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BSc in Engineering Sciences and Industrial Management

COST CALCULATION FRAMEWORK FOR FUEL TRANSITION

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Cost Calculation Framework for Fuel Transition

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ABSTRACT

Global warming has been a growing concern since around 1850, leading to serious repercussions. Its major cause is the emission of greenhouse-effect gases, especially carbon dioxide whose main source is the combustion of fossil fuels. Fossil fuels serve as the primary energy source in many industries, including shipping, which is the focus of this study. One of the measures proposed to tackle the emission of greenhouse-effect gases is the development of green shipping corridors - carbon-free shipping routes that require the transition to alternative fuels, which are gaining competitiveness. One of the reasons for that is carbon pricing, which taxes carbon dioxide emissions. However, the lack of consensus on the most cost-advantageous alternative fuel in the long run results in the delay of the implementation of green shipping corridors.

To facilitate the economic analysis of various alternative fuel options, a framework to determine and minimize the costs of transitioning from fossil fuels to any alternative fuel is proposed, considering the lost opportunity cost, the deployment cost of bunkering vessels at the necessary call ports, the cost of converting the vessel, the carbon emissions tax cost, and the fuel cost. This will allow stakeholders to choose the most economical alternative fuel, accelerating the development of green shipping corridor initiatives. To validate the effectiveness of the framework, it was applied to a hypothetical case study of a shipowner seeking to transition from heavy fuel oil to ammonia, hydrogen, liquefied natural gas, or methanol. The results showed that hydrogen is the most economical fuel until a particular deployment cost per bunkering vessel is reached, after which liquefied natural gas becomes the most economical option regardless of variations in the carbon tax. Furthermore, results demonstrated that heavy fuel oil is still the most economical fuel option, even considering a very high carbon tax.

Keywords: green shipping corridor, alternative fuel, cost calculation framework, optimization, bunkering.

RESUMO

O aquecimento global tem sido uma preocupação crescente desde 1850, resultando em graves repercussões. A principal causa é a emissão de gases com efeito de estufa, especialmente dióxido de carbono, proveniente da combustão de combustíveis fósseis. Estes são a principal fonte de energia em várias indústrias, incluindo o transporte marítimo, objeto deste estudo. Uma das medidas para combater as emissões de gases com efeito de estufa é o desenvolvimento de corredores verdes - rotas de transporte marítimo descarbonizadas que requerem a transição para combustíveis alternativos. Estes são cada vez mais competitivos, nomeadamente devido à precificação do carbono, que taxa as emissões de dióxido de carbono. No entanto, a falta de consenso sobre o combustível alternativo mais vantajoso tem atrasado a implementação dos corredores verdes.

Para facilitar a análise económica das várias opções de combustível alternativo, é proposto um modelo para determinar e minimizar os custos da transição de combustíveis fósseis para alternativos, considerando o custo de oportunidade perdida, o custo de implementação dos navios de abastecimento, o custo de conversão do navio, o custo das emissões de carbono e o custo do combustível. Desta forma, será possível selecionar o combustível mais económico, acelerando o desenvolvimento dos corredores verdes. Para validar o modelo, este foi aplicado ao estudo de caso ilustrativo de um proprietário de um navio que pretende fazer a transição de óleo combustível pesado para amoníaco, hidrogénio, gás natural liquefeito ou metanol. Os resultados mostraram que o combustível mais económico é o hidrogénio até um determinado custo de implementação por navio de abastecimento, a partir do qual passa a ser o gás natural, independentemente das variações na taxa de carbono. Além disso, os resultados demonstraram que o óleo combustível pesado continua a ser o mais económico, mesmo para uma taxa de carbono muito elevada.

Palavras chave: corredor verde, combustível alternativo, modelo de cálculo de custos, otimização, abastecimento.

CONTENTS

1	INTRODUCTION.....	1
1.1	Background	1
1.2	Motivation and Objectives.....	2
1.3	Methodology	3
1.4	Dissertation Structure.....	4
2	SUSTAINABILITY MEASURES TO ADDRESS GLOBAL WARMING.....	7
2.1	Shipping's Role and Impact on GHG Emissions	9
2.2	Measures to Mitigate GHG Emissions from Shipping.....	10
2.2.1	Slow Steaming.....	12
2.2.2	Green Shipping Corridors	13
2.2.3	Prospects for Alternative Fuels	15
2.2.4	Optimization in Shipping	31
3	ROUTE DEFINITION AND LOCATION OPTIMIZATION AND FRAMEWORK PROPOSAL.....	33
3.1	Route Definition Optimization Problem.....	33
3.1.1	Traveling Salesman Problem	34
3.2	Location Optimization Problem.....	37
3.2.1	Facility Location Problem.....	38
3.3	Cost Calculation Framework for Fuel Transition.....	40
3.3.1	Optimization Model for Cost Minimization of the Number and Location of Bunkering Stops.....	41

4	CASE STUDY	45
4.1	Details of the Route and Bunkering Infrastructure.....	46
4.2	Distance Between Ports i and j (d_{ij}).....	47
4.3	Sailing Speed	47
4.4	Fuel Consumption.....	47
4.5	Phase 1	49
4.5.1	Required Input for the Optimization Model (CDU and COU)	49
4.5.2	Optimization Results: Determining CD and CO	51
4.6	Phase 2.....	55
4.6.1	Determining CC , CCO_2 and CF	55
4.6.2	Total Cost Assessment	58
5	ANALYSIS AND DISCUSSION OF RESULTS	63
5.1	Comparative Analysis of Fuel Alternatives by Cost Component.....	63
5.1.1	Cost of Converting the Vessel to Transition from HFO to Alternative Fuel (CC)	63
5.1.2	Carbon Emissions Tax Cost (CCO_2)	64
5.1.3	Fuel Cost (CF)	65
5.2	Comparative Analysis of Fuel Alternatives by Total Cost and Fuel Selection.....	66
5.3	Comparing the Research Outcomes with Fuel Projections from Existing Literature..	69
5.4	Impact of Carbon Tax Variations on Total Cost and Fuel Selection.....	70
6	CONCLUSION	75
6.1	Research Overview and Contributions.....	75
6.2	Limitations and Future Work	76
	REFERENCES	79
A	APPENDIX	91
A.1	Python Code for the Optimization Model for Minimizing the Cost of the Number and Location of Bunkering Stops for Ammonia.....	91

A.2	Python Code for the Optimization Model for Minimizing the Cost of the Number and Location of Bunkering Stops for Hydrogen	94
A.3	Python Code for the Optimization Model for Minimizing the Cost of the Number and Location of Bunkering Stops for LNG	97
A.4	Python Code for the Optimization Model for Minimizing the Cost of the Number and Location of Bunkering Stops for Methanol.....	100

LIST OF FIGURES

Figure 1.1 — Methodology Used in the Dissertation	4
Figure 2.1 — Average Annual Temperature Anomaly Compared to the 1961-1990 Average Temperature (in Red), With Upper and Lower Bounds of the 95% Confidence Intervals (in Grey) from 1850 to 2022.....	7
Figure 2.2 — Contribution of Gases to Global GHG Emissions in 2019	8
Figure 2.3 — Distribution of GHG Emissions by Sectors Worldwide in 2022.....	9
Figure 2.4 — Distribution of GHG Emissions in the Transportation Sector Worldwide in 2022	9
Figure 2.5 — Volume of Cargo Transported by Sea between 1991 and 2021.....	10
Figure 2.6 — Number of Ships Adopting Alternative Fuels in the Global Fleet in 2022	16
Figure 2.7 — Projected Annual Ammonia Production in Millions of Tons	20
Figure 3.1 — Cost Calculation Framework for Fuel Transition.....	41
Figure 4.1 — Map of the Route between Call Ports and Availability of Bunkering Services	46
Figure 5.1 — Cost Comparison of Converting the Vessel to Transition from HFO to Ammonia, Hydrogen, LNG, and Methanol	64
Figure 5.2 — Carbon Emissions Tax Cost Comparison for HFO, Ammonia, Hydrogen, LNG, and Methanol.....	65
Figure 5.3 — Fuel Cost Comparison for HFO, Ammonia, Hydrogen, LNG, and Methanol.....	66
Figure 5.4 — Total Cost Assessment at Varying Deployment Costs of a Bunkering Vessel per Voyage at a Sailing Speed of 22 knots.....	68
Figure 5.5 — Total Cost Assessment at Varying Deployment Costs of a Bunkering Vessel at a Sailing Speed of 18 knots.....	68
Figure 5.6 — Total Cost Assessment at Varying Deployment Costs of a Bunkering Vessel and Varying Carbon Taxes at a Sailing Speed of 22 knots	74

Figure 5.7 — Total Cost Assessment at Varying Deployment Costs of a Bunkering Vessel per Voyage and Varying Carbon Taxes at a Sailing Speed of 18 knot.....74

LIST OF TABLES

Table 2.1 — Overview of Hydrogen Production Methods, Production Costs, and Technology Readiness Level	24
Table 2.2 — Properties, Advantages, Disadvantages and Future Perspectives of Ammonia, Hydrogen, LNG, and Methanol	30
Table 5.1 — Information about the Call Ports.....	46
Table 5.2 — Distances between the Consecutive Ports Where the Vessel Stops Along the Route	47
Table 5.3 — Properties and Fuel Consumption of HFO, Ammonia, Hydrogen, LNG, and Methanol.....	48
Table 5.4 — Lost Opportunity Cost per NM When Transitioning from HFO to Ammonia, Hydrogen, LNG, and Methanol	51
Table 5.5 — Consolidated Optimization Results for Ammonia, Hydrogen, LNG, and Methanol	54
Table 5.6 — Cost of Converting the Vessel to Transition from HFO to Ammonia, Hydrogen, LNG, and Methanol.....	56
Table 5.7 — CO ₂ Emission Factor of HFO, Ammonia, Hydrogen, LNG, and Methanol	57
Table 5.8 — CO ₂ Emissions of HFO, Ammonia, Hydrogen, LNG, and Methanol.....	57
Table 5.9 — Carbon Emissions Tax Cost of HFO, Ammonia, Hydrogen, LNG, and Methanol ..	58
Table 5.10 — Fuel Cost of HFO, Ammonia, Hydrogen, LNG, and Methanol	58
Table 5.11 — Aggregated Costs for HFO as Fuel.....	59
Table 5.12 — Aggregated Costs for LNG as Fuel.....	59
Table 5.13 — Aggregated Costs for Methanol as Fuel	59
Table 5.14 — Sum of the Cost of Converting the Vessel, the Carbon Emissions Tax Cost, and the Fuel Cost of Ammonia	60

Table 5.15 — Sum of the Cost of Converting the Vessel, the Carbon Emissions Tax Cost, and the Fuel Cost of Hydrogen.....	61
Table 5.16 — Aggregated Costs for Hydrogen as Fuel above which It Becomes Less Cost-Advantageous than LNG.....	61
Table 5.17 — Aggregated Costs for Hydrogen as Fuel above which It Becomes Less Cost-Advantageous than Methanol.....	62
Table 6.1— Comparative Analysis of Most Advantageous Alternative Fuels and Parameters Considered in Different Studies	70
Table 6.2 — Impact of Carbon Tax on Carbon Emissions Tax Cost and Total Cost for HFO, LNG, and Methanol.....	72

ACRONYMS

ATSP	Asymmetric Traveling Salesman Problem
BC	Black carbon
BOG	Boil-Off Gas
BO-InTSP	Bi-Objective Insular Traveling Salesman Problem
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
CFLP	Capacitated Facility Location Problem
CII	Carbon Intensity Indicator
DNV	Det Norske Veritas
ED	Energy Density
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
ETS	Emissions Trading Schemes
EU	European Union
FC	Fuel Consumption
FLP	Facility Location Problem
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change

IRENA	International Renewable Energy Agency
ITF	International Transport Forum
GHG	Greenhouse gas
GWG	Greenhouse warming potential
GWP20	20-Year global warming potential
GWP100	100-Year global warming potential
HFO	Heavy fuel oil
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MIP	Mixed-integer program
MOP	Multi-objective optimization problem
mTSPPD- TWDL	Multi-ship Traveling Salesman Problem with Pickups and Deliveries, Time Windows, and Draft Limits
NM	Nautical Mile
PM	Particular Matter
SCR	Selective catalytic reduction
SEEMP	Ship Energy Efficiency Management Plan
SMR	Steam methane reforming
STSP	Symmetric Traveling Salesman Problem
TRM	Tri-reforming of methane
TSP	Traveling Salesman Problem
TSPPD- TWDLTA	Traveling Salesman Problem with Pickups and Deliveries, Time Windows, Draft Limits, and Tank Allocation
TSPPD-TWDL	Traveling Salesman Problem with Pickups and Deliveries, Time Windows, and Draft Limits

UFLP Uncapacitated Facility Location Problem

US United States

SYMBOLS

A	Set of arcs between ports indexed by i and j
C^C	Cost of converting the vessel to transition from HFO to alternative fuel
C^{CO_2}	Carbon emissions tax cost
C^D	Deployment cost of bunkering vessels at the necessary call ports
C^{DU}	Deployment cost of a bunkering vessel
C^F	Fuel cost
CH_3OH	Methanol
CH_4	Methane
CO	Carbon monoxide
C^O	Lost opportunity cost of the voyage
CO_2	Carbon dioxide
C^{OU}	Lost opportunity cost per nautical mile
d_{ij}	Distance between ports i and j
d_l	Distance of the longest arc (i, j) traveled by the vessel without bunkering
e	End port (node)
H_2	Hydrogen
NH_3	Ammonia
N_2O	Nitrous oxide
NO_x	Nitrogen oxide

P	Set of ports (nodes) where the vessel stops along the route, indexed by i and j
s	Start port (node)
SO_x	Sulfur oxide
x_i	1 if the vessel bunkers at port i , 0 otherwise
y_{ij}	1 if the vessel sails between ports i and j without bunkering, 0 otherwise

INTRODUCTION

1.1 Background

Since the period between 1850 and 1900, global warming has been progressively increasing, with devastating consequences. Natural disasters and environmental imbalances caused by rising temperatures are causing the destruction of the environment. This not only endangers the survival of species but also has significant implications for the global economy. The emission of greenhouse-effect gases (GHG) is the primary driver of global warming [1], with carbon dioxide (CO₂) as the main contributor [2].

Among all sectors that contribute to GHG emissions, transport dominates with the highest growth rate of GHG emissions [3]. Therefore, it becomes crucial to implement measures to minimize GHG emissions in the sector. Over the past years, the volume of goods transported by sea has continuously increased, reaching 80% of the global trade volume in 2021 [4]. As a result, shipping stands out as a highly significant subsector of transportation, deserving special attention. Since fossil fuels are still the primary energy source used in shipping [5], strategies for decarbonizing the subsector must be developed, as fuel consumption, and consequently, GHG emissions, rise in pace with the volume of goods being delivered by sea [6].

The efforts of countries to mitigate GHG emissions in shipping are evident. In 2015, 197 countries committed to maintaining the rise in global temperature below 2 degrees Celsius (°C) in this century, with efforts to limit it to 1,5°C, through the Paris Agreement [7]. In line with the temperature goals of the Paris Agreement, in 2018, the International Maritime Organization (IMO) established the goal of reducing CO₂ emissions in international shipping by at least 40% by 2030 and by at least 50% by 2050, while making an effort to reach a 70% reduction by 2050 [8]. In 2023, this goal was revised and a new target of achieving zero-emissions by or around 2050 was established [9].

In 2021, during COP26, 24 countries signed the Clydebank Declaration, in which they committed to incentivizing the creation of green shipping corridors as a way to fulfill the objectives of GHG emissions reduction [10]. Green shipping corridors are shipping routes in which maritime transportation is carbon free [11], which requires the switch from fossil fuels to non-petrochemical derived alternative fuels with lower emissions [12].

In the upcoming years, a shift from fossil fuels to alternative fuels is expected [5] since fossil fuels will become increasingly less economically competitive compared to low-carbon fuels. The main driver for this transition is the awareness of the impact of GHG emissions and the consequent implementation of carbon pricing strategies, which involve taxing carbon emissions [13]. This switch is also fueled by a number of other factors, including the maturing of renewable energy [14], scarcity of fossil fuel reserves, rising energy demand, and unpredictability in the supply of fossil fuels [15], [16].

However, according to a report published by the Global Maritime Forum in 2022 [17], it is still uncertain which alternative fuel will be more advantageous in the future. For this reason, the majority of green shipping corridor initiatives are postponing the decision of selecting which alternative fuel to base their initiatives on, which ends up dividing efforts and delaying the development of the initiatives. The decision of the fuel pathway is influenced by many factors, including the cost of each alternative fuel [14], [18].

1.2 Motivation and Objectives

Despite the difficulties expressed by stakeholders involved in green shipping corridor initiatives in deciding on the fuel pathway, the existing literature still lacks a comprehensive framework to guide them in simultaneously determining and minimizing the costs involved in transitioning from fossil fuels to the different alternative fuels, making it challenging to decide which is the most advantageous option. Since 98,8% of the world fleet still relied on conventional fuels in 2022 [19], and the switch to alternative fuels is inevitable due to the eventual unfeasibility of using fossil fuels in the future, the existence of this framework would be highly valuable.

The motivation for the realization of this dissertation is to address this current limitation for stakeholders engaged in green shipping corridor initiatives, as a way to accelerate the development of the initiatives and contribute to the goal of minimizing GHG emissions.

The objective of this study is to propose a framework to find out and minimize the costs of transitioning from fossil fuels to different alternative fuels. The application of this framework would offer guidance to decision-makers in green shipping corridor initiatives in identifying

the most cost-effective fuel pathway in their particular situation. In this way, stakeholders involved could concentrate their efforts in the same direction, paving the way for the successful implementation of green shipping corridors.

To validate its effectiveness, the framework will be applied to a hypothetical case study of an intercontinental shipping route, in which the objective is to transition from heavy fuel oil (HFO), which is the most popular and cheapest but also the most polluting fuel used by ships, to an alternative fuel yet to be decided. The aim is to determine and minimize the costs involved in this transition and decide which is the most suitable alternative fuel for that route.

By addressing the following research questions throughout this dissertation, it will be possible to provide stakeholders involved in green shipping corridor initiatives valuable insights to overcome the identified challenges, contributing to the fulfillment of the aforementioned objective.

- Which alternative fuel provides green shipping corridor initiatives with a greater cost advantage?
- How do variations in carbon pricing influence the selection of alternative fuels?

By identifying the current costs of transitioning from fossil fuels to alternative fuels, the involved stakeholders will have a better understanding of the expenses that this transition implies. Additionally, they will have a foundation from which to conduct an economic analysis of the different options, which will enable them to make more informed decisions on which alternative fuel to adopt.

Variations in carbon pricing may influence the economic competitiveness of each fuel option, which makes the decision of the fuel pathway even more challenging. To address this challenge, this study aims to investigate how carbon pricing influences fuel choice.

1.3 Methodology

The first step of this study consisted of a comprehensive contextualization of a broader problem, in this case, the rising global temperature, which funneled into a more specific problem that this study would address: the difficulty of green shipping corridor initiatives in selecting a fuel path.

The next step involved reviewing the studies already carried out to address this problem, which enabled the identification of a gap in the literature concerning this topic. This paved the way to define the motivation and objective of this research as well as a set of research questions to be answered. This led to the proposal of a framework to address the identified problem.

The framework was further tested in a hypothetical case study, providing a mechanism to assess its effectiveness. The results obtained from the application of the framework to the case study were further analyzed to answer the research questions and draw conclusions essential to address the problem of the difficulty of green shipping corridor initiatives in selecting the fuel path, consequently contributing to addressing the broader problem of global warming.

The methodology used in this dissertation is represented in Figure 1.1.

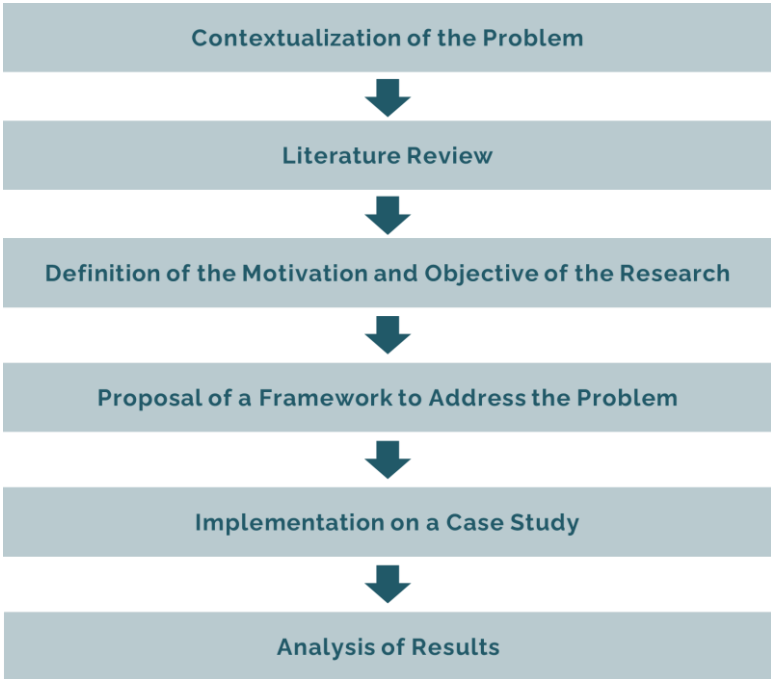


Figure 1.1 — Methodology Used in the Dissertation

1.4 Dissertation Structure

The dissertation follows a logical and structured flow to guide the reader along the research process throughout six chapters. It starts by providing the necessary background that leads to the identification of the core problem that will be addressed in this study. In response to that, a solution to the problem is proposed and employed in a case study to prove its effectiveness, ending with the presentation and analysis of the results.

The first chapter, the Introduction, explains the background and motivation behind this dissertation and presents the objectives for this work, as well as the methodology employed to achieve them. Additionally, the chapter presents an overview of the structure of the dissertation.

The second chapter, Sustainability Measures to Address Global Warming, presents a comprehensive contextualization of the problem addressed in this work, highlighting its pertinence. The chapter starts with a description of the wider scope of the problem, namely the rise of the global temperature verified in the past years and its causes and consequences, funneling down to the transportation sector, in particular the shipping subsector. Following this thread, the measures taken to tackle this issue in the subsector of shipping are mentioned, including the development of green shipping corridor initiatives and the transition from fossil fuels to alternative fuels. In this way, the core of the problem was identified, which is the slow progress of green shipping corridor initiatives due to the postponement of the fuel pathway decision, which is highly influenced by the costs of the different alternative fuels. The application of optimization techniques was another mentioned measure to reduce GHG emissions in shipping. Given the relevance of route definition and location optimization problems to this topic, the third chapter, Route Definition and Location Optimization and Framework Proposal, delved into them. The review conducted on the existing optimization models has revealed that none of them provides the necessary tools for stakeholders involved in green shipping corridor initiatives to simultaneously minimize the costs of the fuel transition and conduct an economic analysis of the different fuel options. This analysis would enable stakeholders to determine which fuel is the most advantageous in terms of costs, consequently accelerating the progress of the initiatives and mitigating the identified core problem. This motivated the development of a framework that provides detailed guidelines, not only on how to determine the costs associated with transitioning from fossil fuels to alternative fuels, but also on how to minimize some of these costs using an optimization model. The formulation of this framework is also presented in the third chapter.

In the subsequent chapter, Case Study, the framework proposed in the previous chapter is employed in a hypothetical case study of a container vessel sailing an intercontinental shipping route, to validate its effectiveness. The results of this case study are then treated in the following chapter, Analysis and Discussion of Results, in which an answer to the research questions is also given.

Finally, in the last chapter, Conclusion, the work done in this dissertation is summarized, and some limitations and recommendations for future research are mentioned.

SUSTAINABILITY MEASURES TO ADDRESS GLOBAL WARMING

Global warming has been scaling over the past decades, constituting a threat to the planet [1]. As illustrated in Figure 2.1, the global temperature have increased by 1 to 1.2°C since the years between 1850 and 1900 [20].

