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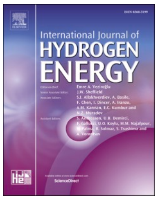

Economic framework for green shipping corridors: Evaluating cost-effective transition from fossil fuels towards hydrogen

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ABSTRACT

Global warming's major cause is the emission of greenhouse-effect gases (GHG), especially carbon dioxide (CO_2) whose main source is the combustion of fossil fuels. Fossil fuels serve as the primary energy source in many industries, including shipping, which is the focus of this study. One of the measures proposed to tackle GHG emissions is the development of green shipping corridors - carbon-free shipping routes that require the transition to alternative fuels, which are gaining competitiveness. One of the reasons for that is carbon pricing, which taxes CO_2 emissions. However, the lack of consensus on the most cost-advantageous alternative fuel in the long run results in the delay of the implementation of green shipping corridors.

To make it more accessible for stakeholders to conduct an economic analysis of the various options, a framework to determine and minimize the costs of transitioning from fossil fuels to any alternative fuel is proposed, over the period of one voyage, considering the lost opportunity cost, the deployment cost of bunkering vessels at the necessary call ports, the cost of converting the vessel, the car-bon emissions tax cost, and the fuel cost. This will allow stakeholders to choose the most economical alternative fuel, accelerating the development of green shipping corridor initiatives. To validate the effectiveness of the framework, it was applied in a case study involving a shipowner seeking to transition from heavy fuel oil (HFO) to Ammonia, Hydrogen, Liquefied Natural Gas (LNG), or Methanol. This study faced limitations due to the unknown costs of installing bunkering vessels for Ammonia and Hydrogen. However, it evaluates the cost-effectiveness of alternative fuels, providing insights into their short-term economic viability. The results showed that Hydrogen is the most cost-advantageous fuel until a deployment cost per bunkering vessel of 1,990,285$ for a sailing speed of 22 knots and 2,190,171$ for a sailing speed of 18 knots is reached, after which LNG becomes the most economical option regardless of variations in the carbon tax. Moreover, a sensitivity analysis was conducted to determine the effects of variations in parameters, such as carbon tax, fuel prices and vessel conversion costs in the total cost of each fuel option. Results highlighted that even though HFO remains the most economical fuel option, even when considering a high increase in carbon tax, the cost gap between HFO and alternative fuels narrows significantly with the increase in carbon tax. Furthermore, the sailing speed impacts the fuels' competitiveness, as the cost difference between HFO and alternative fuels decreases at higher speeds.

1. Introduction

Global warming has been scaling over the past decades, constituting a threat to the planet [1]. Since the period between 1850 and 1900, the global temperature has increased by 1–1.2 °C [2]. This has had catastrophic consequences, including natural disasters, land degradation, rising ocean levels and the spread of diseases, resulting in the destruction of species, habitats, and infrastructures [1]. Furthermore,

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devastating consequences on sectors such as agriculture, fishery, tourism, and energy have had a significant impact on the global economy. The main cause of global warming is the emission of GHG resulting from human activity [1], with CO_2 being the major contributor [3].

The major cause of CO_2 emissions to the atmosphere is the combustion of fossil fuels [4], which have been used as the primary energy source for many sectors over the past decades [5]. Among all the sectors, transport has had the highest growth in GHG emissions, growing at an annual average rate of nearly 1,7% from 1990 to 2021 [6]. In the field of transportation, shipping stands out as a critical subsector for global trade since it offers higher energy efficiency [7], lower cost, larger capacity, and more flexible transportation routes than other subsectors [8]. The volume of cargo carried by sea has generally been increasing over the past years, as shown in Fig. 1, and in 2021, maritime transportation accounted for more than 80% of the global trade volume according to the United Nations [9].

The growth in the volume of cargo transported by sea results in the rise of global fuel consumption [11], namely fossil fuels, which have a substantial impact on air pollution. Therefore, implementing measures to reduce CO_2 emissions in shipping became crucial [12]. Derived from this necessity, the concept of green shipping corridors has emerged. These corridors are shipping routes in which maritime transportation is carbon free [13], which requires the switch from fossil fuels to non-petrochemical derived alternative fuels with lower emissions [14].

In the upcoming years, a shift from fossil fuels to alternative fuels is expected [15] since fossil fuels will become increasingly less economically competitive. However, it is still uncertain which alternative fuel will be more advantageous in the future [16]. For this reason, most green shipping corridor initiatives are postponing the decision of which alternative fuel to base their initiatives on, which ends up delaying the development of the initiatives. Despite this difficulty, the existing literature still lacks a comprehensive framework to guide them in determining and minimizing the costs involved in transitioning from fossil fuels to the different alternative fuels, making it challenging to decide which is the most advantageous option. Since the switch to alternative fuels is inevitable due to the eventual unfeasibility of using fossil fuels in the future, the existence of this framework would be highly valuable.

The objective of this study is to propose a framework to find out and minimize the costs of transitioning from fossil fuels to different alternative fuels, in order to decide which is the most suitable alternative fuel for that route. By addressing the following research questions throughout this study, it will be possible to provide the bodies involved in green shipping corridor initiatives valuable insights to overcome the identified challenge, contributing to the fulfillment of the objective.

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

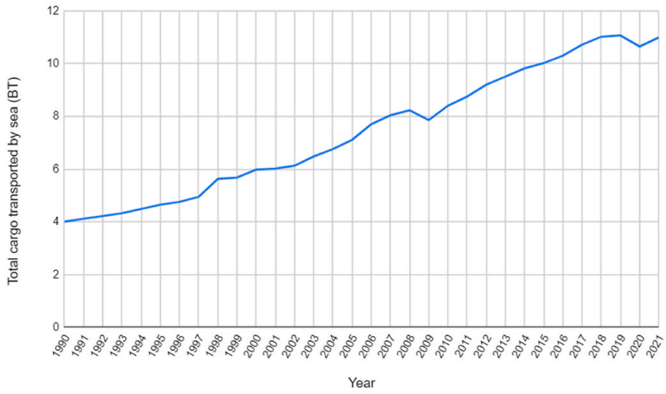

Fig. 1. Volume of cargo transported by sea between 1991 and 2021. Adapted from [10].

According to Ref. [16], governments are under increasing pressure to implement measures to close the cost gap between fossil fuels and alternative fuels in order to discourage the use of HFO and other fossil fuels. For this reason, it is recommended that countries provide financial support for the fuel transition, including funding for technology, infrastructure, and research and development projects. By proposing measures that make the supply of alternative fuels appealing through variations in carbon pricing, there is a chance that alternative fuels become more economical than HFO, as, according to Ref. [17], the price decreases as supply increases.

By identifying the current costs of transitioning from fossil fuels to alternative fuels, the involved stakeholders will have a better understanding of the expenses that this transition implies. Additionally, they will have a foundation from which to conduct an economic analysis of the different options, which will enable them to make more informed decisions on which alternative fuel to adopt. Variations in carbon pricing may influence the economic competitiveness of each fuel option, which makes the decision of the fuel pathway even more challenging. To address this challenge, this study aims to investigate how carbon pricing influences fuel choice by considering both economic and environmental aspects.

2. State of the art

In order to mitigate GHG emissions derived from shipping, several measures have been implemented. The adoption of the International Convention for the Prevention of Pollution from Ships (MARPOL) by IMO in 1973 was a remarkable milestone towards the prevention of pollution of the marine environment caused by shipping, being the primary international convention on this topic. In May 2005, Annex VI of MARPOL, which covers the prevention of air pollution caused by ships, entered into force [18].

