



# PROFIT MAXIMIZATION FOR MARITIME FUEL SUSTAINABLE LOGISTICS

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BSc in Engineering Sciences and Industrial Management





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## **Profit Maximization for Maritime Fuel Sustainable Logistics**

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To my dear parents, who celebrated with me every achievement, big or small.



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"In the middle of every difficulty lies opportunity."

- Albert Einstein



## ABSTRACT

Sustainability awareness has been growing in the shipping industry over the years. While playing a vital role in facilitating the transportation of goods across oceans, the increasing concerns regarding climate change and environmental sustainability resulted in the implementation of ambitious green targets. The use of polluting bunker fuels in the shipping industry must be minimized or even eliminated. Developing a systematic tool to maximize profit while adhering to carbon dioxide (CO<sub>2</sub>) emissions limit and total demand satisfaction in all destinations is the main aim of this master thesis.

Consequently, a Mixed-Integer Linear Programming model was developed to maximize the profit of transporting fuels in a sustainable setting. The transportation is made from a single exportation port (EP) to multiple destinations, considering the transported fuels' availability in the EP, their demands in each destination, the vessels' capacities, and the CO<sub>2</sub> emissions limit imposed by regulatory authorities. The application of the model indicates the quantity of fuel transported in each vessel to each destination and the number of shipments needed to do so. Four scenarios were tested, each varying the bunker fuel options for use. The research findings reveal that to achieve profit maximization in the transitional phase to decarbonization that the industry is currently undergoing, a combination of shipments bunkered with CO<sub>2</sub> emitting fuels and others with zero emission fuels is the sustainable approach.

**Keywords:** Fuel Transportation, Shipping Industry, GHG emissions, Sustainability, Profit Maximization, Bunker Fuels, Optimization, Linear Programming.



## RESUMO

A consciencialização para a sustentabilidade tem vindo a crescer no setor do transporte marítimo ao longo dos anos. Embora desempenhe um papel vital na facilitação do transporte de mercadorias através de oceanos, as preocupações crescentes com as alterações climáticas e a sustentabilidade ambiental resultaram na implementação de objetivos ecológicos ambiciosos. A utilização de combustíveis de propulsão poluentes no sector do transporte marítimo deve ser minimizada ou até mesmo eliminada. O desenvolvimento de uma ferramenta sistemática para maximizar o lucro, respeitando os limites de emissões de dióxido de carbono (CO<sub>2</sub>) e a satisfação total da procura em todos os destinos, é o principal objetivo desta dissertação.

Consequentemente, foi desenvolvido um modelo de Programação Linear Inteira Mista para maximizar o lucro do transporte de combustíveis num cenário sustentável. O transporte é efetuado de um único porto de exportação (EP) para múltiplos destinos, considerando a disponibilidade dos combustíveis transportados no EP, a sua procura em cada destino, as capacidades dos navios e o limite de emissões de CO<sub>2</sub> imposto pelas autoridades reguladoras. A aplicação do modelo indica a quantidade de combustível transportada em cada navio para cada destino e o número de viagens necessárias para o fazer. Foram testados quatro cenários, cada um variando as opções de combustível de propulsão a utilizar. Os resultados da investigação revelam para alcançar a maximização dos lucros na fase de transição para a descarbonização que a indústria está atualmente a atravessar, a abordagem sustentável é uma combinação de viagens que utilizam combustíveis que emitem CO<sub>2</sub> e outras com combustíveis de emissão zero.

**Palavas chave:** Transporte de Combustíveis, Indústria Marítima, Emissões de GEE, Sustentabilidade, Maximização de Lucro, Combustíveis de propulsão, Otimização, Programação Linear.



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## GLOSSARY

<b>Auxiliary system</b>	Machinery other than the main propulsion unit, which ensures good performance for the needs of the vessel. It can be used to maintain temperature or pressure and usually uses the vessel's bunker fuel.
<b>Ballast water</b>	Fresh or salt water stored in the vessel's tanks. It is used to ensure stability during a trip when vessels are not transporting enough cargo to maintain their stability.
<b>Bunker fuels</b>	Fuels used in the vessels' engines for propulsion.
<b>Demurrage</b>	Delay in the delivery of goods.
<b>Idle vessel</b>	Vessel that has been in port without being loaded or unloaded.
<b>Inbound journey</b>	The voyage from the destination to the original point.
<b>Maritime industry</b>	Industry related to ocean, sea, vessels, navigation from one port to another, and other related activities
<b>Outbound journey</b>	The voyage from an origin to a destination.
<b>Recurrent voyages</b>	Repeated voyages with the same round trip with different cargo.
<b>Round trip</b>	A voyage to a place and back usually using the same route.
<b>Shipping industry</b>	Industry related to delivering goods from one port to another. Included in the Maritime Industry.



## ACRONYMS

<b>AER</b>	Annual Efficiency Ratio
<b>AI</b>	Artificial Intelligence
<b>BC</b>	Black Carbon
<b>BWM</b>	Ballast Water Management
<b>CCS</b>	Carbon Capture and Storage
<b>cDIST</b>	Cargo-Distance
<b>CH<sub>4</sub></b>	Methane
<b>CII</b>	Carbon Intensity Indicator
<b>CO<sub>2</sub></b>	Carbon Dioxide
<b>coZEV</b>	Cargo Owners for Zero Emission Vessels
<b>DIST</b>	Distance
<b>DME</b>	Dimethyl Ether
<b>DWT</b>	Dead Weight Tonnage
<b>ECAs</b>	Emission Control Areas
<b>EEDI</b>	Energy Efficiency Design Index
<b>EEOI</b>	Energy Efficiency Operational Indicator
<b>EEPI</b>	Energy Efficiency Performance Indicator
<b>EEXI</b>	Energy Efficiency Existing Ships Index

<b>EP</b>	Exportation Port
<b>ESI</b>	Environmental Ship Index
<b>ET</b>	Event Tree
<b>ETTs</b>	Emerging Transport Technologies
<b>FAME</b>	Fatty Acid Methyl Esters
<b>FT</b>	Fault Tree
<b>GHG</b>	Greenhouse Gas
<b>GZC</b>	Getting to Zero Coalition
<b>H<sub>2</sub></b>	Hydrogen
<b>H<sub>2</sub>O</b>	Water
<b>HFO</b>	Heavy Fuel Oil
<b>HSFO</b>	High Sulphur Fuel Oil
<b>HVO</b>	Hydrotreated Vegetable Oil
<b>IAPH</b>	International Association of Ports and Harbors
<b>IMO</b>	International Maritime Organization
<b>IRP</b>	Inventory Routing Problem
<b>LNG</b>	Liquefied Natural Gas
<b>LPG</b>	Liquefied Petroleum Gas
<b>LSFO</b>	Low Sulphur Fuel Oil
<b>MARPOL</b>	International Convention for the Prevention of Pollution from Ships
<b>MDO</b>	Marine Diesel Oil
<b>MES</b>	Mathematical, Econometric, and Statistical Analysis
<b>MGO</b>	Marine Gas Oil
<b>MILP</b>	Mixed-Integer Linear Programming
<b>MIP</b>	Mixed Integer Programming
<b>MOLP</b>	Multi-Objective Linear Programming

<b>MPPSRP</b>	Multi-Period Petrol Station Replenishment Problem
<b>NH<sub>3</sub></b>	Ammonia
<b>NM</b>	Nautical Miles
<b>NO<sub>x</sub></b>	Nitrous oxide
<b>PAHs</b>	Polycyclic Aromatic Hydrocarbons
<b>PM</b>	Particulate Matter
<b>PSA</b>	Probabilistic Safety Assessment
<b>RVRPTW</b>	Robust Vehicle Routing Problem with Time Windows
<b>SDGs</b>	Sustainable Development Goals
<b>SEEMP</b>	Ship Energy Efficiency Management Plan
<b>SIMP</b>	Solid Isotropic Material with Penalization
<b>SMR</b>	Steam Methane Reforming
<b>SNF</b>	Spent Nuclear Fuel
<b>SO<sub>x</sub></b>	Sulfur Oxide
<b>TEU</b>	Twenty-foot Equivalent Unit
<b>ULCC</b>	Ultra Large Crude Carriers
<b>ULSFO</b>	Ultra Low Sulphur Heavy Fuel Oil
<b>UN</b>	United Nations
<b>UNFCCC</b>	United Nations Framework Convention on Climate Change
<b>USD</b>	United States Dollars
<b>VLSFO</b>	Very Low Sulfur Fuel Oil
<b>VMI</b>	Vendor Management Inventory
<b>ZEVs</b>	Zero Emissions Vessels



## SYMBOLS

$I$	The set of transported fuels, indexed by $i$
$J$	The set of bunker fuels, indexed by $j$
$K$	The set of destinations, indexed by $k$
$P_i^Q$	Transportation price regarding the quantity of transported fuel ( $i$ )
$P_j^D$	Transportation price regarding distance travelled using fuel ( $j$ )
$d_k^{EP}$	Distance between exporting port and destination port ( $k$ )
$M$	Distance factor for a round trip, considering the distance of two separate voyages - one to go and one to come back - and the auxiliary system's contribution of 30% of the export trip
$C_j^b$	Bunker fuel cost for fuel ( $j$ )
$F_j^c$	Fuel consumption for fuel ( $j$ )
$C_i^S$	Normalized Vessel Cost per shipment for fuel ( $i$ )
$C_j^E$	Normalized Engine Cost per shipment for fuel ( $j$ )
$C^e$	Cost of $CO_2$ emissions
$E_j$	$CO_2$ emissions per ton of fuel ( $j$ ) used
$A_i$	Availability of fuel ( $i$ ) in the EP
$D_{ik}$	Demand of fuel ( $i$ ) in destination ( $k$ ) per year
$Q_i^S$	Capacity of the vessel that transports fuel ( $i$ )
$L$	Limit of $CO_2$ emissions per year

$x_{ijk}$	Quantity of fuel ( $i$ ) transported, using vessels fueled with bunker fuel ( $j$ ) to destination ( $k$ ) per year
$y_{ijk}$	Number of shipments transporting fuel ( $i$ ), using fuel ( $j$ ) as bunker fuel to destination ( $k$ ) in a year
$\Sigma$	The sum of terms that follow a pattern.
$\forall$	The "for all" or "for any" symbol.
$\epsilon$	The "belongs to", "is a member of", "is an element of", or "is in" symbol.
$Z$	The set of integer numbers, i.e. {... , -2, -1, 0, 1, 2, ...}

# INTRODUCTION

This master thesis aims to address the problem of sustainably optimizing profitability when transporting different types of fuels. The present chapter introduces the maritime industry's background as well as the research problem's scope. It outlines the significance of maritime transportation in global trade and presents the research objectives. The methodology employed to solve this issue will also be explained. Lastly, the chapter ends with the presentation of the master thesis's structure.

## 1.1 Context and Problem Statement

Maritime and shipping industries, whilst often used interchangeably, actually refer to distinct concepts. The maritime industry encompasses all activities related to the sea, including shipping, but is not solely focused on shipping. According to Meyers et al., (2021) this includes shipbuilding, harbor operations, maritime law and maritime safety. Conversely, Ichimura et al., (2022) defined the shipping industry as a subset of the maritime industry that focusses specifically on transporting goods and people by sea, which includes cargo handling, vessel management and freight forwarding.

The shipping industry delivers more than 80% of the world trade by volume (United Nations Conference & on Trade and Development, 2022), transporting 10 billion tons of goods annually by sea (Mueller et al., 2023). It enables the access of markets in different countries by allowing them to import essential resources and export national products, maintaining the world economy balanced (Tadros et al., 2023; Yan et al., 2021).

Even though maritime transport allows greater quantities of goods to be moved compared to other means of transportation, it is accountable for the emission of 3% of global greenhouse gases (GHG), encompassing carbon dioxide (CO<sub>2</sub>) emissions (Mueller et al., 2023). The need to reduce GHG became obvious and, in 2004, the concept of Green Shipping

emerged (Zhao et al., 2022) and was defined as the controlled use of resources and energy for maritime transportation in a way that reduces the negative impacts of shipping while protecting the environment (Lee & Nam, 2017). Several policies and measures were proposed, analyzed, and put to practice by authorities to help mitigate climate change (F. Wang et al., 2023). The Paris Agreement, which was adopted in 2015 as part of the United Nations Framework Convention on Climate Change (UNFCCC), intends to diminish global climate change committing to reducing emissions by at least 55% by 2030 when compared to pre-industrial levels (European Commission, 2023). The Clydebank Declaration, a pledge formed in 2021 by a cluster of maritime nations, highlights the significance of the maritime industry in accomplishing sustainable development, decarbonization, and environmental preservation (United Kingdom Government, 2022). The International Maritime Organization (IMO), which is a United Nations (UN) specialized entity, establishes rules and specifications for the security, safety, and ecological efficiency of the world's maritime sector (International Maritime Organization, 2019a). The shipping industry is a significant contributor to overall CO<sub>2</sub> emissions, therefore, to address this problem, the IMO has implemented CO<sub>2</sub> emission limits, most notably through indexes and carbon indicators. These regulations encourage the adoption of technologies and practices that enhance fuel efficiency and decrease CO<sub>2</sub> emissions. In relation to the maritime industry, these agreements, declarations and policies, including the emissions limits, collectively emphasize the need for the sector to adopt cleaner technologies, decrease emissions, and contribute to worldwide efforts to combat climate change, ensuring a sustainable future (Tadros et al., 2023).

The shipping industry's future relies on the adoption of new technologies and fuels in order to decarbonize it (Hessevik, 2022). Bhattacharyya et al., (2023) highlighted that there are several fossil fuels that are still being used for vessel propulsion and some proposed alternatives to replace or combine with them. The established fuels mostly derive from sources of petroleum, heavily polluting the environment (Stavroulakis et al., 2023). Emerging fuels can be classified as grey, blue or green fuels, depending on the way the hydrogen is produced (Moreno-Brieva et al., 2023). Grey hydrogen is generated from fossil fuels, namely natural gas. Blue hydrogen uses the same process as grey hydrogen but employs a technology that captures the carbon released during its production. Green hydrogen is produced from water via

renewable energy sources (Moreno-Brieva et al., 2023). Figure 1-1 shows a diagram organizing the different categories of fuels by their level of pollution.



Figure 1-1 - Color-code highlighting the environmental impact of maritime fuels

The maritime fuel's supply chain encompasses the extraction, production, and distribution processes, involving a range of operations (Jaklič et al., 2006). This master thesis explores the distribution of fuels via maritime transport, involving multiple factors related to transported fuels, to bunker fuels and to destinations. The type of fuel that is being transported has an effect on the availability of a fuel, on the capacity of the vessel and on the normalized costs of the vessels. Likewise, bunker fuel influences the bunker fuel cost, the fuel consumption, the normalized engine costs for each vessel and the emissions rate of a fuel. The price for fuel delivery is influenced by the quantity of transported fuel and the distance traveled to each destination, whilst the demand is affected by both the transported fuel and the destination. Economically, besides the costs related to transportation and fuel use, there are costs linked to the emission of CO<sub>2</sub>, namely through a tax imposed by authorities on quantity of emitted CO<sub>2</sub>.

The future is still uncertain since it has not been decided yet which technologies and fuels are more suited for the shipping industry (Hessevik, 2022). Various methods are used to assist this industry both economically and environmentally, namely, linear programming, that is used to generate beneficial optimization models, and literature reviews, that provide decision-makers with valuable insights related to the industry's many aspects, helping them make informed decisions. Some examples are the case of Ye et al. (2017) that used mixed-integer linear programming (MILP) to maintain overall shipping costs minimized, while satisfying various operational constraints, the case of Moretti et al. (2021) that used MILP to create an economic optimization model for a green methanol supply chain and applied it to an Italian case study, and the case of Riera et al. (2023) that summarized the latest optimization models for hydrogen production and supply chains by analyzing and evaluating recent literature.

Research shows various optimization models for fuel transportation and optimal bunker fuel decision, however there is still a research gap, particularly in the development of optimization models, considering the profitable delivery of various fuels while respecting environmental concerns in the same model. Only the research developed by Al-Enazi et al. (2022) was able to optimize economically and environmentally the maritime transportation of several fuels

across seas to different destinations. Al-Enazi et al. (2022) present a multi-objective linear programming (MOLP) optimization model that assesses various scenarios, aiming to maximize profit, minimize GHG emissions, and finding a balance between profit and environmental impact. However, besides being a scenario-based model unable to be adjusted to other case studies, this model considers only fuels originating from natural gas, excluding some of the most attractive fuel alternatives. With the urgent demand for cleaner fuels (F. Wang et al., 2023), new models should also incorporate those fuel alternatives, that most likely reflect the future of shipping. Al-Enazi et al. (2022) model relies on case-specific assumptions which restricts the versatility of the model. The main aim of this master thesis is to close this research gap by developing a versatile, realistic and up-to-date Mixed-Integer Linear Programming (MILP) mathematical optimization model capable of maximizing the profit of a fuel carrier aiming to transport different types of fuel sustainably from a single exportation port (EP) to multiple destinations. The developed model includes different fuel options for transport and bunkering, including several traditional and emerging fuels, demonstrating its versatility. The model is adaptable to a company's needs as it can be applied to different scenarios only changing the EP, destinations, transported and/or bunker fuels. Figure 1-2 displays a simplified schematic overview of the fuel delivery process, highlighting the different combinations of transport and bunker fuels.

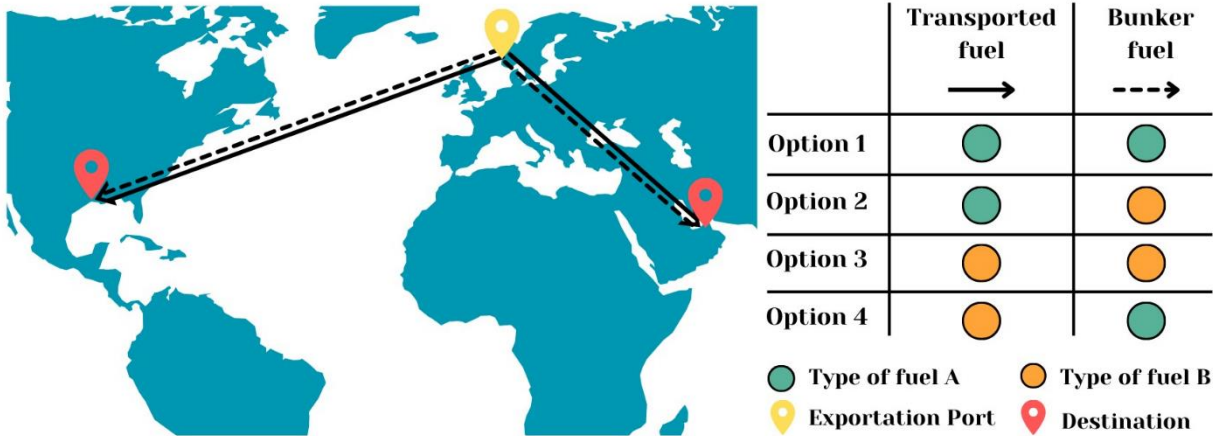


Figure 1-2 - Overview of the fuel delivery process

From Figure 1-2 it is evident that the fuels are transported from the only EP to several destinations. In a shipment, the bunker fuel and the transported fuel must be considered. In a universe where only two different types of fuels - Type A and Type B - exist, there are four options of fuel combinations to be considered for each shipment: Option 1 and Option 3 show

that the same type of fuel can be transported and used for bunker fuel and Option 2 and Option 4 showcase a scenario where the bunker fuel is independent from the transported fuel. In each shipment there is only one transported fuel and one bunker fuel.

The model developed in this master thesis considers the availability of the different types of transported fuels in the EP, the demand of each fuel in each destination, the capacity of the vessels for each type of fuel and the CO<sub>2</sub> emissions' limit that is imposed by regulatory authorities. The model maximizes profit by taking into account the revenue from delivering fuels, the costs associated with transporting them to each destination, the engine and vessel normalized costs, as well as costs regarding CO<sub>2</sub> emissions, allowing the model to be as close as possible to reality. The model proposed in this master thesis can be applicable to an extensive range of scenarios, as it can cover multiple transported and bunker fuel combinations, and it can be customized for any company aiming to export any type of fuel to any destination. By introducing new fuel types, the company ensures their adaptability to market future changes. Solving the aforementioned problem is critical for shipping businesses to thrive financially, by becoming progressively more profitable. As environmental awareness increases and authorities impose regulations and costs concerning carbon emissions, optimizing fuel transportation also includes respecting CO<sub>2</sub> emissions' limit and correctly choosing the appropriate bunker fuel for a shipment.

## 1.2 Objectives and Methodological Approach

The proposed mathematical model developed in this master thesis aims to maximize profit when is imposed total demand satisfaction and compliance with the emissions limit. The results indicate the optimal quantity of fuel transported by each vessel fueled with the bunker fuels chosen and the number of shipments needed to do so. The optimal bunker fuels that should be used is then determined, as well as the profit and the quantity of CO<sub>2</sub> emissions of each scenario. The fundamental aim of the model is to provide decision-makers with a mathematical tool that can be used to make informed decisions about maximizing a company's profit, while satisfying the demand in all destinations and complying with sustainability rules.

Broader goals include providing an overview of fuel transportation optimization models, as well as their objectives and methodologies used, and to encourage the use of cleaner fuels for a future greener industry. Additionally, another objective is to provide a customizable model that is adaptable to any company's needs and requirements, only changing the input

data. The model can be modified and extended to incorporate future situations, namely the inclusion or exclusion of fuels and destinations.

Considering the aforementioned objectives, an appropriate research methodology was established to solve the presented problem. This methodology comprises the following steps:

- i. Research to gain specific knowledge about the industry and the problems faced in it;
- ii. Literature review focusing on the shipping industry, particularly green shipping with use of alternative fuels, and mathematical models, especially the ones referring to transportation of fuels via sea;
- iii. Development of the mathematical optimization model including the objective function and constraints;
- iv. Familiarization with Google Colaboratory, or *Colab*, python programming language and the FICO Xpress algorithms that, combined, allow for the correct application of the model;
- v. Verification of the developed model in Microsoft Excel;
- vi. Retrieval of illustrative data for the model's parameters;
- vii. Implementation of the model to several scenarios to solve the Profit Maximization problem in a set of illustrative contexts;
- viii. Present and analyze the results observed and withdraw conclusions.

### 1.3 Master Thesis's Structure

This master thesis comprises five primary chapters.

This first introductory chapter succinctly shows the background of the shipping industry and its problems followed by an introduction of the research done in the field and the identification of the problem to be solved. The objectives and methodologies to be implemented are also highlighted in this chapter.