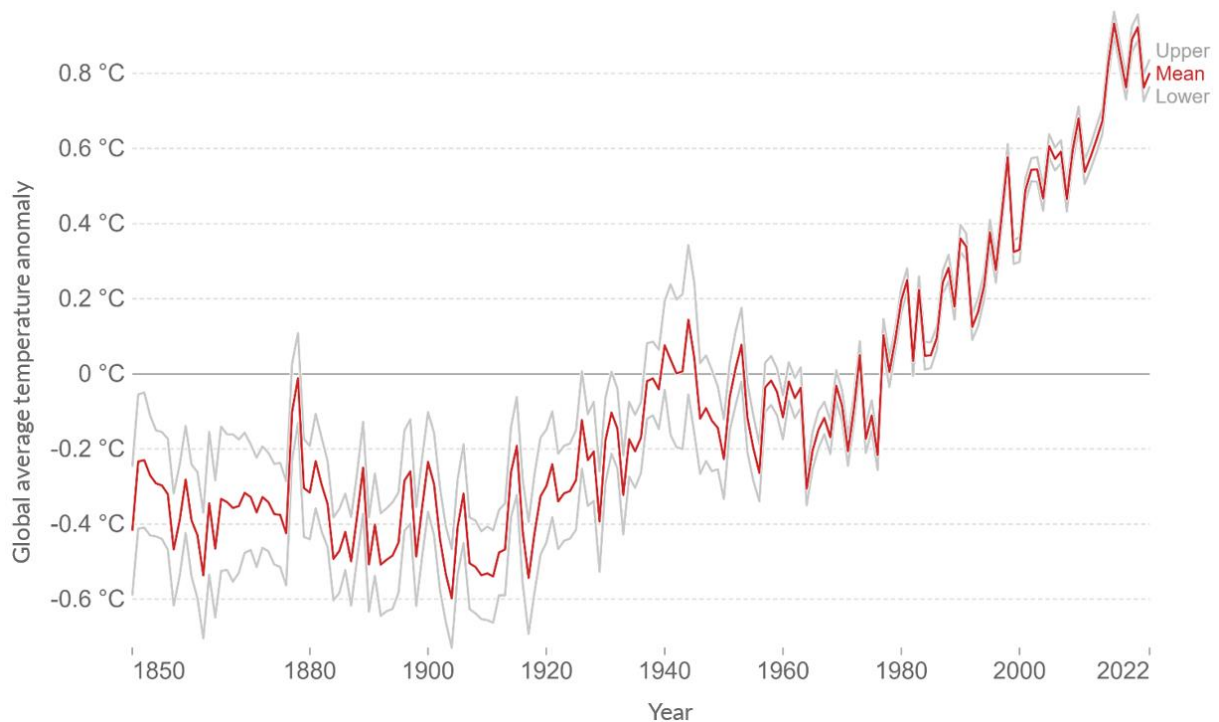


Figure 2.1 — Average Annual Temperature Anomaly Compared to the 1961-1990 Average Temperature (in Red), With Upper and Lower Bounds of the 95% Confidence Intervals (in Grey) from 1850 to 2022. Reprinted from [20]

According to the 2022 report on climate change by the Intergovernmental Panel on Climate Change (IPCC) [1], this rise has had catastrophic consequences, including natural disasters, land degradation, rising ocean levels and the spread of diseases, resulting in the destruction of habitats and infrastructures, scarcity of food, and threat to species health and survival. Furthermore, the devastating consequences on sectors such as agriculture, fishery, tourism, and energy have had a significant impact on the global economy. The lack of resources has also led to political instability [1] and, according to the report Climate Change and Social Inequality United Nations, socio-economic disparities [21].

The main cause of global warming is the emission of GHG resulting from human activity [1], with CO₂ being the major contributor of all GHG, as Figure 2.2 illustrates.

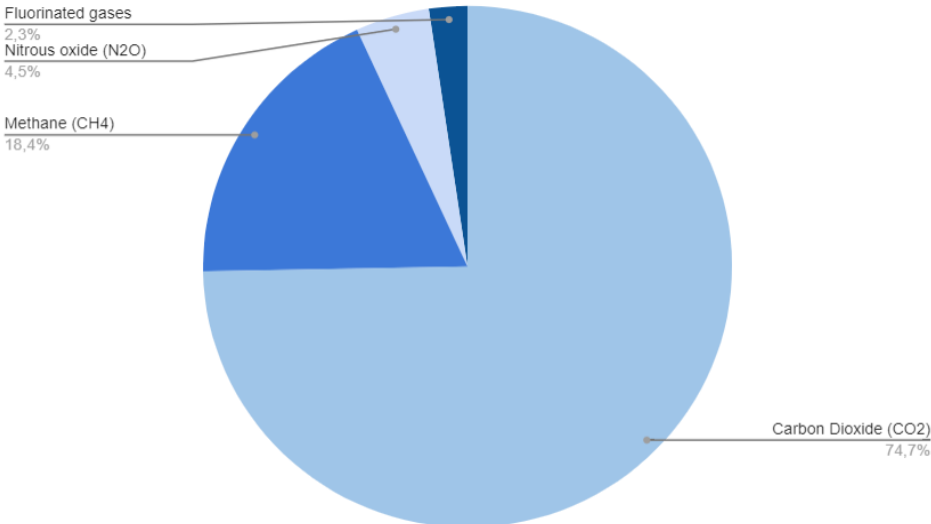


Figure 2.2 — Contribution of Gases to Global GHG Emissions in 2019. Adapted from [2]

According to the Carbon Dioxide Information Analysis Centre, emissions of CO₂ to the atmosphere are mostly caused by the combustion of fossil fuels [22], which have been used as the primary energy source for many sectors over the past decades [15]. Understanding the sources of GHG emissions is essential to reduce them and consequently address the problem of global warming. The chart in Figure 2.3 provides an overview of the sectors where GHG emissions come from [23].

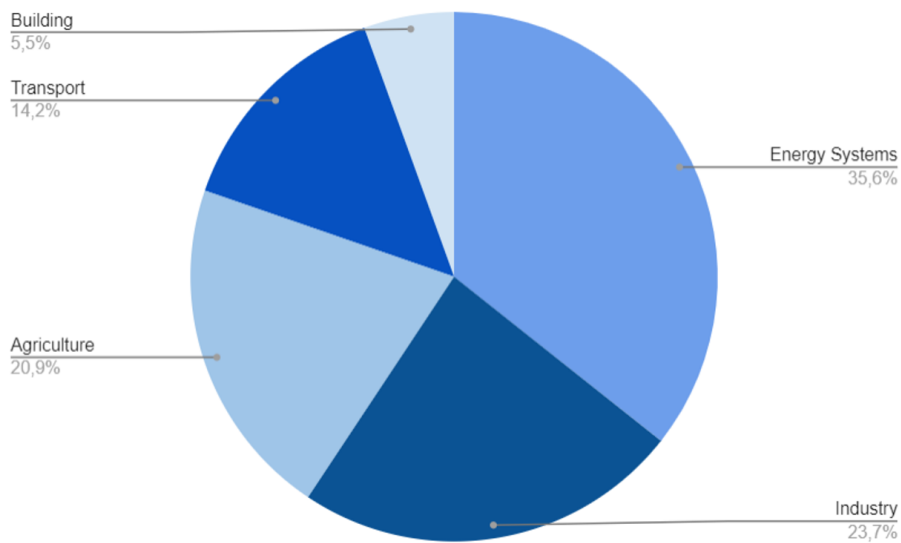


Figure 2.3 — Distribution of GHG Emissions by Sectors Worldwide in 2022

Among all the sectors, transport was the one with the highest growth in GHG emissions, growing at an annual average rate of nearly 1,7% from 1990 to 2021 [3]. Figure 2.4 presents the distribution of GHG emissions among the different subsectors of transport [23].

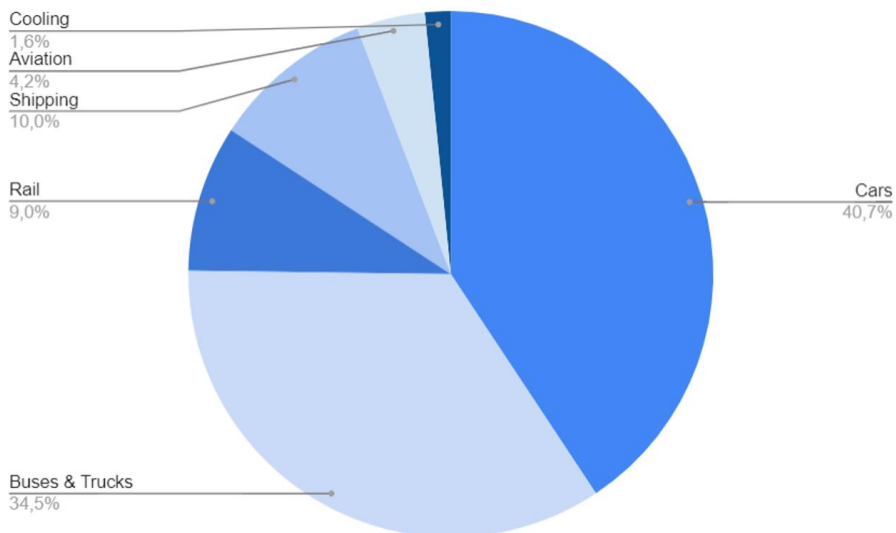


Figure 2.4 — Distribution of GHG Emissions in the Transportation Sector Worldwide in 2022

2.1 Shipping's Role and Impact on GHG Emissions

The subsector of shipping plays a critical role in the global trade market since it offers higher energy efficiency [24], lower cost, larger capacity, and more flexible transportation routes than other subsectors [25]. The volume of cargo carried by sea has been increasing over the past

years, as shown in Figure 2.5, except for 2009, as a consequence of the economic crisis [26], and 2020 due to COVID-19 [4]. In 2021, maritime transportation accounted for more than 80% of the global trade volume according to the United Nations [4].

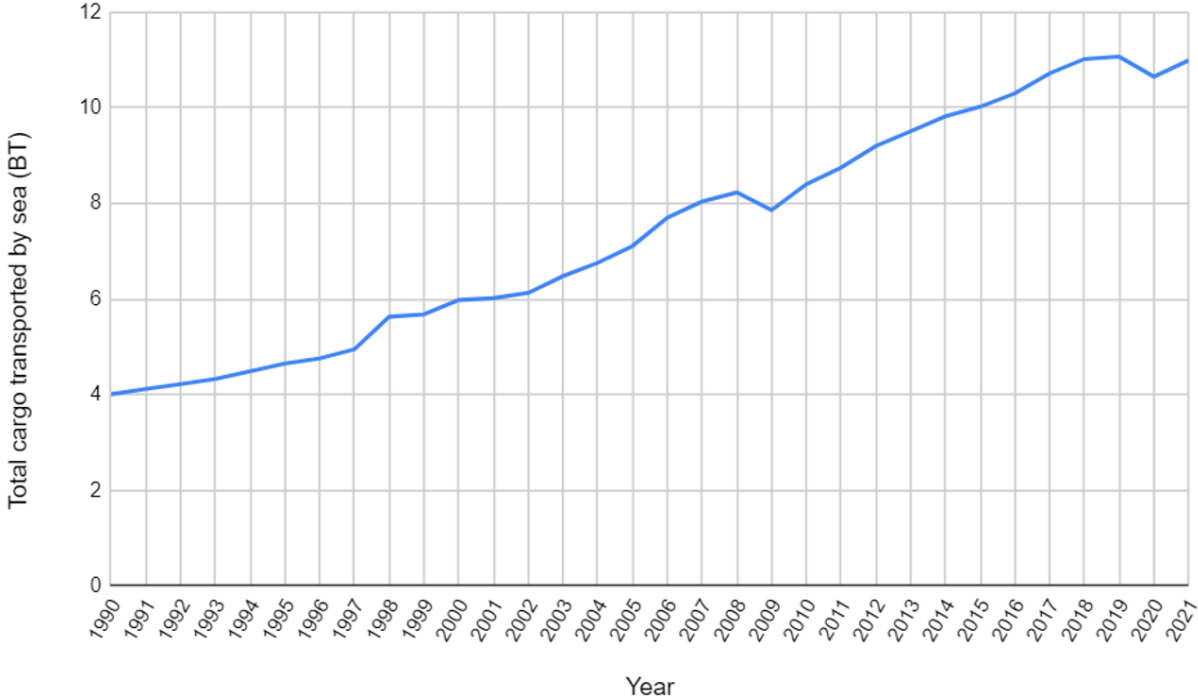


Figure 2.5 — Volume of Cargo Transported by Sea between 1991 and 2021. Reprinted from [27]

The growth in the volume of cargo transported by sea results in the rise of global fuel consumption [6], namely fossil fuels, which have a substantial impact on air pollution. Therefore, implementing measures to reduce CO₂ emissions in shipping became crucial [28]. It was even detected a connection between the quality of governance provided by governments and institutions and lower CO₂ emissions [29].

2.2 Measures to Mitigate GHG Emissions from Shipping

The adoption of the International Convention for the Prevention of Pollution from Ships (MARPOL) by IMO in November 1973 was a remarkable milestone towards the prevention of pollution of the marine environment caused by shipping, being the primary international convention on this topic. In May 2005, Annex VI of MARPOL, which covers the prevention of air pollution caused by ships, entered into force. Since then, the convention has undergone several amendments over the years [30].

In July 2011, the first set of mandatory international measures to improve the energy efficiency in shipping was adopted by MARPOL Annex VI parties. These measures include the Ship Energy Efficiency Management Plan (SEEMP) and the Energy Efficiency Design Index (EEDI) [31]. The SEEMP is a systematic and practical plan designed to assist shipowners and operators to increase the operational efficiency of a ship, and consequently reduce carbon emissions and fuel costs through the adoption of innovative procedures and technologies [32]. The EEDI promotes the use of more energy-efficient engines in new ships. This technical measure sets a minimum energy efficiency requirement per ship's capacity-mile, depending on the ship type and size [33].

In 2015, the Paris Agreement was signed by 197 parties with the goal of keeping the global temperature increase in this century below 2°C, with efforts to limit it to 1,5°C, through the reduction of GHG emissions [7].

More recently, in 2018, IMO established the goal of reducing CO₂ emissions in international shipping by at least 40% by 2030 compared to 2008 and sustaining the efforts towards a reduction of at least 50% of the overall annual GHG emissions by 2050 compared to 2008, while pursuing efforts towards a 70% reduction [8].

In January 2020, IMO set a stricter limit for the sulfur content in fuel oil to reduce sulfur oxide (SO_x) emissions in shipping. There was already a sulfur limit of 3.5% mass by mass (m/m) but due to the importance of minimizing air pollution, a new limit of 0.5% m/m was established. Before this limit reduction, some designated emission control areas already had a limit of 0.1% m/m [34].

In June 2021, short-term mandatory measures were added to the amendments to MARPOL Annex VI in line with the target of 40% reduction in CO₂ emissions. These measures encompassed the Energy Efficiency Existing Ship Index (EEXI) and the annual operational Carbon Intensity Indicator (CII) and respective rating. The EEXI is an indicator of a ship's energy efficiency in relation to a baseline, based on its type and size. Ships over 400 gross tonnage (GT) are required to measure this index and ensure that it meets a specific requirement. On the other hand, the CII is an indicator required for vessels over 5000 GT. Based on the value of the CII, the ship is assigned a rating of its energy efficiency from A to E, with A being the most efficient. While ships rated as A or B are provided compensation, ships rated with D for three consecutive years, or E, are required to submit a corrective action plan to demonstrate that a C or higher rating will be achieved [31].

Recently, in 2023, IMO has updated the goal established in 2018 of achieving a reduction of 50% to ideally 70% in GHG emissions by 2050, compared to 2008. Striving for an even more

ambitious goal, IMO set the new target of zero-emissions approximately by 2050. In addition, it was established that, by 2030, 5% to ideally 10% of the technology and energy sources in shipping need to be carbon-free [9].

Another GHG emissions reduction measure is carbon pricing, which consists of taxing carbon emissions. By setting a tax on CO₂ emissions, fossil fuels are expected to become less financially competitive compared to alternative fuels. In 2022, there were 68 initiatives of carbon pricing worldwide, with 34 being Emissions Trading Schemes (ETS). These initiatives compensated 23% of the global GHG emissions [13]. As an example for the rest of the world, the European Union (EU) has decided to include emissions from the maritime industry in the EU ETS starting in 2023. Regardless of their origin, shipowners who start and/or end their voyages at a port in the EU, must purchase carbon allowances to compensate for the emissions released. Except for offshore oil and gas vessels, this regulation is applicable to vessels over 5 000 GT. In the first year, ship owners will need to acquire allowances covering for 20% of their emissions, but this percentage will increase gradually over the years [35]. In 2024, it will increase to 40%, in 2025 to 70%, until reaching complete coverage in 2026 [36]. The revenue generated from this measure will be used to finance initiatives towards carbon neutrality, such as building facilities for alternative fuels [35].

To contribute to the compliance with the measures established by IMO and other entities to reduce or ideally eliminate GHG emissions, primarily CO₂ emissions, several operational measures have been implemented in the shipping subsector. These measures include renewable-assisted propulsion, ship and engine design improvements, and slow steaming. Among the existing operational measures, slow steaming, which was created to comply with the EEXI and CII measures, has proven to be the most reliable and consistent in reducing GHG emissions [37]. Additionally, more strategies are anticipated to be adopted in the upcoming years, including the adoption of alternative energy sources and the optimization of shipping operations, namely in terms of fleet, energy use [5], and sailing routes [38].

2.2.1 Slow Steaming

Slow steaming consists of significantly reducing the sailing speed of a vessel compared to its design speed, to decrease fuel consumption and, consequently, reduce emissions [39], [40]. This operational measure was adopted to comply with IMO's short-term measures for reducing GHG emissions derived from shipping, namely the EEXI and CII. However, it is not enough to address the long-term goals outlined for 2030 and 2050 [37]. Slow steaming is particularly advantageous for container vessels with a design speed superior to 20 knots [41].

According to [40], slow steaming is not only advantageous in terms of emissions reduction, but also economically. It was demonstrated that the lower the speed of the vessel, the lower the CO₂, nitrous oxide (N₂O), methane (CH₄), and black carbon (BC) emissions. Additionally, according to the research, the 20-year global warming potential (GWP20) and the 100-year global warming potential (GWP100), which assess the impact in global warming of the emissions of a GHG compared to the emissions of CO₂ over 20 and 100 years, respectively [42], are also reduced. Besides, the voyage costs turned out to be lower, and the cost-benefit ratio was better as a consequence of the speed reduction. The study [40] also uncovered that it is possible to acquire and maintain an A CII rating simply by employing slow steaming. Another study, [41], demonstrated that reducing the speed of a post-Panamax container vessel from 23 to 12 knots resulted in a reduction in fuel consumption between 72,36% and 76,25% and CO₂ emissions four times lower. However, it is also mentioned that it is not advisable to sail at a speed lower than 14 knots to prevent a prolonged strain on the engine.

This measure has been in use for some time now, since it is the most straightforward way to minimize emissions [39]. However, reducing the sailing speed may compromise service quality [37]. As the sailing speed is reduced, transport time increases, and a longer delivery time may not be acceptable to all customers [41]. Therefore, there needs to be a balance between the increase of travel time and the reduction in emissions to ensure the quality of the service.

2.2.2 Green Shipping Corridors

Green shipping corridors have been gaining attention as a promising solution for the elimination or minimization of GHG emissions. Green corridors are shipping routes that have conditions to decarbonize maritime transportation, namely infrastructure for the production, storage, distribution and bunkering of alternative fuels [11]. Green corridor initiatives focus on the holistic decarbonization of the supply chain, taking into consideration all its elements: fuel production, port logistics, bunkering, vessels, cargo, end customers, financing, and legislation. These initiatives encourage collaboration among these stakeholders and give them the resources they need to start their path toward decarbonization [43]. This collaboration is even more incentivized by the formation of pre-competitive alliances, which aggregate the demand for alternative fuels and other key elements for the establishment of green corridors. Besides, green shipping corridors create a supportive environment with regulations, safety measures, and financial incentives. Serving as a common ground for all stakeholders involved, the creation of the corridors enables the mobilization of efforts from the stakeholders to accelerate the taking of action towards decarbonization [12].

To meet the objectives of the Paris Agreement, in November of 2021, 24 countries signed the Clydebank Declaration at COP26 and committed to encouraging the creation of green shipping corridors. Some of the measures included in the agreement were the promotion of partnerships between the involved stakeholders to promote the decarbonization and ensure alternative fuel supply, the mitigation of challenges associated with green corridors through the development of regulations and infrastructure, the sharing of knowledge, the inclusion of green corridors in National Action Plans, and accountability for aspects related to sustainability [10]. During the following year, at least 14 events and conferences about green shipping corridors were organized, not only to familiarize stakeholders with the concept, but also to discuss funding and policy [17]. A year after, 40 new projects and initiatives for shipping decarbonization were announced in COP27, over half of which involved the subject of green shipping corridors [44]. Until the end of 2022, at least 17 reports about green shipping corridors had been produced [17]. The shipping industry's efforts to look into green shipping corridors as a means of encouraging decarbonization are evident through all these initiatives. Even though they are only at the initial stages, advancements in green shipping corridors are progressing rapidly [44]. However, there are still many challenges that need to be addressed.

The first challenge is the actual implementation of these initiatives, as there is still limited knowledge on how to turn the theoretical plan of green shipping corridors into practical implementation, as the majority of initiatives are still in the planning phase [43]. Therefore, there should be a focus on the actual implementation, which is the most challenging step, and not only on planning [44]. The Global Maritime Forum argues that a practical approach of learning by doing would be more advantageous than focusing on the development of generic guidelines, because the implementation varies from case to case, making it more productive to invest time in practical experience rather than creating a generic plan. To accelerate the actual implementation of initiatives and overcome challenges, stakeholders should cooperate, share knowledge and solutions, and overcome the reluctance to share information with competitors. Besides, more funding should be allocated to the implementation of green shipping corridor initiatives, namely from governments [17].

Additionally, as stated in the Annual Progress Report on Green Shipping Corridors of 2022 of the Global Maritime Forum [17], attracting all the stakeholders that constitute the supply chain is challenging. Given the involvement of numerous stakeholders in the development of a green corridor, aligning expectations and decision-making becomes challenging [17]. To overcome this, it is necessary to create consensus among the different stakeholders and promote cooperation [44].

Another challenge is the definition of the fuel pathway, as many initiatives are not focused on a specific fuel yet, which delays their development. For the accelerated and successful development of the initiatives, it is essential to focus the efforts on a single fuel strategy. According to the Annual Progress Report on Green Shipping Corridors of 2022 of the Global Maritime Forum [17], at the end of 2022, 41% of green shipping initiatives had not yet decided which fuel to use. Among those who have made a decision, both ammonia and methanol were the preferred options for the majority, as each of them was selected by 16% of the initiatives. Additionally, 9% of the initiatives opted for hydrogen, and another 9% chose advanced biofuels, such as biodiesel and bioethanol derived from biomass [45]. Although the potential for electrification in shipping is limited to short distances and shore power at ports [5], 9% of initiatives moved forward with electric energy sources.

The last bottleneck to highlight is the availability, price, and existing regulation regarding alternative fuels, which currently are not as advantageous as traditional fuels [17].

2.2.3 Prospects for Alternative Fuels

Before getting into alternative fuels strategies, it is important to look into how these fuels are made available to stakeholders, particularly in green shipping corridors. Therefore, in this section, the main bunkering methods that enable the supply of alternative fuels for ships will be described.

Truck-to-ship, ship-to-ship, and from a bunkering station are the three main methods used for bunkering [46]. A bunkering station is a fixed and permanent facility designed for bunkering, and hence provides less flexibility [47]. Normally, bunkering is done via a pipeline connected to the vessel [48]. Besides, the bunkering operation using this method is quick [49]. Nevertheless, bunkering stations require a high investment cost and are designed to handle large volumes of fuel [50]. Truck-to-ship bunkering can either be done by connecting the vessel to a truck tanker for liquid fuels or a tube trailer for gaseous fuels to refuel its tanks [47]. This method is flexible [47], requires a lower initial investment cost and is suitable for small scale bunkering. Yet, this type of bunkering is considerably more time-consuming [49]. Finally, ship-to-ship bunkering, which is the most common of the three [46], refers to the refueling of a vessel by a bunkering ship or barge [51]. This is also a flexible solution since the bunker vessel is movable [48] and does not even need to be docked at a port [47]. Another advantage is that the bunkering operation is quick. Despite the initial investment being high [49], it is still considerably lower than the installation of a bunkering station [51].

The truck-to-ship bunkering method is often viewed as a short-term solution to address the lack of bunkering facilities of alternative fuels. Ports and governments strongly support the establishment of bunkering stations and bunkering vessels as long-term solutions to fulfill the growing demand for alternative fuels [48].

Until now, the shipping sector was no exception when it comes to using fossil fuels, such as oil, as the primary energy source [5]. As shown in Figure 2.6, although some vessels have already started using alternative fuels, the majority of the world's fleet still relies on conventional fuel. However, the number of alternative energy sources in the past two decades has increased [52]. There is an increase in the percentage of ships being designed to use alternative fuels, even though most of the ships are still ordered with conventional fuel as the main source [19].

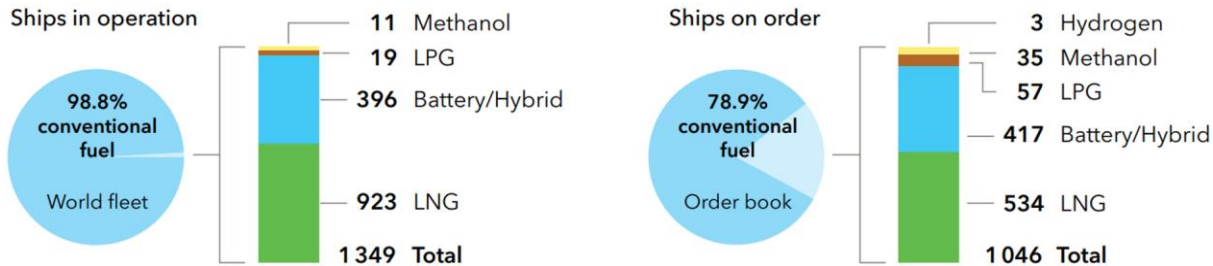


Figure 2.6 — Number of Ships Adopting Alternative Fuels in the Global Fleet in 2022. Reprinted from [19]¹

The shift towards alternative fuels, such as non-petrochemical derived alternative fuels [43], is becoming a priority, not only due to the GHG emissions caused by fossil fuels, but also because of the uncertainty and dependency on fossil fuel suppliers, the scarcity of resources and the rising energy demand, which fueled the need to search for alternative energy sources [15], [16]. Besides, the price difference between traditional fuels and alternative fuels has been decreasing [18]. Consequently, even though HFO is still the most economical fuel at the moment, the price of alternative fuels will become more competitive with time [18].