In 2015, the Paris Agreement was signed by 197 parties with the goal of keeping the global temperature increase in this century below 2 °C, with efforts to limit it to 1,5 °C, through the reduction of GHG emissions [19]. More recently, in 2018, IMO established the goal of reducing CO_2 emissions in international shipping by at least 40% by 2030 compared to 2008 and sustaining the efforts towards a reduction of at least 50% of the overall annual GHG emissions by 2050 compared to 2008, while pursuing efforts towards a 70% reduction [20]. Recently, in 2023, IMO has updated this goal to ideally 70% in GHG emissions by 2050, compared to 2008. Striving for an even more ambitious goal, IMO set the new target of zero-emissions approximately by 2050.

Another GHG emissions reduction measure is carbon pricing. By setting a tax on CO_2 emissions, fossil fuels are expected to become less financially competitive compared to alternative fuels. In 2022, there were 68 initiatives of carbon pricing worldwide, with 34 being Emissions Trading Schemes (ETS) [21]. These initiatives compensated 23% of the global GHG emissions [22]. CO_2 taxes for international commercial maritime shipping play a crucial role in addressing climate change, promoting sustainable practices, and aligning the shipping industry with global efforts to reduce greenhouse gas emissions [23]. Imposing taxes on CO_2 emissions from international maritime shipping, governments aim to incentivize the industry to reduce its carbon footprint [24].

To contribute to the compliance with the measures to reduce or ideally eliminate GHG emissions, primarily CO_2 emissions, several operational measures have been implemented in the shipping subsector. One standout measure, recognized as the most reliable and consistent in reducing GHG emissions [25], is slow steaming, which consists of significantly reducing the sailing speed of a vessel compared to its design speed to decrease fuel consumption and, consequently, reduce emissions. Additionally, more strategies are anticipated to be adopted in the upcoming years, including the adoption of alternative energy sources and the optimization of shipping operations. Other possibilities that are being studied are exploring the integration of additional strategies or technologies, such as wind propulsion technologies for commercial shipping [26–28] as it has a potential to reduce fuel requirement and offer tangible cost savings [29].

2.1. Green shipping corridors

The concept of green corridors have emerged in maritime transportation has a critical strategy for sustainable development and decarbonization in recent years [30]. provided a comprehensive overview of green corridors and defined them as freight transport corridors in which advanced technology and co-modality are used to improve energy efficiency, while reducing environmental impact. In the maritime decarbonization context [31], discussed the concept of green corridors as a strategy to reduce greenhouse gas emissions in shipping and as being part of a broader set of measures aimed at transitioning the maritime industry towards more sustainable practices. The concept of green corridors has been introduced by Ref. [32] that defined as major shipping routes providing or supported by low and zero-carbon maritime transportation solutions [13]. highlighted that the goal of these corridors is to improve and support the implementation of sustainable marine technologies and fuels.

Green corridor initiatives focus on the holistic decarbonization of the supply chain, taking into consideration all its elements: fuel production, port logistics, bunkering, vessels, cargo, end customers, financing, and legislation. These initiatives encourage collaboration among these stakeholders and give them the resources they need to start their path toward decarbonization [33].

In 2021, 24 countries signed the Clydebank Declaration at COP26 and committed to encouraging the creation of green shipping corridors, through the promotion of partnerships between stakeholders, the mitigation of challenges through the development of regulations and infrastructure, the sharing of knowledge, and the inclusion of green corridors in National Action Plans [34]. A year after, 40 initiatives for shipping decarbonization were announced in COP27, over half of which involved the subject of green shipping corridors [35]. Even though they are only at the initial stages, advancements in green corridors are progressing rapidly [35]. However, there are still many challenges that need to be addressed.

The first challenge is the implementation of these initiatives, as there is still limited knowledge on how to turn the theoretical plan of green shipping corridors into practical implementation, as the majority of initiatives are still in the planning phase [33]. To accelerate the actual implementation, the involved parties should share knowledge and solutions [16].

Additionally, given the involvement of numerous parties, aligning expectations and decision-making becomes challenging [16], so it is necessary to create consensus among the different parties and promote cooperation [35].

Another challenge is the definition of the fuel pathway, as many initiatives are not focused on a specific fuel yet. For the accelerated and successful development of the initiatives, it is essential to focus the efforts on a single fuel strategy. However, all corridors will focus on a single fuel strategy but will aim for being able to run on several fuels. At the end of 2022, 41% of green shipping initiatives had not yet decided which fuel to use [16]. Among those who have decided, both ammonia and methanol were the preferred options, as each of them was selected by 16% of the initiatives. Additionally, 9% of the initiatives opted for hydrogen [16], and another 9% chose advanced biofuels, as incentivized by EU in Ref. [36]. The last bottleneck to highlight is the availability, price, and regulation regarding alternative fuels, which currently are not as advantageous as traditional fuels [16].

2.2. Prospects for alternative fuels

Until now, the shipping sector was no exception when it comes to using fossil fuels as the primary energy source [15]. As shown in Fig. 2, although some vessels have already started using alternative fuels, the majority of the world's fleet still relies on conventional fuel. However, the number of alternative energy sources in the past two decades has increased [37]. There is an increase in the percentage of ships being designed to use alternative fuels, even though most of the ships are still ordered with conventional fuel as the main source [38].

The shift towards alternative fuels, such as non-petrochemical derived alternative fuels [33], is becoming a priority, not only due to the GHG emissions caused by fossil fuels, but also because of the uncertainty and dependency on fossil fuel suppliers, the scarcity of resources and the rising energy demand, which fueled the need to search for alternative energy sources [5,39]. Besides, the price difference between traditional fuels and alternative fuels has been decreasing [40]. Consequently, even though HFO is still the most economical fuel, the price of alternative fuels will become more competitive with time [40].

In the upcoming years, the fuel mix in maritime transportation is expected to undergo a turnaround, with alternative energy sources taking a larger share than oil [15]. However, despite existing studies providing prospects for the future fuel mix, there is not yet a consensus regarding which fuel will prevail. The results from different studies, aimed at determining the most advantageous alternative fuel, are summarized in Table 1. The table also includes the parameters, namely the cost components, considered in each study to determine the most favorable alternative fuel. It was observed that ammonia, hydrogen, LNG, and methanol are the most prevalent fuels in the fuel mix projections. Eight out of ten studies concluded that hydrogen and/or LNG are the most advantageous alternative fuels. As indicated in the table, studies [7,11,40–42] pointed out hydrogen as the most cost-advantageous alternative fuel in the long run, whereas studies [7,40,43,44] considered LNG a more favorable option, but most of them for the short term. When it comes to other fuels, fewer studies include ammonia and methanol in their fuel mix projections. Four studies highlighted ammonia as the most favorable alternative fuel [15,41,42,45], while only one relied on methanol [45]. Except for [7,11], the studies do not disclose the costs and other parameters considered. Besides, none of the existing studies are concerned with the minimization of costs.

This overview has revealed that there is currently no consensus on which fuel will be more advantageous in the long run, namely in terms of costs. However, most studies include ammonia and hydrogen in long-term fuel mix projections, and some also incorporate methanol. LNG is recognized as a prominent fuel due to its competitive cost and higher availability but only in the short-term for being a fossil fuel-based fuel. The main properties of these fuels were looked into and are compiled in Table 2.

3. Cost calculation framework for fuel transition

The review conducted on the existing studies predicting the composition of the fuel mix in the future has revealed that they do not fully meet the needs of the green shipping corridors initiatives. Most studies focus on techno-economic assessments and life cycle analysis, emphasizing life cycle costs and environmental impacts, such as [47–51]. Others focused exclusively on economic analyses, such as [52,53], that consider carbon pricing and other economic parameters. Some of the review models fail to provide an overview of the costs and other parameters considered to make those predictions, and none of them are concerned with cost minimization. To fill in this gap, a framework to calculate and minimize the costs of transitioning from fossil fuels to alternative fuels is proposed.