Chapter 2 is dedicated to an extensive review of the literature regarding the shipping industry, its importance and the viability of its future. Different marine bunker fuels and types of vessels are reviewed as well as the fuel's environmental impacts. A detailed description of sustainable practices in the industry is made, focusing on the green practices and their environmental benefits. The chapter ends with a review of the mathematical models created to assist the industry, focusing on the ones that reference the optimization of fuel allocation and transportation.

In chapter 3 it is presented a comparison between the developed model and the model that inspired it - Al-Enazi et al. (2022) model - followed by a comprehensive elucidation of the developed model and its mathematical formulation. The decision variables, objective function

and constraints are distinctly defined as well as the assumptions made to simplify the model. Chapter 4 includes a verification of the proposed model and presents the data retrieved for the illustrative case study as well as the scenarios developed. Results of the application of the developed model are also presented in this chapter, including the optimal amount of each transported fuel, the number of shipments needed to satisfy the demand in each destination, the total profit, the bunker fuels chosen and the total emissions for all scenarios. An interpretation of the findings is also presented in this chapter.

In Chapter 5, the conclusions of the research carried out are presented, as well as its contributions and suggestions for the progress of future research.



## LITERATURE REVIEW

In this second chapter, it is provided an overview of the current state of the art regarding the master thesis's topic. Firstly, a brief review of the shipping industry will be presented, exploring its significance, challenges, and impact on global trade. Additionally, an overview of the most important documents, declarations and organizations concerning the green shipping industry are covered. This is followed by a review of the various fuels currently used for vessel propulsion and the sustainable alternatives presented for the progress of the industry. Afterwards, a description of the different types of vessels used in the maritime industry is presented, including an identification of the ones appropriate for transporting each type of fuel. The chapter ends with a detailed review of the different mathematical models encountered in the literature regarding the maritime transportation of fuels.

### 2.1 The Shipping Industry

For centuries, maritime transportation has been a major form of communication between nations (Prabowo et al., 2019). Sailing vessels were the first means of transportation and continued to be used until the 20<sup>th</sup> century (Geels, 2002), even though the invention of the steam engine triggered the Industrial Revolution (Shahbakhsh et al., 2022) in the late 18<sup>th</sup>/early 19<sup>th</sup> century. Shipping became faster and more reliable as steam vessels started to slowly replace the use of wind conditions as a factor for transportation (Rojon & Dieperink, 2014).

Shipping has a vital role in international commerce since it allows the import and export of crucial goods as well as economic growth and human welfare (Bhattacharyya et al., 2023; H. Wang et al., 2023). Regarding the bulk transportation of products over vast distances, shipping is believed to be the most economically efficient type of transportation (Bhattacharyya et al.,

2023; Rojon & Dieperink, 2014). Although the maritime transportation routes serve as sea highways for cargo transportation, the environmental impact of the shipping industry on Earth has become an urgent problem. The shipping industry mainly uses fossil fuels as its means for propulsion of vessels, leading to these fuels' depletion (Lv et al., 2023). Their use releases CO<sub>2</sub>, methane (CH<sub>4</sub>) and nitrous oxides (NO<sub>x</sub>) that trap the heat in the atmosphere intensifying global warming, the acidification of the oceans, the melting of glaciers and ice sheets, and the rise in sea level (Yasmin et al., 2022). The industry also emits sulfur oxide (SO<sub>x</sub>) and other pollutants harmful to human health, namely particulate matter (PM) and black carbon (BC) (Mueller et al., 2023).

Governments and countries are joining forces to achieve carbon neutrality targets through several policies, agreements, and regulations (Tadros et al., 2023). Efficient operations are possible by changing the design, the materials and the technologies used in the industry, contributing to make it more sustainable. However, the main obstacle is finding a way to reduce or replace the use of fossil fuels (Tsouri et al., 2022). Most of the fuels used currently derive from sources of petroleum, seriously harming the earth's atmosphere with consequences on ecosystems and human health (Stavroulakis et al., 2023). Fuels with lower or even no emissions are being explored to serve as cleaner alternatives (Ashrafi et al., 2022). The release of GHG emissions is causing major disturbance to the welfare of the planet, including the health of mankind, fauna and flora (Mueller et al., 2023). Although the obstacles to increasing sustainability in the industry are still numerous, it is imperative to develop alternatives and solutions to lighten the climate change problem (Tsouri et al., 2022). Switching to more clean fuels for vessel propulsion is the most discussed solution, since the fuels in use nowadays are mostly derived from sources of petroleum, releasing CO<sub>2</sub> into the atmosphere along with other harmful air pollutants that trap the heat and lead to the increase of temperature (Tadros et al., 2023).

A new revolution is happening in the industry since the introduction of smart and autonomous shipping: the industry 4.0 digital revolution (Shahbakhsh et al., 2022). By exploring the articles related to the shipping industry it is possible to gain some perspective on the best ways to benefit it. According to Yan et al., (2021), research methods such as mathematical, econometric, and statistical analysis (MES), literature review, case studies and simulations are among the most utilized by authors. However, there is still a gap in the literature about using a MILP optimization approach to enhance the profitability of transportation of various types of fuels to several destinations, while reducing the impact of maritime transportation on the environment, that reflects the transitional phase of the shipping industry to decarbonization.

## 2.2 Green Shipping

Throughout the years the world has been realizing the repercussions of the shipping industry on the environment. The pressing necessity to make the industry more environmentally friendly has inspired the creation of green shipping corridors, which is defined as routes including at least one port, where there is zero emission of GHG (United Kingdom Government, 2022), consequentially stimulating the use of clean fuels and the advancements on marine technologies (H. Wang et al., 2023).

The Paris Agreement is an international treatment signed by 196 countries with the goal of limiting global warming at least below 2°C, ideally to 1,5°C compared to pre-industrial levels (European Commission, 2023). The urgent need to guide the shipping industry to decarbonization has led countries, governments, and specific organizations to create regulations and agreements to motivate the industry's sustainability (Hessevik, 2022).

Innumerable measures have been planned to improve the sustainability of the maritime industry, with greater focus on the shipping industry. IMO is the UN entity entrusted with overseeing the safety, security, and sustainability of maritime transport. Since its foundation in 1948 (International Maritime Organization, 2019a), it has been recognizing the need for targeted solutions, establishing specialized organizations, conventions, and regulations to address each sustainability issue, counting with 175 member states and 50 conventions and protocols (International Maritime Organization, 2019e).

To effectively measure the industry's sustainability levels, IMO created metrics that are able to quantify it, such as Annual Efficiency Ratio (AER), Energy Efficiency Performance Indicator (EEPI), Cargo-Distance (cDIST), Energy Efficiency Operational Indicator (EEOI), Distance (DIST) or TIME that are meant to calculate the carbon intensity of vessels (International Maritime Organization, 2021; Tadros et al., 2023). Additionally, sustainability has been encouraged through the implementation of indices, namely Energy Efficiency Design Index (EEDI), which sets energy efficiency limits for new vessels, Ballast Water Management (BWM), which monitors ballast water to prevent the transfer of harmful substances to ecosystems, Energy Efficiency Existing Ships Index (EEXI), a certification that verifies minimum energy efficiency in vessel design, and Carbon Intensity Indicator (CII), a rating system that evaluates vessels' operational carbon intensity based on performance (Tadros et al., 2023).

Throughout its existence, the IMO has introduced various regulations such as Emission Control Areas (ECAs), which designate controlled regions for GHG emissions, and conventions, such as the International Convention for the Prevention of Pollution from Ships (MARPOL),

made to facilitate agreements among nations and governments on sustainability matters (International Maritime Organization, 2019d; Tadros et al., 2023). Moreover, the IMO has issued a Ship Energy Efficiency Management Plan (SEEMP) which are recommendations for optimizing the vessels' energy efficiency, incorporating the application of some of the aforementioned metrics (Marine Environment Protection Committee, 2012).

The International Association of Ports and Harbors (IAPH) has also taken significant steps in fostering sustainability within the industry. Their initiative, Environmental Ship Index (ESI), serves as an incentive for shipowners who effectively reduce emissions sent to the atmosphere (Irigoyen et al., 2020).

Several other organizations have spearheaded initiatives to promote sustainability within the maritime industry. Notable examples include the Getting to Zero Coalition (GZC), which focusses in transforming the industry into one with zero vessel emissions through infrastructure development (Global Maritime Forum, 2020). Furthermore, Cargo Owners for Zero Emission Vessels (coZEV), a network of cargo owners, collaborates to encourage the adoption of sustainable practices and rules (Cargo Owners for Zero Emission Vessels, 2023). Lastly, the Clydebank Declaration involves multiple countries expressing environmental concerns regarding the maritime industry and pledging efforts towards improvement (United Kingdom Government, 2022). Table 2-1 provides a chronological overview of the current projects, regulations and agreements that have been established to promote sustainability within the shipping industry.

## 2.3 Fuel Types

Maritime transport, despite being a widely used form of trade, is facing a major challenge regarding meeting the goals outlined in the Paris Agreement (Malmborg, 2023). Dominioni, (2023) emphasizes that the fastest method to accomplish sustainability goals in the maritime industry is to reduce or even eliminate GHG emissions. Over the years, numerous options have been explored to make change happen. However, the transition from fossil fuels to green fuels has emerged as the most prominent solution (F. Wang et al., 2023).

Table 2-1 - Green Shipping: Document Classification, Descriptions, and Starting Years

Designation	Classification	Description	Starting year	References
<b>International Maritime Organization (IMO)</b>	Organization	Specialized agency of the UN with a mission to promote efficient, safe, environmentally sound, secure, and sustainable shipping through international coordination. Its main goal is to develop and maintain a regulatory framework that ensures safety, security, and environmental protection without compromising on efficiency. This organization serves as the forum where regulations, practices, and standards are agreed upon, adopted, and implemented worldwide. IMO is actively working towards the UN Sustainable Development Goals (SDGs) contributing to a green economy while focusing on developing and implementing global standards related to energy efficiency, latest technologies and innovations in the maritime industry.	1958	(a), (b), (c)
<b>International Convention for the Prevention of Pollution from Ships (MARPOL)</b>	Convention	International Agreement that addresses the prevention of marine contamination generated by vessels, whether on account of operational or accidental causes. MARPOL is regularly updated through amendments, and it currently comprises six technical Annexes. The regulations are designed to prevent and minimize pollution from vessels including special areas with rigorous supervisions on operational discharges to protect sensitive marine environments.	1983	(d)
<b>Prevention of Air Pollution from Ships (MARPOL Annex VI)</b>	Convention	Annex to the international Agreement focused on regulating air pollution from vessels. It establishes specific limits on emission of NO <sub>x</sub> and SO <sub>x</sub> from vessel exhausts, as well as limits on PM emissions. Besides prohibiting intentional emissions from vessels of ozone-destructing substances it also establishes Emission Control Areas (ECAs) and energy efficiency measures, with the ambition of diminish the consequences of vessel pollution in climate change.	2005	(d)
<b>Emission Control Areas (ECAs)</b>	Regulation	Specific areas where stringent controls on NO <sub>x</sub> and SO <sub>x</sub> emissions from vessels are enforced to minimize airborne pollution. These areas are listed in Annex VI of MARPOL being updated every year. Within these areas, vessels must adhere to strict emission standards. Vessels operating in ECAs must comply with the limits of NO <sub>x</sub> emissions proposed by the IMO and use fuels containing a content of sulfur not exceeding 0,1%, in order to help protect the environment and improve air quality in these sensitive sea regions.	2006	(e)

Table 2 1 - Green Shipping: Document Classification, Descriptions, and Starting Years. (Cont.)

Designation	Classification	Description	Starting year	References
<b>Annual Efficiency Ratio (AER)</b>	Metric	One of the four metrics used to measure the carbon intensity of vessels. It is a ratio that calculates the annual CO <sub>2</sub> emissions of a specific vessel by dividing it by the product of the vessel's deadweight and the length navigated in a year. This is considered a "supply-based" approach. AER is a way to evaluate the energy efficiency of vessels and is part of the four metrics of carbon intensity, along with EEOI, DIST, and TIME. AER encompasses two variants (cDIST and EEPI) that are discussed further down this table. Different carbon intensity metrics have different outcomes, resulting in varying results indicating the same performance level and percentage changes. The AER metric is suitable for typical cargo and passenger vessels although, despite every effort, the IMO has not yet agreed on a clear measurement for computing carbon intensity and evaluating the energy efficiency of vessels.	2008	(f), (g)
<b>Energy Efficiency Performance Indicator (EEPI)</b>	Metric	Variant of AER metric used to measure carbon intensity using time and is expressed in units of tonCO <sub>2</sub> /hr (tons of CO <sub>2</sub> emitted per hour of operation). EEPI uses laden distance instead of total distance at sea and it is suitable for the same specific types of vessels as the abovementioned metric, since it is a variant of AER.	2008	(g)
<b>Cargo-Distance (cDIST)</b>	Metric	Variant of AER metric used to measure carbon intensity using distance and is expressed in units of CO <sub>2</sub> grams per capacity per nautical mile (gram CO <sub>2</sub> /capacity/NM). The capacity can be measured in TEU (Twenty-foot Equivalent Unit), cubic meters, or other relevant parameters specific to certain vessel types. cDIST is used in studies to assess the carbon intensity performance of international shipping during specific periods, such as from 2012 to 2018 and 2008. These metrics help gain understanding of the environmental impact and energy efficiency of vessels. As a variant of AER, it is suitable for the same specific types of vessels as the abovementioned metric.	2008	(g)
<b>Energy Efficiency Operational Indicator (EEOI)</b>	Metric	One of the four metrics used to measure carbon intensity in the shipping industry. It is expressed in CO <sub>2</sub> grams per ton per nautical mile (g CO <sub>2</sub> /t/NM). EEOI, along with other metrics like AER, cDIST, and EEPI, provides insights into the environmental impact and energy efficiency of vessels. EEOI and AER are two different ways to rate a vessel's energy efficiency and, although both metrics use total CO <sub>2</sub> emissions over a year as the numerator, they differ in the denominator used for calculation. For EEOI, the denominator is the actual ton-miles hauled by the vessel over one year, taking into account the vessel's payload and speed profiles, causing this strategy to be considered a "demand-based" approach. Different carbon intensity metrics have different outcomes, resulting in varying results indicating the same performance level and percentage changes. EEOI, along with other relevant metrics, is potentially applicable to assess the energy efficiency and carbon intensity of typical cargo and passenger vessels in the maritime industry.	2008	(f), (g)

Table 2 1 - Green Shipping: Document Classification, Descriptions, and Starting Years. (Cont.)

Designation	Classification	Description	Starting year	References
<b>Distance (DIST)</b>	Metric	One of the four metrics used to measure the carbon intensity of vessels based on distance traveled and it is expressed in kilograms of CO <sub>2</sub> per nautical mile (kg CO <sub>2</sub> /NM). DIST is one of the carbon intensity metrics used to assess the vessels' energy efficiency and environmental impact. DIST and its possible variations are better suited for assessing the energy efficiency and emissions performance of service, working, or fishing vessels, providing valuable insights into the environmental impact of vessel operations per nautical mile traveled.	2008	(g)
<b>TIME</b>	Metric	One of the four metrics used to measure the carbon intensity of vessels based on time and it is expressed in tons of CO <sub>2</sub> emitted per hour of operation (t CO <sub>2</sub> /hr). TIME is one of the carbon intensity metrics used to evaluate the vessels' energy efficiency and environmental impact throughout their operational hours. TIME, and its possible variations, is better suited for assessing the energy efficiency and emissions performance of service, working, or fishing vessels, providing valuable insights into the environmental impact of vessel operations per hour of operation.	2008	(g)
<b>Environmental Ship Index (ESI)</b>	Index	Initiative that identifies seagoing vessels that decrease air emissions more than the current emission standards set by the IMO. It assesses the quantity of NO <sub>x</sub> and SO <sub>x</sub> released by a vessel, as well as its GHG emissions and serves as an indication of the environmental performance of ocean-going vessels, helping to identify cleaner vessels in a general sense. The ESI database is under the administration of the International Association of Ports and Harbors (IAPH) and has achieved considerable expansion. With over 8,000 registered vessels, the ESI has become the standard tool used by ports worldwide to reward and incentivize vessel owners who surpass the IMO emissions standards, serving as a valuable instrument for all stakeholders in maritime transport.	2011	(h)
<b>Ship Energy Efficiency Management Plan (SEEMP)</b>	Guidelines	Plan designed to enhance the vessels and fleet's energy efficiencies over time since it provides a framework for monitoring and optimizing their performance and operation. In view of the fact that each vessel and shipping company is unique, the SEEMP should be tailored considering their conditions. This plan encompasses four key stages - planning, implementation, monitoring, and self-evaluation and improvement -, maintaining a continuous cycle of development. The energy efficiency of a vessel should be monitored quantitatively using one of the established methods such as the aforementioned EEOI, or others that may be suited.	2012	(i)

Table 2 1 - Green Shipping: Document Classification, Descriptions, and Starting Years. (Cont.)

Designation	Classification	Description	Starting year	References
<b>Energy Efficiency Design Index (EEDI)</b>	Index	Measure determined to reduce GHG emissions from vessels since it proposes a minimum energy efficiency level for new vessels, encourages continuous technical development to improve fuel efficiency and separates technical and design-based measures from operational and commercial aspects. The EEDI incorporates in its formula a minimum safe speed that allows the vessel to navigate at low velocity without decreasing fuel efficiency. It is expected that by 2030, the EEDI implementation will lead to a reduction of between 180 and 240 million tons of CO <sub>2</sub> annually, contributing significantly to global efforts to combat climate change.	2013	(j)
<b>Ballast Water Management (BWM)</b>	Protocol	The International Convention for the Control and Management of Ships' Ballast Water and Sediments, 2004 (BWM Convention) is an intercontinental treaty supported by the IMO to control and manage vessels' ballast water and sediments to prevent the proliferation of potentially dangerous aquatic entities. Ballast water is used to maintain a vessel's stability and trim when returning with an empty (no cargo) vessel. Usually, vessels intake water from one location and discharge it at another, allowing the rapid transfer of various species between different environments. With this treaty, vessels are required to remove or rendering harmless aquatic organisms and pathogens before the discharge, protecting marine ecosystems and human health.	2017	(k), (l)
<b>Getting to Zero Coalition (GZC)</b>	Initiative	Coalition that comprises over 120 companies working towards transforming the shipping industry into a decarbonized sector by developing the infrastructure necessary to advance Zero Emissions Vessels (ZEVs) and achieving marketable ZEVs operating along deep-sea commercial routes by 2030. The initiative's ambition is aligned with the temperature objectives proposed in the Paris Agreement, driving the transformation of the shipping industry towards a sustainable and carbon-neutral future.	2018	(m), (n)
<b>Cargo Owners for Zero Emission Vessels (coZEV)</b>	Initiative	Network of cargo owners in the maritime freight industry with a mission to accelerate shipping decarbonization. coZEV aims to provide a collaborative platform for climate-forward cargo owner companies to work together and with other stakeholders to develop concrete initiatives that promote maritime decarbonization. The initiative focuses on promoting the adoption and implementation of zero-emission fuels and technologies and using the collective voice and influence of cargo owner companies to encourage and pressure the industry to accelerate change. Through coZEV, cargo owners can lead, innovate, and set ambitious goals for decarbonizing the maritime sector, aligning with their climate objectives and logistical needs.	2020	(o), (p), (q)

Table 2 1 - Green Shipping: Document Classification, Descriptions, and Starting Years. (Cont.)

Designation	Classification	Description	Starting year	References
<b>Clydebank Declaration</b>	Initiative	Declaration States where the 24 signatories declare their awareness of the current climate situation and show concern for the environmental future, assuring their assistance in establishing a minimum of six green shipping corridors until 2050. They intend to achieve this by aiding in the addition of routes, increasing their distances and the number of vessels operating on these routes. These goals will be assessed by the middle of this decade, with intentions of increasing the number of green corridors in the future.	2021	(r)
<b>Energy Efficiency Existing Ships Index (EEXI)</b>	Index	One-time mandatory certification applied to every vessel above 400 gross tonnages comprised under the MARPOL Annex VI targeting design parameters. Vessels are required to estimate their obtained EEXI to calculate their energy efficiency compared to a baseline. The value of the obtained EEXI must be less than the required EEXI, ensuring that the vessel meets a minimal energy efficiency level. This index serves as an estimation for energy efficiency and is used for communicating the operational CII and CII rating over a year, making sure that vessels meet the minimum energy efficiency standards.	2023	(e), (s)
<b>Carbon Intensity Indicator (CII)</b>	Index	Measure used to determine a vessel's annual reduction factor required for continuous improvement of its operational carbon intensity within a specific rating level which, when obtained, is compared, and verified regarding the required level of CII. According to the vessel's CII, a rating from A to E is assigned, with E being the lowest rate. This performance level is documented and incorporated in the vessel's SEEMP. There are specific rules for vessels with recurrent low rates (D and E) and incentives for vessels with high rates (A and B) in order to encourage the adoption of energy-efficient measures.	2023	(s)

Sources: (a) (International Maritime Organization, 2019a) , (b) (International Maritime Organization, 2019e), (c) (International Maritime Organization, 2019f), (d) (International Maritime Organization, 2019d), (e) (Tadros et al., 2023), (f) (Psaraftis, 2021), (g) (International Maritime Organization, 2021), (h) (Environmental Ship Index, 2023), (i) (Marine Environment Protection Committee, 2012), (j) (International Maritime Organization, 2020), (k) (International Maritime Organization, 2019c), (l) (Scriven et al., 2015), (m) (Fahnestock, 2021), (n) (Global Maritime Forum, 2020), (o) (Cargo Owners for Zero Emission Vessels, 2023), (p) (Cargo Owners for Zero Emission Vessels, 2022), (q) (Irigoyen et al., 2020), (r) (United Kingdom Government, 2022), (s) (International Maritime Organization, 2019b).

Vessel propulsion fuels can be classified as either established or emerging fuels, and currently, the first ones consist of fossil fuels, substances high in carbon content formed through natural terrestrial processes lasting millions of years (Chiari & Zecca, 2011; Stavroulakis et al., 2023). Since their consumption time is much shorter than their formation time, they are categorized as non-renewable sources of energy, which means they can eventually become depleted (Chiari & Zecca, 2011). The combustion of fossil fuels is considered the key driver of global warming (Rennuit-Mortensen et al., 2023).

Alternative fuels are more environmentally friendly options in contrast with petroleum-based fuels. Therefore, they have lower environmental impacts and reduce our dependency on fossil fuels. These fuels should have low or no GHG emissions, being considered renewable energy sources, as they do not deplete and can be produced faster than they are consumed (Tvedten & Bauer, 2022). There is also potential for combining two fuel types to propel vessels. These are called blended fuels and can be used in vessels with specific engines for both types of fuels (Bhattacharyya et al., 2023). The variety of fuels that are currently used or being considered as probable alternatives for maritime transportation, as well as their sources are unveiled in Figure 2-1.