In the upcoming years, the fuel mix in maritime transportation is expected to undergo a turnaround, with alternative energy sources taking a larger share than oil [5]. Recently, ammonia, liquefied natural gas (LNG), and methanol have been gaining attention, particularly for bunkering large vessels [53]. Despite LNG being the predominant choice of alternative fuel for vessels on order [18], [19], some academics anticipate a shift away from LNG and towards other

¹ LNG - Liquefied Natural Gas; LPG - Liquefied Petroleum Gas

alternative fuels. [18] claim that LNG is a prominent fuel for being more economical than the other alternative fuels, but only in the short-term because eventually LNG prices will increase and stop being that competitive. With the maturing of renewable energy and the necessary facilities, the cost of ammonia and hydrogen will decrease and become more viable in the long-term. The authors estimate that hydrogen will be the most promising fuel in the future, with methanol and ammonia still having considerable use. [14] share a similar perspective. According to their economic analysis, LNG is the most cost-effective alternative fuel, followed by hydrogen, ammonia and finally methanol. This analysis not only considered the operational cost, the fuel cost, and the capital cost for the propulsion system, but also crucial factors like safety, reliability of the supply chain, availability of the infrastructure, impact on environment, namely CO₂ emissions, and upcoming policies resultant from IMO measures. The authors also suggest that, in the long-term, hydrogen will become the most cost-effective option, as LNG is only a short-term solution. However, the economic analysis conducted by [6] concluded that LNG is not always more economical than ammonia and hydrogen. If only the fuel consumption cost and the boil-off gas (BOG) combustion costs are considered, ammonia is the most economical fuel, followed by LNG and then hydrogen. However, if a carbon tax of 137 dollars (\$) for each metric tonne of CO₂ emitted is also taken into account, hydrogen overtakes ammonia as the most cost-effective fuel, and LNG comes in last. This divergence may be caused by the different costs being considered in the two economic analyses.

The Mærsk Mc-Kinney Møller Center anticipates that ammonia and methanol will be included in future bunkering strategies [54], while [55] rely on ammonia and hydrogen. Both exclude LNG from their projections. On the other hand, the availability of LNG in comparison to other alternative fuels is mentioned by [56] as an advantage that will make it the dominating fuel in the energy transition. [53] and [57] agree that LNG is a prominent fuel in the transition, not only because of its availability but also its cost-effectiveness, but claim that, in the long-term, a cleaner version of the fuel, such as liquefied biomethane (bio-LNG) or green hydrogen-based LNG (synthetic LNG or e-LNG), will be preferred.

According to the International Transport Forum (ITF), by 2035, about 70% of the ship's mix by type of fuel, will be composed of hydrogen and ammonia collectively and 5% of LNG, while methanol is not explicitly mentioned [58]. On the other hand, the report [59] places a stronger emphasis on LNG, predicting that LNG will account for 41% of the fuel mix by 2035. According to Det Norske Veritas (DNV), in 2050, ammonia is predicted to be the predominant energy source, accounting for a 35% share. Natural gas, which mainly refers to LNG but also

includes liquefied petroleum gas (LPG), is expected to account for 19% of the fuel mix. Once again methanol is not looked at specifically [5].

On the next sections, the most promising alternative fuels will be described, along with details on their characteristics, advantages, drawbacks, and other pertinent factors. This analysis will build upon the predictions for the adoption of the future fuel mix.

2.2.3.1 Ammonia

Ammonia (NH_3) is formed through the Haber-Bosch process, which involves combining hydrogen and nitrogen in a ratio of 3:1 at high pressure (100-1000 atm) and high temperature (400-550°C) [51].

Approximately 200 million tons of ammonia are produced annually [60], with the majority being used in agriculture for fertilizer production (70%) [61]. Ammonia is also applied in other sectors, such as industry, to produce plastic and synthetic fibers, and maritime transportation, as a hydrogen transporter, carrier, and energy source [55].

By 2020, ammonia was already produced in more than 50 countries, with China being the leading producer, followed by India and Russia. Currently, approximately 130 ports are already equipped with the necessary infrastructure to manage ammonia. However, the deployment of ammonia bunker barges, like those used for LNG, is still lacking [51]. According to [18], the development of infrastructures to store and transport ammonia is also lacking. These concerns must be tackled in order for the use of ammonia to rise and satisfy future demand.

The use of ammonia as an energy source is still in its early-stage [61] despite the growing interest, research and initiatives from governments and companies [55]. Although various ammonia-based technologies in shipping are in development, they are not yet available on the market [57]. Besides, it was only in 2022 that the first vessel designed to utilize ammonia as fuel was delivered [11]. The large Suezmax tanker was built for the Greek company Avin International [62].

It was mostly because of its zero carbon emissions that ammonia has been gaining attention [61]. Since ammonia does not have carbon and sulfur in its composition, its combustion does not release CO_2 or SO_x emissions [60]. However, since ammonia contains nitrogen in its composition, its combustion releases more emissions of nitrogen oxides (NO_x) than other fuels [63]. An experiment, where parameters of a natural gas-ammonia dual-fuel engine were varied to analyze the combustion's behavior and emissions, demonstrated that the NO_x emissions increased with the increase of the energy fraction of ammonia [64]. The combustion of ammonia also results in the emission of N_2O , which can cause an impact on GHG emissions worse

than CO₂, since the greenhouse warming potential (GWG) of N₂O is 265–298 times higher than CO₂ [16]. This made ammonia to be considered as one of the top five air pollutants by the UK Government's Clean Air Strategy [63].

Nevertheless, as the study [65] demonstrated, despite the additional emissions of NO_x and N₂O associated with ammonia combustion, the overall GHG emissions are reduced when the fossil fuel is replaced by ammonia because the elimination of CO₂ and NO_x emissions from fossil fuels combustion outweighs NO_x and N₂O emissions from ammonia combustion. Besides, NO_x emissions can be controlled using a Selective Catalytic Reduction (SCR) system onboard. With this technology, NO_x emissions can be reduced by 90% using a catalyst and a reducing agent, such as urea or ammonia itself, to transform NO_x into nitrogen and water [63]. This way, it is possible to comply with the NO_x emission limits established by IMO while using ammonia [60]. The study [66] ratified this by discovering that it is possible to reduce overall GHG emissions by 83,7–92,1% by switching from HFO to ammonia.

Despite ammonia being a green fuel, the production process is not always green, since the Haber-Bosch process not only is responsible for 1,2% of global CO₂ emissions [61], but also requires a lot of energy [55]. Ammonia can be divided into different types, depending on the environmental impact of the production process. The final product is identical, the only difference is in the level of sustainability of the production process [51].

Conventional ammonia uses fossil fuel as feedstock, mostly natural gas, but coal can also be used. Production plants of conventional ammonia usually release 1,6 tons of CO₂ per ton of ammonia produced [51]. Green ammonia uses renewable energy as feedstock such as electricity, wind power, solar power and hydropower [51]. Hybrid green ammonia production occurs in plants that incorporate both fossil fuels and renewable energy sources in the production process, enabling a smoother transition towards the production of green ammonia [51]. Blue ammonia is produced by a process similar to that of conventional ammonia, except that the CO₂ emissions resulting from the production process are captured and stored through Carbon Capture and Storage (CCS) to produce hydrogen, avoiding its release to the atmosphere and contribution to GHG emissions [67].

Nowadays, ammonia producers are looking forward to producing green ammonia [55]. [51] present a vision for the evolution of the production of ammonia in the future, focusing on the growth of green ammonia. This projection is represented in Figure 2.7, where the increasing dominance of green ammonia is evident, while the investment in conventional ammonia stagnated in 2020 and is predicted to continue that way.

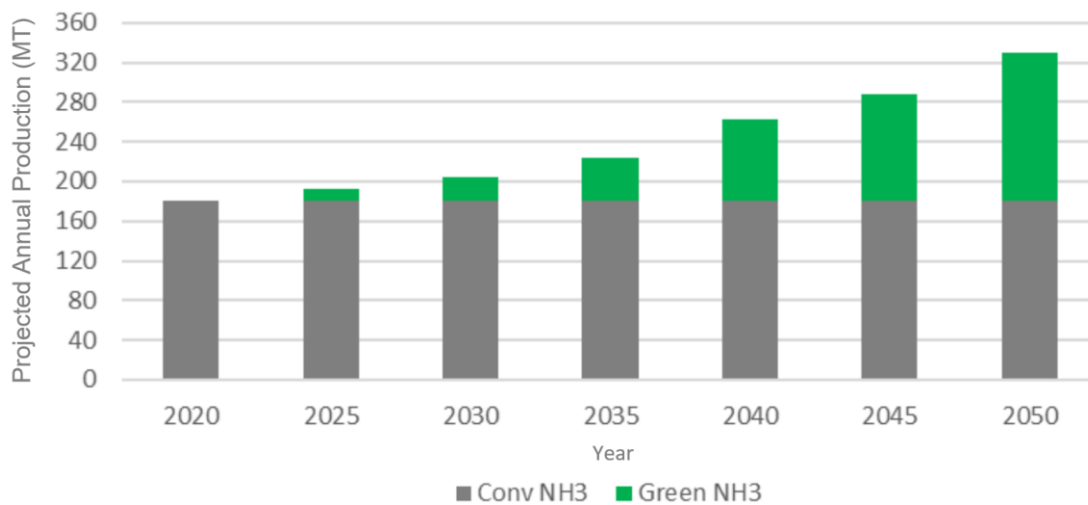


Figure 2.7 — Projected Annual Ammonia Production in Millions of Tons. Reprinted from [51]

In terms of its physical properties, ammonia is colorless and has a strong, distinctive smell [55]. The fuel possesses several advantages, such as biodegradability [65] and the ability to transition easily between gas and liquid phases, which makes it easy to manage and manipulate [22]. Moreover, when ammonia is used, components such as tubes, valves, and tanks made of iron, steel, and other non-ferrous alloys resistant to ammonia do not require regular repair because ammonia does not cause embrittlement problems [55]. However, ammonia corrodes components made of copper, zinc, and other alloys and is only compatible with specific rubbers and polymers [51]. Although these effects can be mitigated if the fuel is transported in liquid form [68], it is important to carefully consider the choice of materials for ammonia applications.

Ammonia is not highly flammable, since it does not sustain itself in the burning process [69], and only ignites at high temperatures (651°C) [70] due to its low reactivity and slow laminar combustion speed [16], [63]. The fuel can be stored either as a refrigerated liquid, at a temperature of -33°C, which is its boiling point [70], and atmospheric pressure, or as a compressed gas, at ambient temperature and a pressure of 20 bar [51]. When stored under pressure, there is the risk of explosion [63]. The toxicity for living beings is another risk of ammonia. In humans, even small quantities of ammonia can cause irritation to the eyes and respiratory system, whereas when inhaled in high concentrations, it can be fatal [60]. Regardless of that, the fuel is not as toxic for marine life as fossil fuel [63].

Compared to HFO, which has an energy density of 35 mega Joules per liter (MJ/L), ammonia has a lower energy density (12,7 MJ/L) [51]. Because the fuel tank takes up more space in the case of ammonia, there is less room for cargo, namely containers. Consequently, the

opportunity to earn more revenue from transporting cargo is sacrificed when HFO is substituted by ammonia [54]. According to [18], replacing HFO with ammonia reduces cargo capacity by 3%.

Since ammonia is one of the most produced chemicals worldwide and is already used in other sectors, the risks and safety measures for managing ammonia are already known [11]. The transportation of ammonia as cargo by sea is not new, so there is already familiarity with the safety measures onboard. However, because the use of ammonia as a fuel is still in its infancy, the development of safety procedures for this particular application is also in the early stages [18].

Some safety measures for managing ammonia onboard include providing crew members with protective equipment, like respiratory and eye protection and clothing that is highly resistant to hazardous gases in case of emergencies, as well as installing decontamination showers onboard (the number of showers depends on the size of the vessel) [51]. The use of ammonia as fuel also presents a risk to the crew during the bunkering operation, therefore requiring the use of protective equipment [11].

Measures concerning the protection against the risks of ammonia have been implemented around the world. In Europe, IMO has established the International Code for the Construction and Equipment of Ships Carrying Liquefied Gas in Bulk to regulate the safety of crew members in ships carrying ammonia [51]. However, IMO has not yet established safety precautions and guidelines to manage ammonia as a fuel [12]. According to a report released by Aramco and Concawe in 2022 [63], exposure limits to ammonia have been established by the European Chemicals Agency. In the United States (US), the Environment Protection Agencies manages the risk of ammonia to safeguard the environment of people outside the workplace, whereas the Occupational Safety and Health Administration is concerned with the safety of workers within the facilities. Standards for the use of ammonia have been developed by the American National Standards Institute and the International Institute of Ammonia Refrigeration, which are compiled in the Ammonia Data Book and other guidelines. In China, the Ministry of Ecology and Environment regulates the impact of ammonia in the maritime environment.

2.2.3.2 Hydrogen

Hydrogen has garnered significant attention in the past years and is one of the energy sources with the greatest potential for the future [71]. It has been applied in various sectors. Transportation is one of them, where hydrogen is used for power generation in combustion engines and in fuel cells, in which the chemical energy of hydrogen is used in combustion and to

produce electricity, respectively [72]. Hydrogen is also employed in industry for refining processes, chemical processing, steel production, and even for commercial and domestic heating [73]. However, the transportation sector contributes only 0,02% to the total hydrogen consumption [71].

Hydrogen is the most abundant element in Nature. However, it is usually bonded to other elements, such as oxygen in water and carbon in hydrocarbon compounds. Due to its scarcity in its elemental form, hydrogen needs to be produced artificially [71]. Even though hydrogen is a carbon-free fuel, its production process may not be [6]. Hydrogen can be produced using either fossil fuels or renewable energy sources. Currently, 96% of hydrogen is still produced using fossil fuels [74]. Only the production of hydrogen using renewable energy sources ensures carbon neutrality [75].

Green hydrogen is produced through the electrolysis of water, splitting it into hydrogen and oxygen using renewable energy like solar, wind or hydropower. After this, the hydrogen is liquified [52]. No polluting gases are released during this process [76]. The improvements in electrolysis technology are making green hydrogen more productive and appealing [65]. However, this is still the least economical of all hydrogen-producing processes since it requires a lot of electricity, which is costly [74]. When the energy is supplied by the power grid, the hydrogen is considered yellow [71].

Grey hydrogen is produced through steam methane reforming (SMR). The process involves the reaction of a hydrocarbon fuel (normally methane, which is present in natural gas) with steam at temperatures around 900°C and pressures between 1,5 and 3,5 megapascal (MPa) to form CO₂ and hydrogen. The hydrogen produced in the gaseous form is then liquefied. Despite being the most common and economical production method, this process results in the release of CO₂ emissions [71], [74]. A study of the environmental impact of various fuels throughout the supply chain has even shown that the global warming potential (GWP) of grey hydrogen is 10% higher compared to LNG because of the emissions released during the SMR process [77].

Blue hydrogen is produced in a similar way but involves the additional procedure of CCS, in which the resulting CO₂ is captured and stored instead of being released. Although this addresses the emissions issue, SMR is not considered efficient due to energy conversion losses from the hydrocarbon fuel [71], [74].

According to [71] and [78], in the production process of turquoise hydrogen, methane is subjected to the pyrolysis process, where it undergoes thermal decomposition, generating

hydrogen and solid carbon. Carbon oxides are not generated in this reaction due to the absence of oxygen.

Coal gasification is another method, which produces black and brown hydrogen. The feedstock can either be bituminous (black) or lignite (brown) coal, which is converted into a gaseous mixture that includes carbon monoxide (CO) and hydrogen through partial oxidation. After this, hydrogen goes through a process of purification [71], [74].

Nuclear power can be used to generate purple or pink hydrogen by several methods, such as thermochemical water splitting, water electrolysis, and SMR. However, the spread of nuclear power as an energy source in hydrogen generation is hampered by the scarcity of uranium-235 and other technical challenges. In the thermochemical water splitting process, water is decomposed to produce hydrogen using high temperatures or redox materials. One example is the copper-chloride reaction, in which copper-chloride is oxidized in a solution of hydrochloric acid to produce hydrogen [71].

Finally, it is important to mention that biomass, which is organic waste from agriculture, animals or forestry activity, can be used as feedstock for hydrogen production [74] via gasification or pyrolysis [76]. When biomass undergoes the process of gasification, it is combusted without oxygen, resulting in a gaseous mixture called syngas, which contains hydrogen, CO, CO₂, and other gases. After that, the syngas needs to go through a purification process to obtain hydrogen. In the process of pyrolysis, organic compounds within the biomass undergo thermal decomposition in the absence of oxygen and using heat. The resulting products can then undergo a reforming process to generate hydrogen. Both processes have a number of drawbacks, including the release of CO and CO₂, the risk of flammability, and the large space required to store and transport biomass [79].

Table 2.1 compiles the primary hydrogen production methods mentioned in the literature, and their respective production costs and technology readiness level, which evaluates the technical maturity on a scale from 0 to 10. In this scale, 0 corresponds to the lowest level of technological readiness, indicating that the technology concept has been proposed but has not yet been verified, while 10 represents the highest level, where the technology has fully matured and demonstrated operational effectiveness.

Table 2.1 — Overview of Hydrogen Production Methods, Production Costs, and Technology Readiness Level

Hydrogen Type	Production Process	Cost (dollars per kilogram, \$/kg)	Technology Readiness Level
Green	Water electrolysis with electricity from wind energy	4,61 - 10,01 [80] 5,89 - 6,03 [81]	9 [82]
	Water electrolysis with electricity from solar photovoltaic energy	7,1 - 14,87 [80] 5,78 - 23,27 [81]	9 [82]
	Water electrolysis with electricity from an unspecified renewable energy source	0,7-2,8 [78] 4 [83]	4 [78]
Grey	SMR	0,7-2,1 [78] 1,03 - 2,16 [80] 2,08-2,27 [83] 2.08 - 2.27 [81]	9 [78], [82]
Blue	SMR with CCS	1,2-2,3 [78] 1,93 - 2,26 [80]	8 [78] 7-8 [82]
Turquoise	Methane pyrolysis	1,6-3,4 [78] 1,36 - 1,79 [80] 1,59 - 1,70 [81]	6 [78] 3-5 [82]
Black/brown	Coal gasification	1,3-2,5 [78] 0,96 - 1,88 [80] 1,34 - 1,63 [83] 1,34 - 1,63 [81]	8 [78] 9 [82]
Pink/purple	Water electrolysis with electricity from nuclear power	4,2-7 [78] 4,99 - 8,21 [80] 4,15 - 7 [81]	8 [78] 9 [82]
	Heat from nuclear power/ nuclear heat for water splitting via thermochemical cycles	2,2-2,8 [78] 1,47 - 2,71 [80] 2,17 - 2,63 [81]	6 [78]
Non-applicable	Biomass pyrolysis	1,77 - 2,05 [81]	Unknown
Non-applicable	Biomass gasification	1,48 - 3 [80] 1,25 - 2,20 [81]	5-6 [82]

According to [71], hydrogen can be stored in three different forms: compressed, liquid or chemically bonded. Among these methods, compressed storage is the most mature. Compressed hydrogen is stored at a temperature of 25°C and a pressure of 70 MPa and has a density of 56,49 kilograms per cubic meter (kg/m³) and an energy density of 6,78 MJ/L. This storage form presents the risk of explosion due to the high pressure [71].

Liquid storage consists of storing hydrogen in its elemental form. Hydrogen exists in a liquid state at a temperature of -253°C , which is its boiling point [70], under atmospheric pressure, with a density of $70,85\text{ kg/m}^3$ [71] and an energy density of $8,5\text{ MJ/L}$ [51]. This storage form presents several disadvantages, such as energy losses, and the need to maintain an extremely low temperature and control vaporization [71]. When liquid hydrogen comes into contact with water and expands into a gaseous state, there is also a risk of explosion. This is known as a cause of rapid phase transition [69].

Chemically bonded hydrogen is stored in a solid state. The most used approach in maritime transportation is to store hydrogen in metal hydrides. In this process, hydrogen molecules split into single hydrogen atoms that are absorbed by the crystal lattice of the metal, forming a solid compound. Not only this storage method is safer but also has a higher energy density. However, this method is not very efficient, since $12,5\text{ kg}$ of metal hydride are needed to store 1 kg of hydrogen [71].

The storage method is chosen based on the amount of hydrogen to be stored. If the quantity to be stored is less than 100 grams (g) , the best method is metal hydride storage. If the amount of hydrogen to be stored is between 100g and 10kg , compression is the best option. For larger amounts of hydrogen exceeding 10kg , the best approach is liquefaction [84].

Hydrogen is odorless, colorless [51], and it is the fuel with the highest energy content per mass [65], [72]. The fast combustion rate is another known characteristic of hydrogen [22]. The fact that hydrogen burns faster than diesel due to its higher flame speed explains why the study [74] concluded that the combustion duration decreases as the proportion of hydrogen increases. The same study has demonstrated that combustion efficiency increases as the hydrogen ratio and combustion temperature increase.

Hydrogen has an auto-ignition temperature of 585°C [70] and can easily ignite and sustain combustion thanks to its wide flammable limit [22]. In addition, hydrogen is not toxic [69] but is extremely flammable and presents the risk of explosion even at low concentrations. Therefore, safety measures must be taken during transportation and storage operations [71]. Hydrogen causes embrittlement of metallic materials, specifically those made of steel [85].

There are a few challenges in the hydrogen supply chain, including difficulties with storage and transportation, namely due to its high flammability and low electroconductivity, as well as high manufacturing costs [73], especially when using renewable energy sources [71]. In addition, the technology and safety procedures associated with the bunkering of hydrogen are still in their infancy. Therefore, the shipping subsector must make an effort to address these challenges in order to meet the demand for the fuel [18].

When shifting from HFO to hydrogen, a larger tank is necessary for traveling the same distance due to the lower energy density of hydrogen. As a result, when hydrogen is used, there is a 5% reduction in cargo capacity as the space is occupied by the fuel tank [18].

In terms of GHG emissions, replacing HFO with hydrogen not only reduces emissions from the combustion of the fuel but also decreases emissions throughout the entire life cycle, including the installation, operation, and maintenance of the vessel and the port, as well as the fuel transport and production [65]. This study also demonstrated that when hydrogen derived from hydropower is utilized, GHG emissions are even lower compared to the use of ammonia. According to [74], on a dual-fuel combustion system using diesel and hydrogen, increasing the proportion of hydrogen results in the decrease of CO₂ and CO emissions but in the increase of NO_x emissions.

Currently, 33 million tons of hydrogen are produced annually, with China leading as the main producer [74]. Countries have been gaining interest in the potential of hydrogen as an energy source. The projected demand is expected to be mainly centered in Europe and Asia. Since 2018, hydrogen national strategies have been announced by 20 countries and are being developed by 19 others. Moreover, until September 2022, more than 680 projects on hydrogen have been announced [73]. Despite various governments' ambition and efforts to engage in hydrogen utilization, there is still a lack of specific policy guidelines [73]. One example is IMO, which has yet to approve guidelines and safety measures for the use of hydrogen as a fuel [12]. In the future, efforts should be done to create and promote uniform guidelines for all hydrogen applications and share information regarding the safety measures and best practices when managing hydrogen, to educate the stakeholders [72].

2.2.3.3 LNG

Liquefied natural gas is derived from natural gas, a fossil fuel. Its primary component is methane but also has other hydrocarbons in its composition, such as ethane, propane and butane, nitrogen and small amounts of sulfur and CO₂ [86], [87]. To obtain LNG, natural gas in gaseous state is liquefied, and its temperature is reduced until it reaches its boiling point of -162°C [52], [70], turning into a cryogenic liquid [56]. The fuel is stored under these conditions, slightly above atmospheric pressure [86].

According to [87], LNG is odorless, colorless, and not corrosive. Besides, it is not toxic, but once released, the air becomes dangerous for breathing and may result in suffocation in unventilated areas [87]. LNG is also not flammable when in liquid form but vapors generated during its combustion may turn explosive and flammable when combined with certain

concentrations of air [87]. Besides, it has a low flame velocity compared to other hydrocarbon fuels [87]. Additionally, it has an auto-ignition temperature of 540°C [70] and an energy density of 22,5 MJ/L [51].

By using LNG, it is possible to eliminate the release of SO_x and Particulate Matter (PM) and reduce CO₂ and NO_x emissions by approximately 20% and 85%, respectively [28]. Due to the abundance of natural gas reserves, LNG has a higher availability than other alternative fuels. Consequently, it is expected to be important in the shift towards the use of cleaner energy sources [56], with its demand and production continuing to grow [86]. In 2019, there were 143 LNG-powered vessels in operation [28], and by 2022, this number had doubled to 286 [52]. By 2024, it is expected that these numbers will exceed 800. The biggest maritime companies have already placed orders for LNG- or dual-fuel-powered vessels. CMA CGM currently operates five LNG-powered vessels with a capacity of 23 000 twenty-foot equivalent units (TEU) and plans to acquire six more. Additionally, HMM has twelve vessels that have been built to be easily converted to use LNG [48]. Currently, the largest exporter of LNG is Australia, which exported 108,1 billion m³ of LNG in 2021, followed by Qatar and the US with 106,8 and 95 billion m³, respectively [88].

