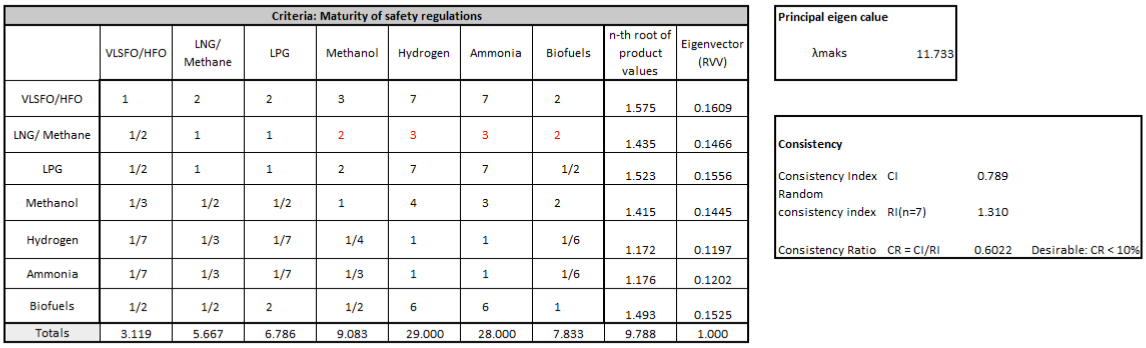
Criteria: Technology maturity of fuel system									
	VLSFO/HFO	LNG/ Methane	LPG	Methanol	Hydrogen	Ammonia	Biofuels	n-th root of product values	Eigenvector (RVV)
VLSFO/HFO	1	2	2	3	7	7	2	1.575	0.1607
LNG/ Methane	1/2	1	1	1/2	8	3	1/2	1.465	0.1495
LPG	1/2	1	1	4	7	3	1/2	1.499	0.1530
Methanol	1/3	2	1/4	1	3	3	1/3	1.388	0.1416
Hydrogen	1/7	1/8	1/7	1/3	1	1	1/5	1.167	0.1191
Ammonia	1/7	1/3	1/3	1/3	1	1	1/5	1.188	0.1213
Biofuels	1/2	2	2	3	5	5	1	1.517	0.1548
Totals	3.119	8.458	6.726	12.167	32.000	23.000	4.733	9.799	1.000

Principal eigen calue

λmaks 11.850

Consistency

Consistency Index	CI	0.808	
Random consistency index	RI(n=7)	1.310	
Consistency Ratio	CR = CI/RI	0.6171	Desirable: CR < 10%



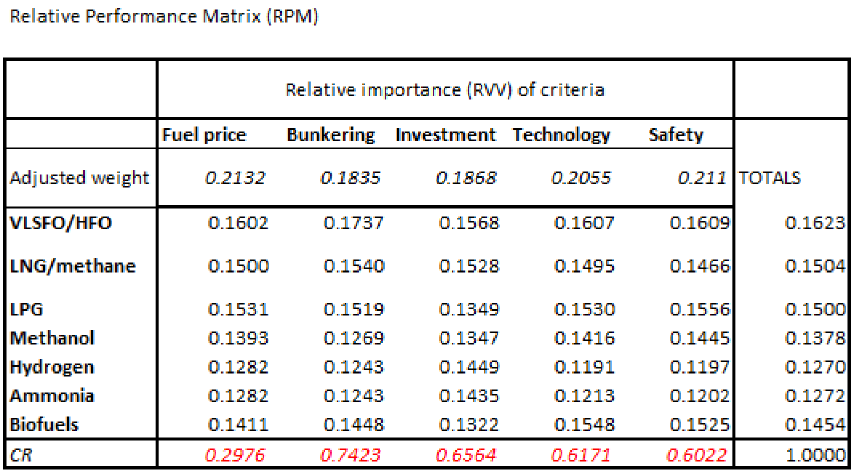
Criteria: Maturity of safety regulations									
	VLSFO/HFO	LNG/ Methane	LPG	Methanol	Hydrogen	Ammonia	Biofuels	n-th root of product values	Eigenvector (RVV)
VLSFO/HFO	1	2	2	3	7	7	2	1.575	0.1609
LNG/ Methane	1/2	1	1	2	3	3	2	1.435	0.1466
LPG	1/2	1	1	2	7	7	1/2	1.523	0.1556
Methanol	1/3	1/2	1/2	1	4	3	2	1.415	0.1445
Hydrogen	1/7	1/3	1/7	1/4	1	1	1/6	1.172	0.1197
Ammonia	1/7	1/3	1/7	1/3	1	1	1/6	1.176	0.1202
Biofuels	1/2	1/2	2	1/2	6	6	1	1.493	0.1525
Totals	3.119	5.667	6.786	9.083	29.000	28.000	7.833	9.788	1.000