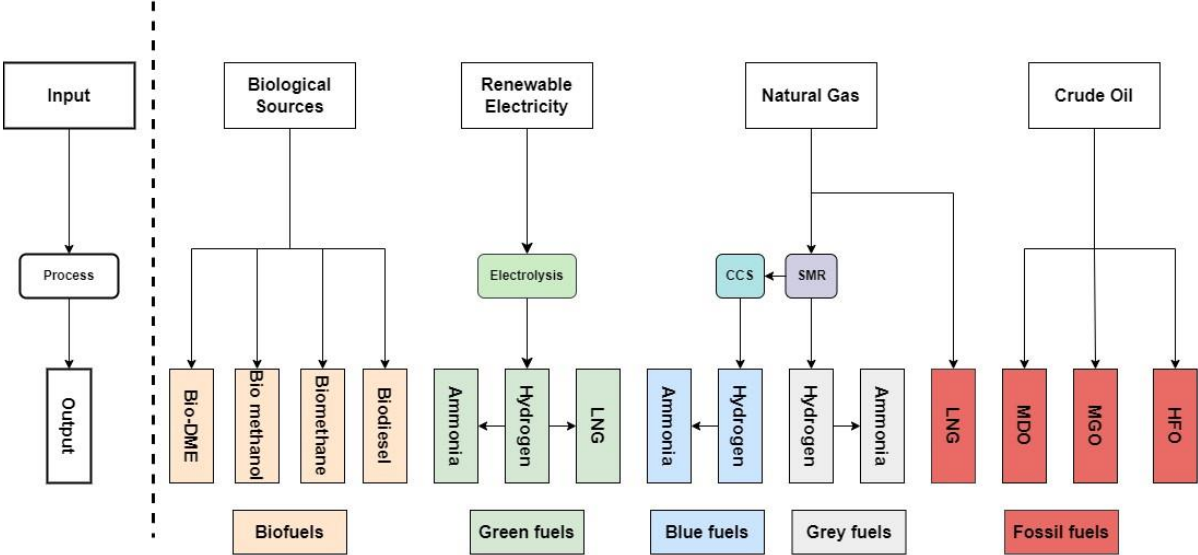


Figure 2-1 - Main fuel pathways for maritime transportation

Established fuels such as heavy fuel oil (HFO), marine gas oil (MGO) and marine diesel oil (MDO) are among the most famous fuels used for vessel propulsion (Stavroulakis et al., 2023). Liquefied natural gas (LNG) can be regarded as an alternative fuel because it emits

significantly less GHG than conventional fuels, despite being derived from natural gas (Ashrafi et al., 2022). The environmental concerns in the maritime transport industry prompted a swift exploration of cleaner alternatives, aiming on achieving zero CO<sub>2</sub> emissions. As a result, the industry is currently considering cleaner fuels, namely hydrogen, ammonia (NH<sub>3</sub>) and other biologically-sourced alternatives (Al-Enazi et al., 2021).

The production method of hydrogen influences the quantity of GHGs released, resulting in a color-coded categorization system as shown previously in Figure 1-1. When hydrogen is processed by steam methane reforming (SMR) it is called a grey fuel as well as other fuels that are produced from it. However, if during the production of hydrogen there is carbon capture and storage (CCS), the fuels originated are categorized as blue fuels, since less GHGs are emitted. Green fuels derive from using renewable electricity in the process of electrolysis when producing hydrogen (Al-Enazi et al., 2021; Ashrafi et al., 2022). Other alternatives that have been explored as marine fuels are biofuels that are obtained from biological sources, since the CO<sub>2</sub> that is released when using it is equivalent to the quantity absorbed by the plant during its lifetime (Bengtsson et al., 2012). It is also being considered the possibility of using wind energy for vessel propulsion again (Rojon & Dieperink, 2014).

The challenges associated with decarbonizing the maritime industry must be considered. The economic challenge consists of the expenses associated with producing, transporting, and storing alternative fuels, together with the potential costs of future regulatory measures (Ashrafi et al., 2022). The costs associated with building infrastructure, engines, fuel tanks, and pipelines compatible with the new fuels, as well as operational costs, including maintenance, insurance, and crew expenses, are also included in this category (Hansson et al., 2019). Due to the difficulty in forecasting the cost of alternative fuels, stakeholders may be hesitant to adopt them (Foretich et al., 2021). Swedish stakeholders in the industry considered fuel cost the principal criterion in alternative fuel adoption (Hansson et al., 2019).

Another difficulty in the adoption of cleaner fuels is their worldwide accessibility. The availability of fuel is conditioned by a variety of factors, namely access to natural resources based on geographical location, and social and political limitations (Ashrafi et al., 2022). Supply chain uncertainties arise for fuels sourced from solar or wind power, which are dependent on the variations of meteorological conditions (Al-Enazi et al., 2021).

One additional challenge is the inadequacy of the infrastructure necessary for the production, supply chain, and distribution of emerging fuels. While exploring the option of reusing existing structures, it became clear that they are insufficient (Ashrafi et al., 2022). A shortage of

infrastructure development at ports, terminals and on vessels may prevent or delay the widespread use of clean fuels (Al-Enazi et al., 2021; Foretich et al., 2021).

A further challenge category concerns technology readiness. Several processes for producing clean fuels require further development to optimize efficiency. Uncertainties regarding technology performance, availability, and pricing have hindered stakeholder investment in cleaner fuels. As a result, decisions regarding the adoption of such fuels have been delayed (Ashrafi et al., 2022).

The following sub-sections provide a comprehensive overview of both the traditional and alternative fuel types, elaborating on their environmental and technical features and subsequently comparing them to one another.

### 2.3.1 Heavy fuel oil

HFO results from the residues left after distilling crude oil and is therefore classified as fossil fuel (Hansen et al., 2021). HFO is identified by its black color, high viscosity, and high percentage of carbon, hydrogen, and sulfur, and its primary benefit is its lower cost in comparison to diesel (Tariq & Saleh, 2023). HFO has been the major fuel type in the marine fuel market since the mid-1900s (Lunde Hermansson et al., 2021). Due to its high calorific value and low price, it is commonly burnt in marine vessels, industrial boilers, and power plants (Jafarian et al., 2023). Combusting HFO leads to significant emissions of CO<sub>2</sub>, SO<sub>x</sub>, NO<sub>x</sub>, PM, inorganic ash, and organometals, which are harmful to both the ecosystem and human health (Hansen et al., 2021; Jafarian et al., 2023). HFO also includes ash, minerals, and water (Tariq & Saleh, 2023).

During the use of HFO, a significant amount of the SO<sub>x</sub> emissions is converted to sulfate through atmospheric oxidation. This contributes to the generation of PM, which has adverse repercussions on human health, in addition to causing ocean acidification. The recent limitation on the sulfur content in marine fuels has put pressure on transitioning from HFO to less toxic fuel alternatives (Lunde Hermansson et al., 2021).

There are several sub-categories of fuel oils, which depend on the amount of sulfur present. Fuel oils with different levels of sulfur content can be categorized as High Sulphur Fuel Oil (HSFO), which contains 3.5% sulfur, Low Sulphur Fuel Oil (LSHFO) with 1% sulfur content, and Ultra Low Sulphur Heavy Fuel Oil (ULSHFO) with a maximum of 0.1% sulfur content (Vierth & Merkel, 2022). These oils cannot be used in diesel engines due to the design of their injection and combustion systems, which are intended for light diesel fuels (Tariq & Saleh, 2023).

If HFO is unintentionally released into marine ecosystems, it forms highly viscous and stable emulsions that can cause severe environmental degradation and catastrophic effects on

marine environments, particularly if it reaches coastal habitats (Hansen et al., 2021; Yacout et al., 2021).

### **2.3.2 Marine Gas Oil**

Fuel oils are categorized as light and heavy based on their molecular weight. Typically, light fuel oils tend to be more toxic than HFO. The light fuel oil category is additionally classified in two groups: MGO-like fuels, which comprise of MGO, diesel, and gasoline and BA-like fuels, which consist of Bunker A fuels and MDO (Sosnowski et al., 2022).

MGO is a mixture of gas oil and HFO and is produced by extracting crude oil and then refining it to produce a ready-to-use fuel (Yacout et al., 2021). It is characterized by high volatility and low viscosity, along with low density and up to 60% aromatic hydrocarbons. The first two characteristics favor its diffusion in the marine environment in the event of an oil spill (Hafez et al., 2021). In this event, the density of MGO makes it likely that the liquid will sink and affect seabed ecosystems (Faksness et al., 2022).

MGO is a light distillate employed in combustion equipments, namely furnaces, boilers or marine diesel engines (DeMiguel-Jiménez et al., 2021; Larsson et al., 2022). This makes it appropriate for smaller vessels such as fast boats, fishing boats, ferries, or tugs, which travel at medium to high speeds (Bilbao et al., 2022; DeMiguel-Jiménez et al., 2021; Hafez et al., 2021).

When comparing different fuel storage choices, one study reported that alternatives are more technologically advanced and cost more per volume stored than MGO, making this fuel a more attractive choice, therefore delaying the adoption of green fuels (Zanobetti et al., 2023).

MGO is commonly employed as a substitute to HFO on account of its low sulfur composition (Yacout et al., 2021). Although HFO is cheaper than MGO, stakeholders are choosing the latter more frequently because certain ECAs allow only low sulfur fuels to be used in vessels and MGO meets this requirement (Yoo, 2017).

### **2.3.3 Marine Diesel Oil**

According to Sagerup et al., (2016) MDO is a distillate fuel that is more appropriate for fishing boats, smaller passenger vessels, and local support vessels. It can be pumped without preheating, and combustion in existing diesel engines is efficient even in cold climates (Foretich et al., 2021). MDO is a blended fuel comprising mainly of MGO, and only a small quantity of

HFO (Li et al., 2021). At present, nearly all of the coastal shipping fleet worldwide utilizes fossil fuels, typically MGO and MDO (Bach et al., 2021).

Compared to other fuels, MDO has a higher molecular weight and exhibits low viscosity even at low temperatures, however higher viscosity compared to pure-distillate MGO (Foretich et al., 2021; Li et al., 2021). MDO has higher short-chained hydrocarbon content and a superior capability of biodegradation and dispersion, in contrast to HFO (Sagerup et al., 2016). Some studies have found evidence that in some cases, traditional MDO is a cleaner fuel than LNG, and in other cases, it contributes more to reducing GHG emissions (Ha et al., 2023).

MDO refers to a type of very low sulfur fuel oil (VLSFO) that contains sulfur content lower than 0.5% (Li et al., 2021). Restrictions on sulfur levels at several locations have led to a gradual decrease in the use of HFO indicating that MGO and MDO will likely become the primary fuel options in the near future (Foretich et al., 2021; Sagerup et al., 2016). Therefore, there has been a recent shift towards lighter fuels such as MDO (Sagerup et al., 2016). In comparison to HFO, MDO emits a slightly lower amount of CO<sub>2</sub> but significantly lower amounts of SO<sub>x</sub>, PM, and NO<sub>x</sub> (Pérez Osses et al., 2022). Due to the existing sulfur restrictions in the area, MDO is a recommended hydrocarbon fuel for vessels operating in the Arctic (Sagerup et al., 2016). Low sulfur fuel alternatives like MDO should be used to minimize the formation of SO<sub>x</sub>, that are prejudicial to human health (Pérez Osses et al., 2022).

In an oil spill scenario, a substantial part of MDO components evaporates. It is probable that polycyclic aromatic hydrocarbons (PAHs) found in MDO can cause alterations in behavior and properties of fish, thereby triggering biological effects (Sagerup et al., 2016).

### **2.3.4 Liquefied Natural Gas**

Natural gas was first recognized as a potential fuel for marine vessels in 1996 (Tvedten & Bauer, 2022). Since then, its consumption has substantially increased, primarily due to rising energy demands and the enforcement of sustainability policies aimed at limiting CO<sub>2</sub> emissions from fossil fuels (Filimonova et al., 2022). LNG primarily consists of CH<sub>4</sub> and is stored more efficiently after being liquefied at -162 degrees Celsius under pressure. LNG is a cryogenic liquid that is non-toxic, non-corrosive and odorless (Ashrafi et al., 2022). Global shipment of natural gas is enabled by its liquefaction (Tvedten & Bauer, 2022). LNG exports are projected to increase, with an estimated demand of 450 to 700 million tons per year by the year 2040 (Al-Yafei et al., 2022). Compared to other alternatives, LNG is perceived as a low-cost fuel, making it an attractive option for shipowners looking to manage their costs (Mukherjee et al.,

2023). LNG is among the suggested alternatives to crude oil fuels, as it emits fewer GHG emissions than conventional fuels (Tvedten & Bauer, 2022).

In the LNG supply chain, natural gas is extracted, purified, and undergoes the cryogenic process to become a liquid. The LNG is stored in a liquefaction plant under high pressure and low temperature. It is then transported and stored temporarily at the final destination before being delivered to the end consumer as an energy source (Ashrafi et al., 2022; Eriksen et al., 2022). Advanced cooling technology is required for the third step in the supply chain. Natural gas is converted to LNG from gaseous to liquid state, reducing its volume by over 600 times, allowing easier and safer transportation and storage. LNG upon reaching destination undergoes a regasification process to convert it back to natural gas applicable to industries and heating (Tvedten & Bauer, 2022). Although natural gas is commonly transported through pipelines, demand is expected to rise in developing countries that do not have the means to invest in pipeline infrastructure. LNG serves as a solution to this issue of limited investment capability in pipeline infrastructure (Eriksen et al., 2022).

Global investment in LNG bunkering is increasing. However, the breakdown of fossil fuels, such as LNG, releases  $\text{CO}_2$ ,  $\text{NO}_x$ ,  $\text{SO}_x$ , PM and other components into the atmosphere. The literature suggests that LNG as a bunker fuel is highly effective in reducing  $\text{SO}_x$  and PM emissions, being able to decrease  $\text{NO}_x$  emissions by 80-90% when compared to traditional fuels (Tvedten & Bauer, 2022). Hydrocarbons and some impurities are present in natural gas and, as long as LNG production persists, it will keep polluting the atmosphere with harmful gases that contribute to global environmental concerns (Al-Yafei et al., 2022). The accidental release of unburned  $\text{CH}_4$  into the atmosphere is a crucial concern, given that it is more potent as a GHG than  $\text{CO}_2$ , and can cause severe damage to the environment (Ashrafi et al., 2022).

Green LNG, which can also be referred to as synthetic LNG or e-LNG, can be produced without relying on natural gas.  $\text{CO}_2$  and hydrogen are synthesized to obtain synthetic LNG. If the production of hydrogen occurs solely via the electrolysis process powered by renewables and the  $\text{CO}_2$  is captured from industrial processes through CCS, then the resultant synthetic LNG is said to be carbon neutral. Classified as a hydrocarbon e-fuel, green LNG can be blended with fossil LNG. Thus, it may be employed on current LNG-ready vessels without any modifications, new bunkering infrastructure or crew training, which reduces investment costs. When produced exclusively from renewable energy sources, this clean alternative can reduce GHG emissions by up to 100% (Lindstad et al., 2021). Compared to other alternative fuels, green LNG is one of the most expensive, meaning that replacing fossil LNG with the sustainable alternative may not be as imminent as expected (Mukherjee et al., 2023). The demand for e-LNG

in the future is still uncertain, as other clean alternatives are becoming more prominent in the maritime industry (Galimova et al., 2023).

### 2.3.5 Hydrogen

Hydrogen does not occur naturally as an unpaired atom and therefore forms compounds with other elements to create molecules, like water ( $H_2O$ ). The hydrogen ( $H_2$ ) separated in the laboratory is odorless, colorless and a highly flammable diatomic gas, having the highest energy per unit mass as a fuel (Ashrafi et al., 2022; Moreno-Brieva et al., 2023). This gas can be used in industries for generating electricity, heating and transportation and is also employed in generating  $NH_3$  (Ajanovic et al., 2022; Ashrafi et al., 2022). Hydrogen is a promising fuel for the shipping industry since it can be used in either liquid or compressed form (Ashrafi et al., 2022). Hydrogen is usually classified based on the amount of GHG emissions released during its production and therefore affiliated with different colors (Moreno-Brieva et al., 2023). The most common hydrogen is produced from natural gas and is referred to as grey hydrogen. It represents the largest available quantity of hydrogen at present (Ajanovic et al., 2022; Moreno-Brieva et al., 2023).

When natural gas undergoes the SMR process it produces grey hydrogen. This technology subjects  $CH_4$  from natural gas to high temperatures and low pressures in the presence of catalysts to produce synthetic gas. This gas is mainly composed of hydrogen, carbon monoxide and a small amount of  $CO_2$ . Using identical processes, more hydrogen and  $CO_2$  are produced from this gas. The  $CO_2$  and impurities are removed to obtain a final product that is essentially pure hydrogen (Ashrafi et al., 2022). The process of producing hydrogen from fossil fuels offers a stable and relatively inexpensive supply of hydrogen. Moreover, its technology is mature (Hienuki et al., 2021). Around 80% of hydrogen is originated from the process of SMR of natural gas (Rahim Malik et al., 2023).

The downside of producing hydrogen by the SMR process is that it produces large amounts of  $CO_2$  (Ashrafi et al., 2022). The environmental outcomes regarding the process of reforming fossil fuels are exceptionally high (Rahim Malik et al., 2023). The excessive release of  $CO_2$  during hydrogen production can be addressed by adopting the CCS process, which can decrease hydrogen's carbon intensity by up to 90%. The refined product is recognized as blue hydrogen. Considering the potential inclusion of fossil fuels in the production process, it is vital to investigate a production pathway that employs renewable energy sources (Ashrafi et al., 2022). Blue hydrogen's production is viewed as a transitional phase in the move towards green hydrogen. One arising issue is finding sufficient storage space for all the carbon captured in

the CCS process (Ajanovic et al., 2022). Technologies that reform with integrated carbon capture are still in the experimental prototype phase. The prevailing choice for hydrogen production currently lies with fossil fuel reforming due to the abundance of resources and infrastructure, as it increases efficiency up to 85% (Rahim Malik et al., 2023).

Hydrogen production from water by means of electrolysis, a process that separates hydrogen from oxygen in a machine called 'electrolyzer', generates green hydrogen which can also be referred to as low-carbon hydrogen, renewable hydrogen or clean hydrogen (Ajanovic et al., 2022; Ashrafi et al., 2022). Hydrogen produced from electrolysis has the advantage of having a purity level of over 99.95% (Ajanovic et al., 2022). Nevertheless, for a process to be considered completely green, the energy required by the electrolysis must originate from renewable sources like solar or wind power (Ashrafi et al., 2022). The production process for green hydrogen is viewed as ecologically clean, although complications with stability and cost still exist (Hienuki et al., 2021).

Other fossil fuels, namely oil and coal, may also be employed for the production of hydrogen, however it is commonly referred to as black or brown hydrogen (Moreno-Brieva et al., 2023). During the coal gasification process, hydrogen is produced as a by-product (Ajanovic et al., 2022). Hydrogen in the pink or purple spectrum is produced through the employment of both electrolysis and nuclear energy. Hydrogen in the turquoise spectrum is produced utilizing natural gas and the pyrolysis process that does not emit CO<sub>2</sub>. Additionally, another path to produce hydrogen is to submit biogenic raw materials to processes, namely fermentation, gasification, reforming, pyrolysis, and bio-photolysis (Moreno-Brieva et al., 2023). The use of grid electricity from non-renewable sources in water electrolysis to produce hydrogen originates the color yellow in the hydrogen's spectrum (Griffiths et al., 2021). Figure 2-2 illustrates the multiple pathways of hydrogen production and their colors, including their initial outputs, the processes they undergo, their final outputs and the different GHG footprints of hydrogen.

Due to the high GHG emissions associated with hydrogen produced from fossil fuels, it is considered to have a high carbon footprint. Conversely, hydrogen originating from renewable energy sources has minimal GHG emissions (Hienuki et al., 2021). The carbon footprint of grey and turquoise hydrogen is considered to be medium, whereas blue hydrogen has a low one. A minimal footprint is considered for both pink and green hydrogen. Although blue hydrogen is currently an affordable option, reducing GHG emissions by up to 90%, the favorable option in the long term is green hydrogen due to its minimal repercussions on climate change. Biomass hydrogen, while less efficient than blue hydrogen, is another affordable alternative that utilizes renewable power. The grey, blue, turquoise, and biomass hydrogen's production

costs are very similar. As there is a risk of nuclear accidents, that can cause drastic economic and environmental impacts, pink hydrogen is less attractive (Moreno-Brieva et al., 2023).

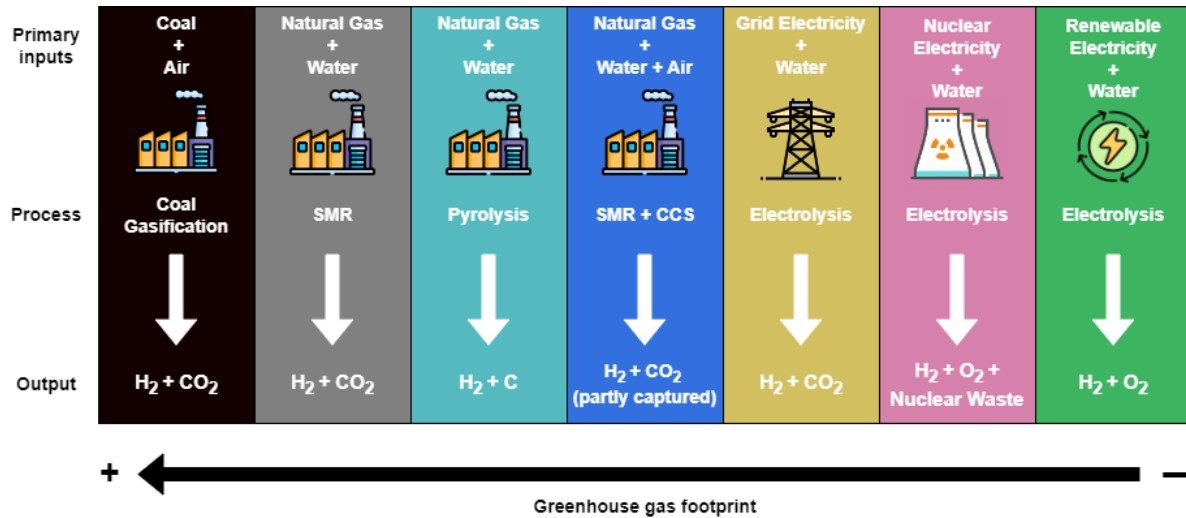


Figure 2-2 - Hydrogen production pathways, colors and greenhouse gas footprint.