The major reluctance in transitioning from HFO to LNG is the lost opportunity for transporting cargo due to the lower energy density of LNG compared to HFO. This results in more space on the vessel being occupied by fuel tanks instead of cargo [56]. [18] estimated that when HFO is substituted by LNG, the cargo capacity is reduced by 1%. Another challenge regarding the use of LNG is the lack of availability of bunkering facilities [89]. In comparison to other alternative fuels, LNG has several advantages, including reduced emissions, namely of NO_x, which minimize the need for after-treatment equipment like selective catalytic reduction (SCR) systems and scrubbers, lower operational and maintenance costs [90], and longer duration of the vessel's equipment [48].

2.2.3.4 Methanol

Methanol (CH₃OH), also known as methyl alcohol [69], is mostly used in the chemical industry to produce hydrocarbons such as acetic acid, methyl acetates, and formaldehyde [91], components for gasoline (ethers and higher alcohols) and kerosene, and in transportation as a fuel experiencing a growing trend [29]. In 2021, methanol production reached 110 million metric tons [92] and, according to the International Renewable Energy Agency (IRENA), it is expected to increase fivefold until 2050, with half of the production using renewable energy sources. Asia, the Middle East, Europe, and North America are the main methanol consumers [29].

Methanol is a colorless liquid [69] kept at ambient pressure [68] and temperature, making it easy to store and transport [91]. Besides, it has an energy density of 15,5 MJ/L and a boiling point of 65°C [51]. Methanol is considered a good alternative to traditional fuels due to its low GHG emissions. Its combustion involves a higher proportion of air, which results in reduced emissions of NO_x and soot [29]. More specifically, NO_x emissions can be reduced by 60% compared to HFO [58]. In terms of other gases, CO₂ emissions can be reduced by 25%, SO_x emissions by 99% and PM by 95% compared to HFO [58].

In terms of safety, methanol is flammable, corrosive, and has a low toxicity level, which makes exposure to high concentrations of the fuel harmless, especially when inhaled or when in contact with the skin. However, it can cause blindness and death when ingested [69], [93]. If released, methanol can be easily dissolved in water without harming the environment or aquatic life. Additionally, methanol has a low flash point, meaning it does not need a high temperature and energy to ignite [68]. It has a lower auto-ignition temperature (464°C) than ammonia, hydrogen, and LNG [70]. To prevent hazard due to toxicity, protective equipment must be used when managing methanol and a gas detector must be used to monitor the exposure to the fuel. Because of methanol's flammability, it is essential to keep ignition sources away from the bunkering infrastructure, deploy bunker connections in open areas, and establish static electricity preventive measures between the provider and the receiver of methanol to prevent ignition. Additionally, equipment for gas detection, alarms and automatic shutdown systems for when high levels are reached must be installed. Finally, it is important to use materials compatible with methanol to prevent corrosion [93].

Most methanol is produced using natural gas as feedstock [58], even though coal, CO₂ [29] and biomass [57] can also be used. When natural gas is used as feedstock, the processes of SMR, partial oxidation, auto-thermal cracking [29], and catalytic conversion of methane [92] are applied for producing methanol. Due to the GHG emissions resulting from the natural gas supply chain, gas reforming, and methanol synthesis that characterize the production process, this is not the most sustainable method of production. As a result, the emissions generated over the fuel's life cycle are 10% higher when natural gas is utilized as the feedstock for the production of methanol than they are for HFO [57]. Methanol can also be produced through the hydrogenation of CO and hydrogen (H₂), in which both are combined to form methanol. Hydrogen can also be combined with CO₂ through hydrogenation to form methanol, which, although more complicated than CO hydrogenation [29], [91] is the most economical of all methanol production methods [29]. Photocatalytic conversion of CO₂ and electrocatalytic reduction of CO₂ are additional processes that also use CO₂ as feedstock to produce methanol

[92]. When employing the process of photocatalytic conversion of CO₂, methanol can be separated from the other components that constitute the reaction using a membrane, even though it is not the most efficient and durable process due to the limited lifetime of the membrane, despite the potential for sustainability [29]. Utilizing CO₂ as a feedstock has the benefit of reusing CO₂ and reducing GHG emissions that would be generated when using coal or natural gas. When CO₂ obtained through carbon capture and utilization (CCU) and CO₂ obtained through tri-reforming of methane (TRM) are used as feedstock for methanol production, the reduction in CO₂ emissions is approximately 0,41 and 1,75 kg of CO₂ per kg of methanol, respectively, compared to when natural gas is used as the feedstock for methanol production [94]. However, the most sustainable production method of methanol uses biomass as feedstock. In this case, CO₂ emissions are not accounted for because they result from biological processes [57].

The first vessel converted to use methanol was the passenger ferry Stena Germanica in 2015. Regardless of the project's cost of 22 million euros, it is predicted that the subsequent conversion project would only require 30 to 40% of this cost [50]. Currently, Maersk is planning to launch the first dual-fuel engine retrofit using methanol in 2024 [95]. Methanol is a step forward compared to ammonia and hydrogen, which do not have specific guidelines and measures set by IMO. Methanol has already been approved by IMO as a safe alternative fuel and has clearer guidelines available [12].

Methanol also has a lower energy density than HFO. Therefore, there is a missed opportunity to generate revenue from cargo due to the increased space occupied by fuel tanks, leaving less space available for cargo [54]. Specifically, according to [18], the capacity is reduced by 2% when methanol is used instead of HFO.

2.2.3.5 Comparative Analysis of Alternative Fuels

The aforementioned properties, advantages, and disadvantages and perspectives for the future adoption of the four alternative fuels under analysis in the future are consolidated in Table 2.2.

Table 2.2 — Properties, Advantages, Disadvantages and Future Perspectives of Ammonia, Hydrogen, LNG, and Methanol

Fuel	Energy Density (MJ/L) ²	Flammability	Toxicity	Auto-ignition Temperature (°C)	Boiling Point (°C)	Corrosivity	Lost Cargo Capacity When Switching from HFO (%) ³	Advantages	Disadvantages	Future Perspectives
Ammonia	12,7 [51]	Low [69]	High [60]	651 [70]	-33 [70]	Yes [51]	3 [18]	No SO _x emissions [60]; carbon neutrality ⁴ [60]; familiarity by already being present in many fields, namely shipping [18]	Lack of bunker barges [51]; difficulty in storage and transportation [18]; NO _x [63] and N ₂ O [16] emissions; risk of explosion [63]	Interest in the long-term from a large number of stakeholders [8], [18], [54], [55], [58]
Hydrogen	8,54 [51]	Extremely high [71]	Null [69]	585 [70]	-253 [70]	Yes [85]	5 [18]	Carbon neutrality ² [6]; highest energy content per mass [51]; efficient combustion [74]	Safety measures and storage and transportation procedures on their infancy [73]; lack of specific guidelines [73]; NO _x emissions [74]; risk of explosion ⁵ [73]; energy loss and need for control of temperature and vaporization during storage ⁴ [71]; not efficient storage ⁷ [73]	Interest in the long-term from a large number of stakeholders [6], [14], [18], [55], [58]
LNG	22,5 [51]	Null [87]	Null [87]	540 [70]	-162 [52], [70]	No [87]	1 [18]	Highest availability [56]; lower costs [14], [18]; longer lifetime of equipment [48]; less NO _x emissions [28]; no SO _x emissions [28]	Fossil fuel-based fuel [86], [87]	Interest in the short-term from a lot of stakeholders [14], [18], [53], [57], [59]
Methanol	15,5 [51]	High [69], [93]	Low [93]	464 [70]	65 [51]	Yes [69], [93]	2 [18]	Ease of storage and transportation [91]; less NO _x emissions [58]; almost no SO _x emissions [58]	Most methanol is produced using natural gas as a feedstock [58]	Interest in the long-term from some stakeholders [18], [54]

² The energy density of HFO is 35 MJ/L.

³ Given the lower energy density of alternative fuels compared to HFO, a larger fuel volume is necessary when utilizing these alternatives. As a result, the fuel tank occupies more space on a vessel when using alternative fuels than when using HFO, leading to a reduction in cargo capacity during the transition from HFO to alternative fuel.

⁴ When produced using renewable energy sources.

⁵ When stored as compressed hydrogen.

⁶ When stored as liquid hydrogen.

⁷ When stored as compressed chemically bonded hydrogen.

This overview of future projections and properties of alternative fuels has revealed that there is currently no consensus on which fuel will be more advantageous in the long run, namely in terms of costs. However, most studies include ammonia and hydrogen in long-term fuel mix projections, and some also incorporate methanol. LNG is recognized as a prominent fuel due to its competitive cost and higher availability but only in the short-term for being a fossil fuel-based fuel.

2.2.4 Optimization in Shipping

Optimization techniques have been applied to a wide variety of dimensions within the shipping subsector. The literature includes models that optimize several aspects, including sailing speed [96]–[98], fuel consumption [99], and the scheduling of shipping operations [97], [99], [100]. Fleet deployment is another aspect covered by optimization models [96]–[98], [100]–[102], which involves the selection of ships that compose a fleet and the allocation of vessels to shipping operations to meet customer demand. Another aspect of shipping that optimization models tackle is route definition [100], [103], [104], which plays a crucial role in the subsector of shipping [105]. By defining adequate shipping routes, it is possible for carriers to reduce costs, increase profit and position themselves more competitively in the market [106]. Additionally, route selection is crucial for achieving large-scale decarbonization and ensuring the technical and economic feasibility of implementing green shipping corridors [107]. The definition of more efficient routes also contributes to the reduction of GHG emissions, as the shorter the distance sailed, the less the fuel consumed [108], and thus less GHG emissions are released [6].

One additional aspect covered by optimization models in shipping that is worth mentioning is the selection of optimal locations, namely for bunkering infrastructure [109]–[113], which is an essential component within the subsector. The lack of infrastructure was a challenge identified in the transition to alternative fuels within the transportation sector [114]. Shipping is no exception, as there is limited availability of alternative fuels compared to traditional fuels, as mentioned earlier. The determination of the optimal location of the necessary infrastructure for supplying alternative fuels at the lowest possible cost, not only enhances the availability of infrastructures, but also bridges the previously recognized price disparity between traditional and alternative fuels.

Given the importance of route definition and location optimization problems and their pertinence to the subject of GHG emissions reduction, they will be investigated in more detail in chapter 3.

ROUTE DEFINITION AND LOCATION OPTIMIZATION AND FRAMEWORK PROPOSAL

Among the several topics covered by optimization problems in shipping, route definition and location optimization problems are particularly relevant to the subject of GHG emissions reduction. Therefore, in this chapter, these problems will be further analyzed, with special attention given to the classical optimization problems of the Traveling Salesman Problem (TSP) in the context of route optimization, and the Facility Location Problem (FLP) in the context of location optimization. The existing studies in literature that have used this optimization methods in the shipping industry will also be looked into.

3.1 Route Definition Optimization Problem

The problem of route definition has been studied from multiple perspectives. This has resulted in a wide variety of models in the literature that aim to optimize the definition of shipping routes.

The optimization model for route planning proposed by [104] is multi-objective and stochastic. Multi-objective optimization problems (MOPs) involve a trade-off between two or more objectives in conflict, contrary to single-objective problems. Additionally, the model is stochastic, as it is subject to fluctuations in operating times and weather and ocean conditions. [103] have also presented a stochastic optimization model for route planning. Its dynamic nature enables the requests that come in during the shipping operation to be handled in addition to those already known since the beginning. In contrast, [115] proposed a deterministic model, in which the demand is known prior to the vessel's departure. The second author's approach is based on a mixed-integer nonlinear programming model, similar to the models proposed in

[100] and [116]. In mixed-integer programming, there are both integer variables, which are limited to take specific values, which is the case of binary variables, and continuous variables, which can assume any real value within a given interval [117].

A vast number of studies have approached the optimization problem of defining shipping routes by modeling it as a variation of the classical TSP, which determines the optimal route between a set of locations with minimal travel costs [118] or distances [119].

Given the potential applicability of the TSP in shipping, the following section will outline the theoretical formulation of the problem and an overview of existing studies that have utilized this optimization method in the subsector.

3.1.1 Traveling Salesman Problem

The TSP was originally presented by Hassler Whitney in a seminar discussion at Princeton University in 1934 [120], and has been one of the most extensively researched combinatorial optimization problems. The aim of the original TSP is to find the shortest path that allows a traveling salesman to visit each city in a set exactly once and then return to the starting point [121].

The TSP is represented by the graph $G = (V, E)$, which is defined by the set of vertices $V = \{0, 1, \dots, n\}$ indexed by i and j (representing the cities), and the set of edges connecting the vertices $E = \{(i, j) | i, j \in V, i \neq j\}$ [122]. The objective is for the salesman to make the tour passing through n cities with the minimum cost. The binary decision variable x_{ij} takes the value of 1 if city j is visited immediately after city i and 0 otherwise. There is a cost for traveling between each pair of cities (i, j) (c_{ij}), which is defined in a cost matrix [119].

The TSP has applications in several fields, with routing being the most significant one. Determining the route for a bus, mail delivery, or even waste collection to minimize distance or cost are examples of the routing application [119]. In the context of shipping, it can be employed to reduce travel costs, with seaports being the vertices and the routes between the ports being the edges [118].

The TSP can either be asymmetric (ATSP) or symmetric (STSP). The ATSP is represented by a directed graph and the cost matrix is asymmetric ($\forall i, j: c_{ij} \neq c_{ji}$) because the distance between cities i and j is not the same in both directions. On the other hand, the STSP, which is a particular case of the ATSP, is defined by an undirected graph and the cost matrix is symmetric ($\forall i, j: c_{ij} = c_{ji}$) because the distance between cities i and j is the same in both directions [123]. The mathematical formulation of the ATSP is the following [122], [124]:

Objective function

$$\text{Minimize } \sum_{(i,j) \in E} c_{ij} x_{ij} \quad (3.1)$$

Subject to:

$$\sum_{i \in V} x_{ij} = 1, j = 1, \dots, n \quad (3.2)$$

$$\sum_{j \in V} x_{ij} = 1, i = 1, \dots, n \quad (3.3)$$

$$\sum_{i \in S} \sum_{j \in V \setminus S} x_{ij} \geq 1, S \subset V: S \neq \emptyset \quad (3.4)$$

$$x_{ij} \in \{0, 1\}, \forall (i, j) \in E \quad (3.5)$$

Constraint (3.2) ensures that only one arc enters a node, which means that when the salesman visits a city j , he must have come from one city i only. On the other hand, constraint (3.3) requires that only one arc leaves a node, which means that after visiting a city i , the salesman visits only one city j . Constraint (3.4) ensures the connectivity of the entire tour, eliminating the existence of subtours. Finally, constraint (3.5) defines the binary nature of the variable x_{ij} .

Given the importance of defining efficient routes in shipping, several studies have incorporated the TSP in the context of the shipping industry. [125] developed a model in the scope of containership routing and speed optimization based on the TSP. The aim of the model was to determine the optimal sequence of ports to call, the most efficient sailing speed, and the ideal number of vessels in order to minimize the fuel cost. [106] also focused on minimizing fuel costs, but they concentrated specifically on containership routing, as the optimization objective included the selection of ports to visit by a containership but did not take into consideration the speed and number of vessels. These studies only considered the fuel cost since it accounts for 60% of the ship's total operating cost [106]. However, shipping operations entail numerous additional costs beyond fuel. Therefore, other authors decided to be more comprehensive in their research, including more costs besides the fuel cost.

[105] considered the overall cost of sailing between ports and the cost of calling the ports. Additionally, the travel time between ports was also included in the objective function

to be minimized. Another point of differentiation of this study is that, contrary to the traditional TSP, not all ports need to be visited, and each port can be visited more than once.

[126] developed a Bi-Objective Insular TSP (BO-InTSP), which has two objective functions: it simultaneously determines which ports to visit and the route sequence to minimize transportation costs both at sea and inland.

[127] also focused on improving the economic aspect but, while the other studies aimed to minimize costs, this research's objective was to maximize the total profit. The mixed-integer nonlinear programming model aims to determine the optimal sequence of ports to call, the cargo allocation to each containership, and the number of voyages each one makes in a defined period. The total profit is calculated by subtracting the cost of operating a containership from port i to port j , including the port expenses, from the revenue charged for transporting a container from i to j .

[128] address a route length minimization problem that is equivalent to the TSP. The objective of the proposed model is to minimize the cargo delivery route length of a feeder vessel, which can correspond to either distance or time. In contrast to other studies looked into so far, the economic aspect of the shipping route is also considered, but in an indirect way. The authors assume that by minimizing the length of the cargo delivery route, the cargo delivery cost is also minimized, as the total cost is equivalent to the sum of the lengths of the tours sailed by the feeders.

[118] also adopt an indirect economic approach. The ATSP was utilized in this study to minimize the tour distance with the start and end points in Prague and passing through the Black Sea ports. It is assumed that by minimizing the distance, the total cost is also minimized. One significant takeaway from the results is that the optimal sequence of stops varies when traveling in one direction compared to the opposite direction. Additionally, due to the asymmetry of the distance matrix, the total distance also differs between the two directions.

For other authors, the priority is to minimize time rather than cost. [129] proposed a model to minimize the completion time of port operations for ships picking up and/or delivering cargo in multiple ports. The model was developed to address a multi-ship TSP with Pickups and Deliveries, Time Windows, and Draft Limits (mTSPPD-TWDL) since it took into account the time intervals during which pickups and deliveries had to be made and the terminal draft limits. The draft limit corresponds to the maximum vertical distance allowed between the waterline and the bottom of the hull of a vessel, which varies depending on the weight of the cargo [130]. This measure is usually employed in ports to define the maximum allowed load on a ship calling at that port [122]. The aim of the model was to determine the sequence of

ports to call as well as the schedule for each ship's port visits. In a similar vein, [131] proposed a model with the same objective but for a single ship (TSPPD-TWDL).

[132] also proposed a model to minimize the completion time of the port operations of a single ship but with the additional aspect of determining the optimal tank allocation plan. The model proposed in this research addressed a TSP with Pickups and Deliveries, Time Windows, Draft Limits, and Tank Allocation (TSPPD-TWDLTA) since it also considered the tank allocation restrictions. The aim was to determine the optimal sequence of ports to call, the schedule for the port visits and the cargo allocation plan for the ship. The study [133] took a different approach, developing a model to minimize the maximum completion time for loading and unloading containers based on the ATSP, to improve the efficiency of a container terminal.

This overview of existing studies in the literature makes it clear that the majority of studies propose models to minimize costs, while some focus on minimizing time. Some models aim to minimize the distance traveled, but as a means to achieve the goal of minimizing cost. Despite the significant contribution to the literature of the models aiming to minimize costs, those interested in replicating these models may encounter a lack of clarity and detail regarding the costs considered. Many studies fail to provide a detailed overview of the costs in their models and how they are obtained. Therefore, it would be useful to provide a more comprehensive framework with detailed costs to guide stakeholders in implementing these models in their case studies.

It is also important to note that none of the studies takes environmental factors into account, namely the reduction of GHG emissions along shipping routes. However, [106] acknowledges the relevance of including environmental aspects in future research, given the growing importance of the topic in the shipping subsector.

3.2 Location Optimization Problem

When it comes to location optimization problems, despite the amount of research in the literature not being particularly broad, the variety of models used remains significant.

[109] and [113] took different approaches to solve the same problem. In [109], a mixed-integer nonlinear model is proposed, while [113] employ graph theory to model the problem of location optimization.

Meanwhile, [110] developed a model to determine the optimal location of call ports based on the model developed by O'Kelly. O'Kelly introduced the hub location problem, which is based on location analysis and spatial interaction theory. The objective of hub locations is to

aggregate flows from different origins but with the same destination, in order to take advantage of scale economies.

The models proposed in the studies [111] and [112] are variations on the FLP. Because this is the classical optimization problem for location optimization, the section that follows presents the theoretical formulation of the problem as well as a review of existing studies that have used this optimization method in the shipping industry.

3.2.1 Facility Location Problem

Since the 1960s, operational research has focused on the study of facility location problems. The FLP is a classical optimization problem, whose objective is to either maximize profit or minimize costs by choosing the optimal location from multiple options for the installation of one or more facilities, in order to satisfy customer demand. A facility can be a warehouse, a supermarket, or any other supply chain node where the aim is to satisfy the needs of consumers [134], [135].

FLPs can have several variants. Firstly, customers' preferences can either be considered or not. If they are not considered, the facilities are considered homogeneous. If they are considered, the facilities are considered heterogeneous, and various factors, such as the type of service or, most frequently, the distance, can affect consumers' preferences [135]. According to [136], these problems can also be divided into capacitated facility location problems (CFLPs) and uncapacitated facility location problems (UFLPs), based on whether the facilities have limited or unlimited supply capacity, respectively. Usually, both are formulated as a mixed-integer program (MIP). In the case of CFLPs, since the customers' demand may not be satisfied in every facility because of the limited supply, it may not be possible for customers to be supplied from the nearest facility. The mathematical formulation of a general CFLP is represented below.

Sets	
N	Set of facilities, indexed by i
M	Set of customers, indexed by j
Parameters	
f_i	Fixed cost of an open facility i
k_i	Maximum capacity of facility i
d_j	Total demand of customer j
t_{ij}	Transportation cost between facility i and customer j

Decision Variable

x_i | 1 if facility i is open, 0 otherwise

Nonbinary Variable

y_{ij} | Fraction of the total demand d_j of customer j satisfied by facility i

Objective Function

$$\text{Minimize } \sum_{i=1}^N \sum_{j=1}^M d_j t_{ij} y_{ij} + \sum_{i=1}^N f_i x_i \quad (3.6)$$

Subject to:

$$\sum_{i=1}^N y_{ij} = 1, \forall j \in \{1, \dots, M\} \quad (3.7)$$

$$\sum_{j=1}^M d_j y_{ij} \leq k_i x_i, \forall i \in \{1, \dots, N\} \quad (3.8)$$

$$y_{ij} \geq 0 \forall i \in \{1, \dots, N\}, \forall j \in \{1, \dots, M\} \quad (3.9)$$

$$x_i \in \{0, 1\}, \forall i \in \{1, \dots, N\} \quad (3.10)$$

Constraint (3.7) ensures that the total demand of each customer is totally satisfied. Constraint (3.8) ensures that the total demand of customers satisfied by a facility does not exceed its maximum capacity. Constraint (3.9) ensures the non-negativity of variable y_{ij} . Finally, constraint (3.10) defines the binary nature of the variable x_i .

In the case of an UFLP, which is a simple FLP [135], the mathematical formulation is almost the same. The difference is that k_i is assumed to be a sufficiently large constant to satisfy the customer's demand and y_{ij} is as a binary variable, taking the value of 1 if facility i supplies customer j and 0 otherwise.

Currently, the lack of infrastructure to support the transition to alternative fuels, namely fuel stations, constitutes a significant obstacle to the attempt to reduce GHG emissions within the transportation sector [114]. To fill this gap in the transport sector and accelerate the transition to alternative fuels, many studies have been carried out. Some of these studies focused on developing optimization models to determine the optimal locations for these facilities, using the FLP as a basis. However, there are practically no studies in the context of shipping as

most of these studies focus on road transportation (e.g., the model in [137] aims at obtaining the number and location of stores supplied by a central warehouse, using truck transportation, to minimize GHG emissions; the model in [114] determines fuel stations locations to minimize the cost in refueling detours; the model in [138] aims at minimizing the total cost of transferring hydrogen from storage areas to retail stations).

When it comes to the subsector of shipping, there is a clear lack of research on the application of the FLP. Only one study was found in the shipping subsector [111], and another study covered all the subsectors of transportation, including shipping [112]. The first one, [111], uses an UFLP to decide whether to transport the goods directly from the source to the destination or via a consolidation terminal, which is assumed to be a facility, in order to minimize costs. The second one, [112], aims to minimize the costs of transporting fuel and of establishing facilities, which are petroleum deposits, refineries, main distribution plants and secondary bases. It encompasses the entire transportation sector, using pipelines, ships, and tank trucks.

However, neither of these studies addresses the issue of the absence of infrastructure to support the transition to alternative fuels and does not contribute to the reduction of GHG emissions.

Similar to the models analyzed in the scope of TSP, the costs to be minimized in these models are not detailed, and it is not explicit exactly what they include. As a result, these models may fail to provide the necessary support to stakeholders who need more in-depth guidelines for applying them to their particular situations.

3.3 Cost Calculation Framework for Fuel Transition

The review conducted on the existing studies in literature presenting optimization models addressing the TSP and the FLP has shown that none of the models tackle both problems, focusing on each problem separately. Besides, these models do not fully meet the needs of the green shipping corridors initiatives. Most of them fail to provide a comprehensive overview of the costs employed and how they are estimated and do not consider environmental factors, making it hard for stakeholders to employ these models. To fill in this gap, a framework to calculate and minimize the costs of transitioning from fossil fuels to alternative fuels is proposed in this section.

The Cost Calculation Framework for Fuel Transition is divided into two phases. The first phase consists of an optimization model to determine the optimal solution for the location and number of bunkering stops that minimizes costs. In this phase, the costs that are intended

to be determined are the deployment cost of bunkering vessels at the necessary call ports per voyage (C^D) and the lost opportunity cost of the voyage resulting from the reduction in cargo capacity of the vessel due to the space occupied by the fuel tank when using an alternative fuel (C^O). The missed opportunity to generate revenue from cargo happens because alternative fuels are generally less dense than HFO, which means that the fuel tank takes up more space which could have been utilized to convey cargo. This results in a missed opportunity to generate revenue from cargo. The optimization model is detailed in section 3.3.1.