The Cost Calculation Framework for Fuel Transition is divided into two phases. The first consists of an optimization model to determine the

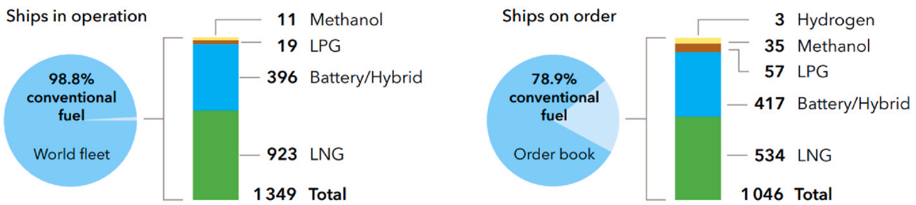

Fig. 2. Number of ships adopting alternative fuels in the global fleet in 2022. Taken from [38].

Table 1
Comparative analysis of most advantageous alternative fuels and parameters considered in different studies.

Study	Most Advantageous Fuel	Parameters Considered in the Analysis and Selection of the Fuel
[15]	Ammonia	Parameters not revealed in the study
[11]	Hydrogen	Fuel consumption cost, boil-off gas (BOG) combustion cost, and carbon tax
[7]	Hydrogen in the long-term LNG in the short-term	Operational cost, fuel cost, capital cost for the propulsion system, and other parameters (safety, reliability of the supply chain, availability of the infrastructure, impact on environment)
[40]	Hydrogen in the long-term LNG in the short-term	Parameters not revealed in the study
[43]	Bio-LNG, synthetic LNG, or e-LNG In the long-term LNG in the short-term	Parameters not revealed in the study
[45]	Ammonia and methanol	Parameters not revealed in the study
[41]	Ammonia and hydrogen	Parameters not revealed in the study
[44]	LNG	Parameters not revealed in the study
[46]	Bio-LNG, synthetic LNG, or e-LNG In the long-term LNG in the short-term	Parameters not revealed
[42]	Ammonia and hydrogen	Parameters not revealed
[47]	Ammonia and methanol	Total cost of ownership: fuel production costs, propulsion cost, on-board fuel storage cost and a cost for reduced cargo space
[48]	Ammonia and methanol	Life cycle costs (capital, maintenance, repair and disposal costs, cost flows of expenses and revenue), other parameters (human toxicity, resource use, water use)
[49]	Ammonia	Carbon abatement cost, other parameters (human toxicity, freshwater ecotoxicity)
[50]	Biogas, Dimethyl ether, Ethanol, LNG, Liquefied petroleum gas, Methanol, Ammonia and Biodiesel	Environmental damages during life cycle (human health, ecosystem, resource utilization, emission inventory and social costs)
[51]	Ammonia, Biodiesel, Dimethyl ether, electro Fischer Tropsch diesel fuel, electro methanol, Fischer Tropsch diesel fuel, Hydrogen, LNG, Liquefied petroleum gas, marine diesel oil, marine gas oil, marine bio-oil, Methanol, pyrolysis oil, renewable diesel, straight vegetable oil and ultra-low sulfur heavy fuel oil	Climate change, acidification, freshwater ecotoxicity, marine eutrophication, terrestrial eutrophication, non-cancer human toxicity, particulate matter and photochemical ozone formation criteria
[52]	Diesel, Electricity, Methanol, Dimethyl ether, Natural gas, Hydrogen, Biodisel	Carbon allowance scenarios and other economic parameters
[53]	LNG, Ammonia, Methanol and other biofuels	Carbon pricing of each fuel and other economic parameters
[54]	Hydrogen (H_2 Polymeric Electrolytic Membrane Fuel Cell and H_2 Internal Combustion Engine)	GHG emissions, resource use, toxicity potential, among other environmental issues
[55]	HFO, Marine gas Oil, Gas-to-Liquid fuel, LNG	Acidification and eutrophication potentials, energy use and global warming potential

optimal solution for the location and number of bunkering stops that minimizes costs. In this phase, the costs to be determined are the deployment cost of bunkering vessels at the necessary call ports per voyage C^D and the lost opportunity cost of the voyage resulting from the reduction in cargo capacity of the vessel due to the space occupied by the fuel tank when using an alternative fuel $\left(C^O\right)$. The missed opportunity to generate revenue from cargo happens because alternative fuels are generally less dense than HFO, which means that the fuel tank takes up more space which could have been utilized to convey cargo. This results in a missed opportunity to generate revenue from cargo. The mathematical formulation of the optimization model is detailed in section 3.1.

In the second phase, the assessment of the total cost for the multiple fuel alternatives is conducted. The total cost includes C^D and C^O, obtained from the optimization model, the fuel cost $\left(C^F\right)$, the carbon emissions tax cost $\left(C^{CO_2}\right)$, and the cost of converting the vessel to transition from HFO to alternative fuel $\left(C^C\right)$. Because C^F, C^{CO_2}, and C^C do not influence the selection of the location and number of bunkering stops, the costs were not included into the optimization model.

By applying this framework to different alternative fuels, it becomes possible to determine the total costs for each one, thereby facilitating the selection of the most economical fuel path.

3.1. Optimization model for cost minimization of the number and location of bunkering stops

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

The model was developed considering the following assumptions.

- The vessel may only bunker at the call ports included in the predetermined route in which commercial trades are done, where commercial trades occur, and cargo is both loaded and offloaded.
- The sequence of ports to call is fixed and predetermined before the voyage begins.
- Given the flexibility [66,71], promptness [72], and long-term potential [66] of the ship-to-ship bunkering method, this framework assumes the deployment of bunkering vessels to perform the bunkering operation whenever the port of call does not already provide bunkering services for the chosen alternative fuel. This bunkering method is preferable to a bunkering station since it is a fixed and permanent facility, providing less flexibility [71] and requiring a higher investment cost [50]. On the other hand, truck-to-ship bunkering is flexible [71], requires a lower initial investment cost, and is suitable for small-scale bunkering. However, it is considerably more time-consuming [72]. Besides, the truck-to-ship bunkering method is often viewed as a short-term solution to address the lack of bunkering facilities for alternative fuels, being discouraged by ports and governments in comparison with the establishment of bunkering stations and bunkering vessels, which are viewed as long-term solutions to fulfill the growing demand for alternative fuels [66].

Table 2
Properties, advantages, disadvantages and future perspectives of ammonia, hydrogen, LNG, and methanol.

Fuel	Energy Density (MJ/L)[1]	Flammability	Toxicity	Auto-ignition Temperature (°C)	Boiling Point (°C)	Corrosivity	Lost Cargo Capacity When Switching from HFO (%)	Advantages	Disadvantages	Future Perspectives
Ammonia	12,7 [56]	Low [57]	High [58]	651 [59]	−33 [59]	Yes [56]	3 [40]	No SO_X emissions [58]; carbon neutrality[2] [58]; familiarity by already being present in many fields, namely shipping [40]	Lack of bunker barges [56]; difficulty in storage and transportation [40]; NO_X [60] and N_2O [39] emissions; risk of explosion [60]	Interest in the long-term from a large number of stakeholders [20,40–42,45]
Hydrogen	8,54 [56]	Extremely high [61]	Null [57]	585 [59]	−253 [59]	Yes [62]	5 [40]	Carbon neutrality[2] [11]; highest energy content per mass [56]; efficient combustion [63]	Safety measures and storage and transportation procedures on their infancy [64]; lack of specific guidelines [64]; NO_X emissions [63]; risk of explosion[3] [4] [64]; energy loss and need for control of temperature and vaporization during storage[4] [61]; not efficient storage[5] [64]	Interest in the long-term from a large number of stakeholders [7,11,40–42]
LNG	22,5 [56]	Null [65]	Null [65]	540 [59]	−162 [37,59]	No [65]	1 [40]	Highest availability [44]; lower costs [7,40]; longer lifetime of equipment [66]; less NO_X emissions [12]; no SO_X emissions [12]	Fossil fuel-based fuel [65,67]	Interest in the short-term from a lot of stakeholders [7,40,43,46, 68]
Methanol	15,5 [56]	High [57,69]	Low [69]	464 [59]	65 [56]	Yes [57, 69]	2 [40]	Ease of storage and transportation [70]; less NO_X emissions [42]; almost no SO_X emissions [42]	Most methanol is produced using natural gas as a feedstock [42]	Interest in the long-term from some stakeholders [40,45]

[1] The energy density of HFO is 35 MJ/L.
[2] When produced using renewable energy sources.
[3] When stored as compressed hydrogen.
[4] When stored as liquid hydrogen.
[5] When stored as compressed chemically bonded hydrogen.