Sources: Ajanovic et al., (2022) and Moreno-Brieva et al., (2023).

### 2.3.6 Ammonia

Ammonia has been discussed as a prospective fuel since it has potential uses in power generation, heating, fuel and energy storage (Machaj et al., 2022; H. Wang et al., 2023). It has a promising potential to carry, store, and transport renewable energy worldwide. Because ammonia reduces NO<sub>x</sub> emissions and does not emit SO<sub>x</sub> or PM, it may become an attractive bunker fuel. Ammonia results from both nitrogen and hydrogen undergoing the Haber-Bosch industrial process developed in 1914 (Mayer et al., 2023). This important process is currently the primary industrial technique utilized globally for synthesizing ammonia. Nitrogen and hydrogen are recognized as the two primary raw materials utilized in the creation of ammonia. Nitrogen is separated from the air using an air separation unit, and as a result, air can also be considered as a raw material during the process (Yüzbaşıoğlu et al., 2021).

At present, global ammonia production amounts to approximately 170 million tons annually and over 96% of the hydrogen's production utilized for producing ammonia is derived from fossil fuels (Mayer et al., 2023; Yüzbaşıoğlu et al., 2021). From these, natural gas accounts for over 73% of the hydrogen used to produce ammonia, while the rest (27%) comes from coal gasification (Mayer et al., 2023). The ammonia synthesis industry emits approximately 2% of CO<sub>2</sub> emissions and even the production plant with the best efficiency generates 1,6 tons of CO<sub>2</sub> per ton of ammonia produced (Machaj et al., 2022; Yüzbaşıoğlu et al., 2021). Alternative

approaches for ammonia production, such as employing CCS technologies or renewable energies, are presently under consideration for future applications (Yüzbaşıoğlu et al., 2021).

The color code of ammonia is determined by the process used to produce hydrogen (Mayer et al., 2023). Grey ammonia is produced using hydrocarbons through the Haber-Bosch process, that is considered the standard process of production. Blue ammonia applies the same procedure as grey ammonia but utilizes CCS technologies (Yüzbaşıoğlu et al., 2021). This type may represent a viable and sustainable production alternative, provided that any natural gas leaks are effectively minimized. Ammonia produced using green hydrogen is referred to as green ammonia (Mayer et al., 2023). This is a product of the electrolysis of water using renewable energies to produce hydrogen (Yüzbaşıoğlu et al., 2021). According to an economic analysis done by Mayer et al., (2023), green ammonia would not be profitable even if the current hydrogen price was optimistic, due to the latest ammonia fares.

Ammonia offers various benefits as a fuel option, namely possessing large-scale distribution infrastructure that is already in place and is used in the fertilizer industry, and having a small flammability range (Herbinet et al., 2022; Mayer et al., 2023). This allows a dependable, quick, and secure distribution of ammonia (Mayer et al., 2023). One of the merits of ammonia is that it remains in a liquid state even at  $-33.4\text{ }^{\circ}\text{C}$  and 1 bar, which makes it more convenient to store and transport over long distances (Arnaiz del Pozo et al., 2023). The drawbacks of ammonia include its harmful nature, generation of  $\text{NO}_x$  and  $\text{NH}_3$  residues during the combustion process, and low level of reactivity as fuel (Herbinet et al., 2022). Ammonia poses several safety risks to humans given its corrosive and toxic properties (Mayer et al., 2023).

### **2.3.7 Biofuels**

An increasing number of countries are investigating circular economy strategies to decrease and recycle waste. One approach involves utilizing waste to create fuels that substitute traditional hydrocarbon-based fuels (Al-Enazi et al., 2021). Biofuels are obtained from sustainable biological sources and are produced at reasonable costs (Tadros et al., 2023). According to Solakivi et al., (2022), biofuels represent the most prevalent non-fossil fuel alternative currently. To be economically competitive, biofuels need to be priced in the absence of financial or market measures in order to compel their use. Feedstock, investment requirements and energy costs are critical factors in reducing the price of biofuels (Foretich et al., 2021). The feedstock sources for biofuel production are categorized as animal, plant, algae, and industrial waste. Processes like conventional combustion, fermentation, gasification, anaerobic digestion

and pyrolysis can convert biomass (Singh et al., 2022). Anaerobic digestion denotes the decay of organic matter by microorganisms in an environment free of oxygen (Mukherjee et al., 2020).

Biofuels are regarded as carbon neutral on account of the raw material from which they are produced being expected to absorb an amount of CO<sub>2</sub> during its lifetime equal to the CO<sub>2</sub> emitted during its use (Solakivi et al., 2022). These alternative fuels are being considered as suitable candidates for the near future as marine fuels because they reduce emissions, particularly of SO<sub>x</sub>, have a high energy density, being able to blend with current fuels (Foretich et al., 2021). Most biofuels are blended with their fossil fuel counterpart, creating a final blend termed Bxx, whereby xx denotes the percentage of biofuel in the mixture. B100 refers to a pure biofuel that can potentially produce no SO<sub>x</sub> emissions (Tadros et al., 2023). Biofuels have the added benefit of being more compatible with current infrastructures than other eco-friendly options while providing a significant degree of GHG mitigation. They have drawbacks such as competition from the aviation, automotive, maritime, and petrochemical industries, and fragmentation due to numerous feedstocks and biofuel types (Mukherjee et al., 2020).

Biofuels are typically categorized into four generations based on the origin of the raw materials. First-generation biofuels, for example, are derived from food crops, namely sugar and starch that are transformed into bio alcohols through fermentation (Mahmud et al., 2022; Singh et al., 2022). One drawback of first-generation biofuels is that they use food resources as their raw materials (Kiehadrouinezhad et al., 2023). Second-generation biofuels, also known as cellulosic biofuels, arise from using non-edible feedstocks and agricultural residues derived from edible feedstocks as raw material, such as sugarcane bagasse, rice husk and rice straw. Third-generation biofuels are derived from sources that do not compete for land, such as microalgae, waste cooking oil and waste animal fat. Algae and microalgae species are employed to synthesize third-generation biofuels. Fourth-generation biofuels are comprised of solar fuels and electrofuels (Mahmud et al., 2022; Singh et al., 2022). These biofuels consist of genetically modified feedstocks and genomically engineered microorganisms (Kiehadrouinezhad et al., 2023).

Within the maritime context, biodiesel - in the form of fatty acid methyl esters (FAME) or hydrotreated vegetable oil (HVO), bio methanol, and bio-dimethyl ether (bio-DME) are the most commonly discussed biofuels (Mukherjee et al., 2020; Solakivi et al., 2022).

### **Biodiesel**

Biodiesel has been identified as a viable alternative to petroleum-based fuels on account of its likelihood to meet global energy demand (Che Wan et al., 2018). Biodiesel

possesses numerous advantages, being biodegradable, renewable, oxygenated, low in emissions and aromas, and, in comparison to fossil diesel, less toxic and more viscous. Although it is harder to use directly, it possesses a higher heat content (Singh et al., 2022). Biodiesel may be applied to diesel engines directly without needing infrastructure changes, as the characteristics of both homonymous fuels are very similar (Che Wan et al., 2018). Biodiesel can be derived from both edible and non-edible oils, animal fat or vegetable oils using chemical or enzymatic transesterification, requiring only feedstock, methanol/ethanol, and a catalyst (Mahmud et al., 2022; Singh et al., 2022). FAME biodiesel is produced by the transesterification of edible oils, meaning its commercial use is restricted (Hunicz et al., 2022). HVO biodiesel is created through the hydrogenation of diverse vegetable oils, animal fats and waste materials. It possesses low viscosity and a high heating value. In diesel engines, HVO can be utilized either as a standalone substance or together with diesel oil (Dobrzyńska et al., 2020).

### **Biomethane**

Biomass may undergo conversion into biogas with the aid of an anaerobic digester. Biogas consists of both  $\text{CH}_4$  and  $\text{CO}_2$ , whereby removing the  $\text{CO}_2$  yields biomethane. Bio-LNG is liquified biomethane, which can primarily be produced through anaerobic digestion or catalytic upgrading of syngas (Mukherjee et al., 2020). Biogas serves as a fuel source for chemicals, hydrogen and synthetic gases production (Singh et al., 2022). It is a viable substitute for natural gas and is created through the process of anaerobic digestion of organic matter (Kiehadrouinezhad et al., 2023). To utilize biomethane, certain modifications to engines and fuel infrastructure are necessary (Solakivi et al., 2022). It is feasible to extract approximately 120 cubic meters of biomethane from each ton of organic waste (Kiehadrouinezhad et al., 2023).

### **Bio methanol**

Bio methanol is a biofuel created through the process of microbial fermentation using biomass and biodegradable wastes that contain sugar and starch (Awogbemi & Kallon, 2022). Syngas is produced from gasifying biomass, which then catalyzes to produce methanol (Mukherjee et al., 2020). With greater mitigating potential compared to other bio alcohols, bio methanol is a second-generation biofuel (Yang et al., 2021). The use of bio methanol in the transportation industry ensures thorough and effective combustion, resulting in lower GHG emissions. Nevertheless, bio methanol has a limited energy content, and its combustion produces pollutants (Awogbemi & Kallon, 2022), necessitating adaptations to engines and fuel infrastructure to enable its use (Solakivi et al., 2022).

## Bio-DME

At room temperature, DME is found in its gaseous state, however it can become a liquid when subjected to high pressures. The compatibility between DME and diesel engines is superior to the one verified with methanol, requiring only minor modifications to the engine for its use. The production of Bio-DME can involve anaerobic digestion followed by catalytic reforming or gasification, direct hydrogenation of CO<sub>2</sub>, catalyzed dehydration of methanol or the synthesis of methanol from syngas (de Jong et al., 2023; Mukherjee et al., 2020).

### 2.3.8 Fuel environmental comparison

To conduct a comprehensive comparison of fuels, it is imperative to gather information regarding the quantity of GHG released per metric ton of each fuel as well as other pollutants. Such data is available for fuels that are already in use (International Maritime Organization, 2016, 2021). Nonetheless, certain fuels that have been analyzed are regarded as emerging, and consequently, there is no quantitative data on CO<sub>2</sub>, NO<sub>x</sub> or SO<sub>x</sub> emissions that may arise upon combustion. Only the potential of alternative fuels in addressing environmental concerns is currently known (McKinlay et al., 2021). Table 2-2 is a broad comparison between several fuels, identifying the fuels that are currently employed, those that are deemed carbon-free, and those that release CO<sub>2</sub> either throughout production or combustion.

From Table 2-2, it is evident that fossil fuels cannot be perceived as carbon-free due to their consumption of non-renewable resources and the release of GHGs during their production and combustion, which are detrimental to the environment. The data also suggests a correlation between the CO<sub>2</sub> released during fuel production and consumption and their carbon-free status. Hence, it can be concluded that CO<sub>2</sub> emissions disqualify fuels as carbon-free. However, there is an exception when it comes to biofuels, which can be considered carbon-free despite emitting CO<sub>2</sub> during use. This is due to the fact that the biomass used to produce the fuels absorbs CO<sub>2</sub> from the atmosphere during its lifetime (Solakivi et al., 2022). It is also possible to conclude that the emission of CO<sub>2</sub> in the production or consumption of fuels is directly related to the raw material that gives rise to it. This is because if the raw material contains carbon, such as in fossil fuels or biomass, CO<sub>2</sub> will always be emitted. Conversely, when exclusively employing carbon-free raw materials and renewable processes and energies, almost no CO<sub>2</sub> is released. Moreover, it should be emphasized that with blue fuels, such as hydrogen and ammonia, CCS technologies are available which, once perfected, could mean that no CO<sub>2</sub> emissions are released (Moberg & Bartlett, 2022).

Table 2-2 - Environmental comparison of both established and emerging marine fuels

Fuel		Currently used	Carbon free	CO <sub>2</sub> Emissions
		[a]	[a], [b], [c], [d], [e], [f]	[a], [b], [c], [d], [e], [f]
Heavy Fuel Oil (HFO)		Y	N	Y
Marine Gas Oil (MGO)		Y	N	Y
Marine Diesel Oil (MDO)		Y	N	Y
Liquefied Natural Gas (LNG)	Grey	Y	N	Y
	Green	N	Y	N
Hydrogen	Grey	N	N	Y
	Blue	N	N	Y
	Green	N	Y	N
Ammonia	Grey	N	N	Y
	Blue	N	N	Y
	Green	N	Y	N
Biofuels	Biodiesel	N	Y*	Y
	Biomethane	N	Y*	Y
	Bio methanol	N	Y*	Y
	Bio-DME	N	Y*	Y

Key: Y = Yes; N = No.

\*Biofuels emit CO<sub>2</sub> during their consumption however they may be considered carbon neutral.

Sources: [a]-(McKinlay et al., 2021); [b]-(International Maritime Organization, 2021); [c]-(International Maritime Organization, 2016); [d]-(Lindstad et al., 2021); [e]-(Ajanovic et al., 2022); [f]-(Mayer et al., 2023); [g]-(Moberg & Bartlett, 2022)

## 2.4 Vessel Types

Maritime transportation has become an increasingly feasible option with the construction of larger, faster vessels that are capable of travelling greater distances. Each vessel is equipped with its own propulsion system and is therefore both a consumer of resources and a converter of resources into energy (Schnurr & Walker, 2019). The IMO stipulates the construction and technical structure of tanker vessels, which are periodically revised to ensure the safe transportation of fragile cargo (Mohit, 2021). Legislative measures may fluctuate depending on the type of vessel (Knapp & Franses, 2023).

Vessels can be classified, among other factors, depending on their size, cargo type and intended use. Notable classification categories (Knapp & Franses, 2023; Raunek, 2021) are explained below and an example of each may be viewed in Figure 2-3:

- **Container Ships** (Figure 2-3a) - designed to carry large quantities of cargo in various containers. Additionally, there are refrigerated container ships which transport cargo requiring low temperatures (Raunek, 2021). The potential load of this mode of transportation can be quantified in terms of container units, or TEU, as a result of the standard size of each container. These containers are not only transportable via vessels but also by trains, lorries, and other modes of transport, thereby enabling inter-modal transport (Schnurr & Walker, 2019).
- **Bulk Carriers** (Figure 2-3b) - specific vessel type that moves dry bulk cargo which typically doesn't have any designated packaging or container. It typically transports food grains, ores, coals, and even cement.
- **Tanker Ships** (Figure 2-3e,f,g) - specialized vessels that carry large quantities of liquid cargo, including crude oil, petroleum, LNG, wine, and other fluids, making them well-suited for transporting fuels. The size of tanker ships depends on its Dead Weight Tonnage (DWT), the unit used to measure its carrying capacity (Mohit, 2021). Tankers are categorized into different types according to the cargo they carry (Ghosh, 2022), such as:
  - **Oil tankers** (Figure 2-3f) - can be divided into two types, namely crude oil tankers and product tankers. The first ones are used for transporting crude oil via maritime routes. Product tankers, on the other hand, are used for carrying refined products such as petrol, gasoline, and MDO. The largest tanker ships in use are Ultra Large Crude Carriers (ULCC), which can carry a maximum of 550000 tons. Oil tankers are required to have a ventilation system to permit vaporous gases to exit the oil, thereby avoiding ignition risks.
  - **Gas Carriers** (Figure 2-3g) - specialized vessels designed to carry gaseous substances in their liquid form, such as LNG or liquefied petroleum gas (LPG) (Mohit, 2021). Unlike oil tankers that carry substances that are originally in liquid form like crude oil, petrol and diesel, gas tankers transport substances that would be in a gaseous state at room temperature but have been manipulated to be in liquid form. According to Ghosh (2022), there are over 200 LNG carriers that transport almost 80 million tons of cargo annually, a number that continues to rise due to growing global demand. These vessels carry gases including CH<sub>4</sub>, ethane, and LPG (Liquefied Petroleum Gas). Gas tanker ships can carry a volume ranging from 500 to 100,000 cubic meters depending on the vessel's size. The most recent LNG carrier models are capable of transporting as much

as 150000 cubic meters (Ghosh, 2022). Unlike oil tankers, gas carrier vessels feature a temperature and pressure system that keeps the gases liquid.

- **Chemical tankers** (Figure 2-3e) - employed for the transportation of chemical gases such as  $\text{NH}_3$ .
- **Passenger Ships** (Figure 2-3c) - carry passengers and are mainly classified as ferries, transporting people and vehicles over short distances, and cruise ships, providing leisure activities and long-term journeys at sea for people.
- **Fishing Ships** (Figure 2-3d) - boats or vessels used for either recreational or commercial fishing (Raunek, 2021).



Figure 2-3 - Types of vessels

Note: (a) - Container ship; (b) - Bulk carrier; (c) - Passenger ship; (d) - Fishing ship; (e) - Chemical tanker; (f) - Oil tanker; (g) - Gas carrier. Adapted from Boonzaier, (2021); Chakraborty, (2021); Church, (2022a), (2022b); Paris, (2019); Raunek, (2021); and Williamson, (2023).

According to 2018 data, the world's fleet of vessels was composed of 43% dry bulk carriers, 35% tanker ships, and 13% container ships (Schnurr & Walker, 2019). In 2010, HFO was favored by most of the shipping fleet for propulsion. Only a small percentage opted for MDO or MGO. Today, most container ships and product/chemical tankers stick with this trend, but a small percentage of bulk carriers and crude oil tankers now use LNG as their propulsion fuel. The prediction for 2030 infers that at least half of the container ships, bulk carriers, and tanker ships will continue to run on HFO, with a low percentage running on MGO and MDO, although greater uptake of fuels such as LSHFO and LNG is expected. Low-carbon or alternative fuels account for only about 1% of the world fleet (Schnurr & Walker, 2019). It is evident that hydrogen can be carried by sea in liquid or gaseous form in tankers (Moreno-Brieva et al., 2023). Table 2-3 displays the appropriate tanker types for the transportation of each fuel variety.

Table 2-3 - Tanker options for marine fuel transportation

Fuel	Product tanker	Chemical tankers	Gas carriers
Heavy Fuel Oil (HFO)	X		
Marine Gas Oil (MGO)	X		
Marine Diesel Oil (MDO)	X		
Liquefied Natural Gas (LNG)			X
Hydrogen		X	X*
Ammonia		X	
Biofuels	Biodiesel	X	
	Biomethane		X*
	Bio methanol		X*
	Bio-DME		X*

Sources: (Schnurr & Walker, 2019), (Knapp & Franses, 2023), (Raunek, 2021), (Mohit, 2021), (Ghosh, 2022), (Moreno-Brieva et al., 2023).

\*Liquified form

## 2.5 Mathematical Models in Fuel Transportation

Fuels can be transported using a variety of methods, including road-based lorries, rail-based trains, pipelines, or tankers for sea-based transportation (Strogen et al., 2016). Various models have been developed in the context of shipping, such as for route optimization (e.g. Erdoğan, 2017) or for optimizing the distribution of goods (e.g. Grifoll et al., 2022). Most mathematical models use optimization techniques to enhance efficiency and reduce costs whilst also improving operations. These techniques can even aid in reducing environmental impact

by minimizing fuel consumption and emissions (Karatuğ et al., 2023). Linear programming is a commonly used optimization technique to determine the best solution for a given mathematical model. Each model has its own specifications and considerations, aiming to replicate real-world scenarios as closely as possible. This ensures model users can make well-informed decisions (Yan et al., 2021). In the shipping industry, the efficient transportation of fuels is crucial for the proper functioning of economies, societies, and industries. Fuel transportation is a complex process, thus it is essential to develop mathematical models to optimize the dynamics involved and to facilitate decision-making (Al-Enazi et al., 2022).

Fuel transport is the focus of this sub-chapter, with the objective of identifying articles pertaining to fuel transport in which mathematical models have been utilized to optimize it. Only cases that clearly indicate a fuel transport model have been taken into consideration. To locate articles in Science Direct within this category, the following combination of keywords has been employed: "model" AND "maritime transportation" AND ("fuel transport" OR "fuel delivery"). Initially, 45 articles were retrieved from this search on the 28th of August of 2023. Only original articles were considered to ensure the quality of the sample for analysis. This reduced the number of articles to 31. After analyzing the title, keywords, and abstract, 16 articles were selected for further analysis, with all documents lacking mathematical models related to fuel transportation being discarded. After delimiting the search, a total of 10 articles were identified, which accounts for approximately 22% of the initially identified articles. Table 2-4 presents the selected articles, summarizing them and the applied methodology, the model's objective, the transported fuels, the type of transportation used, and whether a case study was applied, indicating the country where it was conducted.

After analyzing the acquired data extensively, it was feasible to deduce that the majority of the case studies were executed within the past 4 years. Merely four models were utilized in case studies, which can be attributed to the challenge of making theoretical models applicable to real cases as all the requisite factors need to be incorporated. Linear programming and heuristics have emerged as the most frequently employed methodologies. Five articles present an economical model aiming to reduce costs or increase profit, while the other five concentrate on safety and sustainability models in fuel transportation. Six of the analyzed articles focus on transport by sea, though not exclusively. Of these six articles, only three focus solely on maritime transport. The transported fuels vary widely, but only three articles concentrate on the transport of multiple fuels. Even though Cornillier et al. (2008) concentrate on petroleum products and Stroger et al. (2016) concentrate on liquid fuels, only Al-Enazi et al. (2022) concentrate on fuels that require different types of vessels for transport.

Table 2-4 - Mathematical models and attributes for fuel transportation

Publication	Paper objective	Model methodology	Model goal	Transported fuels	Type of transportation	Case study	Country
<b>Cornillier et al., (2008)</b>	<p>Develop a heuristic solution approach for the multi-period petrol station replenishment problem (MPSRP) that involves optimizing the delivery of different petroleum products to a set of petrol stations over a given planning horizon.</p> <p>Determine delivery quantities, loading strategies, and vehicle routes to maximize the overall profit, taking into account factors like routing costs, regular costs, and overtime costs.</p>	- Heuristic	Maximize the total profit calculated as the revenue generated from deliveries minus the sum of routing costs, regular costs, and overtime costs.	Petroleum products	Road	No	Not applicable
<b>Vidović et al., (2014)</b>	<p>Address the multi-product multi-period Inventory Routing Problem (IRP) in the context of fuel delivery by presenting solution approaches to simultaneously optimize both inventory control and vehicle routing decisions in a Vendor Management Inventory (VMI) environment, where suppliers determine the quantities and time periods of deliveries.</p>	- Mixed Integer Programming (MIP) - Heuristic	To optimize the trade-off between inventory and routing costs in fuel delivery by determining the optimal quantities and time periods of deliveries, as well as the optimal vehicle routing.	Not specified	Not specified	No	Not applicable

Table 2-4 - Mathematical models and attributes for fuel transportation (cont.)