In the second phase, the assessment of the total cost for the multiple fuel alternatives is conducted. The total cost includes C^D and C^O , obtained from the optimization model, the fuel cost (C^F), the carbon emissions tax cost (C^{CO_2}), and the cost of converting the vessel to transition from HFO to alternative fuel (C^C). Because C^F , C^{CO_2} , and C^C do not influence the selection of the location and number of bunkering stops, the costs were not included into the optimization model. By applying the framework for economic analysis of the transition to alternative fuels to different fuels, it becomes possible to determine the total costs for each one, thereby facilitating the selection of the most economical fuel path. Figure 3.1 presents a visual representation of the proposed framework.

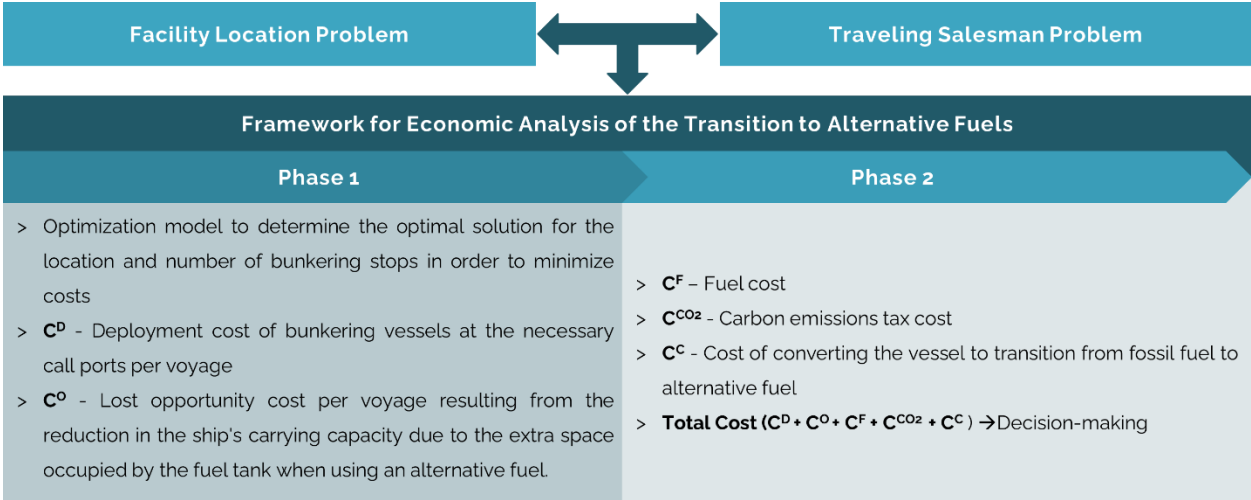


Figure 3.1 — Cost Calculation Framework for Fuel Transition

3.3.1 Optimization Model for Cost Minimization of the Number and Location of Bunkering Stops

The proposed optimization model aims to determine the optimal solution for the location and number of bunkering stops in order to minimize costs. By solving the model, it becomes possible to determine the lowest cost achieved by the optimal solution.

The mathematical formulation of the model incorporated some aspects from the definition and the general mathematical formulation of the classical TSP and FLP (see sections 3.1.1 and 3.2.1, respectively).

The model was developed considering the following assumptions:

- The vessel may only bunker at the call ports included in the predetermined route.
- The sequence of ports to call is fixed and predetermined before the voyage begins.
- Given the flexibility [47], [48], promptness [49], and long-term potential [48] of the ship-to-ship bunkering method, this framework assumes the deployment of bunkering vessels (or bunkering barges) to perform the bunkering operation whenever the port of call does not already provide bunkering services for the chosen alternative fuel.
- If a selected call port does already provide bunkering services for the alternative fuel under study, there is no need to establish a bunkering vessel at that call port, resulting in a deployment cost of zero.
- If the optimal solution of the model indicates a bunkering stop at a port of call that does not provide bunkering services for a particular alternative fuel, it is assumed that the port authority accepts the deployment of a bunkering vessel for that fuel at the port.

3.3.1.1 Mathematical Formulation

Sets

P	Set of ports (nodes) where the vessel stops along the route, indexed by i and j
A	Set of arcs between ports indexed by i and j

Parameters

C^{DV}	Deployment cost of a bunkering vessel per voyage (monetary unit per bunkering vessel, MU/bunkering vessel)
C^{OU}	Lost opportunity cost per nautical mile (MU/NM)
d_{ij}	Distance between ports i and j (NM)
s	Start port (node)
e	End port (node)

Decision Variable

x_i	1 if the vessel bunkers at port i , 0 otherwise
-------	---------------------------------------------------

Additional Variables

y_{ij}	1 if the vessel sails between ports i and j without bunkering, 0 otherwise
d_l	Distance of the longest arc (i, j) traveled by the vessel without bunkering (NM)

Objective Function

$$\text{Minimize } \sum_{i \in P} C^{DU} x^i + C^{OU} d_l \quad (3.11)$$

Subject to:

$$\sum_{j \in P \setminus \{s\}} y_{sj} = 1 \quad (3.12)$$

$$\sum_{i \in P \setminus \{e\}} y_{ie} = 1 \quad (3.13)$$

$$\sum_{i \in P} y_{ij} - \sum_{i \in P} y_{ji} = 0, \forall j \in P \setminus \{s, e\} \quad (3.14)$$

$$y_{ij} \cdot d_{ij} \leq d_l, \forall \{i, j\} \in P \quad (3.15)$$

$$y_{ij} \leq x_i, \forall \{i, j\} \in P \quad (3.16)$$

$$y_{ij} \leq x_j, \forall \{i, j\} \in P \quad (3.17)$$

$$y_{ij} \in \{0, 1\}, \forall \{i, j\} \in P \quad (3.18)$$

$$x_i \in \{0, 1\}, \forall \{i\} \in P \quad (3.19)$$

$$d_l \geq 0 \quad (3.20)$$

The objective function (3.11) minimizes the combination of the deployment cost of bunkering vessel(s) and the lost opportunity cost of the voyage. The deployment cost of a bunkering vessel is considered whenever a bunkering stop is made at a port, in other words, when

the binary decision variable x_i equals 1. The lost opportunity cost of the voyage is determined by the longest distance traveled by the vessel without bunkering. As d_i increases, more capacity needs to be allocated to accommodate fuel. Consequently, less capacity is available for transporting cargo, resulting in the loss of the opportunity to generate revenue from the cargo.

There is a trade-off between the lost opportunity cost and the deployment cost. As the number of bunkering stops increases, the longest distance traveled by the vessel without refueling decreases. Consequently, less capacity is occupied by fuel in the vessel, allowing for more space to be allocated for cargo. This would lead to a reduction in the lost opportunity cost, but it would also result in a higher deployment cost. On the other hand, adopting the opposite approach would lower the deployment cost but increase the lost opportunity cost.

The objective function is subject to multiple constraints. Constraint (3.12) ensures that exactly one arc departs from the start node s , guaranteeing that the first arc of the route departs from the start node. Similarly, constraint (3.13) ensures that exactly one arc enters the end node e , ensuring that the final arc of the route arrives at the end node. Constraint (3.14) ensures flow conservation throughout the network by guaranteeing that, for any node in the network, except the start and end nodes, the total number of arcs entering the node must be equal to the total number of arcs leaving that same node. Constraint (3.15) ensures that the distance of the longest arc (i, j) traveled by the vessel without bunkering is the highest value of the distance traveled between two ports without bunkering.

If the vessel is intended to bunker at the start node, it is necessary to include constraint (3.16), which ensures that if an arc departs from a node, then a bunkering stop must be made at that node. Similarly, if the vessel is intended to bunker at the end node, it is necessary to consider constraint (3.17), which stipulates that if an arc enters a node, then a bunkering stop must be made at that node. Finally, constraints (3.18) and (3.19) ensure the binary nature of the variables x_i and y_{ij} and constraint (3.20) ensures the non-negativity of variable d_i .

By finding the optimal solution of the optimization model, it becomes possible to determine C^D and C^O . The value of C^D is calculated by multiplying the value of C^{DU} by the number of bunkering vessels deployed. The value of C^O is calculated by multiplying the value of C^{OU} by d_i .

CASE STUDY

To validate the effectiveness of the framework for calculating and minimizing the costs of transitioning from fossil fuel to different alternative fuels, it was applied to a case study. Given the unavailability of a real-world case study, a hypothetical case study with real data was developed to apply the framework and draw conclusions regarding the most cost-effective alternative fuel. The data used in this case study was mainly collected from shipping companies' reports and scientific articles. To ensure the transparency of the methodology, the assumptions upon which the case study was based were explicitly stated in this chapter.

The hypothetical case under study addresses the situation of a ship owner operating the shipping route from Shanghai, China, to Lagos, Nigeria, aiming to minimize the impact of its shipping operations on GHG emissions. The ship is a five-year container vessel with a capacity of 15 000 TEUs, currently configured to operate exclusively using HFO.

Until now, slow steaming has been used when a longer transit time is acceptable without compromising service quality. However, the ship owner is now looking forward to contributing to the long-term emission reduction measures established by IMO, by transitioning from HFO to an alternative fuel. To achieve this, a bunkering strategy needs to be defined, which will involve determining the location and number of bunkering stops along the route and selecting the most appropriate alternative fuel that assures minimum cost. The alternative fuels that will be compared in terms of cost are ammonia, liquid hydrogen (from now on referred to as "hydrogen"), LNG, and methanol, which were identified as the four most promising alternative fuels in section 2.2.3.

4.1 Details of the Route and Bunkering Infrastructure

The route sailed by the vessel is illustrated in Figure 4.1. It starts in Shanghai, China (port 0) and ends in Lagos, Nigeria (port 6). The numerical markings from 0 to 6 in the figure indicate the order of ports called along the route. After reaching Lagos, the vessel returns to Shanghai making stops at the same ports along the way.

It is assumed that the vessel bunkers at the beginning and at the end of the voyage, at the start port and the end port, respectively. The availability of bunkering services for the selected fuels in the call ports was assessed [139] and is also represented in Figure 4.1. Hydrogen is not included because no bunkering services are available for this fuel along this route. Table 4.1 summarizes the information about the call ports.

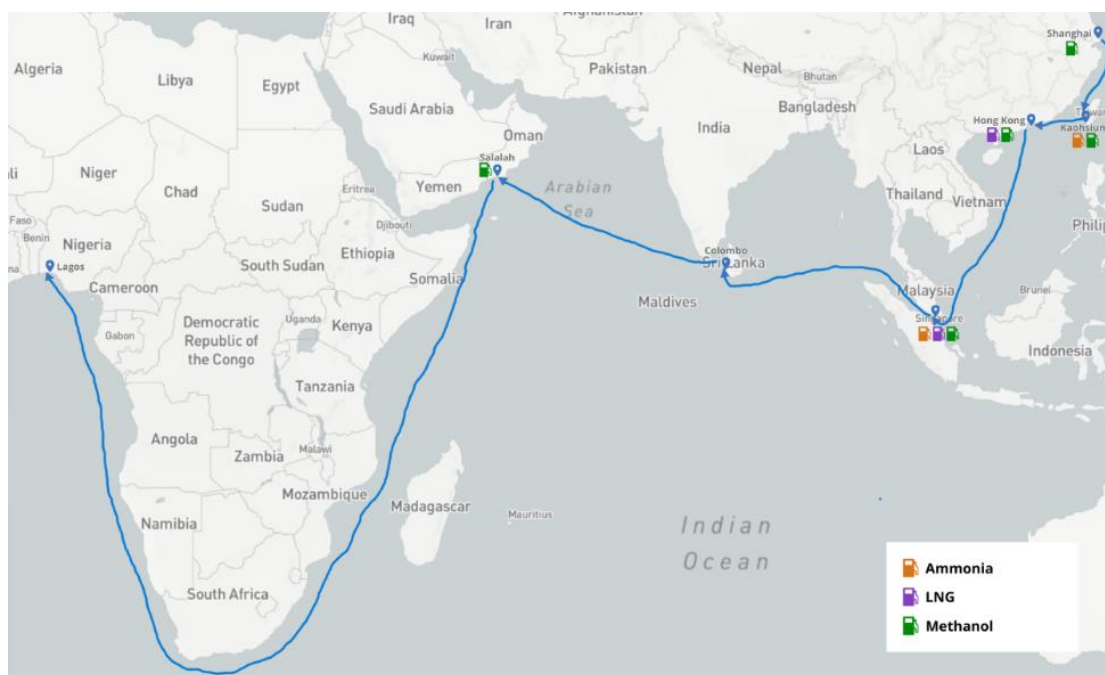


Figure 4.1 — Map of the Route between Call Ports and Availability of Bunkering Services

Table 4.1 — Information about the Call Ports

Port Name	Port Number	Bunkering Services
Shanghai	0	Methanol
Kaohsiung	1	Ammonia, Methanol
Hong Kong	2	LNG, Methanol
Singapore	3	Ammonia, LNG, Methanol
Colombo	4	-
Salalah	5	Methanol
Lagos/Tincan	6	-

4.2 Distance Between Ports i and j (d_{ij})

The distances between the consecutive call ports where the vessel stops along the route [140] are represented on Table 4.2. The total distance sailed by the vessel along the route corresponds to the sum of these distances, equaling 12 254 NM.

Table 4.2 — Distances between the Consecutive Ports Where the Vessel Stops Along the Route

Origin Port	Destination Port	Distance (NM)
0	1	628
1	2	360
2	3	1444
3	4	1610
4	5	1635
5	6	6577

4.3 Sailing Speed

Due to the economic crisis of 2008, the average sailing speed of larger container vessels, like the one under study, decreased to 20-22 knots [141]. For this case study, it was assumed the normal sailing speed is 22 knots. When the customers tolerate a longer transit time, the ship owner adopts a slow steaming approach, and the sailing speed is reduced to 18 knots to minimize the fuel consumption and, consequently, reduce emissions.

4.4 Fuel Consumption

For the vessel under study, it is known that the average fuel consumption while using HFO is 240 tons/day when the average sailing speed is 22 knots, and 125 tons/day when the average sailing speed is 18 knots [142]. Considering that the vessel operates 24 hours (h) per day, these values can be converted to 0,455 tons/NM = 0,412 tonnes/NM = 412 kg/NM and 0,289 tons/NM = 0,262 tonnes/NM = 262 kg/NM respectively.

According to the study [143], the same vessel requires an equivalent amount of energy to sail the same distance, independently of the fuel used. However, different masses of each fuel are required because of the disparity between the energy content per unit of mass of the different fuels.

To determine the amount of each alternative fuel required in comparison to HFO, [143] used the concept of energy density, which is the amount of energy per unit of mass (MJ/kg). This allowed the comparison between the fuels to be done using the same basis. Considering these insights from the study, equations (4.1), (4.2) and (4.3) will be utilized in this case study to determine the fuel consumption of each alternative fuel f .

$$\begin{aligned} & \text{Energy required to sail one unit of distance using alternative fuel } f \text{ (MJ} \\ & \quad \text{/NM)} \\ & = \text{Energy required to sail one unit of distance using HFO (MJ/NM)} \end{aligned} \quad (4.1)$$

The energy required to sail one unit of distance (MJ/NM) can be obtained by multiplying the energy density (ED) by the fuel consumption (FC), which is the mass required to sail one unit of distance (kg/NM). Therefore, equation (4.1) is equivalent to:

$$ED_f \text{ (MJ/kg)} \times FC_f \text{ (kg/NM)} = ED_{HFO} \text{ (MJ/kg)} \times FC_{HFO} \text{ (kg/NM)} \quad (4.2)$$

Which can also be written as:

$$FC_f \text{ (kg/NM)} = \frac{ED_{HFO} \text{ (MJ/kg)} \times FC_{HFO} \text{ (kg/NM)}}{ED_f \text{ (MJ/kg)}} \quad (4.3)$$

The values of energy density in MJ/kg used to calculate the fuel consumption of each alternative fuel are listed in Table 4.3. These values were obtained by dividing the energy density, in mega Joules per cubic meter (MJ/m³), by the mass density, in kg/m³, which are also presented in the table.

The fuel consumption, expressed in kg/NM, obtained for each fuel at a sailing speed of 22 knots and 18 knots is presented on Table 4.3.

Table 4.3 — Properties and Fuel Consumption of HFO, Ammonia, Hydrogen, LNG, and Methanol

Fuel	Energy Density (MJ/m ³) [51]	Mass Density (kg/m ³) [51]	Energy Density (MJ/kg)	Fuel Consumption at 22 knots (kg/NM)	Fuel Consumption at 18 knots (kg/NM)
HFO	0,0350	1010	3,47E-05	412	262
Ammonia	0,0127	618	2,06E-05	695,35	442,64
Hydrogen	0,0085	71	1,20E-04	119,36	75,98
LNG	0,0225	450	5,00E-05	285,79	181,93
Methanol	0,0155	780	1,99E-05	719,09	457,75

4.5 Phase 1

4.5.1 Required Input for the Optimization Model (C^{DU} and C^{OU})

4.5.1.1 Deployment Cost of a Bunkering Vessel per Voyage (C^{DU})

In the current situation, as the vessel already operates the route using existing bunkering facilities for HFO, there is no need for the deployment of a bunkering vessel specific for this fuel. Consequently, there is no deployment cost for HFO.

A potentially feasible solution for the bunkering of ammonia in this case study is the installation of floating bunkering terminals at called ports because of their flexibility and mobility, like the ones being developed by the fertilizer company Yara International and the technology company Azane Fuel Solutions, whose focus is the development of solutions for the bunkering of ammonia [144]. However, these terminals are still in an immature stage of development, hence the associated costs have not been documented in the literature, nor the companies responsible for developing these infrastructures have made this information publicly available. The same applies to hydrogen, for which bunkering vessels are still in the development phase. An example of this is the hydrogen bunkering vessel Elemanta H2, which is being developed by HDF Energy, Améthyste, ArianeGroup, Cetim, Rubis Terminal and Sofresid and will be available in 2025 [145]. Therefore, the costs have not yet been disclosed. Since the deployment cost is not defined for ammonia and hydrogen yet, it will be determined at which value the use of both fuels becomes less advantageous than LNG and methanol.

A viable bunkering solution for LNG would be a bunkering vessel, which costs 30 million \$ [50]. To determine the deployment cost per voyage, this value needs to be divided by the number of voyages the containership under study is expected to undertake during the lifetime of the deployed bunkering vessel(s), which corresponds to the number of times the containership is expected to utilize it/them. To determine the number of voyages the containership is expected to undertake, the first step was to determine the total time of a voyage, which is the sum of the time spent sailing and the time spent in ports during the voyage. When the vessel sails at a speed of 22 knots, the vessel takes 557,10 h to sail the total distance of the voyage, which is 12 254 NM. At a sailing speed of 18 knots, the vessel takes 680,78 h to complete the total distance of the voyage.

According to [146], in 2018, containerships spent an average of 23,5 h in a port call. This value will be used as the port call time in this case study. Despite there are a total of 7 ports, given that the vessel completes a round trip, the final port of one journey corresponds to the

starting port of the next one. To prevent the time spent at the starting and ending ports from being counted twice, the starting port of each trip was excluded from the count, as the time spent there is already included when it is considered as the ending port. Consequently, to determine the time spent in ports during the voyage, 6 ports are considered. Therefore, the total time spent in ports during the voyage is obtained by multiplying the average time spent in a port of 23,5 h by the number of ports where the vessel stops in each voyage, which is 6, resulting in a value of 141 h.

As a result, the total time for a voyage is 839,10 h at a sailing speed of 22 knots and 821,78 h at a sailing speed of 18 knots. Considering that one year has 8 760 h and assuming that the vessel operates 24 h per day, it is possible to make 10,44 voyages per year at a sailing speed of 22 knots and 10,66 voyages at a sailing speed of 18 knots. Both of these values were rounded down to 10 voyages per year.

According to [147], the average duration of a vessel is 25 to 30 years. The worst case was assumed, so the operational lifespan of each bunkering vessel was considered to be 25 years. This means that, over the lifetime of the deployed bunkering vessel(s), the containership under study is expected to undertake 250 voyages. As a result, the total deployment cost of a bunkering vessel of LNG of 30 million \$ results in a deployment cost per voyage of 120 000 \$.

Because methanol and HFO have similar properties, existing bunkering infrastructures for HFO can be easily converted to accommodate the alternative fuel with minimal adjustments [50]. Taking as an example a bunker vessel with a deadweight tonnage of 4999, built in 2019 and listed for sale for 7,5 million \$ [148], and knowing that it would cost around 1,5 million \$ to convert it to use methanol instead of HFO [50], a methanol bunker vessel can be obtained for 9 million \$. The same approach used for LNG was applied to methanol to determine the deployment cost of a bunkering vessel per voyage. Because the containership under study is estimated to make 250 voyages, thereby utilizing the deployed bunkering vessel(s) 250 times, the deployment cost of a methanol bunkering vessel per voyage is 36 000 \$.

4.5.1.2 Lost Opportunity Cost per NM (C^{OU})

According to [18], the capacity of the fuel tank required for alternative fuels to travel a given distance is 1,8 to 4,5 times higher than the volume required for HFO. As a result of the varying energy densities of different fuels, the cargo capacity of a vessel in tons is reduced by 3%, 5%, 1%, and 2% when the vessel switches from HFO to ammonia, hydrogen, LNG, and methanol, respectively. Since the lost opportunity cost aims to compare the missed opportunity due to

the use of alternative fuels, this cost will only be considered for the alternative fuels, not for HFO.

To quantify this lost opportunity cost, it is crucial to quantify the revenue generated by the cargo. Since the average revenue is not publicly available, the Containerized Freight Index was used as an approximation. Historically, events such as a pandemic caused an increase in the value of the Containerized Freight Index. To remove the influence of COVID-19, the value of containerized cargo from the second semester of 2019 has been considered. The containerized freight index for the route under study (Shanghai-Lagos) lies between 2000 and 3000 [149]. The worst-case scenario was assumed, so 3000 \$/TEU was the considered value. To make this value proportional to the distance, it is divided by the total distance sailed along the route (12 254 NM) [140]. The result is 0,245 \$/TEU/NM. The resulting lost opportunity costs for ammonia, hydrogen, LNG, and methanol, expressed in \$/TEU/NM, considering the reductions in cargo capacity due to the varying energy densities of these fuels, are $7,34 \times 10^{-3}$, $12,2 \times 10^{-3}$, $2,45 \times 10^{-3}$ and $4,90 \times 10^{-3}$, respectively for ammonia, hydrogen, LNG, and methanol.

In the ITF report [150], a vessel utilization rate of 85% was assumed. This assumption has been applied in this case study to determine the lost opportunity cost for the entire cargo capacity of the vessel. Consequently, the costs were multiplied by 12 750 TEUs, which corresponds to 85% of the vessel's total capacity of 15 000 TEUs. Since these values are independent of the sailing speed, the lost opportunity cost is the same whether the vessel sails at normal speed or at slow steaming speed. The resulting values of C^{OU} are presented on Table 4.4.

Table 4.4 — Lost Opportunity Cost per NM When Transitioning from HFO to Ammonia, Hydrogen, LNG, and Methanol

Fuel	C^{OU} (\$/NM)
Ammonia	93,64
Hydrogen	156,07
LNG	31,21
Methanol	62,43

4.5.2 Optimization Results: Determining C^D and C^O

The optimization model was programmed in Python, using the FICO Xpress optimizer, to obtain the optimal solution for the number and location of bunkering stops, allowing for the determination of both C^D and C^O .

4.5.2.1 Ammonia

Because the bunkering vessels for ammonia are still under development and not yet commercially available, the value of C^{DU} when using this fuel remain uncertain. Therefore, the Python program was run to obtain the solutions for all possible values of C^{DU} between 0 and 1 000 000 000 (an excessively high value).

Taking this into account, the results obtained for the use of ammonia demonstrate a shift in the solution when C^{DU} changes from 303 860 to 303 861 \$. For a value of $C^{DU} \leq 303 860$ \$/bunkering vessel, the total cost, which in this initial phase corresponds to the sum of C^D and C^O , is minimized with five bunkering stops at Shanghai (0), Kaohsiung (1), Singapore (3), Salalah (5), and Lagos (6). Since ammonia bunkering services are already available at the ports of Kaohsiung and Singapore, it is only necessary to deploy bunkering vessels at Shanghai, Salalah, and Lagos. In this case, d_l is 6 577 NM, C^O is 615 870,28 \$, and the total cost is lower or equal to 1 527 450,28 \$. For a value of $C^{DU} \geq 303 861$ \$/bunkering vessel, the minimum cost is achieved when the number of bunkering stops is reduced to four, at Shanghai (0), Kaohsiung (1), Singapore (3), and Lagos (6). In this case, d_l and C^O increased to 9 822 NM and 919 732,08 \$, respectively, resulting in a total cost equal to or higher than 1 527 454,08 \$.

4.5.2.2 Hydrogen

The bunkering vessels for hydrogen are also not yet commercially available, leading to uncertainty regarding the value of C^{DU} . Hence, similarly to what was done for ammonia, the Python program was run to obtain the solutions for all possible values of C^{DU} between 0 \$ and 1 000 000 000 \$.