- If a selected call port does already provide bunkering services for the alternative fuel under study, there is no need to establish a bunkering vessel at that call port, resulting in a deployment cost of zero.
- If the optimal solution of the model indicates a bunkering stop at a port of call that does not provide bunkering services for a particular alternative fuel, it is assumed that the port authority accepts the deployment of a bunkering vessel for that fuel at the port.

3.1.1. Mathematical formulation

SETS	
P	Set of ports (nodes) where the vessel stops along the route, indexed by i and j
A	Set of arcs between ports indexed by i and j
PARAMETERS	
C^{DU}	Deployment cost of a bunkering vessel per voyage (monetary unit per bunkering vessel, MU/bunkering vessel)
C^{OU}	Lost opportunity cost per nautical mile (MU/NM)
d_{ij}	Distance between ports i and j (NM)
s	Start port (node)
e	End port (node)
DECISION VARIABLE	
x_i	1 if the vessel bunkers at port i, 0 otherwise
ADDITIONAL VARIABLES	
y_{ij}	1 if the vessel sails between ports i and j without bunkering, 0 otherwise
d_l	Distance of the longest arc (i, j) traveled by the vessel without bunkering (NM)

(continued on next column)

(continued)

Objective function

$$Minimize \sum_{i\in P} C^{DU} x^{i} + C^{OU} d_l \tag{1}$$

Constraints

$$\sum_{j\in P\setminus\{s\}} y_{sj} = 1 \tag{2}$$

$$\sum_{i\in P} y_{ij} - \sum_{i\in P} y_{ji} = 0, \forall j \in P\setminus\{s, e\} \tag{3}$$

$$\sum_{i\in P\setminus\{e\}} y_{ie} = 1 \tag{4}$$

$$y_{ij} \cdot d_{ij} \leq d_l, \forall \{i,j\} \in P \tag{5}$$

$$y_{ij} \leq x_i, \forall \{i,j\} \in P \tag{6}$$

$$y_{ij} \leq x_{j,} \ \forall \{i,j\} \in P \tag{7}$$

$$y_{ij} \in \{0,1\}, \forall \{i,j\} \in P \tag{8}$$

$$x_i \in \{0,1\}, \forall \{i\} \in P \tag{9}$$

$$d_l \geq 0 \tag{10}$$

The objective function (1) minimizes the combination of the deployment cost of bunkering vessel(s) and the lost opportunity cost of the voyage. The deployment cost of a bunkering vessel is considered whenever a bunkering stop is made at a port, in other words, when the binary decision variable x_i equals 1. In this scenario, the model considers the specific deployment cost associated with the bunkering vessel at that port, which is provided as an input in the optimization process. The lost opportunity cost of the voyage is determined by the longest distance traveled by the vessel without bunkering. As d_l increases, more capacity needs to be allocated to fuel. Consequently, less capacity is available for transporting cargo, resulting in the loss of the opportunity to generate revenue from the cargo. This happens because compared to HFO, alternative fuels have a lower energy density [56], therefore, a higher volume of fuel is needed to sail the same distance. Therefore, there is less room for cargo. Consequently, the opportunity to earn more revenue from transporting cargo is sacrificed when HFO is substituted by alternative fuels like ammonia, hydrogen, LNG and methanol [45].

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

The objective function is subject to multiple constraints. Constraint (2) ensures that exactly one arc departs from the start node s, guaranteeing that the first arc of the route departs from the start node. Similarly, constraint (3) ensures that exactly one arc enters the end node e, ensuring that the final arc of the route arrives at the end node. Constraint (4) ensures flow conservation throughout the network by guaranteeing that, for any node in the network, except the start and end nodes, the total number of arcs entering the node must be equal to the total number of arcs leaving that same node. Constraint (5) ensures that the distance of the longest arc (i,j) traveled by the vessel without bunkering is the highest value of the distance traveled between two ports without bunkering.

If the vessel is intended to bunker at the start node, it is necessary to include constraint (6), which ensures that if an arc departs from a node, then a bunkering stop must be made at that node. Similarly, if the vessel is intended to bunker at the end node, it is necessary to consider constraint (7), which stipulates that if an arc enters a node, then a bunkering stop must be made at that node. Finally, constraints (8) and (9) ensure the binary nature of the variables x_i and y_{ij} and constraint (10) ensures the non-negativity of variable d_l.

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

4. Case study

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

Until now, slow steaming has been used when a longer transit time is acceptable without compromising service quality. However, the ship owner is now looking forward to transition from HFO to an alternative fuel. To achieve this, a bunkering strategy needs to be defined, which will involve determining the location and number of bunkering stops along the route and selecting the most appropriate alternative fuel that assures minimum cost. The alternative fuels that will be compared in terms of cost are ammonia, liquid hydrogen, LNG, and methanol.

4.1. Details of the route and bunkering infrastructure

The route sailed by the vessel is illustrated in Fig. 3, starting in Shanghai, and ending in Lagos. The numerical markings from 0 to 6 in the figure indicate the order of ports called along the route. After reaching Lagos, the vessel returns to Shanghai making stops at the same ports along the way.

It is assumed that the vessel operates 24 h per day and bunkers at the beginning and at the end of each voyage. The availability of bunkering services in the call ports is represented in Fig. 3 [73]. Table 3 summarizes the information about the call ports.

The distances between consecutive call ports on the route [74] are represented on Table 4, totaling 12,254 NM.

The normal sailing speed of the vessel is 22 knots [75], but when the customers tolerate a longer transit time, a slow steaming approach is adopted, and the speed is reduced to 18 knots.

The vessel takes 557,10 and 680,78 h to complete each voyage (12,554 NM) when sailing at 22 and 18 knots, respectively. Besides, it spends approximately 141 h in call ports per voyage, as the average time spent in a call port is 23,5 h [76], and the vessel stops at 6 ports in each voyage. This leads to a total voyage time of 839,10 and 821,78 h at sailing speeds of 22 and 18 knots, respectively, resulting in approximately 10 voyages annually.

It is known that the average fuel consumption of the vessel under study while using HFO is 240 tons/day when the average sailing speed is 22 knots, and 125 tons/day when the average sailing speed is 18 knots [77]. Considering that the vessel operates 24 h (h) per day, these values can be converted to 412 kg/NM and 262 kg/NM, respectively.

According to the study [78], the same vessel requires an equivalent amount of energy to sail the same distance, independently of the fuel used. However, different masses of each fuel are required because of the disparity between the energy content per unit of mass of the different fuels.