Publication	Paper objective	Model methodology	Model goal	Transported fuels	Type of transportation	Case study	Country
<b>Strogen et al., (2016)</b>	Assess the environmental, public health, and safety impacts associated with different modes of fuel transportation, including pipelines, trucks, rail, and barges. Provide a comprehensive analysis of the strengths and weaknesses of each mode to support informed decision-making regarding fuel transportation infrastructure.	- Estimation metrics	Provide a comprehensive assessment of the environmental, public health, and safety impacts associated with different fuel transportation modes. Quantify the externalities of each mode, including their contribution to GHG emissions, air pollution-related health impacts, occupational safety incidents, and employment opportunities.	Liquid fuels	Pipelines Road Rail Maritime	Yes	United States of America
<b>Christian-sen et al., (2017)</b>	Address the operational problem of routing and scheduling a fleet of fuel supply vessels used to service customer vessels anchored outside a major port.	- MIP	Minimize transportation costs, including variable sailing costs and fixed daily costs of vessel usage.	Not specified	Maritime	No	-

Table 2-4 - Mathematical models and attributes for fuel transportation (cont.)

Publication	Paper objective	Model methodology	Model goal	Transported fuels	Type of transportation	Case study	Country
<b>Iannaccone et al., (2019)</b>	<p>Perform a comparative analysis of the inherent safety performance of various technologies for LNG bunkering for vessels.</p> <p>Compare the safety issues associated with LNG technologies to conventional marine diesel fuels.</p> <p>Identify inherently safer solutions for maritime fuel bunkering and provide insights into the safety challenges for the future development of green shipping technologies.</p>	- Comparison methods	<p>Assess and compare the inherent safety performance of different technologies for marine fuel bunkering.</p> <p>Evaluate the potential consequences and inherent hazards associated with various equipment and processes involved in bunkering operations.</p>	LNG	Maritime	No	-
<b>Lu &amp; Gzara, (2019)</b>	<p>Address the robust vehicle routing problem with time windows (RVRPTW) under demand uncertainty, focusing on scenarios such as fuel delivery to gas stations, farms, or production plants, where the demand varies within certain intervals.</p> <p>Develop robust vehicle routes that remain feasible in terms of vehicle capacity constraints when customer demands vary within predefined sets.</p>	- Column generation (branch-and-price-and-cut)	Find robust vehicle routes that account for demand uncertainty while minimizing costs.	Not specified	Road	No	-

Table 2-4 - Mathematical models and attributes for fuel transportation (cont.)

Publication	Paper objective	Model methodology	Model goal	Transported fuels	Type of transportation	Case study	Country
<b>Hagos &amp; Ahlgren, (2020)</b>	Explore cost-effective solutions for deep decarbonization in transportation in Denmark's future energy system under various scenarios. Analyze the role of different transport technologies and fuels in achieving fossil independence and reducing GHG emissions.	- TIMES-DKGAS model, a long-term energy system optimization model	Capture emerging transport technologies (ETTs) and their associated infrastructure, vehicle heterogeneity, and consumer preferences. Optimize the societal surplus by considering different scenarios, time horizons, and technology pathways to achieve deep decarbonization.	Gas	Maritime Road	Yes	Denmark
<b>Jeong et al., (2021)</b>	Designing an optimum conceptual tie-down structure for safely transporting a metal cask containing spent nuclear fuel (SNF). Ensure structural integrity and compliance with domestic and international regulations.	- Solid Isotropic Material Penalization (SIMP) method - ANSYS software	Find an optimum layout for the tie-down structure that ensures the safe transportation of the metal cask containing SNF while meeting yield stress and volume constraints.	SNF	Road Rail Maritime	No	-

Table 2-4 - Mathematical models and attributes for fuel transportation (cont.)

Publication	Paper objective	Model methodology	Model goal	Transported fuels	Type of transportation	Case study	Country
Tao et al., (2021)	Develop an integrated risk assessment method for SNF transportation accidents under complex environments. Address the incomplete consideration of risk factors and the use of general particle diffusion models in current risk assessments for SNF transportation accidents.	- Integrated risk assessment method; - "Man-machine-environment" three-dimensional comprehensive system; - Probabilistic Safety Assessment (PSA) method; - Event Tree (ET) model; - Fault Tree (FT) model; - $k-\epsilon$ model.	Provide a comprehensive risk assessment of SNF transportation accidents, considering various risk factors, accident scenarios, and consequences. Quantify the risk associated with different accident scenarios and to identify key risk factors that contribute to the dispersion of radionuclides.	SNF	Road	Yes	China

Table 2-4 - Mathematical models and attributes for fuel transportation (cont.)

Publication	Paper objective	Model methodology	Model goal	Transported fuels	Type of transportation	Case study	Country
Al-Enazi et al., (2022)	<p>Evaluate the utilization of clean fuels in maritime applications through a techno-economic supply chain optimization, focusing on how LNG exporters can reduce the environmental impact of shipping activities by using cleaner fuel alternatives such as hydrogen and ammonia.</p> <p>Test the notion that demand for alternative fuels will increase as the transportation sector integrates cleaner options to comply with environmental regulations.</p>	- Multi-Objective Linear programming	Find optimal solutions for the maritime supply chain, considering various objectives and constraints related to fuel choice, demand, emissions, and profitability. Identify the most economically and environmentally viable options for fuel choices either for transporting or use for propulsion, considering different scenarios and factors affecting the maritime shipping operations.	HFO Grey LNG Grey hydrogen Grey ammonia 50% blend of grey LNG and grey hydrogen 50% blend of grey hydrogen and grey ammonia	Maritime	Yes	Qatar



## FUEL TRANSPORTATION MODEL

In this chapter the model that was developed to overcome the problem exposed formerly will be presented. Firstly, a description of the proposed model including its main objectives, a short description of the decision variables and the assumptions made are presented. Afterwards, the model's mathematical formulation is displayed comprising the parameters, decision variables, objective function, and constraints.

### 3.1 Model Description

The problem of maximizing profit considering that different types of fuels are transported and used in vessels for bunkering can be approached using several mathematical models. This master thesis presents a MILP model that is applicable to companies with a fleet of vessels that transport various fuels and wish to maximize their profit. The determination of the optimal quantities of the different fuels to be transported to numerous destinations, from a single EP, and the needed shipments to do so are presented as the solution (Figure 1-2).

On a strategic level, decision makers can benefit from the developed model, as it assists in assessing current and future bunker fuel options for delivering fuel. The model determines profit by subtracting costs of using fuel for propulsion and auxiliary systems on vessels, costs of operating the vessel and engine, and CO<sub>2</sub> emissions costs from the revenue generated by delivering fuels to various destinations. The second aim is to offer a transport service where the fuel transported is independent of the fuel used in the vessel's propulsion system, thereby increasing the company's choice of vessel options to transport the same fuel. The third aim is to present a sustainability model that takes into account CO<sub>2</sub> emissions limits and the adverse financial impact of excessive use of fuels that emit CO<sub>2</sub>, which reduces the company's profits and helps achieve a balance in the use of fossil fuels. Overall, the model enables the company to calculate profit, determine the most suitable fuels for use in its vessels, and satisfying the

demand of each fuel to each destination, while staying within the environmental limits set by regulatory authorities.

### 3.1.1 Assumptions

Several assumptions have been outlined below to simplify the problem, namely:

1. Fuels are supplied to several receiving terminals (destinations) around the globe.
2. There is only one EP.
3. The trip is made directly from the EP to the receiving terminal with no stops.
4. Inbound voyages are equivalent to outbound voyages in terms of weight. This results from the necessity of utilizing ballast water to uphold the vessel's balance.
5. Recurrent voyages are feasible.
6. The fleet size is infinite.
7. All vessels that transport the same type of fuel have the same capacity.
8. There is always a vessel available at the time of loading, eliminating any waiting costs.
9. Both exporting and receiving ports are available during loading/unloading, eliminating any penalties that may be applied for delays.
10. The cost of idle vessels, voyage delay penalties, demurrage costs, canal passage charge and cost of receiving terminal regasification slot are neglected.
11. The auxiliary system, which is used for ensuring optimal fuel conditions (i.e., temperature, pressure), uses the same fuel that is being used for propulsion.
12. The auxiliary system consumes 30% of the overall fuel used for propulsion of an outbound trip (based on Al-Enazi et al., (2022) similar assumption).
13. There is only consumption of fuel for auxiliary systems in the outbound journey.
14. All vessels maintain a consistent speed for the duration of their entire shipment.
15. The availability of bunker fuels is considered infinite in the EP.

### 3.1.2 Comparative Analysis: Developed Model vs. Source Model

The model developed in this master thesis was mildly based on the mathematical model proposed by Al-Enazi et al., (2022). The latter shares several similarities with the developed model, however there are also a number of divergences. It must be acknowledged that both models have similar objectives, although with some distinctions. However, regarding their mathematical formulation, the parameters, their units of measure, the decision variables, the

objective function, and the constraints differ significantly. Table 3-1 illustrates the similarities found between the two models with respect to the type of similarity.

Table 3-1 - Shared characteristics between the proposed model and Al-Enazi et al., (2022) model

<b>Similarities with the research of Al-Enazi et al., (2022)</b>	
<b>General characteristics</b>	<ul style="list-style-type: none"> <li>• Application of optimization methods;</li> <li>• Focus on the maritime transportation of fuels;</li> <li>• Incorporation of multiple fuel options;</li> <li>• Singular EP consideration;</li> <li>• Multiple destinations included;</li> <li>• Assumption of auxiliary system fuel consumption at 30% of total fuel usage.</li> </ul>
<b>Parameters</b>	<ul style="list-style-type: none"> <li>• Distance between ports;</li> <li>• Bunker fuel cost;</li> <li>• Fuel consumption;</li> <li>• Normalized vessel costs;</li> <li>• Normalized engine costs;</li> <li>• Demand for a specific fuel;</li> <li>• Vessel capacity.</li> </ul>
<b>Unit of measure</b>	<ul style="list-style-type: none"> <li>• Utilization of the currency United States Dollars (USD) for pricing.</li> </ul>
<b>Decision Variables</b>	<ul style="list-style-type: none"> <li>• Utilization of the number of shipments to each destination as decision variable.</li> </ul>
<b>Objective Function</b>	<ul style="list-style-type: none"> <li>• Integration of transportation cost;</li> <li>• Consideration of normalized vessel and engine costs.</li> </ul>
<b>Constraints</b>	<ul style="list-style-type: none"> <li>• Demand;</li> <li>• CO<sub>2</sub> emission limits.</li> </ul>

In order to understand the improvements implemented in the model developed in this master thesis, Table 3-2 outlines the differences between the two models. This analysis provides a foundation for the exploration of the developed model, highlighting its potential applications and impact on the maritime fuel transport industry.

The developed model and Al-Enazi et al. (2022) model share a common emphasis on using linear programming techniques to optimize maritime fuel transportation (Table 3-1). However, notable differences exist between the two models (Table 3-2). The developed model offers a broader scope by considering a diverse range of fuels, including more emerging alternatives, and provides a versatile framework adaptable to various scenarios. In contrast, Al-Enazi et al. (2022) model primarily concentrates on liquefied natural gas (LNG) and associated products and is a scenario-based model, limiting its adaptability. Although the ultimate objective of Al-Enazi et al. (2022) model is to use the same fuel for both transportation and bunker fuel, the developed model only considers the independence between the two fuels.

Table 3-2 - Differences between the developed and Al-Enazi et al., (2022) models

	<b>Proposed model</b>	<b>Al-Enazi et al., (2022) model</b>
<b>General Characteristics</b>	Focuses on a broad range of fuels prevalent in the shipping industry;	Primarily emphasizes LNG and associated natural gas product transport;
	Incorporates clean fuel options;	Excludes consideration of clean fuels;
	Elaborates general assumptions;	Relies on case-specific assumptions;
	Designed as a versatile model adaptable to different case studies;	Not designed as a versatile model adaptable to various case studies;
	Adapts vessel capacity according to the transported fuel;	Presumes a fixed vessel capacity of 140 000 m <sup>3</sup> ;
	Accounts for CO <sub>2</sub> emissions exclusively;	Accounts for emissions of NO <sub>x</sub> , SO <sub>x</sub> , and CO <sub>2</sub> ;
	Bunker fuel is independent of transported fuel, allowing application to diverse scenarios;	Offers two distinct scenario sets: one with bunker fuel independence and one without;
<b>Parameters</b>	All scenarios aimed at maximizing profit. Objectives of satisfying demand, emissions limit or both;	Conducts scenarios aimed at maximizing profit, minimizing emissions, or addressing both objectives;
	Exclusively addresses fuel transportation within its scope.	Encompasses both fuel selling and transportation in the model's scope.
	Considers the transportation prices for different fuels;	Addresses the selling prices of fuels;
	Accounts for CO <sub>2</sub> emissions associated with fuel usage;	Accounts for emissions in fuel production;
	Includes availability of various fuels;	Includes production capacity of fuels;
<b>Unit of measure</b>	Limit on total CO <sub>2</sub> emissions;	Limits on emissions, including CO <sub>2</sub> , NO <sub>x</sub> , and SO <sub>x</sub> ;
	Others: Incorporates costs related to CO <sub>2</sub> emissions.	Others: Encompasses fuel production costs, fuel density, and fuel low heating value parameters.
	Distance is quantified in nautical miles (NM);	Distance is measured in kilometers (km);
	Vessel capacity is expressed in tons;	Vessel capacity is denoted in cubic meters (m <sup>3</sup> );
<b>Decision Variables</b>	CO <sub>2</sub> emissions are quantified in tons;	CO <sub>2</sub> emissions are measured in kilograms (kg);
	The quantity of fuel is measured in tons.	The quantity of fuel is specified in megajoules (MJ).
<b>Objective Function</b>	Quantity of transported fuel to each destination	Number of shipments to each destination
	Revenue of transporting the fuels;	Revenue of selling and transporting the fuels;
	Costs of transportation;	Costs of production and transportation;
<b>Constraints</b>	Costs of CO <sub>2</sub> emissions.	Does not include GHG's emissions costs.
	Availability;	Production Capacity;
	CO <sub>2</sub> emissions limit;	CO <sub>2</sub> , NO <sub>x</sub> and SO <sub>x</sub> emissions limit;
	Shipping capacity.	Does not include shipping capacity constraint.

This approach provides greater flexibility in fuel selection. While Al-Enazi et al. (2022) incorporates both revenues and costs associated with the production and transportation of fuels in their model, the developed model focus solely on transportation since the entities responsible for fuel production and transportation are not the same, showcasing a more realistic approach of fuel delivery. The decision to exclude NO<sub>x</sub> and SO<sub>x</sub> emissions in the developed model, in contrast to the approach taken by Al-Enazi et al. (2022), lies in the specific context and priorities of this research that aims to prioritize CO<sub>2</sub> emissions due to its significant contribution to climate change, allowing for a more targeted analysis while avoiding unnecessary complexity. Overall, while both models have the same theoretical objective, the developed model overcomes limitations observed in Al-Enazi et al. (2022) model, this way being more up-to-date, versatile, realistic and focused.

## 3.2 Mathematical Model

In this section, the mathematical model formulation is presented.

### Sets and Indices

In the proposed model, three independent sets and their respective indices are considered.  $I$  encompasses the fuels  $i$  that are transported i.e.  $\{i_1, i_2, \dots, i_n\}$ .  $J$  includes the fuels used in the vessels' engines for propulsion i.e.  $\{j_1, j_2, \dots, j_n\}$ . Lastly,  $K$  considers all the destinations to where there is a transported fuel demand i.e.  $\{k_1, k_2, \dots, k_n\}$ .

$I$  - the set of transported fuels, indexed by  $i$

$J$  - the set of bunker fuels, indexed by  $j$

$K$  - the set of destinations, indexed by  $k$

### Parameters

The parameters are crucial foundations that facilitate the accurate correlation between themselves and the decision variables, thus ensuring that the model functions efficiently. For the proposed model, fourteen parameters and their respective units are defined and listed in **Error! Not a valid bookmark self-reference..**

Table 3-3 - Model's Parameters

Parameter	Description	Units
$P_i^Q$	Transportation price regarding the quantity of transported fuel ( $i$ )	$\frac{\text{USD}}{\text{ton fuel } i}$
$P_j^D$	Transportation price regarding distance travelled using fuel ( $j$ )	$\frac{\text{USD}}{\text{NM}}$
$d_k^{EP}$	Distance between exporting port and destination port ( $k$ )	NM
$M$	Distance factor for a round trip, considering the distance of two separate voyages - one to go and one to come back - and the auxiliary system's contribution of 30% of the export trip	2,3
$C_j^b$	Bunker fuel cost for fuel ( $j$ )	$\frac{\text{USD}}{\text{ton fuel } j}$
$F_j^c$	Fuel consumption for fuel ( $j$ )	$\frac{\text{ton fuel } j}{\text{NM}}$
$C_i^S$	Normalized Vessel Cost per shipment for fuel ( $i$ )	$\frac{\text{USD}}{\text{shipment}}$
$C_j^E$	Normalized Engine Cost per shipment for fuel ( $j$ )	$\frac{\text{USD}}{\text{shipment}}$
$C^e$	Cost of $CO_2$ emissions	$\frac{\text{USD}}{\text{ton } CO_2}$
$E_j$	$CO_2$ emissions per ton of fuel ( $j$ ) used	$\frac{\text{ton } CO_2}{\text{ton fuel } j}$
$A_i$	Availability of fuel ( $i$ ) in the EP	$\frac{\text{ton fuel } i}{\text{year}}$
$D_{ik}$	Demand of fuel ( $i$ ) in destination ( $k$ ) per year	$\frac{\text{ton fuel } i}{\text{year}}$
$Q_i^S$	Capacity of the vessel that transports fuel ( $i$ )	$\frac{\text{ton fuel } i}{\text{shipment}}$
$L$	Limit of $CO_2$ emissions per year	$\frac{\text{ton } CO_2}{\text{year}}$

### Decision Variables

The decision variables determine the output, representing the optimum solution for the problem. Their values, unlike parameters which have predefined values, are obtained from the optimization process of the model. There are two decision variables in the proposed model, which are detailed in Table 3-4, along with their units.

Table 3-4 - Model's decision variables

Decision Variable	Description	Units
$x_{ijk}$	Quantity of fuel ( $i$ ) transported, using vessels fueled with bunker fuel ( $j$ ) to destination ( $k$ ) per year	$\frac{\text{ton fuel } i}{\text{year}}$
$y_{ijk}$	Number of shipments transporting fuel ( $i$ ), using fuel ( $j$ ) as bunker fuel to destination ( $k$ ) in a year	$\frac{\text{shipments}}{\text{year}}$

### Model formulation

The model is formulated with an objective function (eq. 3-1), which quantifies the specific goal that the model is trying to achieve, and constraints (eq. 3-2 to eq. 3-7), which define the limits and restrictions that the solution must obey.

$$\max \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} [P_i^Q x_{ijk} + 2P_j^D d_k^{EP} y_{ijk} - MC_j^b F_j^c d_k^{EP} y_{ijk} - (C_i^S + C_j^E) y_{ijk} - MC^e E_j F_j^c d_k^{EP} y_{ijk}] \quad (\text{eq. 3-1})$$

Subject to:

$$\sum_{j \in J} \sum_{k \in K} (x_{ijk}) \leq A_i \quad \forall i \in I \quad (\text{eq. 3-2})$$

$$\sum_{j \in J} (x_{ijk}) = D_{ik} \quad \forall i \in I, k \in K \quad (\text{eq. 3-3})$$

$$x_{ijk} \leq Q_i^S y_{ijk} \quad \forall i \in I, k \in K \quad (\text{eq. 3-4})$$

$$\sum_{i \in I} \sum_{j \in J} \sum_{k \in K} [ME_j F_j^c d_k^{EP} y_{ijk}] \leq L \quad \forall i \in I, j \in J, k \in K \quad (\text{eq. 3-5})$$

$$x_{ijk}, y_{ijk} \geq 0 \quad \forall i \in I, j \in J, k \in K \quad (\text{eq. 3-6})$$

$$y_{ijk} \in Z \quad \forall i \in I, j \in J, k \in K \quad (\text{eq. 3-7})$$

The aim is to maximize the total profit of a company specializing in the transport of fuel, which is calculated by subtracting the sum of all costs from the sum of all revenues. The revenue includes only the one made by delivering the fuels. The costs entail the expenses of transportation, normalized vessel and engine costs, and CO<sub>2</sub> emissions costs.

The delivering revenue is represented in eq. 3-1 by the following term,

$$P_i^Q x_{ijk} + 2P_j^D d_k^{EP} y_{ijk} \quad (\text{eq. 3-8})$$

Equation 3-8 is composed by two terms. The first term is the revenue generated in connection with the quantity transported to every destination. This is obtained by multiplying the price of transporting one ton of fuel with the number of tons transported. The second term refers to the revenue generated from fuel transportation over distance. Its calculation involves multiplying the transport price per nautical mile by the distance travelled by the vessel from an EP to a specific destination, and then doubling that value to encompass the return trip. All is then multiplied by the number of shipments necessary to deliver all types of transported fuels, using all types of bunker fuels and repeating the process for all destinations.

The transportation costs are represented in eq. 3-1 by the following term,

$$MC_j^b F_j^c d_k^{EP} y_{ijk} \quad (\text{eq. 3-9})$$

which is obtained from,

$$2C_j^b F_j^c d_k^{EP} y_{ijk} + 0,3C_j^b F_j^c d_k^{EP} y_{ijk} \quad (\text{eq. 3-10})$$

The two terms in eq. 3-10 refer to the travelling costs related to consuming the necessary bunker fuel for vessel propulsion and for the auxiliary system. The first term accounts for the round trip costs, as bunker fuel is consumed both ways. The second term only accounts for the outbound journey as the auxiliary system is only used when transporting fuel, which is not the case on the return trip. The costs in eq. 3-9 are calculated by multiplying the cost for bunker fuel with the fuel consumption of that same fuel and the distance travelled by the vessel. The result is then multiplied by the necessary number of shipments, ensuring that all trips are accounted for.

The normalized vessel and engine costs are represented in eq 3-1 by the following term,

$$(C_i^S + C_j^E) y_{ijk} \quad (\text{eq. 3-11})$$

which is obtained from,

$$C_i^S y_{ijk} + C_j^E y_{ijk} \quad (\text{eq. 3-12})$$

The first term in eq. 3-12 is an estimated cost of utilizing the vessel while the second term a cost approximation of the usage of the vessel's engine. Both added totalize the normalized costs that are then multiplied by the number of shipments to calculate the costs for all trips, as shown in eq. 3-11.