Principal eigen calue

λmaks 11.733

Consistency

Consistency Index	CI	0.789	
Random consistency index	RI(n=7)	1.310	
Consistency Ratio	CR = CI/RI	0.6022	Desirable: CR < 10%

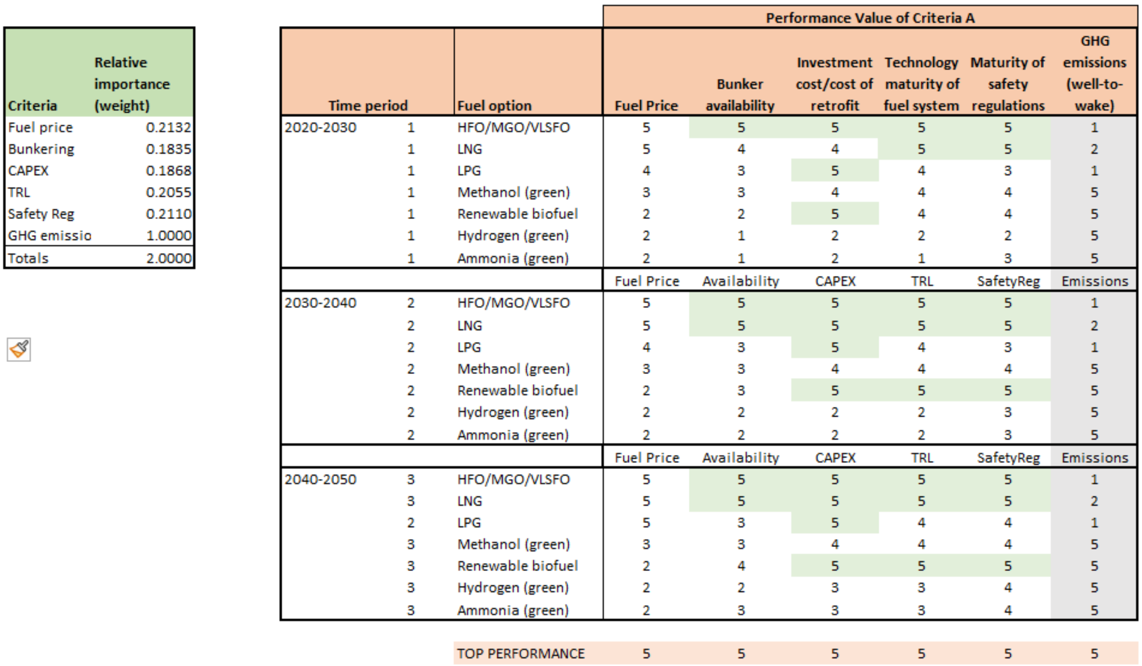


Relative Performance Matrix (RPM)

	Relative importance (RVV) of criteria					
	Fuel price	**Bunkering**	**Investment**	**Technology**	**Safety**	
Adjusted weight	*0.2132*	*0.1835*	*0.1868*	*0.2055*	*0.211*	TOTALS
VLSFO/HFO	0.1602	0.1737	0.1568	0.1607	0.1609	0.1623
LNG/methane	0.1500	0.1540	0.1528	0.1495	0.1466	0.1504
LPG	0.1531	0.1519	0.1349	0.1530	0.1556	0.1500
Methanol	0.1393	0.1269	0.1347	0.1416	0.1445	0.1378
Hydrogen	0.1282	0.1243	0.1449	0.1191	0.1197	0.1270
Ammonia	0.1282	0.1243	0.1435	0.1213	0.1202	0.1272
Biofuels	0.1411	0.1448	0.1322	0.1548	0.1525	0.1454
CR	*0.2976*	*0.7423*	*0.6564*	*0.6171*	*0.6022*	1.0000