The C^{DU} value has a turning point between 885 641 and 885 642 \$/bunkering vessel. For a value of $C^{DU} \leq 885 641$ \$/bunkering vessel, the total cost is minimized with three bunkering stops at Shanghai (0), Salalah (5), and Lagos (6). In this case, d_l is 6 577 NM, C^O is 1 026 472,39 \$, and the total cost is lower or equal to 3 683 395,39 \$. On the other hand, for a value of $C^{DU} \geq 885 642$ \$/bunkering vessel, the total cost is minimized when the vessel only bunkers at the starting port, Shanghai (0), and at the ending port, Lagos (6). In this case d_l is 12 254 NM, C^O is 1 912 481,78 \$ and the total cost is equal or higher than 3 683 765,78 \$. The deployment of bunkering vessels is necessary at all the ports where the vessel stops to bunker as hydrogen bunkering services are not available at any of them.

4.5.2.3 LNG

When the vessel runs on LNG, the total cost - which corresponds to the sum of C^D and C^O - is minimized with three bunkering stops at ports of Shanghai (0), Singapore (3) and Lagos (6). Since the port of Singapore already offers LNG bunkering services, only two bunkering vessels need to be deployed in Shanghai and Lagos. Under these conditions, d_l is 9 822 NM, C^D is 240 000 \$ and C^O is 306 544,62 \$, which results in a total cost of 546 544,62 \$.

4.5.2.4 Methanol

When methanol is used, the minimum total cost is achieved with three bunkering stops at the ports of Shanghai (0), Salalah (5), and Lagos (6). Bunkering vessels only need to be deployed in Lagos, as the ports of Shanghai and Salalah already provide methanol bunkering services. In this case, d_l is 6 577 NM, and the total cost is 446 602,11 \$, where C^D is 36 000 \$ and C^O is 410 602,11 \$.

4.5.2.5 Consolidated Optimization Results for the Alternative Fuels

The outcomes resulting from the Python implementation of the optimization model for minimizing the costs associated with the number and location of bunkering stops for ammonia, hydrogen, LNG, and methanol are consolidated in Table 4.5.

Table 4.5 — Consolidated Optimization Results for Ammonia, Hydrogen, LNG, and Methanol

Fuel		Ammonia		Hydrogen		LNG	Methanol
Input	C^{OU} (\$/NM)	93,64		156,07		31,21	62,43
	C^{DU} (\$/ bunkering vessel)	$\leq 303\ 860$	$\geq 303\ 861$	$\leq 885\ 641$	$\geq 885\ 642$	120 000	36 000
Results	Ports (nodes) between which the vessel travels without bunkering	(0, 1), (1, 3), (3, 5), (5, 6)	(0, 1), (1, 3), (3, 6)	(0, 5), (5, 6)	(0, 6)	(0, 3), (3, 6)	(0, 5), (5, 6)
	d_l (NM)	6 577	9 822	6 577	12 254	9 822	6 577
	Number of bunkering stops	5	4	3	2	3	3
	Number of bunkering vessels deployed	3	2	3	2	2	1
	Ports where a bunkering vessel is deployed	0, 5, 6	0, 6	0, 5, 6	0, 6	0, 6	6
	Ports where the existing bunkering service is utilized	1, 3	1, 3	-	-	3	0, 5
	Total cost ($C^O + C^D$) (\$)	\leq 1 527 450,28	\geq 1 527 454,08	\leq 3 683 395,39	\geq 3 683 765,78	546 544,62	446 602,11
	C^O (\$)	615 870,28	919 732,08	1 026 472,39	1 912 481,78	306 544,62	410 602,11
	C^D (\$)	\leq 911 580	\geq 607 722	\leq 2 656 923	\geq 1 771 284	240 000	36 000

4.6 Phase 2

4.6.1 Determining C^C , C^{CO_2} and C^F

4.6.1.1 Cost of Converting the Vessel to Transition from HFO to Alternative Fuel (C^C)

Switching the fuel of a vessel requires complex and costly modifications since the vessel is not prepared to transition to alternative fuels [54]. This cost will not be considered for HFO, as the vessel already operates using this fuel.

The costs of retrofitting a five-year-old 15 000 TEU container vessel, similar to the one in this case study, were collected from other studies (indicated below for each fuel) and applied to this research.

- Ammonia

In the case of ammonia, the cost of converting the vessel to use this alternative fuel was obtained from the report [54], which refers a study that assessed retrofitting costs for two scenarios: the full range and the reduced range. The full range corresponds to the normal range of a 15 000 TEU container vessel, which is 225 000 NM and requires a fuel tank with a capacity of 16 000 m³ of fuel. On the other hand, the reduced range requires only 10 000 m³ of fuel and can be applied to sail shorter distances without bunkering, requiring a smaller fuel tank. Since in the reduced range scenario less capacity is occupied by the fuel tank, this is a viable alternative for expanding the volume of cargo that can be carried.

In this case study, if the vessel carries out the entire voyage without bunkering at call ports, except for the start and end ports (which is mandatory in this case study), 13 787,76 m³ of fuel would be required if the vessel sails at a normal speed of 22 knots and 8 776,93 m³ when the vessel sails at the slow steaming speed of 18 knots. Therefore, the costs of the full range scenario are more appropriate for this case study since the tank's capacity in the reduced range scenario would not be sufficient to hold all the fuel needed when the vessel is required to sail at 22 knots. Although the fuel tank capacity in the reduced range scenario would be enough if the vessel sailed at 18 knots, it is necessary to adopt the full range scenario, which is compatible with both sailing speed scenarios, given that the vessel alternates between 22 and 18 knots. C^C of the full range scenario amounts to 70 million \$.

- Hydrogen

The conversion cost of hydrogen was assumed to be equivalent to the capex considered in the study [151], which includes the necessary changes in the engine and the storage tanks of the vessel under study to use hydrogen. Since no data for an equivalent vessel like the one under study was found in the literature, the value used for the cost of converting the vessel to transition to hydrogen was gathered from the aforementioned study, which was conducted on a passenger ferry with an unknown capacity. Hence, the value of C^C was estimated to be 23,55 million \$.

- LNG

The data utilized for LNG was collected from the report [152], which describes the project in which a five-year-old 15 000 TEU container ship was converted to be powered by LNG instead of HFO, becoming the first large container ship to transition from a completely HFO propulsion system to an LNG propulsion system, resulting in a C^C of 28 million \$.

- Methanol

The cost of converting the vessel to use methanol was also obtained from the report [54], similarly to the cost of modifying it to use ammonia. Since 11 297,07 m³ of fuel would be required for the vessel to carry out the entire voyage at a speed of 22 knots without bunkering at call ports, except for the start and end ports, and 7 191,42 m³ at the slow steaming speed of 18 knots, the costs used were those from the full range scenario for the same reason as ammonia. This led to a C^C of 42 million \$.

- Consolidated Values of C^C for the Alternative Fuels

The values of C^C for ammonia, hydrogen, LNG and methanol are presented on Table 4.6.

Table 4.6 — Cost of Converting the Vessel to Transition from HFO to Ammonia, Hydrogen, LNG, and Methanol

Fuel	C^C (\$)
Ammonia	70 million [54]
Hydrogen	23,55 million [151]
LNG	28 million [152]
Methanol	42 million [54]

4.6.1.2 Carbon Emissions Tax Cost (C^{CO_2})

One of the measures implemented to encourage the reduction of CO_2 emissions is the carbon tax. To effectively achieve this reduction, the implementation of a carbon tax of at least 50 \$ per tonne of CO_2 emitted is required [59].

To calculate the carbon emissions tax cost, it is necessary to determine the total amount of CO_2 emissions generated throughout the route. The CO_2 emissions are calculated using equation (4.4) [153].

$$CO_2 \text{ emissions} = \text{Fuel consumption} \times \text{Fuel } CO_2 \text{ Emission Factor} \quad (4.4)$$

The CO_2 emission factor indicates the tonnes of CO_2 emitted per tonne of fuel resulting from the fuel combustion in the engine, without taking into account the other processes in the fuel's life cycle, namely, the production process [154].

Since ammonia and hydrogen are carbon-free, CO_2 is not released during the combustion of these fuels. Therefore, their CO_2 emission factors are 0 [6]. The CO_2 emission factors of HFO, ammonia, LNG, and methanol are displayed on Table 4.7.

Table 4.7 — CO_2 Emission Factor of HFO, Ammonia, Hydrogen, LNG, and Methanol

Fuel	CO_2 Emission Factor (tonnes CO_2 /tonne fuel)
HFO	3,114 [154]
Ammonia	0 [6], [51]
Hydrogen	0 [155]
LNG	2,75 [154]
Methanol	1,375 [154]

Table 4.8 displays the calculated values for the CO_2 emissions while using HFO, ammonia, hydrogen, LNG, and methanol, obtained by using equation (4.4).

Table 4.8 — CO_2 Emissions of HFO, Ammonia, Hydrogen, LNG, and Methanol

Fuel	CO_2 Emissions When Sailing at 22 knots (tonnes CO_2 /NM)	CO_2 Emissions When Sailing at 18 knots (tonnes CO_2 /NM)
HFO	1,284	0,817
Ammonia	0	0
Hydrogen	0	0
LNG	0,786	0,500
Methanol	0,989	0,629

To calculate the carbon emissions tax cost per NM, it was necessary to multiply the calculated CO_2 emissions for the carbon tax. Subsequently, to determine the carbon emissions tax cost for the voyage (C^{CO_2}), the values were multiplied by the total distance sailed by the vessel along the route (12 254 NM). All the calculated costs for HFO, ammonia, hydrogen, LNG, and methanol are presented on Table 4.9.

Table 4.9 — Carbon Emissions Tax Cost of HFO, Ammonia, Hydrogen, LNG, and Methanol

Fuel	Carbon Emissions Tax Cost When Sailing at 22 knots (\$/NM)	Carbon Emissions Tax Cost When Sailing at 18 knots (\$/NM)	C^{CO_2} for the Entire Voyage When Sailing at 22 knots (\$)	C^{CO_2} for the entire Voyage When Sailing at 18 knots (\$)
HFO	64,20	40,87	786 755,02	500 827,85
Ammonia	0	0	0	0
Hydrogen	0	0	0	0
LNG	39,30	25,02	481 537,68	306 534,40
Methanol	49,44	31,47	605 805,47	385 640,06

4.6.1.3 Fuel Cost (C^F)

The cost of HFO, ammonia, hydrogen, LNG, and methanol in \$ per volume unit is indicated on Table 4.10. The values were converted to \$/NM based on the fuel consumption of the vessel at normal speed (22 knots) and slow steaming (18 knots). After that, the values of C^F for each fuel under study were obtained by multiplying the fuel cost per NM for the total distance sailed by the vessel along the route, both at normal and slow steaming speeds. All the values are presented on Table 4.10.

Table 4.10 — Fuel Cost of HFO, Ammonia, Hydrogen, LNG, and Methanol

Fuel	Fuel Cost	Fuel Cost at 22 knots (\$/NM)	Fuel Cost at 18 knots (\$/NM)	C^F for the Entire Voyage at 22 knots (\$)	C^F for the Entire voyage at 18 knots (\$)
HFO	2500 \$/ton [156]	113,64	72,34	1 392 500,00	886 429,40
Ammonia	539,3 \$/tonne [6]	375,00	238,72	4 595 288,23	2 925 241,35
Hydrogen	2738,20 \$/tonne [6]	326,83	208,05	4 004 996,79	2 549 477,12
LNG	692 \$/tonne [6]	197,77	125,89	2 423 447,82	1 542 704,05
Methanol	643 \$/tonne [91]	462,37	294,34	5 665 933,33	3 606 786,27

4.6.2 Total Cost Assessment

4.6.2.1 HFO

The total cost of the current scenario, which corresponds to the utilization of HFO, for both sailing speeds of 22 and 18 knots, is presented on Table 4.11. The total cost is the sum of C^{CO_2} and C^F , which are the only costs applicable to this fuel.

Table 4.11 — Aggregated Costs for HFO as Fuel

Speed (knots)	22	18
C^{CO_2} (\$)	786 755,02	500 827,85
C^F (\$)	1 392 500,00	886 429,40
Sum (Total Cost) (\$)	2 179 255,02	1 387 257,25

4.6.2.2 LNG

Table 4.12 displays the values of C^C , C^{CO_2} , C^F , C^D and C^O for the scenario in which LNG is used, as well as the sum of these costs, which represents the total cost.

Table 4.12 — Aggregated Costs for LNG as Fuel

Speed (knots)	22	18
C^{CO_2} (\$)	481 537,68	306 534,40
C^F (\$)	2 423 447,82	1 542 704,05
C^C (\$)	30 000 000	30 000 000
C^O (\$)	306 544,62	306 544,62
C^D (\$)	240 000,00	240 000,00
Sum (Total Cost) (\$)	33 451 530,12	32 395 783,07

4.6.2.3 Methanol

The values of C^C , C^{CO_2} , C^F , C^D and C^O for the situation in which methanol is used as a fuel, as well as the total cost, which is the sum of these costs, are presented on Table 4.13.

Table 4.13 — Aggregated Costs for Methanol as Fuel

Speed (knots)	22	18
C^{CO_2} (\$)	605 805,47	385 640,06
C^F (\$)	5 665 933,33	3 606 786,27
C^C (\$)	42 000 000,00	42 000 000,00
C^O (\$)	410 602,11	410 602,11
C^D (\$)	36 000,00	36 000,00
Sum (Total Cost) (\$)	48 718 340,91	46 439 028,43

4.6.2.4 Ammonia

Since the value of C^{DU} for ammonia is not defined yet, it is not possible to determine C^D and C^O using the optimization model, as it depends on the parameter C^{DU} . Therefore, it was determined at which values of C^D and C^O the use of ammonia is no longer advantageous compared

to LNG and methanol. The first step was to calculate the sum of the costs already known (C^C , C^{CO_2} and C^F), which is presented on Table 4.14.

Table 4.14 — Sum of the Cost of Converting the Vessel, the Carbon Emissions Tax Cost, and the Fuel Cost of Ammonia

Speed (knots)	22	18
C^{CO_2} (\$)	0	0
C^F (\$)	4 595 288,23	2 925 241,35
C^C (\$)	70 000 000	70 000 000
Sum (\$)	74 595 288,23	72 925 241,35

- Determining C^D and C^O above which Ammonia Becomes Less Cost-Advantageous than LNG

Given that the total cost when LNG is used as fuel (33 451 530,12 \$ and 32 395 783,07 \$ for sailing speeds of 22 and 18 knots, respectively) is lower than the sum of the costs already known (C^C , C^{CO_2} and C^F) of ammonia, without taking C^D and C^O into account, there are no values of C^D and C^O for which using ammonia is more cost-effective than using LNG.

- Determining C^D and C^O above which Ammonia Becomes Less Cost-Advantageous than Methanol

Because the total cost when methanol is used as fuel (48 718 340,91 \$ and 46 439 028,43 \$ for sailing speeds of 22 and 18 knots, respectively) is lower than the sum of the costs already known (C^C , C^{CO_2} and C^F) of ammonia, without accounting for C^D and C^O , there are no values of C^D and C^O for which using ammonia is more economical than using methanol.

4.6.2.5 Hydrogen

For the same reason as ammonia, it is not possible to determine C^D and C^O when the vessel runs on hydrogen using the optimization model. As a result, it was calculated at which values of C^D and C^O the use of hydrogen is no longer advantageous compared to LNG and methanol.

For this, it was necessary to calculate the sum of the costs already known (C^C , C^{CO_2} and C^F), which is presented on Table 4.15.

Table 4.15 — Sum of the Cost of Converting the Vessel, the Carbon Emissions Tax Cost, and the Fuel Cost of Hydrogen

Speed (knots)	22	18
C^{CO_2} (\$)	0	0
C^F (\$)	4 004 996,79	2 549 477,12
C^C (\$)	23 553 482,00	23 553 482,00
Sum (\$)	27 558 478,79	26 102 959,12

- Determining C^D and C^O above which Hydrogen Becomes Less Cost-Advantageous than LNG

After determining the sum of hydrogen's C^C , C^{CO_2} and C^F , these values were subtracted from the total cost of LNG. This allowed for the calculation of the combined value of C^D and C^O for which the adoption of LNG is more economical than hydrogen's. This value is 5 893 051,33 \$ for a sailing speed of 22 knots and 6 292 823,95 \$ for a sailing speed of 18 knots. Both values exceed 3 683 765,78 \$, which is the combined value of C^D and C^O for which a shift in the solution of the optimization model was verified in section 4.5.2.2. In this situation, two bunkering vessels are deployed, d_l is 12 254 NM and C^O is 1 912 481,78 \$. The resulting value of C^D can be obtained by subtracting C^O from the combined value of C^D and C^O , leading to a value of 3 980 569,55 \$ at 22 knots and a value of 4 380 342,17 \$ at 18 knots. This results in a deployment cost per bunkering vessel of 1 990 284,78 \$ (22 knots) and 2 190 171,09 \$ (18 knots).

Table 4.16 displays the values of C^C , C^{CO_2} and C^F when hydrogen is used as a fuel, the values of C^D and C^O above which hydrogen becomes less cost-advantageous than LNG and their sum, in other words, the total cost.

Table 4.16 — Aggregated Costs for Hydrogen as Fuel above which It Becomes Less Cost-Advantageous than LNG

Speed (knots)	22	18
C^{CO_2} (\$)	0	0
C^F (\$)	4 004 996,79	2 549 477,12
C^C (\$)	23 553 482,00	23 553 482,00
C^O (H-LNG) (\$)	1 912 481,78	1 912 481,78
C^D (H-LNG) (\$)	3 980 569,55	4 380 342,17
Sum (Total Cost) (H-LNG) (\$)	33 451 530,12	32 395 783,07

- Determining C^D and C^O above which Hydrogen Becomes Less Cost-Advantageous than Methanol

The process of determining the values of C^D and C^O for hydrogen above which this fuel becomes less economically favorable than LNG, as described in the previous section has been replicated for methanol. The values of C^C , C^{CO_2} and C^F of hydrogen were deducted from the total cost of methanol, resulting in the estimation of the combined values of C^D and C^O of 21 159 862,13 \$ for a sailing speed of 22 knots and 20 336 069,31 \$ for a sailing speed of 18 knots, above which methanol is more cost-advantageous than hydrogen. Since both values are higher than 3 683 765,78 \$, which is the combined value of C^D and C^O for which a shift in the solution of the optimization model was verified in section 4.5.2.2. Besides, the number of bunkering vessels deployed is two, d_l is 12 254 NM and C^O is 1 912 481,78 \$. By subtracting the last one from the combined value of C^D and C^O , it was possible to determine the value of C^D , which is 19 247 380,35 \$ (9 623 690,17 \$/bunkering vessel) for a sailing speed of 22 knots and 18 423 587,53 \$ (9 211 793,77 \$/bunkering vessel) for a sailing speed of 18 knots.

The values of C^C , C^{CO_2} and C^F , the values of C^D and C^O above which hydrogen becomes less economical than methanol, and the total cost resulting from their sum, are presented on Table 4.17.

Table 4.17 — Aggregated Costs for Hydrogen as Fuel above which It Becomes Less Cost-Advantageous than Methanol

Speed (knots)	22	18
C^{CO_2} (\$)	0	0
C^F (\$)	4 004 996,79	2 549 477,12
C^C (\$)	23 553 482,00	23 553 482,00
C^O (H-Me) (\$)	1 912 481,78	1 912 481,78
C^D (H-Me) (\$)	19 247 380,35	18 423 587,53
Sum (Total Cost) (H-Me) (\$)	48 718 340,91	46 439 028,43

ANALYSIS AND DISCUSSION OF RESULTS

The aim of this chapter is to analyze the results of the implementation of the framework developed to find out and minimize the costs of the fuel transition, and to provide an answer to the research questions regarding which alternative fuel offers a greater cost advantage and how variations in carbon pricing influence the alternative fuel selection.

5.1 Comparative Analysis of Fuel Alternatives by Cost Component

For a segmented overview of the economic impact of selecting each fuel, it will be assessed how different alternative fuels perform within each cost component. This allows for a more detailed analysis of the results obtained from the implementation of the framework. This assessment was only done for the costs already known for all the alternative fuels under study: C^C , C^{CO_2} and C^F .

5.1.1 Cost of Converting the Vessel to Transition from HFO to Alternative Fuel (C^C)

The results indicate that converting vessels to transition from HFO to any alternative fuel requires significant funding, which is in line with the study conducted by the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping [54].

When it comes to the cost of converting the vessel to transition from HFO to an alternative fuel, ammonia is the most expensive one, followed by methanol. This outcome is not surprising since, as mentioned in section 404941600.465.803432.0•, the costs of the full range scenario, which assumes a fuel tank capacity of 16 000 m³, were considered. In the case of

ammonia, the fuel tank capacity in the full range scenario exceeds the required capacity for this case study by 16% at a sailing speed of 22 knots (13 787,76 m³) and by 82% at 18 knots (8 776,93 m³). For methanol, the excess capacity is 42% at 22 knots and 122% at 18 knots, as the required fuel tank capacities are 11 297,07 m³ and 7 191,42 m³, respectively. When considering the costs of a scenario in which the fuel tank has a capacity greater than what is actually required, it is logical that the cost is higher compared to the other fuels for which a fuel tank with extra capacity was not considered.

LNG turned out to have the second-lowest cost of converting the vessel from HFO, after hydrogen, which has the lowest conversion cost. However, there might be a bias in this result since the cost considered for hydrogen was based on the conversion of a passenger ferry with an unknown capacity, as mentioned in section 404941600.465.804460.0. As a result, the engine and storage tank specifications for the container vessel under study might vary. Therefore, this cost must be taken with care.

Figure 5.1 displays the results of the cost of converting the vessel to transition from HFO to the different alternative fuels.

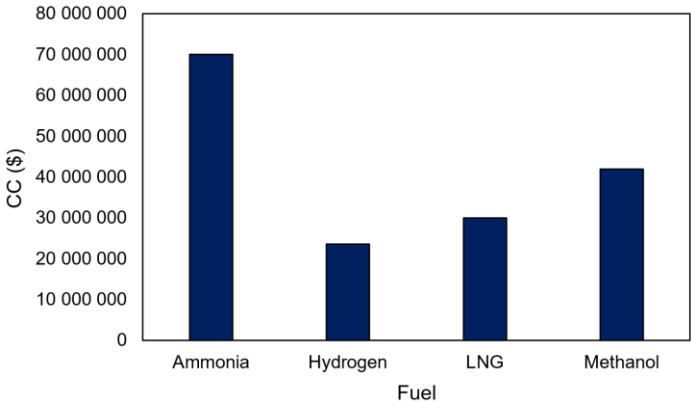


Figure 5.1 — Cost Comparison of Converting the Vessel to Transition from HFO to Ammonia, Hydrogen, LNG, and Methanol

5.1.2 Carbon Emissions Tax Cost (C^{CO₂})

HFO is the fuel that releases the highest amount of CO₂ emissions when combusted, which was already expected since it is a fossil fuel, and thus emits significantly more CO₂ when combusted compared to alternative fuels. Following are LNG and then methanol. On the other hand, ammonia and hydrogen do not release CO₂ emissions. Based on this trend, it is possible to conclude that the more CO₂ emissions released during the combustion of a fuel, the higher the carbon emissions tax cost of that fuel.

The results obtained for HFO support the necessity for a shift away from this fuel. Aside from contributing to global warming and damaging not only the environment but also the global economy, it also has the economic disadvantage of implying a substantially higher carbon emissions tax cost compared to alternative fuels.

The results obtained for ammonia and hydrogen support the fuel mix perspectives for their long-term use identified in the literature (section 2.2.3). The lack of CO₂ emissions not only offers these fuels an environmental advantage but also a cost advantage, making them promising candidates for future adoption.

On the other hand, the results of the application of the framework obtained for LNG and methanol were unforeseen. The literature review revealed that the reduction of CO₂ emissions resultant from the switch away from HFO is more significant when using methanol (25% [58]) than when using LNG (20% [28]), leading to a trend towards the inclusion of methanol rather than LNG in long-term fuel mix projections. However, the results of the application of the framework demonstrated the contrary. For both sailing speeds under study, switching from HFO to LNG resulted in a 39% reduction in CO₂ emissions, while switching from HFO to methanol resulted in a 23% reduction. This happened because, even though the amount of CO₂ emitted per tonne of fuel combusted is higher for LNG, fuel consumption is significantly higher for methanol, resulting in a higher value of CO₂ emissions and, consequently, a higher carbon emissions tax cost for methanol. The results of the carbon emissions tax cost per fuel are represented in Figure 5.2.

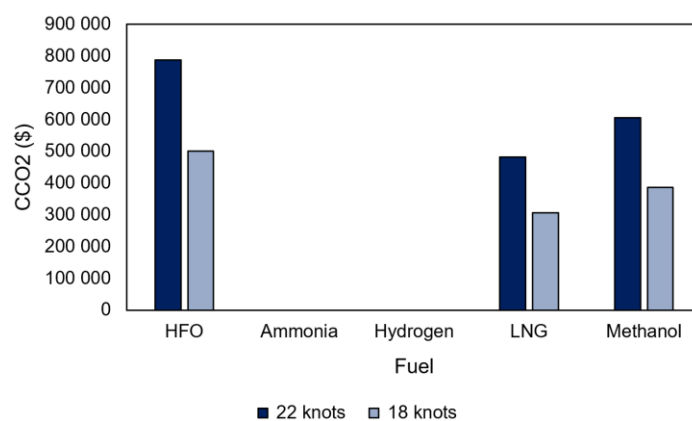


Figure 5.2 — Carbon Emissions Tax Cost Comparison for HFO, Ammonia, Hydrogen, LNG, and Methanol

5.1.3 Fuel Cost (C^F)

The outcomes of the application of the framework confirmed that HFO, as a fossil fuel, continues to be economically favorable in terms of fuel cost in the current horizon when compared

to alternative fuels. Among all the alternative fuels, LNG stood out as the most economical in terms of the cost of the fuel itself. Despite being the alternative fuel with the second-lowest cost per tonne of fuel, as described in section 4.6.1.3, methanol has the highest fuel cost due to its higher fuel consumption.