The costs related to CO<sub>2</sub> emissions are represented in eq. 3-1 by the following term,

$$MC^e E_j F_j^c d_k^{EP} y_{ijk} \quad (\text{eq. 3-13})$$

which is obtained from,

$$2C^e E_j F_j^c d_k^{EP} y_{ijk} + 0,3C^e E_j F_j^c d_k^{EP} y_{ijk} \quad (\text{eq. 3-14})$$

The costs of CO<sub>2</sub> emissions are considered only for bunker fuels since their use requires combustion. Both costs for emissions from bunker fuel used for propulsion and for auxiliary systems are added, as shown in eq. 3-14. The cost itself is calculated by multiplying the CO<sub>2</sub> emission fee by the amount of emissions generated and the amount of fuel used to travel the distance for all shipments, as shown in eq. 3-13.

The availability constraint in eq. 3-2 ensures that the sum of the total quantity of a type of fuel ( $i$ ) that is being transported to all destinations does not exceed the availability in the EP of that same fuel. Constraint represented by eq. 3-3 ensures a demand satisfaction, which means that the amount of fuel ( $i$ ) that is being transported to a destination ( $k$ ) must meet the demand for that fuel in that destination for all fuels and destinations. The shipping capacity constraint, expressed in eq. 3-4, ensures that the quantity of a fuel that is being transported per shipment cannot exceed the capacity of the vessel, which is the same for each type of fuel ( $i$ ). There is also an emission limit constraint represented by eq. 3-5 that ensures that the sum of the total amount of CO<sub>2</sub> emissions emitted as a result of the consumption of all fuels ( $j$ ) for all destinations should not exceed the specified emissions limit of CO<sub>2</sub> in a year. Constraints of eq. 3-6 and eq. 3-7 ensure that the decision variables are positive, and that the  $Y$  decision variable only takes on integer numbers, respectively.

The solution to this linear programming model provides the optimal quantities of different types of fuels that should be transported to different destinations to maximize the profit of the company, the best bunker fuels to use in the vessels and the optimal amount of shipments needed for delivery in a year, while meeting the availability, demand, capacity, and emissions constraints.



## ILLUSTRATIVE CASE STUDY

In this chapter, a practical implementation of the developed model described in the previous chapter is presented. Initially, a verification of the model was carried out with few variables and arbitrary data to ensure its good performance. The data for the baseline scenario of the model is presented, as well as the exploration of multiple scenarios to test the model and reveal its performance under various circumstances. The outcomes of the scenarios are then highlighted, along with some concluding remarks.

### 4.1 Model Implementation and Verification

The model implementation was developed on the Google Collaboratory platform, also known as *Colab*, and the optimal solution was achieved by employing the Python programming language in the FICO Xpress software. The implementation of the model using the Python language in the *Colab* platform is available online at [https://colab.research.google.com/drive/1ullu8a8hZmFsYv8\\_OV8r-gkXCkIMNVnq#scrollTo=6yazdlcS4fpb&line=79&uniqifier=1](https://colab.research.google.com/drive/1ullu8a8hZmFsYv8_OV8r-gkXCkIMNVnq#scrollTo=6yazdlcS4fpb&line=79&uniqifier=1) and is displayed in [Annex A](#).

The model went through a verification process in which its correct implementation was confirmed. This process entailed the deployment of the model in the spreadsheet editor Microsoft Excel, employing a limited dataset comprising two transported fuels ( $i_1$  and  $i_2$ ), two bunker fuels ( $j_1$  and  $j_2$ ), and two destination ports ( $k_1$  and  $k_2$ ). The dataset used for the verification process was selected using a convenience criteria, considering suitable values for all parameters, with the primary objective of enhancing the clarity and comprehensibility of the resultant outcomes. The input data used for the model verification is presented from Table 4-1 to Table 4-4.

Table 4-1 - Input data for verification - Parameters with dataset (i)

		Parameters					DESTINATIONS		
		PQi - Transportation price regarding the quantity of transported fuel (i)	Ai - Availability of fuel (i)	Qsi - Capacity of the vessel that transports fuel (i)	CSi - Normalized Vessel Cost per shipment for fuel (i)	Dik -Demand of fuel (i) per year in destination (k)	k1	k2	
TRANSPORTED FUELS	i1	50	40 000 000	50 000	5 000	TRANSPORTED FUELS	i1	300 000	800 000
	i2	150	85 000 000	5 000	10 000		i2	400 000	1 500 000
UNITS		USD/ton	ton/year	ton/shipment	USD/shipment	UNITS		ton/year	

Table 4-2 - Input data for verification - Parameters with dataset (j)

		Parameters				
		Cbj -Bunker fuel cost for fuel (j)	Fcj - Fuel consumption for fuel (j)	CEj - Normalized Engine Cost per shipment for fuel (j)	Ej - CO <sub>2</sub> emissions per ton of fuel (j) used	PDj - Transportation price regarding distance travelled using fuel (j)
BUNKER FUELS	j1	500	0,20	2 000	3,00	50
	j2	4 000	0,05	3 000	0	100
UNITS		USD/ton	ton/NM	USD/shipment	ton CO <sub>2</sub> /ton fuel	USD/NM

Table 4-3 - Input data for verification - Parameter dEPk

		Parameter
		dEPk - Distance between EP and destination port (k)
DESTINATIONS	k1	10 000
	k2	1 000
UNITS		NM

Table 4-4 - Input data for verification - Parameters M, Ce and L

		Parameter		
		M -Distance factor	Ce - Cost of CO <sub>2</sub> emissions	L - Limit of CO <sub>2</sub> emissions
		2,3	20	50 000
UNITS		N/A	USD/ton CO <sub>2</sub>	ton CO <sub>2</sub> /year

N/A – Not Applicable

The Microsoft Excel solver tool was employed as an optimization tool to achieve the maximum total profit. The implementation of the solver parameters is shown in Figure 4-1.

Data from Table 4-1 to Table 4-4 was used to create coefficients for the objective function which were multiplied with the decision variables proposed by the solver tool. The goal was to maximize the total profit cell, which corresponds to the sum of all coefficients multiplied by their respective decision variable values, while ensuring that constraints from eq. 3-2 to eq. 3-7 are respected. The objective was set to maximize the total profit cell and the decision variable cells were selected to change according to the result proposed by excel. The constraints were added by correlating the values dependent from the decision variables with fixed values from the left and right sides of the constraints, respectively.

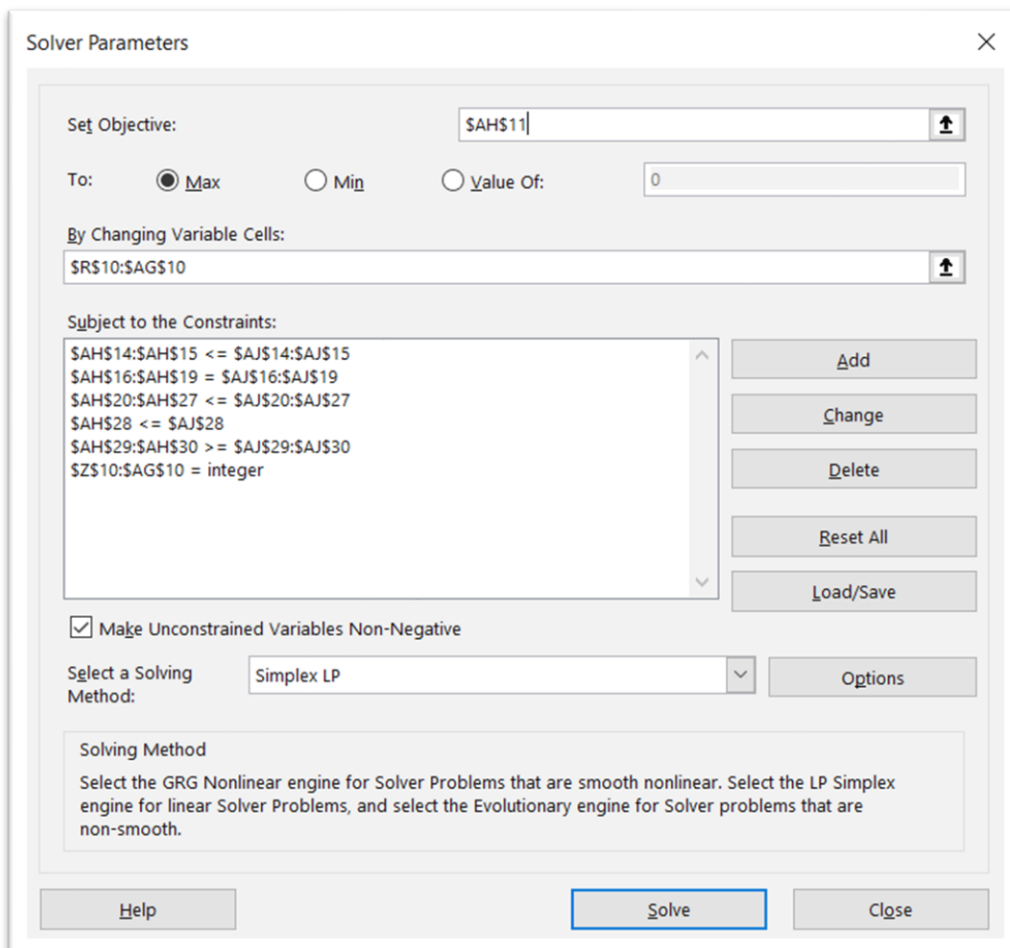


Figure 4-1- Solver parameters application

### 4.1.1 Verification Results and Analysis

The results of the application of the solver tool are displayed in Table 4-5. To confirm the robustness of the model's construction, the same data (from Table 4-1 to Table 4-4) was applied to the model through the *Colab* platform. The results were transferred to an Excel table for better visualization.

Table 4-6 illustrates the obtained results from both platforms and summarizes the decision variables outcomes for each (i), (j) and (k), as well as the total profit, for both the Solver tool in Excel and the Python implementation in *Colab*. By examining Table 4-6, it is evident that the decision variables' outcomes, for each datasets (i), (j) and (k) from the Excel results, vary from the homonymous outcomes from the *Colab* results.

Nevertheless, both yield identical totals for the combined sum of  $X_{ijk}$  - Quantity of fuel (i) transported, using vessels fueled with bunker fuel (j) to destination (k) per year - and  $Y_{ijk}$  - Number of shipments transporting fuel (i), using fuel (j) as bunker fuel to destination (k) in a year. The values for the total profit are also the same in both cases. It is demonstrated that both platforms reached the optimal solution of the profit value (32 846 400) by different paths, proving that there is more than one approach to achieve the optimal solution. This confirms the developed model and affirms its positive performance.

Furthermore, it is possible to conclude that  $j_2$  bunker fuel is an environmentally friendly fuel, since its emissions rate is zero as observed in the parameter "E<sub>j</sub>" in Table 4-2. This makes it possible to observe how the model behaves when given the choice of using green fuels or not. According to Table 4-5, the total emissions was (49 680) which nearly reached the CO<sub>2</sub> emissions limit (50 000). Thus, we can infer that the model utilizes non-green fuel as bunker fuel until the limit is reached, and then switches to green fuel to satisfy the remaining demand.

## 4.2 Input Data

Case-specific data, in particular the values for the parameters for i, j and k, were collected using an Artificial Intelligence (AI) application, namely ChatGPT. To ensure the accuracy of the data, the parameters' values were retrieved from the AI application in accordance with the following rules:

1. The questionnaire is made for a single parameter at a time.
2. The initial question for all parameters was formulated as follows: What are the numerical values for the [insert parameter description] in [insert parameter units] when [insert indices involved (i, j and/or k)] is: [insert indices' types]?

Table 4-5 - Solver implementation in Microsoft Excel

Decision Variables (x10 <sup>3</sup> )	Xijk (tons/year)								Yijk (shipments/year)								Total Profit	Units			
	Xi1 j1k1	Xi1 j1k2	Xi1 j2k1	Xi1 j2k2	Xi2 j1k1	Xi2 j1k2	Xi2 j2k1	Xi2 j2k2	Yi1j1k1	Yi1j1k2	Yi1j2k1	Yi1j2k2	Yi2j1k1	Yi2j1k2	Yi2j2k1	Yi2j2k2					
	0	750	300	50	0	105	400	1395	0	15	6	1	0	21	80	279	<b>32846400</b>	USD			
<b>Coefficients Objective Function</b>	50	50	50	50	150	150	150	150	-1583 x10 <sup>3</sup>	-164,6 x10 <sup>3</sup>	-2608 x10 <sup>3</sup>	- 268 x10 <sup>3</sup>	-1588 x10 <sup>3</sup>	-169,6 x10 <sup>3</sup>	-2613 x10 <sup>3</sup>	-273 x10 <sup>3</sup>	<b>32846400</b>	USD			
																	Left side	Type	Right side	Units	
Constraints	Availability i1	1	1	1	1												1,1x10 <sup>6</sup>	= <	40x10 <sup>6</sup>	ton/year	
	Availability i2					1	1	1	1								1,9x10 <sup>6</sup>	= <	85x10 <sup>6</sup>	ton/year	
	Demand i1 to k1	1		1													300x10 <sup>3</sup>	=	300x10 <sub>3</sub>	ton/year	
	Demand i1 to k2		1		1												800x10 <sup>3</sup>	=	800x10 <sub>3</sub>	ton/year	
	Demand i2 to k1					1		1									400x10 <sup>3</sup>	=	400x10 <sub>3</sub>	ton/year	
	Demand i2 to k2						1	1									1,5x10 <sup>6</sup>	=	1,5x10 <sup>6</sup>	ton/year	
	Capacity i1 j1 to k1	1								-50x10 <sup>3</sup>							0	= <	0	ton	
	Capacity i1 j1 to k2		1								-50x10 <sup>3</sup>						0	= <	0	ton	
	Capacity i1 j2 to k1			1								-50x10 <sup>3</sup>					0	= <	0	ton	
	Capacity i1 j2 to k2				1								-50x10 <sup>3</sup>				0	= <	0	ton	
	Capacity i2 j1 to k1					1								-50x10 <sup>3</sup>			0	= <	0	ton	
	Capacity i2 j1 to k2						1								-50x10 <sup>3</sup>		0	= <	0	ton	
	Capacity i2 j2 to k1							1								-50x10 <sup>3</sup>	0	= <	0	ton	
	Capacity i2 j2 to k2								1							-50x10 <sup>3</sup>	0	= <	0	ton	
	Emissions of all j to all destinations k									13800	1380	0	0	13800	1380	0	0	<b>49680</b>	= <	50000	tonCO <sub>2</sub> /year
	Non negativity Yijk									1	1	1	1	1	1	1	1	402	= >	0	N/A
Non negativity Xijk	1	1	1	1	1	1	1	1									3x10 <sup>6</sup>	= >	0	N/A	
Integer Yijk									1	1	1	1	1	1	1	1	402	int	N/A	N/A	

Table 4-6 - Results from both platforms

Excel Results	Xijk (tons/year)								Total Xijk (tons/year)
	Xi1j1k1	Xi1j1k2	Xi1j2k1	Xi1j2k2	Xi2j1k1	Xi2j1k2	Xi2j2k1	Xi2j2k2	
	0	750000	300000	50000	0	105000	400000	1395000	3 000 000
Colab Results	Yijk (shipments/year)								Total Yijk (tons/year)
	Yi1j1k1	Yi1j1k2	Yi1j2k1	Yi1j2k2	Yi2j1k1	Yi2j1k2	Yi2j2k1	Yi2j2k2	
	0	15	6	1	0	21	80	279	402
									Total Profit
									32 846 400
Excel Results	Xijk (tons/year)								Total Xijk (tons/year)
	Xi1j1k1	Xi1j1k2	Xi1j2k1	Xi1j2k2	Xi2j1k1	Xi2j1k2	Xi2j2k1	Xi2j2k2	
	0	0	300000	800000	0	180000	400000	1320000	3 000 000
Colab Results	Yijk (shipments/year)								Total Yijk (tons/year)
	Yi1j1k1	Yi1j1k2	Yi1j2k1	Yi1j2k2	Yi2j1k1	Yi2j1k2	Yi2j2k1	Yi2j2k2	
	0	0	6	16	0	36	80	264	402
									Total Profit
									32 846 400

3. If the initial response did not provide the requested numerical values, a follow-up question was made asking for "rough example numerical values".
4. If the data collected was not suitable compared to real values or did not follow a restriction, a follow-up survey was conducted including the necessary restrictions to ensure the quality of the data.
5. Values with three or more decimal places were rounded to two decimal places.
6. When a range of values was given, the average between the upper and lower values was used as final data.

An example of a survey conducted on the AI application to collect the values of the transportation prices regarding the quantity of transported fuel (i) is available in [Annex B](#).

For the fuel transportation model, 15 fuels to be transported, 15 fuels for the bunkering of the vessels and 5 destinations were considered. The transported fuels are the same as the bunkering fuels and were selected due to their prevalence as established and alternative fuels in the shipping industry. Destinations were selected from the Maritime Fairtrade website (available at: <https://maritimefairtrade.org/top-10-bunkering-ports-to-take-note-in-the-world-2023/>), which lists 10 main ports. The port of Trondheim, located in Norway, was selected as the EP. Using the Ports.com website (available at: <http://ports.com/sea-route/>), the distances between the EP and all 10 destinations were calculated. However, to comply with the number of rows and columns enforced by the *Colab* platform, only the initial five destinations were considered for the model. These were picked for their representation of both short and long

distances. The data retrieved for all parameters is available in [Annex C](#) from Table C-1 to Table C-5.

### 4.3 Scenarios

The practical implementation of the model was divided into four different sets of scenarios. In addition to maximizing the total profit, there are three objectives (A, B and C) in each set, namely:

- Objective A aims to satisfy all demand without considering the imposed CO<sub>2</sub> limit;
- Objective B aims to meet the CO<sub>2</sub> limit even if not all demand can be satisfied;
- Objective C which simultaneously considers the previous two objectives.

The developed model is recommended for Objective C, however a slight modification was required for both Objectives A and B. For Objective A, the limit on CO<sub>2</sub> emissions had to be changed from 50 000 to an almost infinite number. The number 1 000 000 000 was used to represent infinity. For Objective B, the satisfaction constraint regarding demand required modification to ensure that the total quantity of fuels to be transported was equal or inferior to the demand, instead of always being equal. This modification guarantees that the demand will only be fulfilled until it is profitable to do so. Figure 4-2 is a summary of the main assessed scenarios and respective objectives.

Scenarios 1 to 4 differ in the combination of bunker fuels used. All scenarios aim to provide valuable insights and conclusions from the model. By varying the bunker fuel options, it is possible to analyze the impact of different factors on the performance of the model in a way that is useful to any shipping company. Figure 4-3 provides a visual overview of the fuels included in each scenario. All 15 transported fuels and 5 destinations remain the same for all scenarios.

	Scenario			
	1	2	3	4
Objective	A	B	C	
Satisfy all Demand	✓	✗	✓	
Comply with CO <sub>2</sub> limit	✗	✓	✓	

Figure 4-2 - Summary of the scenarios under evaluation

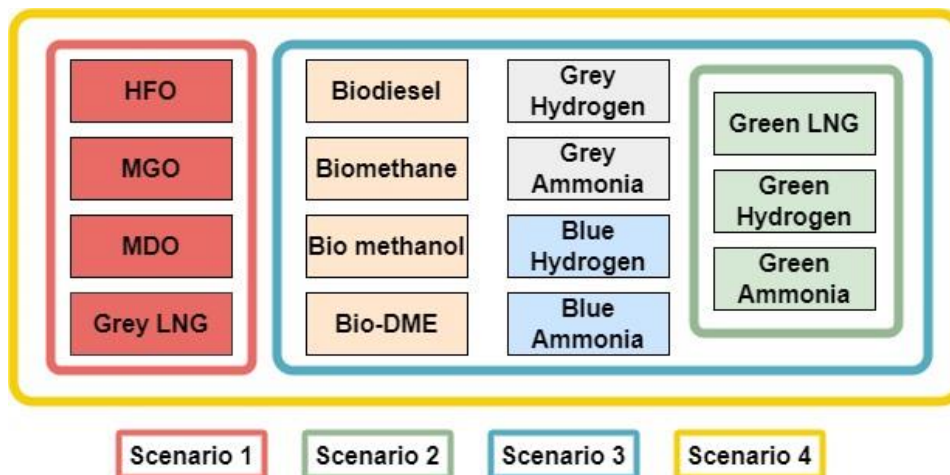


Figure 4-3 - Combination of bunker fuels in each scenario

The fuels considered for transportation are the same ones that are used as bunker fuels, listed in Figure 4-3. The destinations employed for all scenarios are Fujairah in the United Arab Emirates ( $k_1$ ), Houston in the state of Texas in the United States of America ( $k_2$ ), the city of Singapore in Singapore ( $k_3$ ), Antwerp in Belgium ( $k_4$ ) and Rotterdam in the Netherlands ( $k_5$ ).

### 4.3.1 Scenario 1

In this scenario it is exclusively used as bunker fuels fossil fuels, namely HFO, MGO, MDO, and grey LNG. The scenario is constructed with 15 transported fuels ( $i$ ), 4 bunker fuels ( $j$ ), and 5 destinations ( $k$ ).

The main aim of Scenario 1 is to determine the most profitable fossil fuel choice for bunkering vessels. Additionally, the scenario offers insights on the environmental sustainability of the selected fossil bunker fuels. The investigation seeks to establish whether these fossil fuel options surpass the limit of CO<sub>2</sub> emissions and, if so, the total emissions limit required to meet the demand. The maximum total demand required to meet the imposed CO<sub>2</sub> limit is another key conclusion that can be drawn when the imposed limit is maintained but mandatory demand satisfaction is excluded.

Finally, by solely using fossil fuels, this scenario enables a direct comparison of their economic feasibility, taking into consideration elements like cost, emissions, and fuel consumption. Additionally, this scenario provides a vital assessment of environmental sustainability. This data is critical to understand the potential environmental impact of using fossil fuels in maritime fuel transport and can guide decisions towards cleaner and more sustainable alternatives.

### 4.3.2 Scenario 2

This scenario considers that only alternative fuels are allowed as bunker fuels for powering vessels. These alternatives include a vast selection of fuels, such as green LNG, grey hydrogen, blue hydrogen, green hydrogen, grey ammonia, blue ammonia, green ammonia, biodiesel, biomethane, bio methanol, and bio-DME. In summary, there are 15 transported fuels (i), 11 bunker fuels (j), and 5 destinations (k).

The scenario's main objective is to identify the most lucrative alternative bunker fuel. By determining whether the CO<sub>2</sub> emission limit is exceeded, the environmental sustainability of the bunker fuels is assessed. Calculating the total emissions that are necessary to meet the demand provides crucial data on the alternative fuels' actual sustainability. Another important output from this scenario is the maximum total demand required to meet the CO<sub>2</sub> limit, when excluding mandatory demand satisfaction.