APPENDIX C

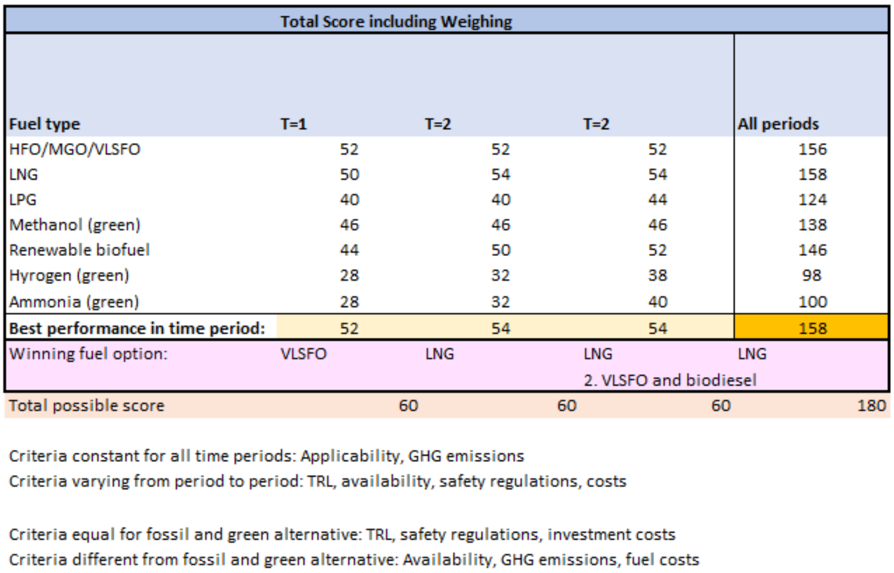
EXCEL SHEET: CASE STUDY



Criteria	Relative importance (weight)
Fuel price	0.2132
Bunkering	0.1835
CAPEX	0.1868
TRL	0.2055
Safety Reg	0.2110
GHG emissio	1.0000
Totals	2.0000

			Performance Value of Criteria A					
Time period		Fuel option	Fuel Price	Bunker availability	Investment cost/cost of retrofit	Technology maturity of fuel system	Maturity of safety regulations	GHG emissions (well-to-wake)
2020-2030	1	HFO/MGO/VLSFO	5	5	5	5	5	1
	1	LNG	5	4	4	5	5	2
	1	LPG	4	3	5	4	3	1
	1	Methanol (green)	3	3	4	4	4	5
	1	Renewable biofuel	2	2	5	4	4	5
	1	Hydrogen (green)	2	1	2	2	2	5
	1	Ammonia (green)	2	1	2	1	3	5
			Fuel Price	Availability	CAPEX	TRL	SafetyReg	Emissions
2030-2040	2	HFO/MGO/VLSFO	5	5	5	5	5	1
	2	LNG	5	5	5	5	5	2
	2	LPG	4	3	5	4	3	1
	2	Methanol (green)	3	3	4	4	4	5
	2	Renewable biofuel	2	3	5	5	5	5
	2	Hydrogen (green)	2	2	2	2	3	5
	2	Ammonia (green)	2	2	2	2	3	5
			Fuel Price	Availability	CAPEX	TRL	SafetyReg	Emissions
2040-2050	3	HFO/MGO/VLSFO	5	5	5	5	5	1
	3	LNG	5	5	5	5	5	2
	2	LPG	5	3	5	4	4	1
	3	Methanol (green)	3	3	4	4	4	5
	3	Renewable biofuel	2	4	5	5	5	5
	3	Hydrogen (green)	2	2	3	3	4	5
	3	Ammonia (green)	2	3	3	3	4	5
		TOP PERFORMANCE	5	5	5	5	5	5