The results of the fuel cost for each fuel option are represented in Figure 5.3.

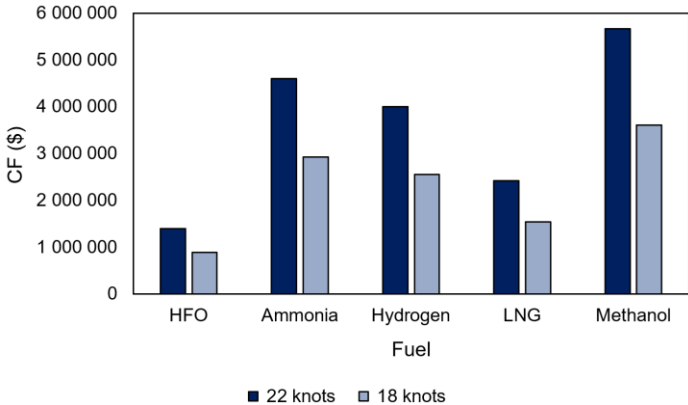


Figure 5.3 — Fuel Cost Comparison for HFO, Ammonia, Hydrogen, LNG, and Methanol

5.2 Comparative Analysis of Fuel Alternatives by Total Cost and Fuel Selection

Analyzing the total cost of the different alternative fuel options was important for determining which fuel path is more cost-effective in this case study.

Since the total cost of hydrogen and ammonia depends on the deployment cost of a bunkering vessel per voyage, which is uncertain, the total cost was calculated for different values of the deployment cost. These results have been represented in charts that display the total cost in relation to the deployment cost of a bunkering vessel per voyage. The chart in Figure 5.4 corresponds to a sailing speed of 22 knots, whereas the chart in Figure 5.5 refers to a sailing speed of 18 knots.

The charts include the total cost obtained for LNG and methanol in order to determine if there is an intersection point with the curves of ammonia and hydrogen, which denotes the point at which the total cost of ammonia and hydrogen surpasses this value. Although HFO is not a viable fuel option for the future, it has also been included in the chart to assess the impact of switching from this fuel to an alternative fuel.

The coordinates on the chart in Figure 5.4, (1 990 284,78; 33 451 530,12) and (9 623 690,17; 48 718 340,91), represent the deployment cost per bunkering vessel per voyage

(1 990 284,78 \$ and 9 623 690,17 \$, respectively) at which, for a sailing speed of 22 knots, the total cost of hydrogen exceeds the total cost of LNG (33 451 530,12 \$) and methanol (48 718 340,91 \$), respectively. By analyzing the chart, it is possible to conclude that, for a sailing speed of 22 knots, hydrogen is the alternative fuel with the lowest total cost when the deployment cost per bunkering vessel is lower than 1 990 284,78 \$, making it the most advantageous fuel option. If the deployment cost per bunkering vessel exceeds this value, LNG becomes the most advantageous alternative fuel in terms of cost.

Similarly, for a sailing speed of 18 knots, the coordinates (2 190 171,09; 32 395 783,07) and (9 211 793,77; 46 439 028,43) displayed on the chart in Figure 5.5 indicate the deployment cost per bunkering vessel per voyage (2 190 171,09 \$ and 9 211 793,77 \$, respectively) above which the total cost of hydrogen is higher than LNG's (32 395 783,07 \$) and methanol's (46 439 028,43 \$). For a sailing speed of 18 knots and a deployment cost per bunkering vessel lower than 2 190 171,09 \$, hydrogen continues to be the most advantageous fuel in terms of costs, as shown in the chart in Figure 5.5. If the deployment cost per bunkering vessel surpasses this value, LNG becomes the most cost-effective fuel.

Furthermore, the curve of ammonia is positioned higher than the curves of the other fuels in both charts and does not intersect them, which indicates that ammonia is the less cost-advantageous fuel option. It is also possible to notice a significant cost difference between HFO and any alternative fuel in both charts, reinforcing that using HFO remains economically advantageous for now.

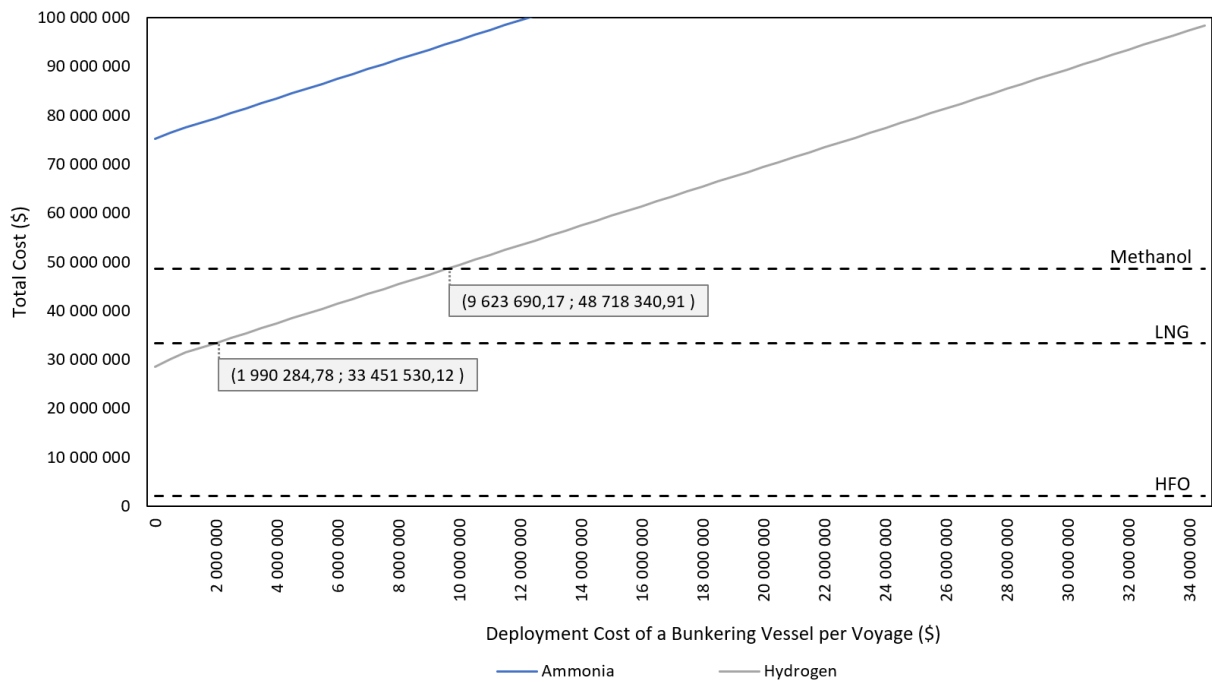


Figure 5.4 — Total Cost Assessment at Varying Deployment Costs of a Bunkering Vessel per Voyage at a Sailing Speed of 22 knots

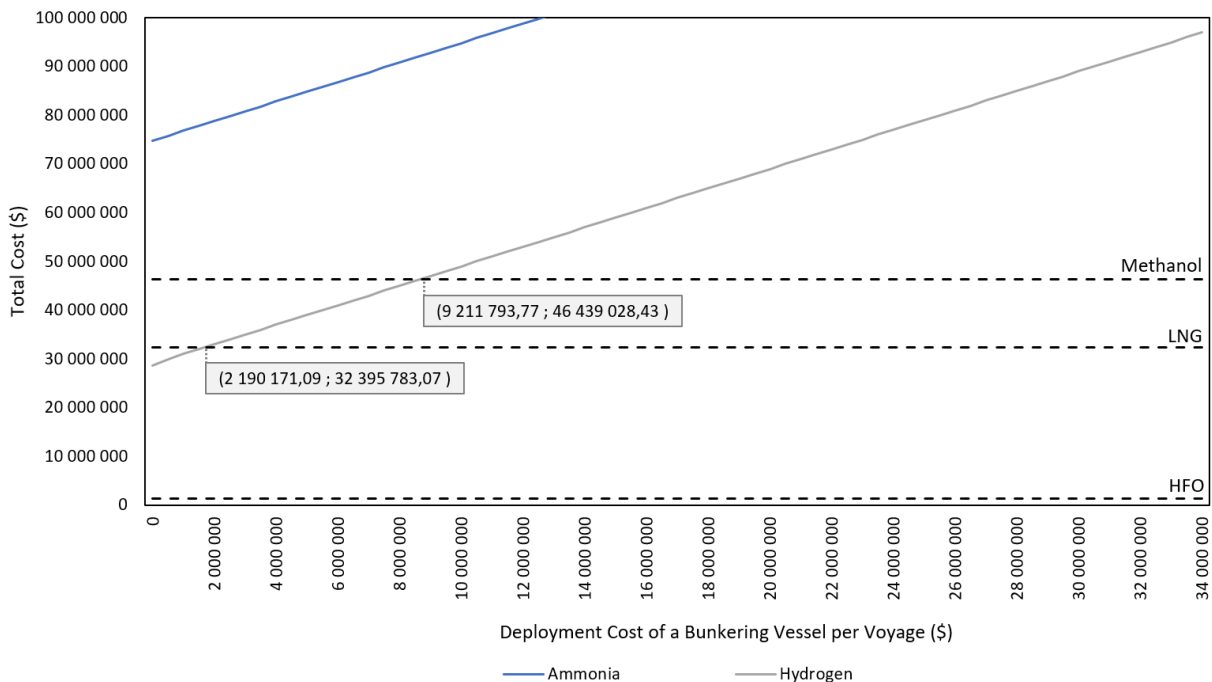


Figure 5.5 — Total Cost Assessment at Varying Deployment Costs of a Bunkering Vessel at a Sailing Speed of 18 knots

To conclude and address the research question regarding which alternative fuel offers a greater cost advantage for green shipping corridor initiatives, this case study revealed that either hydrogen or LNG stand out as the best options, depending on the deployment cost per bunkering vessel.

5.3 Comparing the Research Outcomes with Fuel Projections from Existing Literature

The results of the study carried out in this dissertation regarding which alternative fuel is the most advantageous, as well as the results from studies previously conducted that have already been analyzed in more detail in section 2.2.3, are summarized in Table 5.1. The result of this study aligns with the results of the majority of the other studies, as eight out of ten studies concluded that hydrogen and/or LNG are the most advantageous alternative fuels. As indicated in the table, studies [6], [14], [18], [55], [58] pointed out hydrogen as the most cost-advantageous alternative fuel in the long run, whereas studies [14], [18], [53], [56], [57] considered LNG a more favorable option, but most of them for the short term. When it comes to other fuels, fewer studies include ammonia and methanol in their fuel mix projections. Four studies highlighted ammonia as the most favorable alternative fuel [5], [54], [55], [58], while only one relied on methanol [54], which aligns with the results of this study. Although ammonia revealed to be more expensive than methanol in this study, most literature relies on ammonia rather than methanol, which might be an indicator that there are other factors that discourage the adoption of methanol besides the price. Table 5.1 also includes the parameters, namely the cost components, considered in each study on which the determination of the most favorable alternative fuel is based. In comparison with other studies in literature, this study undertook a significantly more comprehensive analysis of the costs in order to select the most advantageous fuel. Except for [6] and [14], the other studies do not disclose the costs and other parameters considered. Besides, none of the existing studies is concerned with the minimization of costs. Consequently, this study significantly complements the existing literature as it provides a framework with detailed guidelines for determining the costs involved in transitioning from fossil fuels to different alternative fuels, which any stakeholder can apply to a route they aim to decarbonize. This framework goes a step further as it incorporates an optimization model to determine the optimal solution for the location and number of bunkering stops in order to minimize costs.

Table 5.1— Comparative Analysis of Most Advantageous Alternative Fuels and Parameters Considered in Different Studies

Study	Most Advantageous Fuel	Parameters Considered in the Analysis and Selection of the Fuel
Current Study	Hydrogen or LNG	Lost opportunity cost Deployment cost of bunkering vessels at the necessary call ports Cost of converting the vessel Carbon emissions tax cost Fuel cost
[5]	Ammonia	Parameters not revealed in the study
[6]	Hydrogen	Fuel consumption cost Boil-off gas (BOG) combustion cost Carbon tax
[14]	Hydrogen in the long-term LNG in the short-term	Operational cost Fuel cost Capital cost for the propulsion system Other parameters (safety, reliability of the supply chain, availability of the infrastructure, impact on environment)
[18]	Hydrogen in the long-term LNG in the short-term	Parameters not revealed in the study
[53]	Bio-LNG, synthetic LNG, or e-LNG In the long-term LNG in the short-term	Parameters not revealed in the study
[54]	Ammonia and methanol	Parameters not revealed in the study
[55]	Ammonia and hydrogen	Parameters not revealed in the study
[56]	LNG	Parameters not revealed in the study
[57]	Bio-LNG, synthetic LNG, or e-LNG In the long-term LNG in the short-term	Parameters not revealed
[58]	Ammonia and hydrogen	Parameters not revealed

5.4 Impact of Carbon Tax Variations on Total Cost and Fuel Selection

The solution for the optimal fuel path was obtained considering a carbon tax of 50 \$/tonne of CO₂ emitted. However, since C^{CO_2} depends on this tax, a change in the tax might lead to a change in this cost and, consequently, in the total cost, which could alter the optimal fuel selection.

To answer the research question regarding how variations in carbon pricing influence the alternative fuel selection, four scenarios with varying increases in the carbon tax were analyzed:

- Low increase: the carbon tax suffers a 20% increase, resulting in a carbon tax of 60 \$/tonne of CO₂ emitted.

- Moderate increase: the carbon tax suffers a 50% increase, resulting in a carbon tax of 75 \$/tonne of CO₂ emitted.
- High increase: the carbon tax suffers a 200% increase, resulting in a carbon tax of 150 \$/tonne of CO₂ emitted.
- Very high increase: the carbon tax suffers a 1000% increase, resulting in a carbon tax of 550 \$/tonne of CO₂ emitted.

The C^{CO_2} , the total cost, and the increase in total cost compared to the calculated initially for a carbon tax of 50 \$/tonne of CO₂ emitted were determined for the four scenarios, and the results obtained are displayed on Table 5.2. Since the carbon tax has no effect on ammonia and hydrogen because the fuels do not emit CO₂ when combusted, this analysis was limited to HFO, LNG, and methanol.

As shown in Table 5.2, the carbon tax increase has a greater impact on the total cost of HFO, followed by LNG, and finally, methanol. This can be explained by the fact that C^{CO_2} constitutes a substantial fraction of the total cost of HFO (e.g., for a carbon tax of 50 \$/tonne of CO₂ emitted, C^{CO_2} accounts for 36,10% of the total cost for both sailing speeds of 22 knots and 18 knots), whereas for LNG this fraction is considerably less substantial (1,44% for a sailing speed of 22 knots and 0,92% for a sailing speed of 18 knots), and for methanol it is even less significant (1,24% for a sailing speed of 22 knots and 0,79% for a sailing speed of 18 knots). Because the carbon tax increase influences C^{CO_2} , it is logical that the greater the weight of this cost parameter in the total cost, the higher the impact of the carbon tax variation on the total cost.

Table 5.2 — Impact of Carbon Tax on Carbon Emissions Tax Cost and Total Cost for HFO, LNG, and Methanol

Scenario	Original		Low Increase		Moderate Increase		High Increase		Very High Increase	
Increase in the Carbon Tax (%)	0		20		50		200		1000	
Carbon Tax (\$)	50		60		75		150		550	
Speed (knots)	22	18	22	18	22	18	22	18	22	18
C^{CO_2} HFO (\$)	786 755,02	500 827,85	944 106,03	600 993,42	1 180 132,54	751 241,78	2 360 265,07	1 502 483,55	8 654 305,26	5 509 106,36
C^{CO_2} LNG (\$)	481 537,68	306 534,40	577 845,22	367 841,28	722 306,52	459 801,60	1 444 613,04	919 603,21	5 296 914,49	3 371 878,44
C^{CO_2} Methanol (\$)	605 805,47	385 640,06	726 966,56	462 768,07	908 708,20	578 460,08	1 817 416,41	1 156 920,17	6 663 860,16	4 242 040,61
Total Cost HFO (\$)	2 179 255,02	1 387 257,25	2 336 606,03	1 487 422,82	2 572 632,54	1 637 671,17	3 752 765,07	2 388 912,95	10 046 805,26	6 395 535,76
Total Cost LNG (\$)	33 451 530,12	32 395 783,07	33 547 837,66	32 457 089,95	33 692 298,96	32 549 050,28	34 414 605,48	33 008 851,88	38 266 906,93	35 461 127,11
Total Cost Methanol (\$)	48 718 340,91	46 439 028,43	48 839 502,01	46 516 156,44	49 021 243,65	46 631 848,46	49 929 951,85	47 210 308,54	54 776 395,61	50 295 428,99
Increase in Total Cost HFO (%)	-	-	7,22%	7,22%	18,05%	18,05%	72,20%	72,20%	361,02%	361,02%
Increase in Total Cost LNG (%)	-	-	0,29%	0,19%	0,72%	0,47%	2,88%	1,89%	14,40%	9,46%
Increase in Total Cost Methanol (%)	-	-	0,25%	0,17%	0,62%	0,42%	2,49%	1,66%	12,43%	8,30%

For a better visualization of the impact of varying the carbon tax on fuel selection, the charts displaying the total cost in relation to the deployment cost of a bunkering vessel were remade, incorporating the total cost of HFO, LNG, and methanol in the different scenarios of carbon taxes. The chart in Figure 5.6 corresponds to a sailing speed of 22 knots, while the chart in Figure 5.7 refers to a sailing speed of 18 knots.

By analyzing both charts, it is possible to conclude that even as the carbon tax increases, either hydrogen or LNG (depending on the deployment cost per bunkering vessel) remains more cost-effective compared to other alternative fuels. It is also important to note that the higher the carbon tax, the higher the deployment cost per bunkering facility at which LNG becomes more financially advantageous than hydrogen.

Despite the high impact of the increase in the carbon tax on the total cost of HFO, even in the scenario where this increase is very high, resulting in a carbon tax ten times higher than the initial one, HFO continues to be more economical than any alternative fuel. This indicates that a very high carbon tax alone might not be enough to discourage the use of HFO. According to [17], governments are under increasing pressure to implement measures to close the cost gap between fossil fuels and alternative fuels in order to discourage the use of HFO and other fossil fuels. For this reason, it is recommended that countries provide financial support for the fuel transition, including funding for technology, infrastructure, and research and development projects. By proposing measures that make the supply of alternative fuels appealing, there is a chance that alternative fuels become more economical than HFO, as, according to [157], the price decreases as supply increases.

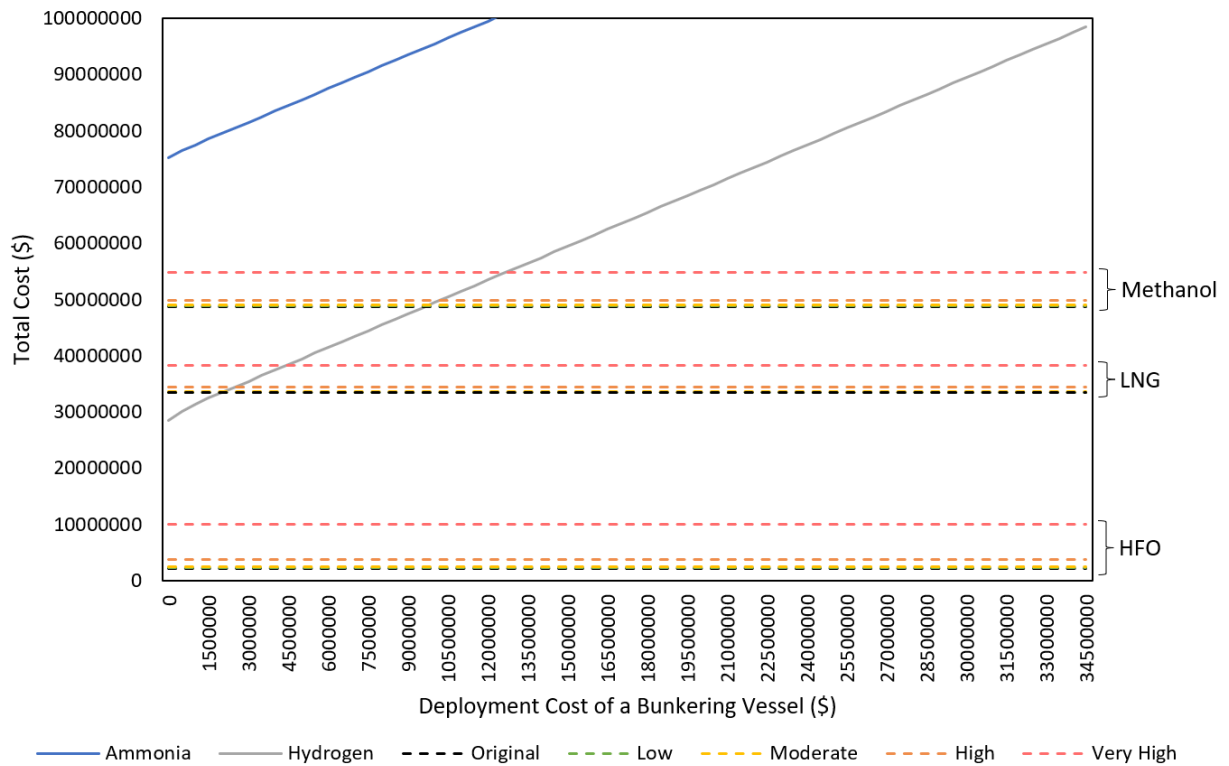


Figure 5.6 — Total Cost Assessment at Varying Deployment Costs of a Bunkering Vessel and Varying Carbon Taxes at a Sailing Speed of 22 knots

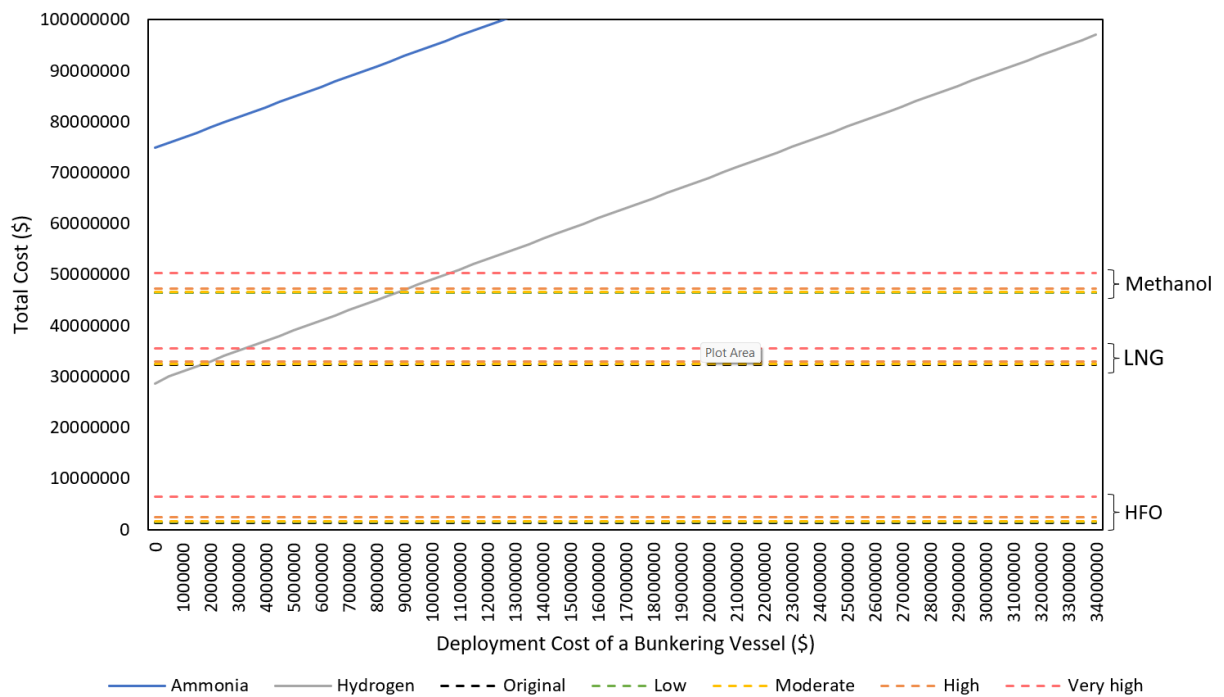


Figure 5.7 — Total Cost Assessment at Varying Deployment Costs of a Bunkering Vessel per Voyage and Varying Carbon Taxes at a Sailing Speed of 18 knot

CONCLUSION

This chapter presents a summary of the work done, demonstrating how it fulfilled the objectives defined for this research. Additionally, the chapter dives into the limitations identified during the study and recommendations for future research.