By solely examining alternative fuels, this scenario presents valuable information on the economic viability and environmental consequences of cleaner fuel options. Determining the most financially beneficial alternative fuel is crucial for promoting eco-friendly shipping and maintaining economic competitiveness. This information provides guidance for making decisions about environmentally sustainable and economically feasible fuels for shipping bunkers.

### 4.3.3 Scenario 3

This scenario is dedicated to exploring the transportation of different fuels while exclusively relying on environmentally sustainable, zero-CO<sub>2</sub> emissions green fuels. The green fuels considered in this scenario are green LNG, green hydrogen and green ammonia. These fuels are produced using renewable energy sources, aligning with a commitment to reducing carbon emissions. The scenario involves 15 transported fuels (i), 3 green bunker fuels (j), and 5 destinations (k).

The main objective of Scenario 3 is to determine the profitability of using only zero emission green fuels as fuel for propulsion. Since only fuels that do not emit CO<sub>2</sub> are under consideration, the total emissions for all objectives will be zero. Nevertheless, it is critical to verify whether the total profit increases, decreases or remains constant when the demand satisfaction constraint is removed. It is also crucial to examine what proportion of the demand is met in this scenario.

This scenario serves as a vital pilot research for sustainable shipping practices allowing to identify if an emissions-free approach can turn out to be financially profitable. In the case

of a positive outcome, this scenario aims to identify the most lucrative green fuel to use. The report provides significant insights into the economic benefits of implementing clean, renewable energy sources in maritime transportation. This not only mitigates the environmental impact but also aligns with the global emphasis on sustainable practices in the shipping industry. Finding the most cost-effective zero-CO<sub>2</sub> emissions fuel contributes to making well-informed strategic decisions for a more environmentally conscious and economically viable shipping sector.

#### 4.3.4 Scenario 4

This scenario encompasses all transported fuels also as bunker fuels, namely HFO, MGO, MDO, grey LNG, green LNG, grey hydrogen, blue hydrogen, green hydrogen, grey ammonia, blue ammonia, green ammonia, biodiesel, biomethane, bio methanol, and bio-DME. Scenario 4 can also be called the base scenario since it uses all data displayed in [Annex C](#) from Table C-1 to Table C-5. This scenario allows for the understanding of the system as a whole.

The scenario's main goal is to identify the most profitable bunker fuel, from both fossil and alternative fuels. For the total demand satisfaction, it is important to calculate the CO<sub>2</sub> emissions and calculate the number of times that it surpassed the limit. When this limit is emplaced, the total demand satisfaction should be calculated in order to verify if it is completed or not. The fuels chosen as bunker fuels when applying objective C (both total demand satisfaction and compliance with the CO<sub>2</sub> limit) give great insights into the most economically advantageous bunker fuel for the present time. It streamlines decision-making by identifying the most cost-efficient options, ultimately contributing to more economically sustainable shipping practices.

### 4.4 Results and analysis

In this sub-chapter the objective's results for each scenario are contextualized, providing a refined insight into the implications, difficulties and prospects arising from the different scenarios. In addition to the numerical results, this chapter also includes a detailed discussion of these outcomes. An interpretation of the results is made to provide stakeholders and readers with a comprehensive understanding of the outcomes and their wider implications.

Table 4-7 to Table 4-12 showcase the results of several key outcomes of the implementation of each objective in each scenario, providing a clear and concise overview of the findings. It facilitates the assessment of the performance of all sets of scenarios.

Table 4-7 shows the annual total quantity of fuel (*i*) transported using vessels fueled with bunker fuel (*j*) to destination (*k*). As expected, the totality of the demand is met in all scenarios of Objective A. In the scenarios of Objective C, the demand satisfaction constraint is active, and scenarios 2 to 4 adhere to the CO<sub>2</sub> limit. However, scenario 1 is infeasible as it fails to satisfy both the demand and CO<sub>2</sub> limit. This is due to the unavailability of zero emission fuels, which forces the use of fossil bunker fuels, so once the overall limit is reached there is no alternative to meeting the remaining demand in a zero emission manner. An additional observation reveals that when a CO<sub>2</sub> limit was introduced, but the obligatory demand fulfillment (Objective B) was not enforced, all scenarios failed to meet the total demand. Scenarios 2 to 4 delivered 96% of the total demand. Scenario 1 only delivered 28%, suggesting that the emissions limit was reached faster in this scenario.

Table 4-7 - Quantity of transported fuel results

	Total Xijk (tons/year)			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
<b>Objective A</b>	15 775 000	15 775 000	15 775 000	15 775 000
<b>Objective B</b>	4 375 000	15 105 000	15 105 000	15 105 000
<b>Objective C</b>	N/A	15 775 000	15 775 000	15 775 000

N/A - Not Applicable

In addition, an in-depth analysis was carried out to determine the percentage of demand satisfied for each destination if Objective B was applied to all scenarios. The results are detailed in Table 4-8. According to Table 4-8, it is evident that Belgium and the Netherlands are the most satisfied destinations. This leads to the conclusion that the order for choosing destinations is based on proximity to the EP, with the closest destinations being preferred over further ones. This can be explained by the direct dependence of transportation and emissions costs on distance travelled.

Table 4-8 - Demand satisfaction for objective B

	Demand satisfaction in each destination (%)			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
<b>k1 Fujairah</b>	0	98,47	98,47	98,47
<b>k2 Houston</b>	3	99,58	99,58	99,58
<b>k3 Singapore</b>	0	79,04	79,04	79,04
<b>k4 Antwerp</b>	98	100	100	100
<b>k5 Rotterdam</b>	98	100	100	100

The total annual number of shipments transporting fuel ( $i$ ), using fuel ( $j$ ) as bunker fuel to destination ( $k$ ) is showcased in Table 4-9. Since the  $Y_{ijk}$  values are directly dependent on the quantity of each fuel ( $i$ ) transported ( $X_{ijk}$ ), it is not surprising that these results are the same for all scenarios in Objective A and for all feasible scenarios in Objective C. For Objective B, as the deliveries are identical for all scenarios between 2 and 4, their  $Y_{ijk}$  values are also identical and, since Scenario 1 fulfils the demand to a much lesser extent in comparison, its shipment count will be correspondingly lower.

Table 4-9 - Number of shipments results

	Total $Y_{ijk}$ (shipments/year)			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Objective A	268	268	268	268
Objective B	70	247	247	247
Objective C	N/A	268	268	268

N/A - Not Applicable

One of the most significant observations from the application of the developed model relates to its sustainability. CO<sub>2</sub> emissions have a direct correlation with the type and quantity of fuel used for bunkering. Determining the level of sustainability of each bunker fuel can be achieved through the examination of the total emissions in the different scenarios and objectives considered, presented in Table 4-10.

Firstly, Table 4-10 shows that in scenario 3, the total emissions of all Objectives are consistently zero. This is due to the fact that all available bunker fuels are green fuels, meaning they do not emit any CO<sub>2</sub>. As a result of this unique characteristic, emissions will always be zero, regardless of the chosen bunker fuel or any imposed emission limits. This indicates that within the proposed, Objectives A and C will produce equivalent results since they function similarly. However, Objective B differs as it is not obligatory to fulfil all demands.

For Objective A, it is anticipated that the total emissions' values will significantly exceed those of the other objectives. As Objectives B and C are both constrained by a CO<sub>2</sub> limit, in these cases the total emissions for all feasible scenarios are expected to be at or slightly below the limit. The value always falls below the limit's value, most likely because the journey of one more shipment using any of the bunker fuels in the scenario would exceed the limit. As there is no limit for Objective A, its values exceed those of the other objectives significantly. The total emissions in scenarios 1 and 4 exceed the limit by 22 times, while in scenario 2, they are 18 times greater than the limit.

Table 4-10 - Total emissions results

	Total emissions (ton CO <sub>2</sub> /year)			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Objective A	1 072 760,74	905 577,33	0,00	1 072 760,74
Objective B	49 998,25	49 790,72	0,00	49 915,12
Objective C	N/A	49 584,36	0,00	49 708,65

N/A - Not Applicable

Moreover, Table 4-11 lists the type of bunker fuel used for each objective in each scenario. According to Table 4-11, scenarios 1 and 4 are identical regarding objective A due to the usage of the same bunker fuel. Therefore, it can be inferred that, from all the fuels (Figure 4-3), MDO is currently the most profitable one. Among alternative fuels, biomethane in scenario 2 has proven to be the most profitable, while green LNG is the most profitable green fuel in scenario 3. The most profitable fuels from the first three scenarios are combined in scenario 4 according to Objectives B and C. MDO is utilized until the emissions limit is close to being exceeded. However, since using MDO for another shipment would lead to exceeding the limit, biomethane in Objective B and grey LNG in Objective C are employed instead to make a few shipments at reasonable costs and emissions before implementing green LNG, which has zero emissions but tends to be costlier.

Table 4-11 - Bunker fuels and their usage rate

	Percentage of dependency of each bunker fuel							
	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	Bunker fuel	(%)	Bunker fuel	(%)	Bunker fuel	(%)	Bunker fuel	(%)
Objective A	MDO	100	Biomethane	100	Green LNG	100	MDO	100
Objective B	MDO	7,14	Green LNG	93,12	Green LNG	100	MDO	2,43
	Grey LNG	92,86	Biomethane	6,88			Green LNG	95,95
							Biomethane	1,62
Objective C	N/A		Green LNG	95,90	Green LNG	100	MDO	2,61
			Biomethane	4,10			Green LNG	97,01
							Grey LNG	0,38

N/A - Not Applicable

The profit comparison displayed in Table 4-12 illustrates the primary objective of the developed model. As anticipated, profits increase significantly when no CO<sub>2</sub> emissions limit is in place (Objective A), as the model selects the most profitable fuel option. The exception is

scenario 3 since the presence of a limit is insignificant for any case. Table 4-12 also confirms the resemblance between Scenario 3 - Objective A and Scenario 3 - Objective C, as well as the similarity between Scenario 1- Objective A and Scenario 4 - Objective A. These last two scenarios achieve the highest profitability. Scenario 4 - Objective C attains the highest profit within the scenarios in this Objective. Compared to Scenario 4 – Objective A, this scenario was able to significantly reduce total CO<sub>2</sub> emissions by up to 95% with a profit reduction of 20%.

This demonstrates that there are sustainable paths to reach profit maximization. By applying the developed model in fuel transportation companies, informed decisions can be made based on both profit and sustainable efficiency.

Table 4-12 - Total profit results

	Total profit (USD)			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Objective A	1 038 468 347	1 002 270 244	825 398 728	1 038 468 347
Objective B	338 351 554	849 819 840	840 095 588	849 982 804
Objective C	N/A	835 084 110	825 398 728	835 261 878

N/A - Not Applicable

## 4.5 Discussion

A comparative analysis to several existing similar studies was carried out. This analysis aimed at identifying the optimal fuel(s) to be used for maritime propulsion, according to specific criteria. Table 4-13 identifies 8 research articles where the goal was to determine the best maritime fuel, according to certain criteria defined by each author. When analyzing the criteria used to define the best fuel(s) for shipping, it is evident that economic factors play an important role in the choice of fuel, with this criteria being emphasized in most of the articles, and thus, considered a relevant factor. Environmental criteria is also highly significant, being highlighted in 7 of the articles. Technical criteria was considered to be pertinent in 4 articles, which also reveals its importance. Other criteria, namely regulatory/compliance, infrastructural and safety, were considered relevant only by 4 authors.

When focusing on the type of fuels used in each article, it is evident that grey LNG is frequently mentioned as a suitable alternative to fossil fuels. Additionally, hydrogen and ammonia are recognized as having potential, but they face several challenges for their dissemination in the industry. Despite good environmental and safety performance, biofuels face

economic and infrastructural challenges. Furthermore, E-fuels are expected to be expensive, and there are concerns about their energy consumption.

Table 4-13 - Comparative analysis of maritime fuels based on specific criteria

Reference	Fuel options	Criteria	Conclusions
<b>Current research</b>	HFO MGO MDO Grey LNG Green LNG Grey Hydrogen Blue Hydrogen Green Hydrogen Grey Ammonia Blue Ammonia Green Ammonia Biodiesel Biomethane Bio Methanol Bio-DME Green LNG Green Hydrogen Green Ammonia	1. Economic 2. Environmental 3. Economic-Environmental	<ul style="list-style-type: none"> <li>- MDO was identified as the most profitable traditional fuel.</li> <li>- Biomethane was recognized as the most profitable alternative fuel.</li> <li>- Green LNG was identified as the most profitable zero-emission fuel.</li> <li>- Grey LNG is the most cost-efficient fuel from the fossil fuels considered.</li> <li>- Green LNG is the most cost-efficient sustainable fuel from all the green fuels considered.</li> <li>- MDO and Grey LNG emerge as the most economically advantageous and environmentally sustainable choices among fossil fuels.</li> <li>- Green LNG and Biomethane emerge as the most economically advantageous and environmentally sustainable choices among fossil fuels.</li> <li>- The sustainable approach to maximize profits is to use MDO, grey LNG and Green LNG.</li> <li>- Fossil fuels should be used until reaching the emission limit, after which a transition to zero-emission fuels is necessary to satisfy the remaining demand.</li> </ul>
<b>Wang &amp; Wright, 2021</b>	LNG Biodiesels Hydrogen Ammonia Battery-Electric Methane Methanol	1. Technical Feasibility 2. Economic Performance 3. Environmental Performance 4. Compliance with regulations	<ul style="list-style-type: none"> <li>- LNG is currently the main alternative to MDO and HFO, offering advantages in local pollution emissions.</li> <li>- Biodiesels have low technical and economic barriers but face sustainability and raw material availability concerns.</li> <li>- Hydrogen and ammonia show potential, but barriers such as high costs and safety issues need to be addressed.</li> <li>- Battery-electric ships have low climate impact but face technical challenges for large-scale commercial use.</li> <li>- Methane and methanol have economic advantages but varied GHG savings depending on feedstocks.</li> </ul>
<b>Al-Enazi et al., 2022</b>	HFO LNG Hydrogen Ammonia Blend of Hydrogen with LNG Blends of Hydrogen with Ammonia	1. Economic 2. Environmental 3. Economic-Environmental	<ul style="list-style-type: none"> <li>- LNG is identified as the most favorable fuel to sell, with high demand and production capacity.</li> <li>- Ammonia emerges as the most favorable fuel for fueling ships, leading to a significant reduction in CO<sub>2</sub> emissions compared to HFO.</li> <li>- Ammonia and blend of hydrogen with LNG, can reduce emissions in the maritime industry, when combining profit maximization and emissions minimization.</li> <li>- Ammonia and hydrogen present challenges related to the underdeveloped infrastructure and supply chains.</li> </ul>
<b>Alam et al., 2022</b>	LNG Hydrogen Ammonia	1. Environmental Aspects 2. Economic Considerations 3. Technological Aspects 4. Socio-political Factors 5. Safety Concerns	<ul style="list-style-type: none"> <li>- LNG has been identified as a suitable alternative marine fuel for the short term.</li> <li>- Ammonia is expected to have an increasing share in the maritime sector, but it did not gain as much attention as LNG in the literature.</li> </ul>

Table 4-13 - Comparative analysis of maritime fuels based on specific criteria (cont.)

Reference	Fuel options	Criteria	Conclusions
<b>Foretich et al., 2021</b>	MGO MDO LPG LNG Methanol Biofuel - Straight vegetable oil Biofuel - HVO Biofuel FAME Biocrude - Hydrothermal liquefaction Bio-oils - Pyrolysis oil Ammonia Hydrogen	1. Infrastructural 2. Technical 3. Economic 4. Safety 5. Environmental	- Biofuels perform well across environmental and safety categories, however economic and infrastructural challenges, including cost competitiveness and production levels, remain significant obstacles. - MGO and MDO score high in infrastructure and economic categories due to low cost and high production volumes. Mixed performance in safety and environmental metrics, with challenges in life cycle GHG emissions, spills, toxicity, and flammability limits. - LPG and LNG face challenges in engine compatibility, retrofit cost, and storage convenience. Methane slippage in LNG limits its life cycle GHG performance. - Bio-oil and Biocrudes show economic competitiveness, however limited research has been done on their evaluation for maritime applications. - Biofuels are promising due to reduced life cycle emissions, high energy density, and compatibility with existing engines but face challenges in price parity and stability issues.
<b>Solakivi et al., 2022</b>	Fossil Fuels: Such as LSMGO (Low Sulfur Marine Gas Oil) and IFO380 (Intermediate Fuel Oil 380). Biofuels: Including HVO and advanced biofuels. E-fuels: Such as hydrogen.	1. Economic	- Prices of low-carbon and carbon-neutral fuels are likely to remain high compared with fossil fuels. - The cost-optimal fuel path complying with the planned regulation is from fossil fuels via biofuels to e-fuels.
<b>Lindstad et al., 2021</b>	MGO VLSFO HFO LNG LPG E-Diesel E-LNG E-Methanol E-Hydrogen E-Ammonia	1. GHG Reduction Potential 2. Energy Usage: 3. Cost Analysis	- E-fuels are projected to be costly, with additional costs depending significantly on renewable electricity prices. - E-Ammonia and E-Hydrogen are highlighted as superior to their non-electrified counterparts in terms of GHG emissions. - E-fuels might lead to a doubling or tripling of the maritime sector's energy consumption Well-to-Wake, depending on the availability of renewable electricity.
<b>Harahap et al., 2023</b>	Advanced biofuels (e.g., biomethanol) Electrofuels (e.g., e-methanol) Hydrogen	1. Techno-Economic Modeling 2. Socio-Technical Transition Studies 3. Supply Chain Optimization 4. Sustainability and Safety Criteria	- Biomethanol, e-methanol and hydrogen are promising maritime fuels to decarbonize the shipping industry. - Biomethanol presents the cheapest technology option, while e-ammonia is the most expensive.

Choosing alternative fuels is a complex decision that involves several criteria. It is important to analyze these criteria together rather than separately. There is no single optimal solution for all cases, as the best choice may depend on specific applications, regulations and technological advances. For this reason, most of the articles reviewed conclude that a combination of fossil and alternative fuels can be used to meet regulations and balance economic and environmental considerations.

The current research provides a comprehensive overview of a wide range of fuel options and evaluates them based on economic and environmental criteria. It covers both traditional fossil fuels and various alternatives, including several zero emission fuels. This approach is valuable for decision-makers in the maritime sector exploring possibilities for their fleets. The research employs a set of criteria that includes economic, environmental, and a combination of economic-environmental factors. This dual focus allows for a more holistic assessment of the fuels, considering both financial viability and environmental impact simultaneously. This research provides specific rankings based on profitability and fuel group type, identifying the most profitable fuels of the fossil, alternative and green groups of fuels. Thus, this information is crucial for stakeholders seeking economically viable options and sustainable ones too. This research proposes as a transition strategy, the use of fossil fuels until emission limits are reached, followed by a shift to zero-emission fuels, complying with sustainability regulations and still maximizing profits. This strategic perspective addresses the practical challenges of transitioning from conventional to alternative fuels and aligns with the evolving regulatory landscape. The current research is comprehensive in its coverage of fuels and balances economic and environmental considerations, making it a valuable resource for stakeholders in the maritime sector seeking informed insights for profitable and sustainable fuel choices.



## CONCLUSIONS

According to Rahmati et al. (2023), the expansion of transport drives economic development but also raises environmental challenges. The shipping industry, responsible for the transportation of goods by sea, is faced with the need to reduce its environmental impact urgently (Mueller et al., 2023). In this final chapter, a summary of the research done is presented as well as the main key findings and their implications. The contributions and recommendations of the research are introduced as well as its limitations. Furthermore, future research directions are suggested.

### 5.1 Summary and Key Findings

The shipping industry is responsible for transporting a significant proportion of goods and plays a key role in international trade, facilitating access to markets across nations and maintaining global economic stability. Despite its importance, there is an urgent need to make shipping more sustainable as it is one of the most polluting industries. In response, the concept of green shipping has come to the forefront with the aim of mitigating the negative impacts of shipping and preserving the environment. Various policies and international agreements have been established to highlight the key role of the maritime industry for achieving sustainability and environmental protection. The IMO has implemented regulations aimed at reducing CO<sub>2</sub> emissions by setting limits on CO<sub>2</sub> and promoting the use of cleaner technologies and practices. The decarbonization of the shipping industry is crucial to its future and requires a shift away from traditional fossil fuels towards more sustainable alternatives.

As the demand for fuels increases and sustainability constraints are imposed for their transportation, shipping companies need to make informed decisions on how to deliver the

fuels in a sustainable manner while still maximizing their profits. To tackle this complex challenge, a mathematical model was developed to optimize the transportation of various fuels fulfilling all demands, maximizing profitability, and meeting CO<sub>2</sub> emissions limits. The developed model allows for versatile adaptation to various scenarios and future bunker fuel alternatives. A critical gap was identified in existing fuel transport optimization models. None of them considered the use of both conventional and emerging bunker fuels in the same model. The proposed model fills this gap, providing a current and multifaceted solution enabling shipping companies to maintain financial success while complying with environmental regulations. The formulation of the model takes various factors into account, such as the availability of fuel, destinations' demand, vessels' capacity, and limitations on CO<sub>2</sub> emissions. Its objective is to optimize profit by balancing revenue and costs, encompassing the costs that arise from CO<sub>2</sub> emissions. This model is a customizable tool adaptable to different company needs and market changes, providing decision-makers with a powerful resource for making informed decisions.

From the results presented in Chapter 4, several conclusions can be highlighted:

- a) The availability of zero emission fuels for bunkering is critical. If zero emissions fuels are not an option and both demand fulfillment and CO<sub>2</sub> emissions constraints are in place, the problem becomes infeasible as the demand cannot be met while adhering to the limit.
- b) When only fossil bunker fuels are used for delivery, the total demand cannot be met under a CO<sub>2</sub> limit, resulting in faster limit attainment.
- c) In cases where no emission limit is imposed, total emissions will exceed the limit by a significant margin unless only green zero emission bunker fuels are used.
- d) There is a direct correlation between the choice of destination and the proximity of the bunker fuel to the destination. The most satisfied destinations in terms of demand are those situated closest to the EP, highlighting the economic influence of distance on transportation and emissions costs.
- e) Green fuels consistently produce zero emissions, highlighting the importance of sustainable and low-carbon fuel choices.
- f) Maximum profit can be obtained when there is no emissions limit, except for the use of zero emissions bunker fuels.
- g) Not fulfilling the total demand while using zero emissions bunker fuels can be more profitable.
- h) MDO was identified as the most profitable traditional fuel.
- i) Biomethane was recognized as the most profitable alternative fuel.

- j) Green LNG has been identified as the most profitable zero emission fuel.
- k) Combining CO<sub>2</sub> emitting fuels with zero emissions fuels is the optimal sustainable approach for profit maximization.