Figure C.1: Scenario 1: Business as usual - inputs



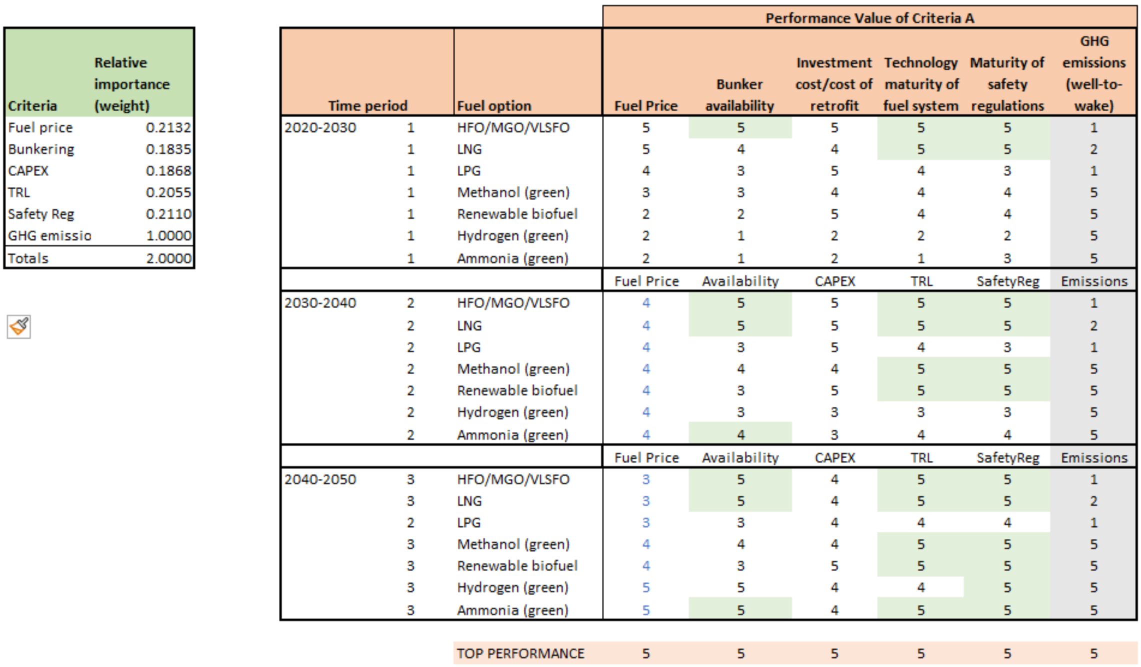
Total Score including Weighing

Fuel type	**T=1**	**T=2**	**T=2**	**All periods**
HFO/MGO/VLSFO	52	52	52	156
LNG	50	54	54	158
LPG	40	40	44	124
Methanol (green)	46	46	46	138
Renewable biofuel	44	50	52	146
Hyrogen (green)	28	32	38	98
Ammonia (green)	28	32	40	100
Best performance in time period:	52	54	54	158
Winning fuel option:	VLSFO	LNG	LNG 2. VLSFO and biodiesel	LNG
Total possible score	60	60	60	180

Criteria constant for all time periods: Applicability, GHG emissions
Criteria varying from period to period: TRL, availability, safety regulations, costs

Criteria equal for fossil and green alternative: TRL, safety regulations, investment costs
Criteria different from fossil and green alternative: Availability, GHG emissions, fuel costs

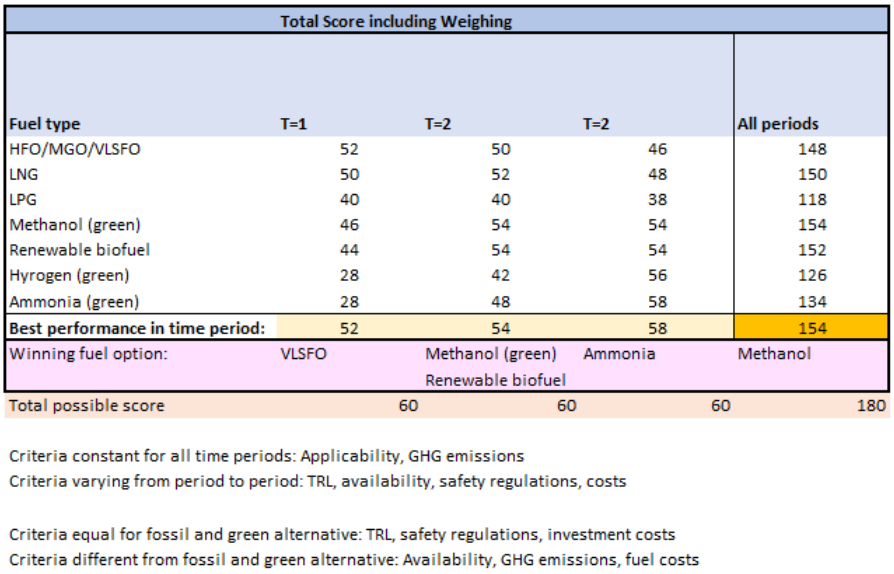
Figure C.2: Scenario 1: Business as usual - outputs



Criteria	**Relative importance (weight)**
Fuel price	0.2132
Bunkering	0.1835
CAPEX	0.1868
TRL	0.2055
Safety Reg	0.2110
GHG emissio	1.0000
Totals	2.0000