6.1 Research Overview and Contributions

This dissertation addressed the pertinent topic of GHG emissions and their contribution to global warming, focusing on the shipping industry. The literature review enabled the consolidation of insightful information about GHG emissions, and the measures being implemented to minimize them, namely slow steaming, green shipping corridors, the adoption of alternative energy sources and the optimization of shipping operations. This review brought to light a gap in the literature: the absence of a tool to guide stakeholders involved in green shipping corridor initiatives in determining and minimizing the costs of transitioning from fossil fuels to alternative fuels, in order to obtain the costs for different alternatives and choose the most economical one. This motivated the definition of the research objective: the proposal of a framework to find out and minimize the costs of transitioning from fossil fuel to different alternative fuels. To fulfill this objective, a comprehensive framework was presented, and its effectiveness was validated through a hypothetical case study.

During the application of the framework to the case study, all the steps that a stakeholder takes to determine which fuel is the most cost-effective were traversed, making it easier for stakeholders to replicate the framework's application. This started with the contextualization of the case study and the collection of the necessary inputs to implement the framework. Following that, the optimization model included in the framework was employed to minimize the applicable costs, leading to the estimation of the total cost for each alternative fuel.

In the absence of the values for the deployment costs of ammonia and hydrogen, it was determined at which value the use of both fuels became less advantageous than LNG and methanol. The assessment of the total cost of the different alternative fuels under study led to the conclusion that the most cost-advantageous alternative fuel is hydrogen for a deployment cost per bunkering vessel per voyage equal to or lower than 1 990 284,78 \$ for a sailing speed of 22 knots and 2 190 171,09 \$ for a sailing speed of 18 knots. For a deployment cost above this value, LNG becomes the most cost-advantageous option.

Moreover, the influence of variations in carbon pricing on fuel choice was analyzed. It was demonstrated that, despite the increase in the carbon tax, either hydrogen or LNG remain more cost-effective than other alternative fuels. It was also noted that the higher the carbon tax, the higher the deployment cost at which hydrogen is more financially advantageous than LNG. However, even in the scenario where the increase in the carbon tax is very high, HFO continues to be more economical than any alternative fuel. This indicates that additional measures to discourage the use of HFO are needed to complement carbon tax. A measure suggested to reduce the cost disparity between fossil and alternative fuels is for governments to provide funds to support the fuel transition, including funding for technology, infrastructure, and research and development initiatives.

In summary, the major contribution of this dissertation is in the providing of a tool that accelerates the implementation of green shipping corridors by guiding stakeholders in the selection of the most economical fuel path. This has a positive impact not only on the environment, given the reduction in emissions and consequent mitigation of global warming, but also on the companies, as the fuel transition would enable them to comply with environmental regulations and demonstrate their commitment to the environment, which would contribute to improve their reputation and competitiveness.

6.2 Limitations and Future Work

Several limitations were identified throughout this study, leaving room for improvement in subsequent research.

Due to the fact that bunkering vessels for ammonia and hydrogen are still under development, the prices of these bunkering facilities have not yet been published, making the results of applying the framework in the case study more subjective. It was not possible to provide an exact answer regarding which alternative fuel was more advantageous in terms of costs because the deployment cost of a bunkering vessel for ammonia and hydrogen is still

uncertain. Since ammonia and hydrogen are included in the majority of the long-term fuel mix projections and bunkering vessels for these fuels are already being developed, their deployment cost is expected to be known in the future. When this happens, it will be possible to apply this framework again to this case study or other situations to obtain an exact answer that guides the stakeholders involved in the fuel transition in a more precise direction.

In this framework, only the costs were considered as a decision factor for determining which alternative fuel to adopt, namely the cost of establishing bunkering vessels. However, the bunkering vessels deployed, in addition to serving the needs of the ship owner, can potentially become a revenue source by being available for other entities to refuel from them, resulting in additional profit for the owner. Therefore, in addition to including the costs of each fuel in the framework, it might be interesting to include the profit potential in future studies.

The proposed model applies to a single vessel, which does not reflect the reality of the majority of shipping companies, which operate a fleet of vessels. This model can be applied in that situation, but it would need to be done for one vessel at a time, which is not practical. For future studies, it is advisable to develop an extension of the model proposed in this study, applicable to a set of several vessels.

For the effective establishment of a green shipping corridor, it is necessary to consider all entities in the value chain [17]. This model is a starting point that takes into account the perspectives of ship owners and port authorities. However, in the future, a framework that considers the other entities that need to be involved in the establishment of green shipping corridors, such as fuel producers, cargo owners, governments, regulatory agencies, and financial institutions, must be developed.

This research is expected to serve as a catalyst for future studies dedicated to mitigating global warming within the shipping industry.

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APPENDIX

The optimization model for minimizing the cost of the number and location of bunkering stops was programmed in Python, using the FICO Xpress optimizer, to obtain the optimal solution for the number and location of bunkering stops. Because the value of some parameters changed from fuel to fuel, the python code used in each fuel (ammonia, hydrogen, methanol, and LNG) will be included in the Appendix.

A.1 Python Code for the Optimization Model for Minimizing the Cost of the Number and Location of Bunkering Stops for Ammonia

```

pip install xpress
import xpress as xp
from xpress import *
def bunk_loc_model(Cdu,Cou,legs,p_bv):

    # Sets
    nP = len(legs)+1 #Number of ports; len returns the number of items;
    Number of legs is the number of segments that the vessel travels between
    ports; number of ports = number of legs + 1
    P = [p for p in range(nP)] #List of all ports; range(nP) generates a
    sequence of numbers from 0 up to (but not including) nP
    A = [(i,j) for i in range(nP) for j in range(i+1,nP)] #List of all
    possible pairs of nodes; all values of j that are greater than i

    d = {a:sum(legs[a[0]:a[1]]) for a in A} #Creates dictionary where
    keys are all possible pairs of ports the vessel can travel between without
    bunkering, and values are the sum of distances between them

```

```

s = P[0] #start node
e = P[-1] #end node

#Define the LP problem
model = xp.problem()

#Decision variables
x = [xp.var(vartype=xp.binary) for i in P]

#Additional variables
y = {a: xp.var(vartype=xp.binary) for a in A}
d_1 = xp.var() #distance of the longest arc traveled by the vessel
without bunkering

model.addVariable(x, y, d_1)

objective = xp.Sum((0 if i in p_bv else Cdu) * x[i] for i in P) + Cou
* d_1

model.setObjective(objective, sense=xp.minimize)

#Constraints

#One arc leaves the start node
c1 = xp.Sum(y[(s, p)] for p in P if p is not s) == 1

#One arc enters the end node
c2 = xp.Sum(y[(p, e)] for p in P if p is not e) == 1

#The arcs that enter a node must also leave that same node
c3 = [xp.Sum(y[(a[0], j)] for a in A if a[1] is j) \
      - xp.Sum(y[(j, a[1])] for a in A if a[0] is j) == 0 \
      for j in P if j not in [s, e]]

#The distance of the longest arc (i,j) traveled by the vessel
without bunkering is the highest value of the distance traveled between
two ports without bunkering
c4 = [d[(a[0],a[1])] * y[(a[0],a[1])] <= d_1 for a in A]

#If an arc leaves a node, a bunkering terminal must be established
in that node (include if a bunkering terminal is required on start node)
c5 = [y[(a[0], a[1])] <= x[a[0]] for a in A]

#If an arc enters a node, a bunkering terminal must be established
in that node (include if a bunkering terminal is required on end node)
c6 = [y[(a[0], a[1])] <= x[a[1]] for a in A]

```

```

model.addConstraint(c1, c2, c3, c4, c5, c6)

# Solve the problem
model.solve()

return model,x,y,d_l

def analyse_solution(model,x,y,d_l,p_bv,P,Cou,A):

    totalCost = sum([(0 if p in p_bv else Cdu) * model.getSolution(x[p])
for p in P]) + Cou * model.getSolution(d_l)
    print("_____ \nTotal Cost:",totalCost)
    bunk_loc = [int(model.getSolution(x[i])) for i in P]
    sailings = {(a[0],a[1]):int(model.getSolution(y[(a[0],a[1]])) for a
in A} #creates a dictionary where each key is a pair of nodes (arc), and
the value is an integer indicating if the vessel travels along that arc
without bunkering or not
    long_dist = model.getSolution(d_l)
    print("dl:",long_dist)

    path = [k for k in sailings.keys() if sailings[k] is 1] # list of all
arcs (pairs of nodes) where the vessel travels without bunkering
    return path , long_dist, totalCost

def Simulation(Cdu):
    #Parameters
    #Cdu Cost of establishing the bunkering terminal at the port
    Cou = 93.64 #Lost opportunity cost due to the volume occupied by the
fuel tank
    legs = [628,360,1444,1610,1635,6577] #legs is the list of distances
between consecutive ports where the vessel stops in its route

    p_bv = [1, 3] #insert ports where bunkering services are already avail-
able

    nP = len(legs)+1 #Number of ports; len returns the number of items;
Number of legs is the number of segments that the vessel travels between
ports; number of ports = number of legs + 1
    P = [p for p in range(nP)]
    A = [(i,j) for i in range(nP) for j in range(i+1,nP)]

    d = {a:sum(legs[a[0]:a[1]]) for a in A}

    model,x,y,d_l = bunk_loc_model(Cdu,Cou,legs,p_bv)
    path, dl, totalCost = analyse_solution(model,x,y,d_l,p_bv,P,Cou,A)
    n_bunk_stops = len(path)+1
    print("Path:",path)

```

```

print("Number of Bunkering Stops:", n_bunk_stops)

return path, dl, totalCost, n_bunk_stops
results = [] # Create an empty list to store the results

for Cdu in range (0,1000000000, 1000000): #As the iterations progressed,
the range and step size were progressively decreased to determine the
exact values of Cdu to which there is a change in the solution of path,
dl, and n_bunk_stops.
    path, dl, totalCost, n_bunk_stops = Simulation(Cdu) #Run the function
to a range of Cdu values; output for each Cdu is a tuple w/ path, dl,
totalCost, n_bunk_stops
    results.append((totalCost, path, Cdu, dl, n_bunk_stops)) #Append the
tuples to the results list

for i in range(len(results)):
    print(results[i]) # Print results for each Cdu value (each result is
a tuple w/ path, dl, totalCost, n_bunk_stops)
print("The simulation is concluded")

```

A.2 Python Code for the Optimization Model for Minimizing the Cost of the Number and Location of Bunkering Stops for Hydrogen

```

pip install xpress
import xpress as xp
from xpress import *
def bunk_loc_model(Cdu,Cou,legs,p_bv):

    # Sets
    nP = len(legs)+1 #Number of ports; len returns the number of items;
Number of legs is the number of segments that the vessel travels between
ports; number of ports = number of legs + 1
    P = [p for p in range(nP)] #List of all ports; range(nP) generates a
sequence of numbers from 0 up to (but not including) nP
    A = [(i,j) for i in range(nP) for j in range(i+1,nP)] #List of all
possible pairs of nodes; all values of j that are greater than i

    d = {a:sum(legs[a[0]:a[1]]) for a in A} #Creates dictionary where
keys are all possible pairs of ports the vessel can travel between without
bunkering, and values are the sum of distances between them
    s = P[0] #start node
    e = P[-1] #end node

```

```

#Define the LP problem
model = xp.problem()

#Decision variables
x = [xp.var(vartype=xp.binary) for i in P]

#Additional variables
y = {a: xp.var(vartype=xp.binary) for a in A}
d_1 = xp.var() #distance of the longest arc traveled by the vessel
without bunkering

model.addVariable(x, y, d_1)

objective = xp.Sum((0 if i in p_bv else Cdu) * x[i] for i in P) + Cou
* d_1

model.setObjective(objective, sense=xp.minimize)

#Constraints

#One arc leaves the start node
c1 = xp.Sum(y[(s, p)] for p in P if p is not s) == 1

#One arc enters the end node
c2 = xp.Sum(y[(p, e)] for p in P if p is not e) == 1

#The arcs that enter a node must also leave that same node
c3 = [xp.Sum(y[(a[0], j)] for a in A if a[1] is j) \
      - xp.Sum(y[(j, a[1])] for a in A if a[0] is j) == 0 \
      for j in P if j not in [s, e]]

#The distance of the longest arc (i,j) traveled by the vessel
without bunkering is the highest value of the distance traveled between
two ports without bunkering
c4 = [d[(a[0],a[1])] * y[(a[0],a[1])] <= d_1 for a in A]

#If an arc leaves a node, a bunkering terminal must be established
in that node (include if a bunkering terminal is required on start node)
c5 = [y[(a[0], a[1])] <= x[a[0]] for a in A]

#If an arc enters a node, a bunkering terminal must be established
in that node (include if a bunkering terminal is required on end node)
c6 = [y[(a[0], a[1])] <= x[a[1]] for a in A]

model.addConstraint(c1, c2, c3, c4, c5, c6)

# Solve the problem

```

```

model.solve()

return model,x,y,d_l

def analyse_solution(model,x,y,d_l,p_bv,P,Cou,A):

    totalCost = sum([(0 if p in p_bv else Cdu) * model.getSolution(x[p])
for p in P]) + Cou * model.getSolution(d_l)
    print("_____ \nTotal Cost:",totalCost)
    bunk_loc = [int(model.getSolution(x[i])) for i in P]
    sailings = {(a[0],a[1]):int(model.getSolution(y[(a[0],a[1]])) for a
in A} #creates a dictionary where each key is a pair of nodes (arc), and
the value is an integer indicating if the vessel travels along that arc
without bunkering or not
    long_dist = model.getSolution(d_l)
    print("dl:",long_dist)

    path = [k for k in sailings.keys() if sailings[k] is 1] # list of all
arcs (pairs of nodes) where the vessel travels without bunkering
    return path , long_dist, totalCost
def Simulation(Cdu):
    #Parameters
    #Cdu Cost of establishing the bunkering terminal at the port
    Cou = 156.07 #Lost opportunity cost due to the volume occupied by the
fuel tank
    legs = [628,360,1444,1610,1635,6577] #legs is the list of distances
between consecutive ports where the vessel stops in its route

    p_bv = [] #insert ports where bunkering services are already available

    nP = len(legs)+1 #Number of ports; len returns the number of items;
Number of legs is the number of segments that the vessel travels between
ports; number of ports = number of legs + 1
    P = [p for p in range(nP)]
    A = [(i,j) for i in range(nP) for j in range(i+1,nP)]

    d = {a:sum(legs[a[0]:a[1]]) for a in A}

    model,x,y,d_l = bunk_loc_model(Cdu,Cou,legs,p_bv)
    path, dl, totalCost = analyse_solution(model,x,y,d_l,p_bv,P,Cou,A)
    n_bunk_stops = len(path)+1
    print("Path:",path)
    print("Number of Bunkering Stops:", n_bunk_stops)

    return path, dl, totalCost, n_bunk_stops

results = [] # Create an empty list to store the results

```

```

for Cdu in range (0,1000000000, 1000000): #As the iterations progressed,
the range and step size were progressively decreased to determine the
exact values of Cdu to which there is a change in the solution of path,
dl, and n_bunk_stops.
    path, dl, totalCost, n_bunk_stops = Simulation(Cdu) #Run the function
to a range of Cdu values; output for each Cdu is a tuple w/ path, dl,
totalCost, n_bunk_stops
    results.append((totalCost, path, Cdu, dl, n_bunk_stops)) #Append the
tuples to the results list

for i in range(len(results)):
    print(results[i]) # Print results for each Cdu value (each result is
a tuple w/ path, dl, totalCost, n_bunk_stops)
print("The simulation is concluded")

```

A.3 Python Code for the Optimization Model for Minimizing the Cost of the Number and Location of Bunkering Stops for LNG

```

pip install xpress
import xpress as xp
from xpress import *
def bunk_loc_model(Cdu,Cou,legs,p_bv):

    # Sets
    nP = len(legs)+1 #Number of ports; len returns the number of items;
Number of legs is the number of segments that the vessel travels between
ports; number of ports = number of legs + 1
    P = [p for p in range(nP)] #List of all ports; range(nP) generates a
sequence of numbers from 0 up to (but not including) nP
    A = [(i,j) for i in range(nP) for j in range(i+1,nP)] #List of all
possible pairs of nodes; all values of j that are greater than i

    d = {a:sum(legs[a[0]:a[1]]) for a in A} #Creates dictionary where
keys are all possible pairs of ports the vessel can travel between without
bunkering, and values are the sum of distances between them
    s = P[0] #start node
    e = P[-1] #end node

    #Define the LP problem
    model = xp.problem()

    #Decision variables

```

```

x = [xp.var(vartype=xp.binary) for i in P]

#Additional variables
y = {a: xp.var(vartype=xp.binary) for a in A}
d_1 = xp.var() #distance of the longest arc traveled by the vessel
without bunkering

model.addVariable(x, y, d_1)

objective = xp.Sum((0 if i in p_bv else Cdu) * x[i] for i in P) + Cou
* d_1

model.setObjective(objective, sense=xp.minimize)

#Constraints

#One arc leaves the start node
c1 = xp.Sum(y[(s, p)] for p in P if p is not s) == 1

#One arc enters the end node
c2 = xp.Sum(y[(p, e)] for p in P if p is not e) == 1

#The arcs that enter a node must also leave that same node
c3 = [xp.Sum(y[(a[0], j)] for a in A if a[1] is j) \
      - xp.Sum(y[(j, a[1])] for a in A if a[0] is j) == 0 \
      for j in P if j not in [s, e]]

#The distance of the longest arc (i,j) traveled by the vessel
without bunkering is the highest value of the distance traveled between
two ports without bunkering
c4 = [d[(a[0],a[1])] * y[(a[0],a[1])] <= d_1 for a in A]

#If an arc leaves a node, a bunkering terminal must be established
in that node (include if a bunkering terminal is required on start node)
c5 = [y[(a[0], a[1])] <= x[a[0]] for a in A]

#If an arc enters a node, a bunkering terminal must be established
in that node (include if a bunkering terminal is required on end node)
c6 = [y[(a[0], a[1])] <= x[a[1]] for a in A]

model.addConstraint(c1, c2, c3, c4, c5, c6)

# Solve the problem
model.solve()

return model,x,y,d_1

```

```

def analyse_solution(model,x,y,d_l,p_bv,P,Cou,A):

    totalCost = sum([(0 if p in p_bv else Cdu) * model.getSolution(x[p])
for p in P]) + Cou * model.getSolution(d_l)
    print("_____ \nTotal Cost:",totalCost)
    bunk_loc = [int(model.getSolution(x[i])) for i in P]
    sailings = {(a[0],a[1]):int(model.getSolution(y[(a[0],a[1]]))) for a
in A} #creates a dictionary where each key is a pair of nodes (arc), and
the value is an integer indicating if the vessel travels along that arc
without bunkering or not
    long_dist = model.getSolution(d_l)
    print("dl:",long_dist)

    path = [k for k in sailings.keys() if sailings[k] is 1] # list of all
arcs (pairs of nodes) where the vessel travels without bunkering
    return path , long_dist, totalCost

def Simulation(Cdu):
    #Parameters
    #Cdu Cost of establishing the bunkering terminal at the port
    Cou = 31.21 #Lost opportunity cost due to the volume occupied by the
fuel tank
    legs = [628,360,1444,1610,1635,6577] #legs is the list of distances
between consecutive ports where the vessel stops in its route

    p_bv = [2, 3] #insert ports where bunkering services are already avail-
able

    nP = len(legs)+1 #Number of ports; len returns the number of items;
Number of legs is the number of segments that the vessel travels between
ports; number of ports = number of legs + 1
    P = [p for p in range(nP)]
    A = [(i,j) for i in range(nP) for j in range(i+1,nP)]

    d = {a:sum(legs[a[0]:a[1]]) for a in A}

    model,x,y,d_l = bunk_loc_model(Cdu,Cou,legs,p_bv)
    path, dl, totalCost = analyse_solution(model,x,y,d_l,p_bv,P,Cou,A)
    n_bunk_stops = len(path)+1
    print("Path:",path)
    print("Number of Bunkering Stops:", n_bunk_stops)

    return path, dl, totalCost, n_bunk_stops

results = [] # Create an empty list to store the results

for Cdu in range (120000,120001):

```

```

    path, dl, totalCost, n_bunk_stops = Simulation(Cdu) #Run the function
to a range of Cdu values; output for each Cdu is a tuple w/ path, dl,
totalCost, n_bunk_stops
    results.append((totalCost, path, Cdu, dl, n_bunk_stops)) #Append the
tuples to the results list

for i in range(len(results)):
    print(results[i]) # Print results for each Cdu value (each result is
a tuple w/ path, dl, totalCost, n_bunk_stops)
print("The simulation is concluded")

```

A.4 Python Code for the Optimization Model for Minimizing the Cost of the Number and Location of Bunkering Stops for Methanol

```

pip install xpress
import xpress as xp
from xpress import *
def bunk_loc_model(Cdu,Cou,legs,p_bv):

    # Sets
    nP = len(legs)+1 #Number of ports; len returns the number of items;
Number of legs is the number of segments that the vessel travels between
ports; number of ports = number of legs + 1
    P = [p for p in range(nP)] #List of all ports; range(nP) generates a
sequence of numbers from 0 up to (but not including) nP
    A = [(i,j) for i in range(nP) for j in range(i+1,nP)] #List of all
possible pairs of nodes; all values of j that are greater than i

    d = {a:sum(legs[a[0]:a[1]]) for a in A} #Creates dictionary where
keys are all possible pairs of ports the vessel can travel between without
bunkering, and values are the sum of distances between them
    s = P[0] #start node
    e = P[-1] #end node

    #Define the LP problem
    model = xp.problem()

    #Decision variables
    x = [xp.var(vartype=xp.binary) for i in P]

    #Additional variables
    y = {a: xp.var(vartype=xp.binary) for a in A}

```

```

    d_l = xp.var() #distance of the longest arc traveled by the vessel
without bunkering

    model.addVariable(x, y, d_l)

    objective = xp.Sum((0 if i in p_bv else Cdu) * x[i] for i in P) + Cou
* d_l

    model.setObjective(objective, sense=xp.minimize)

#Constraints

#One arc leaves the start node
c1 = xp.Sum(y[(s, p)] for p in P if p is not s) == 1

#One arc enters the end node
c2 = xp.Sum(y[(p, e)] for p in P if p is not e) == 1

#The arcs that enter a node must also leave that same node
c3 = [xp.Sum(y[(a[0], j)] for a in A if a[1] is j) \
      - xp.Sum(y[(j, a[1])] for a in A if a[0] is j) == 0 \
      for j in P if j not in [s, e]]

    #The distance of the longest arc (i,j) traveled by the vessel
without bunkering is the highest value of the distance traveled between
two ports without bunkering
    c4 = [d[(a[0],a[1])] * y[(a[0],a[1])] <= d_l for a in A]

    #If an arc leaves a node, a bunkering terminal must be established
in that node (include if a bunkering terminal is required on start node)
    c5 = [y[(a[0], a[1])] <= x[a[0]] for a in A]

    #If an arc enters a node, a bunkering terminal must be established
in that node (include if a bunkering terminal is required on end node)
    c6 = [y[(a[0], a[1])] <= x[a[1]] for a in A]

    model.addConstraint(c1, c2, c3, c4, c5, c6)

# Solve the problem
model.solve()

return model,x,y,d_l

def analyse_solution(model,x,y,d_l,p_bv,P,Cou,A):

    totalCost = sum([(0 if p in p_bv else Cdu) * model.getSolution(x[p])
for p in P]) + Cou * model.getSolution(d_l)

```

```

print("_____ \nTotal Cost:",totalCost)
bunk_loc = [int(model.getSolution(x[i])) for i in P]
sailings = {(a[0],a[1]):int(model.getSolution(y[(a[0],a[1]])) for a
in A} #creates a dictionary where each key is a pair of nodes (arc), and
the value is an integer indicating if the vessel travels along that arc
without bunkering or not
long_dist = model.getSolution(d_l)
print("dl:",long_dist)

path = [k for k in sailings.keys() if sailings[k] is 1] # list of all
arcs (pairs of nodes) where the vessel travels without bunkering
return path , long_dist, totalCost

def Simulation(Cdu):
    #Parameters
    #Cdu Cost of establishing the bunkering terminal at the port
    Cou = 62.43 #Lost opportunity cost due to the volume occupied by the
fuel tank
    legs = [628,360,1444,1610,1635,6577] #legs is the list of distances
between consecutive ports where the vessel stops in its route

    p_bv = [0, 1, 2, 5] #insert ports where bunkering services are already
available

    nP = len(legs)+1 #Number of ports; len returns the number of items;
Number of legs is the number of segments that the vessel travels between
ports; number of ports = number of legs + 1
    P = [p for p in range(nP)]
    A = [(i,j) for i in range(nP) for j in range(i+1,nP)]

    d = {a:sum(legs[a[0]:a[1]]) for a in A}

    model,x,y,d_l = bunk_loc_model(Cdu,Cou,legs,p_bv)
    path, dl, totalCost = analyse_solution(model,x,y,d_l,p_bv,P,Cou,A)
    n_bunk_stops = len(path)+1
    print("Path:",path)
    print("Number of Bunkering Stops:", n_bunk_stops)

    return path, dl, totalCost, n_bunk_stops

results = [] # Create an empty list to store the results

for Cdu in range (36000,36001):
    path, dl, totalCost, n_bunk_stops = Simulation(Cdu) #Run the function
to a range of Cdu values; output for each Cdu is a tuple w/ path, dl,
totalCost, n_bunk_stops

```

```
    results.append((totalCost, path, Cdu, dl, n_bunk_stops)) #Append the
tuples to the results list

for i in range(len(results)):
    print(results[i]) # Print results for each Cdu value (each result is
a tuple w/ path, dl, totalCost, n_bunk_stops)
print("The simulation is concluded")
```




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