To determine the amount of each alternative fuel required in comparison to HFO, the authors of the study [78] used the concept of energy density, which allowed the comparison between the fuels to be done using the same basis. Considering these insights from the study, equation (11) will be utilized in this case study to determine the fuel consumption of each alternative fuel f. The results are presented in Table 5. Similarly to Ref. [79], the same efficiency was applied to all fuels, assuming that switching fuels would not significantly alter the fundamental engine technology.

$$FC_f \ (\text{kg} / \text{NM}) = \frac{ED_{HFO} \ (\text{MJ/kg}) \times FC_{HFO} \ (\text{kg/NM})}{ED_f \ (\text{MJ/kg})} \tag{11}$$

4.1.1. Phase 1: determining C^D and C^O

4.1.1.1. Deployment cost of a bunkering vessel per voyage. The costs of deploying a bunkering vessel for each fuel, accounted for each trip, were assessed and compiled in Table 6.

A potentially feasible solution for the bunkering of ammonia in this

Fig. 3. Map of the route between call ports and availability of bunkering services

Table 3
Information about the call ports.

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

Table 4
Distances between the consecutive ports where the vessel stops along the route.

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

case study is the installation of floating bunkering terminals at called ports because of their flexibility and mobility, like the ones being developed by the fertilizer company Yara International and the technology company Azane Fuel Solutions, whose focus is the development of solutions for the bunkering of ammonia [80]. However, these terminals are still in an immature stage of development, hence the associated costs have not been documented in the literature, nor the companies re-sponsible for developing these infrastructures have made this information publicly available. The same applies to hydrogen, for which bunkering vessels are still in the development phase. An example of this is the hydrogen bunkering vessel Elemanta H2, which is being developed by HDF Energy, Améthyste, ArianeGroup, Cetim, Rubis Terminal and Sofresid and will be available in 2025 [81]. Therefore, the costs have not yet been disclosed. Since the deployment cost is not defined for ammonia and hydrogen yet, it will be determined at which value the use of both fuels becomes less advantageous than LNG and methanol.

A viable bunkering solution for LNG would be a bunkering vessel, which costs 30 million $ [82]. To determine the deployment cost per voyage, this value needs to be divided by the number of voyages the

Table 6
Deployment Cost of a Bunkering Vessel per Voyage using HFO, Ammonia, Hydrogen, LNG, and Methanol.

Fuel	C^{DU} (Deployment Cost of a Bunkering Vessel per Voyage) ($)
HFO	0 (bunkering facilities already available)
Ammonia	Undisclosed because bunkering vessels are still in an immature stage of development [80]
Hydrogen	Undisclosed because bunkering vessels are still in an immature stage of development [81]
LNG	120,000 (the deployment cost per bunkering vessel of 30 million $ [82] is divided by the 250 voyages the containership is expected to make during the vessel's anticipated 25-year lifetime [83])
Methanol	36,000 (the deployment cost per bunkering vessel of 9 million $[1] is divided by the 250 voyages the containership is expected to make during the vessel's anticipated 25-year lifetime [83])

[1] Because methanol and HFO have similar properties, existing bunkering infrastructures for HFO can be easily converted to accommodate the alternative fuel with minimal adjustments [82]. Taking as an example a bunker vessel listed for sale for 7,5 million $ [84] and knowing that it would cost around 1,5 million $ to convert it to use methanol instead of HFO [82], a methanol bunker vessel can be obtained for 9 million $.

Table 5
Properties and fuel consumption of HFO, ammonia, hydrogen, LNG, and methanol.

Fuel	Energy Density (MJ/m^3) [56]	Mass Density (kg/m^3) [56]	Energy Density (MJ/kg)	Fuel Consumption at 22 knots (kg/NM)[1]	Fuel Consumption at 18 knots (kg/NM)
HFO	0,0350	1010	3,47E-05	412	262
Ammonia	0,0127	618	2,06E-05	695,35	442,64
Hydrogen	0,0085	71	1,20E-04	119,36	75,98
LNG	0,0225	450	5,00E-05	285,79	181,93
Methanol	0,0155	780	1,99E-05	719,09	457,75

[1] The fuel consumption can be obtained by dividing the energy density by the mass density.

containership under study is expected to undertake during the lifetime of the deployed bunkering vessel(s), which corresponds to the number of times the containership is expected to utilize it/them. To determine the number of voyages the containership is expected to undertake, the first step was to determine the total time of a voyage, which is the sum of the time spent sailing and the time spent in ports during the voyage. When the vessel sails at a speed of 22 knots, the vessel takes 557,10 h to sail the total distance of the voyage, which is 12,254 NM. At a sailing speed of 18 knots, the vessel takes 680,78 h to complete the total distance of the voyage.

According to Ref. [76], in 2018, containerships spent an average of 23,5 h in a port call. This value will be used as the port call time in this case study. Despite there are a total of 7 ports, given that the vessel completes a round trip, the final port of one journey corresponds to the starting port of the next one. To prevent the time spent at the starting and ending ports from being counted twice, the starting port of each trip was excluded from the count, as the time spent there is already included when it is considered as the ending port. Consequently, to determine the time spent in ports during the voyage, 6 ports are considered. Therefore, the total time spent in ports during the voyage is obtained by multiplying the average time spent in a port of 23,5 h by the number of ports where the vessel stops in each voyage, which is 6, resulting in a value of 141 h.

As a result, the total time for a voyage is 839,10 h at a sailing speed of 22 knots and 821,78 h at a sailing speed of 18 knots. Considering that one year has 8760 h and assuming that the vessel operates 24 h per day, it is possible to make approximately 10 voyages per year for both sailing speeds.

According to Ref. [83], the average duration of a vessel is 25–30 years. The worst case was assumed, so the operational lifespan of each bunkering vessel was considered to be 25 years. This means that, over the lifetime of the deployed bunkering vessel(s), the containership under study is expected to undertake 250 voyages. As a result, the total deployment cost of a bunkering vessel of LNG of 30 million $ results in a deployment cost per voyage of 120,000 $.

Because methanol and HFO have similar properties, existing bunkering infrastructures for HFO can be easily converted to accommodate the alternative fuel with minimal adjustments [82]. Taking as an example a bunker vessel with a deadweight tonnage of 4999, built in 2019 and listed for sale for 7,5 million $ [84], and knowing that it would cost around 1,5 million $ to convert it to use methanol instead of HFO [82], a methanol bunker vessel can be obtained for 9 million $. The same approach used for LNG was applied to methanol to determine the deployment cost of a bunkering vessel per voyage. Because the containership under study is estimated to make 250 voyages, the deployment cost of a methanol bunkering vessel per voyage is 36,000 $.

4.1.1.2. Lost opportunity cost per NM. Due to varying energy densities, the fuel tank capacity needed for alternative fuels to cover a given distance is higher than that for HFO, resulting in the percentages of reduction in cargo capacity indicated in Table 7. To quantify the lost opportunity cost arising from the missed opportunity to generate revenue from cargo due to the extra space occupied when using alternative fuels, it is crucial to assess the revenue that could have been generated. Since the revenue is unknown, the Containerized Freight Index of 3000$/TEU (0,245 $/TEU/NM) for the route Shanghai-Lagos [85] was used as an approximation. Considering the effect of the percentage of cargo capacity reduction on the revenue, the lost opportunity cost per TEU was determined and the values are displayed in Table 7. The loss of revenue depends on the longest distance traveled without bunkering (d_l). The longer the distance traveled without bunkering, the larger the amount of fuel needed to sail that distance. Consequently, a larger fuel tank is required. However, having a larger fuel tank reduces the remaining capacity available for cargo in the vessel.

Table 7
Lost opportunity cost per NM when transitioning from HFO to ammonia, hydrogen, LNG, and methanol.

Fuel	Cargo Capacity Reduction [18]	Lost Opportunity Cost ($/TEU/NM)	C^{OU} ($/NM)[1]
Ammonia	3%	$7{,}34 \times 10^{-3}$	93,64
Hydrogen	5%	$12{,}2 \times 10^{-3}$	156,07
LNG	1%	$2{,}45 \times 10^{-3}$	31,21
Methanol	2%	$4{,}90 \times 10^{-3}$	62,43

[1] The lost opportunity cost was multiplied by 12,750 TEUs, which corresponds to 85% of the vessel's total capacity of 15,000 TEUs, assuming the vessel utilization rate of 85% [86].