			Performance Value of Criteria A					
Time period		**Fuel option**	**Fuel Price**	**Bunker availability**	**Investment cost/cost of retrofit**	**Technology maturity of fuel system**	**Maturity of safety regulations**	**GHG emissions (well-to-wake)**
2020-2030	1	HFO/MGO/VLSFO	5	5	5	5	5	1
	1	LNG	5	4	4	5	5	2
	1	LPG	4	3	5	4	3	1
	1	Methanol (green)	3	3	4	4	4	5
	1	Renewable biofuel	2	2	5	4	4	5
	1	Hydrogen (green)	2	1	2	2	2	5
	1	Ammonia (green)	2	1	2	1	3	5
			Fuel Price	Availability	CAPEX	TRL	SafetyReg	Emissions
2030-2040	2	HFO/MGO/VLSFO	4	5	5	5	5	1
	2	LNG	4	5	5	5	5	2
	2	LPG	4	3	5	4	3	1
	2	Methanol (green)	4	4	4	5	5	5
	2	Renewable biofuel	4	3	5	5	5	5
	2	Hydrogen (green)	4	3	3	3	3	5
	2	Ammonia (green)	4	4	3	4	4	5
			Fuel Price	Availability	CAPEX	TRL	SafetyReg	Emissions
2040-2050	3	HFO/MGO/VLSFO	3	5	4	5	5	1
	3	LNG	3	5	4	5	5	2
	2	LPG	3	3	4	4	4	1
	3	Methanol (green)	4	4	4	5	5	5
	3	Renewable biofuel	4	3	5	5	5	5
	3	Hydrogen (green)	5	5	4	4	5	5
	3	Ammonia (green)	5	5	4	5	5	5
		TOP PERFORMANCE	5	5	5	5	5	5

Figure C.3: Scenario 2: Sustainable development - inputs



Total Score including Weighing

Fuel type	**T=1**	**T=2**	**T=2**	**All periods**
HFO/MGO/VLSFO	52	50	46	148
LNG	50	52	48	150
LPG	40	40	38	118
Methanol (green)	46	54	54	154
Renewable biofuel	44	54	54	152
Hyrogen (green)	28	42	56	126
Ammonia (green)	28	48	58	134
Best performance in time period:	52	54	58	154
Winning fuel option:	VLSFO	Methanol (green) Renewable biofuel	Ammonia	Methanol
Total possible score	60	60	60	180

Criteria constant for all time periods: Applicability, GHG emissions
Criteria varying from period to period: TRL, availability, safety regulations, costs

Criteria equal for fossil and green alternative: TRL, safety regulations, investment costs
Criteria different from fossil and green alternative: Availability, GHG emissions, fuel costs

Figure C.4: Scenario 2: Sustainable development - outputs

APPENDIX D

POTENTIAL AND LIMITING FACTORS IN THE USE OF ALTERNATIVE FUELS IN THE EUROPEAN MARITIME SECTOR

Table 6 from the study "Potential and limiting factors in the use of alternative fuels in the European maritime sector"[9]. Summarize the study findings, aiming to highlight the potential positive and negative impacts of several alternative fuels, in relation to the described aspects.