Broader key findings include providing a pragmatic and data-driven approach to complex logistics challenges. This master thesis achieves its fundamental aim of assisting fuel shipping businesses to make well-informed decisions that combine profitability, customer satisfaction and environmental responsibility through rigorous research and evaluation. By introducing an overview of the various fuel transport optimization models, their objectives and methodologies, it contributes to better identifying the existing gaps in the field. Providing a detailed description of the various green shipping practices and their benefits promotes a greener future for the industry in line with sustainability principles. The development of a customizable model that can be tailored to the specific needs and requirements of each company provides flexibility and adaptability in an ever-changing business environment.

## 5.2 Contributions and Recommendations

This master thesis contributes to the sustainable and profitable evolution of the fuel shipping industry, as it aligns with the industry's ongoing transition to cleaner and more sustainable fuels. The research's importance lies in its comprehensive exploration of the shipping industry's transition towards sustainability, particularly in the context of fuel transportation.

Firstly, this master thesis contributes significantly to fuel transportation optimization by effectively filling the gap encountered in current optimization models in literature. Unlike previous models that focus on particular fuel types or aspects, the proposed mathematical model provides a versatile and adaptable solution, capable of optimizing the transport of both conventional and emerging fuels within a single framework. The model significantly contributes to the shipping industry by enabling decision-making processes that maximize profitability while adhering to CO<sub>2</sub> emissions limit. It enables companies to make informed choices regarding fuel selection and transportation strategies, ensuring economic viability and environmental responsibility. By promoting the use of cleaner and more sustainable fuels, the model is aligned with the global shift towards green shipping practices. Not only does this benefit the environment, but it also positions companies favorably in an industry that is increasingly sensitive to sustainability concerns. The model is customizable, offering shipping companies the flexibility to adapt to evolving market conditions and emerging fuel alternatives. As a result, it enhances the companies' competitiveness. It provides a forward-looking approach that prepares

businesses for future changes within the industry, making it a valuable tool for long-term planning. Furthermore, the model has been implemented using python and is available through a public link, facilitating the replication of the research. This promotes transparency and openness, core values in academic research, enabling peers and other interested parties to review, verify and replicate the research. The model's capacity to optimize profit while concurrently advancing sustainability has policy implications, coinciding with worldwide commitments to decrease GHG emissions. It contributes to the effective implementation of regulations, such as those imposing CO<sub>2</sub> emissions limits, without compromising economic viability.

Some recommendations emerge based on the findings. Firstly, fuel transportation companies are encouraged to adopt and implement the developed mathematical model. Industry's stakeholders should recognize the potential for enhancing both profitability and sustainability through its use. Secondly, raising public awareness about the environmental and economic benefits of green shipping practices and encouraging consumers to support companies that prioritize sustainability is recommended to create market demand for cleaner fuels. Advancements in research focusing on incorporating additional emerging fuel alternatives and adapting the model to diverse scenarios stimulates the continued improvement of the industry. Investments in training and educational programs for industry professionals to facilitate the practical implementation of the developed model are also advised to harness its potential effectively. Finally, to reach carbon neutrality faster, it is recommended to invest in infrastructure for producing clean fuels and in research to produce them more efficiently.

By following these recommendations, the shipping industry can accelerate its transition towards a more sustainable and economically viable future.

### 5.3 Limitations and Future Research

The development of the mathematical model and its implementation represent a significant step towards optimizing the industry's sustainability and profitability. However, some limitations are inherent to the model, and there are always opportunities for future research and improvements, mainly related to real-world application.

The model is built upon a series of simplifying assumptions to make the problem tractable. While these assumptions were necessary for the initial model, they limit the real-world applicability. Future research should focus on altering some of these assumptions to make the model more realistic. For instance, considering multiple EP's, allowing for multiple stops during the voyage, or exploring the impact of varying fleet sizes, instead of assuming an infinite one,

would be a step towards greater realism. Several costs for real world application are neglected and should be incorporated for a more accurate representation of operational costs. Finally, future research should include a partnership with a fuel transportation company in order to incorporate real world data for the model's parameters, leading to the model's adoption in the shipping industry. Addressing these limitations and exploring the future research will further enhance the model's applicability, accuracy and realism, improving the industry's sustainability and profitability.

Furthermore, apart from the specific limitations and potential for further investigation related to the developed mathematical model, there are general limitations and prospects for future research within the broader context of the master thesis's topic.

One of the main challenges in this field is the constantly changing and dynamic nature of the maritime industry. Emerging technologies, regulations, and fuel options pose a constant obstacle to maintaining models and strategies updated. Future studies should focus on developing adaptive and flexible frameworks that can easily accommodate changes in fuel sources, regulations and market dynamics. Moreover, given the global nature of the shipping industry, research must assess the advantages of international coordination and cooperation to achieve sustainable shipping. Future research should evaluate the impact of international agreements and cooperative initiatives in driving real progress in the maritime industry.

Research in this field must take into account the repercussions of transitioning to cleaner fuels and more green shipping practices. Though the advantages to the environment are visible, these changes could affect the economic and social well-being of regions and communities that rely on traditional, high-emission fuels or shipping-related activities. In the future, even if developed countries rely only on alternative fuels, it is likely that less developed countries will continue to use fossil fuels. Ensuring a comprehensive and strategic approach to tackling the potential challenges is essential for a well-informed and conscientious shift towards environmentally friendly shipping. Additionally, research should explore the efficiency of emerging technologies, such as SMR and CCS, as well as the potential role of emerging techniques, such as electric motors, using wind for propulsion, fuel blends - a combination of fossil and alternative fuels -, and hybrid propulsion - a combination of emerging techniques. By addressing these general limitations and identifying future research directions, the master thesis can further contribute to the ongoing efforts to establish a sustainable and environmentally responsible future for the maritime sector.



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# APPENDIX

## Appendix A: Python code implementation in *Colab*

```
[1] 1 pip install xpress
```

```
[2] 1 import xpress as xp
2 import pandas as pd
3 from xpress import *
4
5 # The xpress implementation of the model
6 def transport_fuel_model(dfI,dfJ,dfK,dfD):
7
8     nI = dfI.shape[0]
9     nJ = dfJ.shape[0]
10    nK = dfK.shape[0]
11
12    I = [i for i in range(nI)]
13    J = [j for j in range(nJ)]
14    K = [k for k in range(nK)]
15
16    p = xp.problem()
17
18    # Define decision variables
19    x = {(i,j,k): xp.var(vartype = xp.continuous, lb = 0, name='x_{0}_{1}_{2}'.format(i,j,k)) for i in I for j in J for k in K}
20    y = {(i,j,k): xp.var(vartype = xp.integer ,lb = 0, name='y_{0}_{1}_{2}'.format(i,j,k)) for i in I for j in J for k in K}
21
22    p.addVariable(x,y)
```

```

[2] 23
24 # Define the objective function
25
26 # Delivering Revenue:
27 DR = xp.Sum(x[(i,j,k)] * dfI.loc[i,'PQi']) + (2 * dfK.loc[k,'dEPk'] * y[(i,j,k)] * dfJ.loc[j,'PDj']) for i in I for j in J for k in K)
28
29 # Transportation Costs:
30 TC = xp.Sum(M * dfJ.loc[j,'Cbj'] * dfJ.loc[j,'Fcj'] * dfK.loc[k,'dEPk'] * y[(i,j,k)] for i in I for j in J for k in K)
31
32 # Normalized (Ship and Engine) Costs:
33 NC = xp.Sum((dfI.loc[i,'CSi'] + dfJ.loc[j,'CEj']) * y[(i,j,k)] for i in I for j in J for k in K)
34
35 # Emissions costs (CO2):
36 EC = xp.Sum(M * Ce * dfJ.loc[j,'Ej'] * dfJ.loc[j,'Fcj'] * dfK.loc[k,'dEPk'] * y[(i,j,k)] for i in I for j in J for k in K)
37
38 TotProfit = DR - TC - NC - EC
39
40 p.setObjective(TotProfit, sense=xp.maximize)
41
42 # Add Constraint 1: Availability
43 for i in I:
44     p.addConstraint(xp.Sum(x[(i,j,k)] for j in J for k in K) <= dfI.loc[i, 'Ai'])
45
46 # Add Constraint 2: Demand Satisfaction
47 for i in I:
48     for k in K:
49         p.addConstraint(xp.Sum(x[(i,j,k)] for j in J) == Dik[i][k])
50
51 # Add Constraint 3: Shipping Capacity
52 for i in I:
53     for j in J:
54         for k in K:
55             p.addConstraint(xp.Sum(x[(i,j,k)]) <= dfI.loc[i, 'QSi'] * xp.Sum(y[(i,j,k)]))
56
57 # Add Constraint 4: Emission Limit
58 p.addConstraint(xp.Sum(M * dfJ.loc[j, 'Ej'] * dfJ.loc[j, 'Fcj'] * dfK.loc[k, 'dEPk'] * y[(i, j, k)] for i in I for j in J for k in K) <= L)
59
60 # Add Constraint 5: Non negativity
61 for i in I:
62     for j in J:
63         for k in K:
64             p.addConstraint(x[(i, j, k)] >= 0)
65             p.addConstraint(y[(i, j, k)] >= 0)
66
67 p.solve()
68
69 return p,x,y,TotProfit

```

```
[3] 1 # Define sets and indices
2 I = [i for i in range(2)] # Set of transported fuels
3 J = [j for j in range(2)] # Set of bunker fuels
4 K = [k for k in range(2)] # Set of destinations
5
6 # Define parameters
7 Ce = 20
8 L = 50000
9 M = 2.3
10 Dik=[[300000,800000],
11       [400000,1500000]]
12
13 Dik_dict = {}
14 for i in I:
15     for k in K:
16         Dik_dict[(i,k)] = Dik[i][k]
17
18 # Create Dataframes for testing the model
19
20 dfI = pd.DataFrame.from_dict({'i': ['i1','i2'],
21                             'PQi': [50,150],
22                             'Csi': [5000,10000],
23                             'Ai': [40000000,85000000],
24                             'Qsi': [50000,5000]})
25
26 dfJ = pd.DataFrame.from_dict({'j': ['j1','j2'],
27                             'PDj': [50,100],
28                             'Cbj': [500,4000],
29                             'Fcj': [0.2,0.05],
```

```
30
31                             'CEj': [2000,3000],
32                             'Ej': [3,0]})
33
34 dfK = pd.DataFrame.from_dict({'k': ['k1','k2'],
35                             'dEPk': [10000,1000]})
36
37 dfD = pd.DataFrame.from_dict({'i': [k[0] for k in Dik_dict.keys()], 'k': [k[1] for k in Dik_dict.keys()], 'Dik': list(Dik_dict.values())})
```

```
[4] 1 p,x,y,TotProfit = transport_fuel_model(dfI,dfJ,dfK,dfD)
```

```
[5] 1 p.getSolution(TotProfit)
```

```
[6] 1 p.getSolution(x)
```

```
[7] 1 p.getSolution(y)
```

```

[8] 1 # Initialize dictionaries to store x values for all combinations of i, j, and k
2 x_values = {}
3
4 # Initialize a variable to store the sum of all x
5 total_x = 0
6
7 # Iterate over all combinations of i, j, and k
8 for i in I:
9     for j in J:
10        for k in K:
11            # Calculate the values of x for the current combination
12            x_value = p.getSolution(x[(i, j, k)])
13            # Store the x values in their respective dictionaries with the combination as the key
14            x_values[(i, j, k)] = x_value
15            # Add the current x_value to the total_x
16            total_x += x_value
17
18 # Print the results for x(i,j,k) and total x
19
20 print(f"Total X: {total_x}")

```

```

[9] 1 # Initialize dictionaries to store y values for all combinations of i, j, and k
2 y_values = {}
3
4 # Initialize a variable to store the sum of all y
5 total_y = 0
6
7 # Iterate over all combinations of i, j, and k
8 for i in I:
9     for j in J:
10        for k in K:
11            # Calculate the values of y for the current combination
12            y_value = p.getSolution(y[(i, j, k)])
13            # Store the y values in their respective dictionaries with the combination as the key
14            y_values[(i, j, k)] = y_value
15            # Add the current y_value to the total_y
16            total_y += y_value
17
18 # Print the results for y(i,j,k) and total y
19
20 print(f"Total Y: {total_y}")

```

```

[10] 1 # Initialize dictionaries to store Emissions value for all combinations of i, j, and k
      2 E_values = {}
      3
      4 # Initialize a variable to store the sum of all emissions
      5 total_emissions = 0
      6
      7 # Iterate over all combinations of i, j, and k
      8 for i in I:
      9     for j in J:
     10         for k in K:
     11             # Calculate the values of Emissions for the current combination
     12             E_value = xp.Sum(M * dfJ.loc[j, 'Ej'] * dfJ.loc[j, 'Fcj'] * dfK.loc[k, 'dEPk'] * p.getSolution(y[(i, j, k)]))
     13             # Store the E values in their respective dictionaries with the combination as the key
     14             E_values[(i, j, k)] = E_value
     15             # Add the current E_value to the total_emissions
     16             total_emissions += E_value
     17
     18 # Print the results for Emissions and total emissions
     19
     20 for (i, j, k), E_value in E_values.items():
     21     print(f"E for (i={i}, j={j}, k={k}) = {E_value}")
     22
     23 print(f"Total Emissions: {total_emissions}")

```

Figure A-1 - Python code for model implementation

## Appendix B: Example survey conducted in AI tool

An example of the survey carried out on the AI application to obtain the data for the parameter  $P_i^Q$  is presented. In order to obtain the optimal outcome, a set of systematic questions (Q) was proposed for each answer (A).

### Example survey conducted on AI tool to collect the data

**Q:** What are the numerical values for the transportation price regarding the quantity of transported fuel (i) in USD/ton of fuel (i) when (i) is: i1 HFO i2 MGO i3 MDO i4 Grey LNG i5 Green LNG i6 Grey Hydrogen i7 Blue Hydrogen i8 Green Hydrogen i9 Grey Ammonia i10 Blue Ammonia i11 Green Ammonia i12 Biodiesel i13 Biomethane i14 Bio methanol i15 Bio-DME ?

**A:** "I'm sorry, but I don't have access to specific pricing data, and the prices for transportation of different types of fuels can vary greatly depending on various factors including location, market conditions, and other variables. To find the current numerical values for the transportation price of each of these fuel types, you would need to consult industry reports, market analysis, or contact relevant transportation and logistics companies for their specific rates. The prices for fuel transportation can change over time, so it's important to obtain up-to-date information for accurate cost calculations."

**Q:** Can you find rough example numerical values for the Transportation price regarding the quantity of transported fuel (i) in USD/ton of fuel (i) when (i) is: i1 HFO i2 MGO i3 MDO i4 Grey LNG i5 Green LNG i6 Grey Hydrogen i7 Blue Hydrogen i8 Green Hydrogen i9 Grey Ammonia i10 Blue Ammonia i11 Green Ammonia i12 Biodiesel i13 Biomethane i14 Bio methanol i15 Bio-DME?

**A:** "Certainly, here are rough estimates for the transportation cost per ton of various types of fuel based on general knowledge up to 2021. Keep in mind that these values can vary widely based on location, mode of transport, and market conditions, and are only meant to provide a very approximate idea of the costs:

1. HFO (Heavy Fuel Oil): USD20 - USD50 per ton
2. MGO (Marine Gas Oil): USD40 - USD80 per ton
3. MDO (Marine Diesel Oil): USD40 - USD80 per ton
4. Grey LNG (Liquefied Natural Gas): USD50 - USD100 per ton

5. Green LNG (Sustainable Liquefied Natural Gas): USD70 - USD150 per ton
6. Grey Hydrogen: USD100 - USD200 per ton
7. Blue Hydrogen: USD120 - USD220 per ton
8. Green Hydrogen: USD150 - USD250 per ton
9. Grey Ammonia: USD80 - USD160 per ton
10. Blue Ammonia: USD100 - USD180 per ton
11. Green Ammonia: USD120 - USD200 per ton
12. Biodiesel: USD60 - USD120 per ton
13. Biomethane: USD50 - USD100 per ton
14. Bio methanol: USD70 - USD140 per ton
15. Bio-DME: USD80 - USD160 per ton

Please note that these are very rough estimates, and actual costs can vary significantly based on a wide range of factors. For precise pricing, you should consult industry-specific sources or transportation service providers."

**Q:** All types of hydrogen should have the same pricing as it is the same fuel. The same goes for ammonia and LNG.

**A:** "You are correct that within a specific category, such as hydrogen, ammonia, or LNG, the transportation cost should be relatively consistent for the same quantity of fuel. Here are rough estimates for the transportation cost per ton of fuel within these categories:

**Hydrogen:**

- Grey Hydrogen: USD100 - USD200 per ton
- Blue Hydrogen: USD100 - USD200 per ton
- Green Hydrogen: USD100 - USD200 per ton

**Ammonia:**

- Grey Ammonia: USD80 - USD160 per ton
- Blue Ammonia: USD80 - USD160 per ton
- Green Ammonia: USD80 - USD160 per ton

**LNG (Liquefied Natural Gas):**

- Grey LNG: USD50 - USD100 per ton
- Green LNG: USD50 - USD100 per ton

Please keep in mind that these are still rough estimates, and the actual costs may vary depending on factors like location, transportation methods, and market conditions. For precise pricing information, it is advisable to consult industry sources or transportation service providers."

The data retrieved for this parameter can be consulted in Table C-1 of [Annex C](#).

## Appendix C: Database for Model Implementation

Table C-1 - Input data for parameters with dataset (i)

TRANSPORTED FUELS	Parameters			
	PQi - Transportation price regarding the quantity of transported fuel (i)	Ai - Availability of fuel (i) in the EP	Qsi - Capacity of the vessel that transports fuel (i)	CSi - Normalized Vessel Cost per shipment for fuel (i)
i1 HFO	35	2 000 000	85 000	1 000
i2 MGO	60	2 500 000	85 000	1 200
i3 MDO	60	2 000 000	85 000	1 150
i4 Grey LNG	75	4 000 000	135 000	800
i5 Green LNG	75	1 000 000	135 000	800
i6 Grey Hydrogen	150	500 000	22 500	1 500
i7 Blue Hydrogen	150	750 000	22 500	1 500
i8 Green Hydrogen	150	300 000	22 500	1 500
i9 Grey Ammonia	120	800 000	40 000	1 200
i10 Blue Ammonia	120	1 200 000	40 000	1 200
i11 Green Ammonia	120	400 000	40 000	1 200
i12 Biodiesel	90	1 000 000	85 000	1 100
i13 Biomethane	75	600 000	135 000	1 080
i14 Bio methanol	105	900 000	40 000	1 150
i15 Bio-DME	120	300 000	40 000	1 070
UNITS	USD/ton	ton/year	ton/shipment	USD/shipment

Table C-2 - Input data for parameters with dataset (j)

BUNKER FUELS	Parameters				
	Cbj - Bunker fuel cost for fuel (j)	Fcj - Fuel consumption for fuel (j)	CEj - Normalized Engine Cost per shipment for fuel (j)	Ej - CO <sub>2</sub> emissions per ton of fuel (j) used	PDj - Transportation price regarding distance travelled using fuel (j)
j1 HFO	400	0,35	450	3,20	15
j2 MGO	800	0,18	550	2,70	23
j3 MDO	700	0,11	625	2,80	19
j4 Grey LNG	600	0,14	450	2,10	23
j5 Green LNG	1 500	0,12	450	0	60
j6 Grey Hydrogen	3 500	0,07	775	9,25	90
j7 Blue Hydrogen	4 500	0,06	775	4,25	105
j8 Green Hydrogen	5 000	0,05	775	0	120

Table C-2 - Input data for parameters with dataset (j) (cont.)

BUNKER FUELS	Parameters				
	C <sub>bj</sub> -Bunker fuel cost for fuel (j)	F <sub>cj</sub> - Fuel consumption for fuel (j)	CE <sub>j</sub> -Normalized Engine Cost per shipment for fuel (j)	E <sub>j</sub> - CO2 emissions per ton of fuel (j) used	PD <sub>j</sub> - Transportation price regarding distance travelled using fuel (j)
j9 Grey Ammonia	1 400	0,12	700	6,40	60
j10 Blue Ammonia	2 600	0,10	700	2,25	75
j11 Green Ammonia	3 800	0,08	700	0	90
j12 Biodiesel	600	0,23	750	2,75	45
j13 Biomethane	800	0,13	690	2,00	37
j14 Bio methanol	900	0,18	760	1,75	30
j15 Bio-DME	1 000	0,18	775	1,75	42
UNITS	USD/ton	ton/NM	USD/shipment	ton CO <sub>2</sub> /ton fuel	USD/NM

Table C-3 - Input data for parameter Dik

TRANSPORTED FUELS	Parameter				
	Dik -Demand of fuel (i) per year in destination (k)				
	DESTINATIONS				
	k1 Fujairah	k2 Houston	k3 Singapore	k4 Antwerp	k5 Rotterdam
i1 HFO	600 000	500 000	400 000	250 000	250 000
i2 MGO	400 000	600 000	400 000	150 000	350 000
i3 MDO	400 000	500 000	300 000	200 000	200 000
i4 Grey LNG	1 000 000	1 200 000	800 000	400 000	600 000
i5 Green LNG	250 000	200 000	150 000	100 000	300 000
i6 Grey Hydrogen	75 000	175 000	40 000	60 000	50 000
i7 Blue Hydrogen	150 000	200 000	100 000	75 000	50 000
i8 Green Hydrogen	80 000	60 000	40 000	30 000	20 000
i9 Grey Ammonia	150 000	200 000	120 000	80 000	50 000
i10 Blue Ammonia	300 000	400 000	150 000	100 000	250 000
i11 Green Ammonia	80 000	100 000	60 000	70 000	50 000
i12 Biodiesel	200 000	250 000	150 000	100 000	200 000
i13 Biomethane	100 000	150 000	30 000	80 000	70 000
i14 Bio methanol	100 000	150 000	50 000	75 000	75 000
i15 Bio-DME	30 000	40 000	25 000	20 000	15 000
UNITS	ton/year				

Table C-4 - Input data for parameters with no dataset

Parameter		UNITS
M -Distance factor	2,30	N/A
Ce - Cost of CO <sub>2</sub> emissions	20	USD/ton CO <sub>2</sub>
L - Limit of CO <sub>2</sub> emissions	50 000	ton CO <sub>2</sub> /year

Table C-5 - Input data for parameter dEPk

	Parameter
DESTINATIONS	dEPk - Distance between EP and destination port (k)
k1 Fujairah	7 711
k2 Houston	5 902
k3 Singapore	10 224
k4 Antwerp	1 029
k5 Rotterdam	945
UNITS	NM



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