4.1.1.3. Optimization results. The optimization model was programmed in Python, using the FICO Xpress optimizer, to obtain the optimal solution for the number and location of bunkering stops, allowing for the determination of both C^D and C^O. The outcomes resulting from the Python implementation for ammonia, hydrogen, LNG, and methanol are consolidated in Table 8. For a better understanding of the results obtained for ammonia and hydrogen, it is important to explain the outcomes for these fuels.

Concerning ammonia, for a $C^{DU} \leq 303{,}860$ $, the total cost (sum of C^D and C^O) is minimized with five bunkering stops. In this case, d_l is 6577 NM, C^O is 615,870,28 $, and total cost $\leq$ 1,527,450,28 $. For a $C^{DU} \geq 303{,}861$ $, the minimum cost is achieved with four bunkering stops, resulting in a d_l of 9822 NM, a C^O of 919,732,08$ and a total cost $\geq$ 1,527,454,08 $.

In the case of hydrogen, for a value of $C^{DU} \leq 885{,}641$ $, the total cost is minimized with three bunkering stops. In this case, d_l is 6577 NM, C^O is 1,026,472,39 $, and the total cost $\leq$ 3,683,395,39$. On the other hand, for a $C^{DU} \geq 885{,}642$ $, the total cost is minimized with two bunkering stops, leading to a d_l of 12,254 NM, a C^O of 1,912,481,78 $ and a total cost $\geq$ 3,683,765,78 $.

4.1.2. Other resources phase 1: determining C^C, C^{CO_2} and C^F

4.1.2.1. Cost of converting the vessel to transition from HFO to alternative fuel. Switching the fuel of a vessel requires complex and costly modifications since the vessel is not prepared to transition to alternative fuels [45]. This cost will not be considered for HFO, as the vessel already operates using this fuel. The costs of retrofitting a five-year-old 15,000 TEU container vessel, similar to the one in this case study, were collected from other studies that can be found in Table 9.

In the case of ammonia, the cost of converting the vessel to use this alternative fuel was obtained from the report [45], which refers a study that assessed retrofitting costs for two scenarios: the full range and the reduced range. The full range corresponds to the normal range of a 15,000 TEU container vessel, which is 225,000 NM and requires a fuel tank with a capacity of 16,000 m^3 of fuel. On the other hand, the reduced range requires only 10,000 m^3 of fuel and can be applied to sail shorter distances without bunkering, requiring a smaller fuel tank. Since in the reduced range scenario less capacity is occupied by the fuel tank, this is a viable alternative for expanding the volume of cargo that can be carried.

In this case study, if the vessel carries out the entire voyage without bunkering at call ports, except for the start and end ports (which is mandatory in this case study), 13,787,76 m^3 of fuel would be required if the vessel sails at a normal speed of 22 knots and 8 776,93 m^3 when the vessel sails at the slow steaming speed of 18 knots. Therefore, the costs of the full range scenario are more appropriate for this case study since the tank's capacity in the reduced range scenario would not be sufficient to hold all the fuel needed when the vessel is required to sail at 22 knots. Although the fuel tank capacity in the reduced range scenario would be enough if the vessel sailed at 18 knots, it is necessary to adopt the full range scenario, which is compatible with both sailing speed scenarios, given that the vessel alternates between 22 and 18 knots. C^C of the full

Table 8
Consolidated optimization results for ammonia, hydrogen, LNG, and methanol.

Fuel		Ammonia		Hydrogen		LNG	Methanol
Input	C^{OU} ($/NM)	93,64		156,07		31,21	62,43
	C^{DU} ($/bunkering vessel)[1]	≤303,860	≥303,861	≤885,641	≥885,642	120,000	36,000
Results	**Ports (nodes) between which the vessel travels without bunkering**	(0, 1), (1, 3), (3, 5), (5, 6)	(0, 1), (1, 3), (3, 6)	(0, 5), (5, 6)	(0, 6)	(0, 3), (3, 6)	(0, 5), (5, 6)
	d_l (NM)	6577	9822	6577	12,254	9822	6577
	Number of bunkering stops	5	4	3	2	3	3
	Number of bunkering vessels deployed	3	2	3	2	2	1
	Ports where a bunkering vessel is deployed	0, 5, 6	0, 6	0, 5, 6	0, 6	0, 6	6
	Ports where the existing bunkering service is utilized	1, 3	1, 3	–	–	3	0, 5
	Total cost ($C^O + C^D$) ($)	≤ 1,527,450,28	≥ 1,527,454,08	≤3,683,395,39	≥ 3,683,765,78	546,544,62	446,602,11
	C^O ($)	615,870,28	919,732,08	1,026,472,39	1,912,481,78	306,544,62	410,602,11
	C^D ($)	≤911,580	≥ 607,722	≤2,656,923	≥1,771,284	240,000	36,000

[1] Because the value of C^{DU} when using ammonia and hydrogen remain uncertain, the Python program was run to obtain the solutions for all possible values of C^{DU} between 0 and 1,000,000 000 (an excessively high value).

Table 9
Cost of converting the vessel to transition from HFO to ammonia, hydrogen, LNG, and methanol.

Fuel	C^C ($)
Ammonia	70 million [45]
Hydrogen	23,55 million [87]
LNG	28 million [88]
Methanol	42 million [45]

range scenario amounts to 70 million $.

The conversion cost of hydrogen was assumed to be equivalent to the capex considered in the study [87], which includes the necessary changes in the engine and the storage tanks of the vessel under study to use hydrogen. Since no data for an equivalent vessel like the one under study was found in the literature, the value used for the cost of converting the vessel to transition to hydrogen was gathered from the aforementioned study, which was conducted on a passenger ferry with an unknown capacity. Hence, the value of C^C was estimated to be 23,55 million $.

The data utilized for LNG was collected from the report [88], which describes the project in which a five-year-old 15,000 TEU container ship was converted to be powered by LNG instead of HFO, becoming the first large container ship to transition from a completely HFO propulsion system to an LNG propulsion system, resulting in a C^C of 28 million $.

The cost of converting the vessel to use methanol was also obtained from the report [45], similarly to the cost of modifying it to use ammonia. Since 11,297,07 m^3 of fuel would be required for the vessel to carry out the entire voyage at a speed of 22 knots without bunkering at call ports, except for the start and end ports, and 7 191,42 m^3 at the slow steaming speed of 18 knots, the costs used were those from the full range scenario for the same reason as ammonia. This led to a C^C of 42 million $.

The costs of retrofitting a vessel similar to the one in this case study, as represented in Table 9, were collected from other studies and applied to this research.

4.1.2.2. Carbon emissions tax cost. One of the measures implemented to encourage the reduction of CO_2 emissions is the carbon tax, which effectiveness requires the implementation of a carbon tax of at least 50 $/tonne of CO_2 emitted [68]. To calculate the carbon emissions tax cost, it is necessary to determine the total amount of CO_2 emissions generated throughout the route using equation (12) [89].

$$CO_2\ emissions = Fuel\ consumption \times Fuel\ CO_2\ Emission\ Factor \tag{12}$$

The CO_2 emission factors of the different fuels and the resulting value of CO_2 emissions are displayed in Table 10. To determine the carbon emissions tax cost for the voyage $\left(C^{CO_2}\right)$, it was necessary to multiply the calculated CO_2 emissions for the carbon tax and by the total distance of the route (12,254 NM).

4.1.2.3. Fuel cost. Based on the fuel consumption, it was possible to determine the cost of the different fuels in $/NM. These values were subsequently multiplied by the total distance, in order to obtain the values of C^F displayed in Table 11.