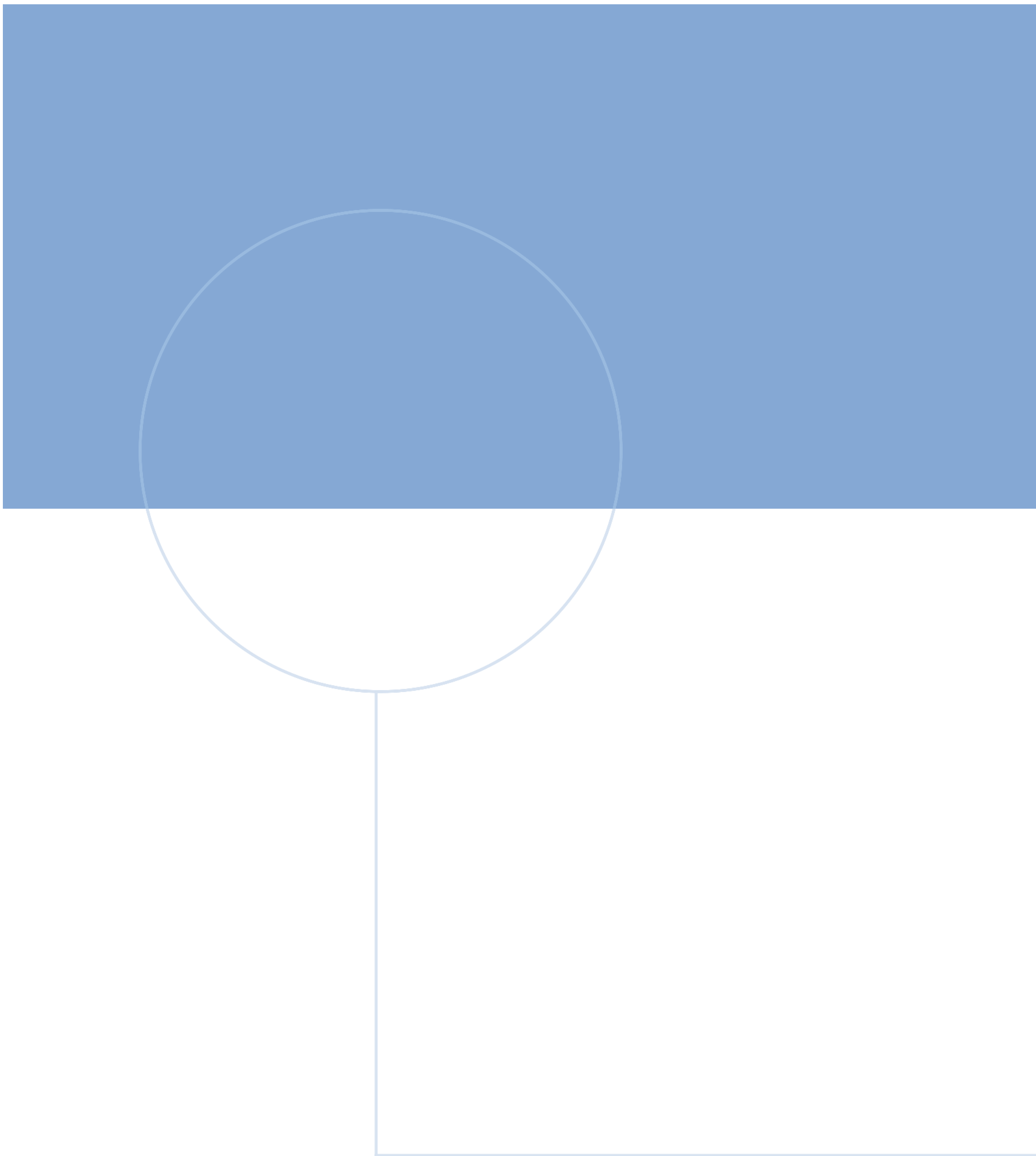
Type of Fuel	Note	Emissions (WTT)	Costs	Availability	Technical maturity	Blendability	Supply and infrastructure availability	Interaction with other sectors	Expertise	Competition with other technologies	Commercial implications
HFO	Benchmark	-	-	-	-	-	-	-	-	-	-
LNG	*from fossil sources*	No Significant Advantages	LOW (but retrofitting needed)	YES	YES	NO	YES/NO	YES	YES	YES	Existing technology with an existing market
	Bio-derived	YES	HIGH	YES/NO	YES	YES with fossil LNG	YES/NO	YES	YES	YES	Costs and availability
Methanol	*from fossil sources*	No Significant Advantages	TbD	TbD	YES	Partly	NO	Partly with Road and Aviation	NO	YES	TbD
	Bio-derived	YES	HIGH	TbD	YES/NO	YES with fossil Methanol	NO	Partly with Road and Aviation	NO	YES	TbD
FAME	*Biodiesel*	YES	HIGH	YES	YES	Partly	YES	YES	YES	YES	Costs
HVO		YES	HIGH	YES	YES	YES	YES	YES	YES	YES	Costs
Ammonia		YES/NO (depend on the source of H2)	HIGH	TbD	NO	NO	YES/NO - Easy to store	NO	YES/NO - Toxic and corrosive	TbD	Ammonia tankers already interested
Electricity		YES/NO - Depend of source	TbD	TbD	YES/NO	NO	NO/YES	YES	NO/YES	YES - with other alt.Fuels	TbD
H2 from RES	*From NG*	No Significant Advantages	TbD	YES	NO	NO	NO	Possibly	NO	YES	Costs, tech. Maturity and availability
	From RES	YES	HIGH	NO	NO	NO	NO	Possibly	NO	YES	Costs, tech. Maturity and availability

Potential **negative** impact
Potential **positive** impact
TbD
YES/NO - **Possibly**

Figure D.1: Comparative analysis of alternative fuels for shipping sector (Tab. 6 in [9])

APPENDIX E

SURVEY REPORT



Dorthe Alida A. Slotvik

Decision support for future proof ship fuel selection

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Kunnskap for en bedre verden