4.1.2.4. Total Cost Assessment. The total cost was assessed for the different fuel alternatives to determine which is the most economical (see Table 12). In the absence of the values for the deployment cost of ammonia and hydrogen, it was determined at which value the use of both fuels became less advantageous than LNG and methanol.

4.1.2.4.1. HFO, LNG and methanol. .

4.1.2.4.2. Ammonia. Since the value of C^{DU} for ammonia is not defined yet, it is not possible to determine C^D and C^O using the optimization model, as it depends on the parameter C^{DU}. Therefore, it was determined at which values of C^D and C^O the use of ammonia is no longer advantageous compared to LNG and methanol. For this, it was necessary to calculate the sum of the costs already known (C^C, C^{CO_2} and C^F), which is presented on Table 13.

Given that the total cost when LNG and methanol are lower than the sum of the costs already known (C^C, C^{CO_2} and C^F) of ammonia, without taking C^D and C^O into account, there are no values of C^D and C^O for which using ammonia is more cost-effective than using LNG or methanol.

4.1.2.4.3. Hydrogen. For the same reason as ammonia, it is not possible to determine C^D and C^O when the vessel runs on hydrogen using the optimization model. As a result, it was calculated at which values of C^D and C^O the use of hydrogen is no longer advantageous compared to LNG and methanol. The first step was to calculate the sum of C^C, C^{CO_2} and C^F, which is presented on Table 14.

After determining the sum of hydrogen's C^C, C^{CO_2} and C^F, these values were subtracted from the total cost of LNG. This allowed for the calculation of the combined value of C^D and C^O for which the adoption of LNG is more economical than hydrogen's. This value is 5,893,051,33 $ for a sailing speed of 22 knots and 6,292,823,95 $ for a sailing speed of 18 knots. Both values exceed 3,683,765,78 $, which is the combined value of C^D and C^O for which a shift in the solution of the optimization model was verified in section 4.1.1.3. In this situation, two bunkering vessels are deployed, d_l is 12,254 NM and C^O is 1,912,481,78 $. The

Table 10
CO_2 emission factor, CO_2 emissions, and carbon emissions tax cost of HFO, ammonia, hydrogen, LNG, and methanol.

Fuel	CO_2 Emission Factor (tonnes CO_2/tonne fuel)	CO_2 Emissions When Sailing at 22 knots (tonnes CO_2/NM)	CO_2 Emissions When Sailing at 18 knots (tonnes CO_2/NM)	C^{CO_2} for the Entire Voyage when Sailing at 22 knots ($)	C^{CO_2} for the entire Voyage when Sailing at 18 knots ($)
HFO	3114 [90]	1284	0,817	786,755,02	500,827,85
Ammonia	0 [56]	0	0	0	0
Hydrogen	0 [37]	0	0	0	0
LNG	2,75 [90]	0,786	0,500	481,537,68	306,534,40
Methanol	1375 [90]	0,989	0,629	605,805,47	385 0,06

Table 11
Fuel cost of HFO, ammonia, hydrogen, LNG, and methanol.

Fuel	Fuel Cost	Fuel Cost at 22 knots ($/NM)	Fuel Cost at 18 knots ($/NM)	C^F for the Entire Voyage at 22 knots ($)	C^F for the Entire voyage at 18 knots ($)
HFO	2500 $/ton [91]	113,64	72,34	1,392,500,00	886,429,40
Ammonia	539,3 $/tonne [11]	375,00	238,72	4,595,288,23	2,925,241,35
Hydrogen	2738,20 $/tonne [11]	326,83	208,05	4,004,996,79	2,549,477,12
LNG	692 $/tonne [11]	197,77	125,89	2,423,447,82	1,542,704,05
Methanol	643 $/tonne [45]	462,37	294,34	5,665,933,33	3,606,786,27

resulting value of C^D can be obtained by subtracting C^O from the combined value of C^D and C^O, leading to a value of 3,980,569,55 $ at 22 knots and a value of 4,380,342,17 $ at 18 knots. This results in a deployment cost per bunkering vessel of 1,990,284,78 $ (22 knots) and 2,190,171,09 $ (18 knots).

Table 15 displays the values of C^C, C^{CO_2} and C^F when hydrogen is used as a fuel, the values of C^D and C^O above which hydrogen becomes less cost-advantageous than LNG and their sum, in other words, the total cost.

The process of determining the values of C^D and C^O for hydrogen above which this fuel becomes less economically favorable than LNG has been replicated for methanol. The values of C^C, C^{CO_2} and C^F of hydrogen were deducted from the total cost of methanol, resulting in the estimation of the combined values of C^D and C^O of 21,159,862,13 $ for a sailing speed of 22 knots and 20,336,069,31 $ for a sailing speed of 18 knots, above which methanol is more cost-advantageous than hydrogen. Since both values are higher than 3,683,765,78 $, which is the combined value of C^D and C^O for which a shift in the solution of the optimization model was verified in section 4.1.1.3. Besides, the number of bunkering vessels deployed is two, d_l is 12,254 NM and C^O is 1,912,481,78 $. By subtracting the last one from the combined value of C^D and C^O, it was possible to determine the value of C^D, which is 19,247,380,35 $ (9,623,690,17 $/bunkering vessel) for a sailing speed of 22 knots and 18,423,587,53 $ (9,211,793,77 $/bunkering vessel) for a sailing speed of 18 knots.

The values of C^C, C^{CO_2} and C^F, the values of C^D and C^O above which hydrogen becomes less economical than methanol, and the total cost resulting from their sum, are presented on Table 16.

Table 13
Sum of the cost of converting the vessel, the carbon emissions tax cost, and the fuel cost of ammonia.

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

Table 14
Sum of the cost of converting the vessel, the carbon emissions tax cost, and the fuel cost of hydrogen.

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

Table 15
Aggregated Costs for Hydrogen as Fuel above which It Becomes Less Cost-Advantageous than LNG.

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

Table 12
Aggregated costs for HFO, LNGs and methanol as fuels.

Fuel	HFO		LNG		Methanol	
Speed (knots)	22	18	22	18	22	18
C^{CO_2} ($)	786,755,02	500,827,85	481,537,68	306,534,40	605,805,47	385,640,06
C^F ($)	1,392,500,00	886,429,40	2,423,447,82	1,542,704,05	5,665,933,33	3,606,786,27
C^C ($)	-	-	30,000,000	30,000,000	42,000,000,00	42,000,000,00
C^O ($)	-	-	306,544,62	306,544,62	410,602,11	410,602,11
C^D ($)	-	-	240,000,00	240,000,00	36,000,00	36,000,00
Total Cost ($)	**2,179,255,02**	**1,387,257,25**	**33,451,530,12**	**32,395,783,07**	**48,718,340,91**	**46,439,028,43**

Table 16
Aggregated Costs for Hydrogen as Fuel above which It Becomes Less Cost-Advantageous than Methanol.

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

5. Analysis and discussion of result

5.1. Comparative analysis of fuel alternatives by total cost and fuel selection

Analyzing the total cost of the different alternative fuels was important for determining which is more cost-effective in this case study. Since the total cost of hydrogen and ammonia depends on the deployment cost of a bunkering vessel per voyage, which is uncertain, the total cost was calculated for different values of the deployment cost. These results have been represented in charts that display the total cost in relation to the deployment cost of a bunkering vessel per voyage. The chart in Fig. 5 corresponds to a sailing speed of 22 knots, whereas the chart in Fig. 6 refers to a sailing speed of 18 knots.

The charts include the total cost obtained for LNG and methanol in order to determine if there is an intersection point with the curves of ammonia and hydrogen, which denotes the point at which the total cost of ammonia and hydrogen surpasses this value. The coordinates on both charts represent the deployment cost per bunkering vessel per voyage at which the total cost of hydrogen exceeds the total cost of LNG and methanol.

It is possible to conclude that hydrogen is the alternative fuel with the lowest total cost when the deployment cost per bunkering vessel is lower than 1,990,284,78 $ for a sailing speed of 22 knots and 2,190,171,09 $ for a sailing speed of 18 knots. If the deployment cost per bunkering vessel exceeds this value, LNG becomes the most advantageous alternative fuel in terms of cost for both sailing speeds.

Furthermore, it is evident that ammonia is the less cost-advantageous fuel option, as the total cost when using this fuel exceeds the cost of using any of the other fuels under study for any value of deployment cost per bunkering vessel per voyage. The cost parameter that contributes the most to this cost discrepancy between ammonia and other fuels is the cost of converting the vessel to transition from HFO to alternative fuel. This cost is significantly higher for ammonia compared to the others, as illustrated in the graph in Fig. 4.

It is also possible to notice a significant cost difference between HFO and any alternative fuel, reinforcing that using HFO is still economically advantageous.

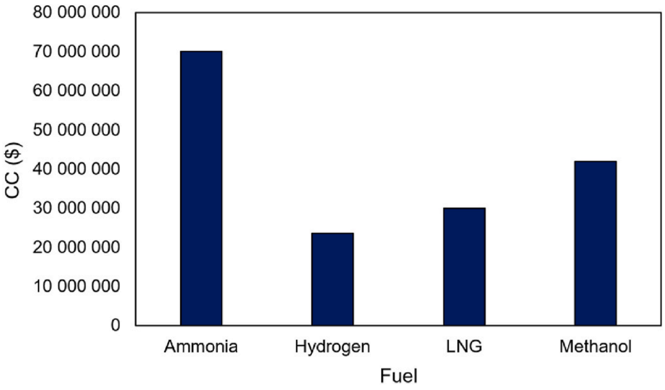

Fig. 4. Cost comparison of converting the vessel to transition from HFO to ammonia, hydrogen, LNG, and methanol

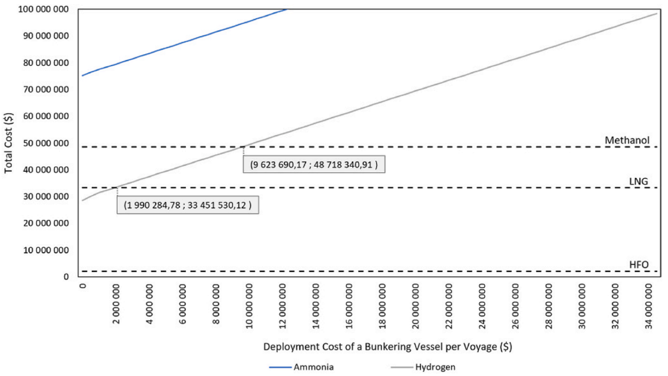

Fig. 5. Total Cost Assessment at Varying Deployment Costs of a Bunkering Vessel per Voyage at a Sailing Speed of 22 knots

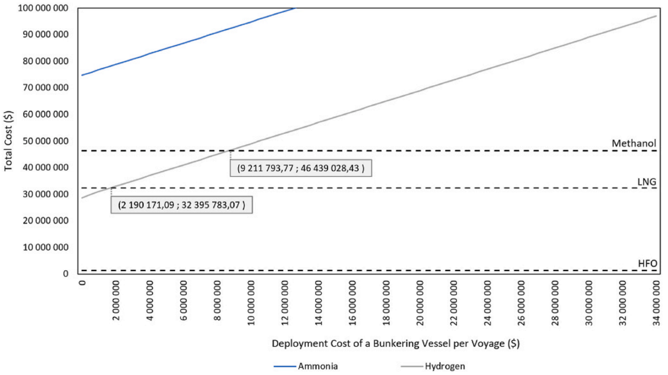

Fig. 6. Total Cost Assessment at Varying Deployment Costs of a Bunkering Vessel per Voyage at a Sailing Speed of 18 knots

The result of this study aligns with the results of the majority of the other studies since, as mentioned in section 2.1.2, eight out of ten studies concluded that hydrogen and/or LNG are the most advantageous alternative fuels. Besides, in comparison with other studies in literature, this study undertook a significantly more comprehensive analysis of the costs to select the most advantageous fuel. Except for [7,11], the other studies do not disclose the costs and other parameters considered. Besides, none of the existing studies are concerned with the minimization of costs. Consequently, this study significantly complements the existing literature as it provides a framework with detailed guidelines for determining the costs involved in transitioning from fossil fuels to different alternative fuels, which any interested party can apply to a route they aim to decarbonize. This framework goes a step further as it incorporates an optimization model to determine the optimal solution for the location and number of bunkering stops to minimize costs.

5.2. Impact of carbon tax variations on total cost and fuel selection

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

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

- Low: the carbon tax suffers a 20% increase, resulting in 60 \$/tonne of CO_2 emitted.
- Moderate: the carbon tax suffers a 50% increase, resulting in 75 \$/tonne of CO_2 emitted.
- High increase: the carbon tax suffers a 200% increase, resulting in 150 \$/tonne of CO_2 emitted.
- Very high increase: the carbon tax suffers a 1000% increase, resulting in 550 \$/tonne of CO_2 emitted.

Since the carbon tax has no effect on ammonia and hydrogen because the fuels do not emit CO_2 when combusted, this analysis was limited to HFO, LNG, and methanol.

To visualize the impact of varying the carbon tax on fuel selection, the charts displaying the total cost in relation to the deployment cost of a bunkering vessel were remade, incorporating the total cost of HFO, LNG, and methanol in the different scenarios of carbon taxes. The chart in Fig. 7 corresponds to a sailing speed of 22 knots, while the chart in Fig. 8 refers to a sailing speed of 18 knots. By analyzing both charts, it is possible to conclude that even as the carbon tax increases, either hydrogen or LNG (depending on the deployment cost per bunkering vessel) remains more cost-effective compared to other alternative fuels. Besides, the higher the carbon tax, the higher the deployment cost per bunkering facility at which LNG becomes more economical than hydrogen.

Even in the scenario where this increase is very high, resulting in a carbon tax ten times higher than the initial one, HFO continues to be more economical than any alternative fuel. This indicates that a very high carbon tax alone might not be enough to discourage the use of HFO. It is recommended that countries provide financial support for the fuel transition, including funding for technology, infrastructure, and research and development projects. By proposing measures that make the supply of alternative fuels appealing, alternative fuels might become more economical than HFO, as, according to Ref. [17], the price decreases as supply increases.

The C^{CO_2}, the total cost, and the increase in total cost compared to the calculated initially for a carbon tax of 50 \$/tonne of CO2 emitted were determined for the four scenarios, and the results obtained are displayed on Table 17. Since the carbon tax has no effect on ammonia and hydrogen because the fuels do not emit CO2 when combusted, this analysis was limited to HFO, LNG, and methanol.

As shown in Table 17, the carbon tax increase has a greater impact on the total cost of HFO, followed by LNG, and finally, methanol. This can be explained by the fact that C^{CO_2} constitutes a substantial fraction of the total cost of HFO (e.g., for a carbon tax of 50 \$/tonne of CO2 emitted, C^{CO_2} accounts for 36,10% of the total cost for both sailing speeds of 22 knots and 18 knots), whereas for LNG this fraction is considerably less substantial (1,44% for a sailing speed of 22 knots and 0,92% for a sailing speed of 18 knots), and for methanol it is even less significant (1,24% for a sailing speed of 22 knots and 0,79% for a sailing speed of 18 knots). Because the carbon tax increase influences C^{CO_2}, it is logical that the greater the weight of this cost parameter in the total cost, the higher the impact of the carbon tax variation on the total cost.

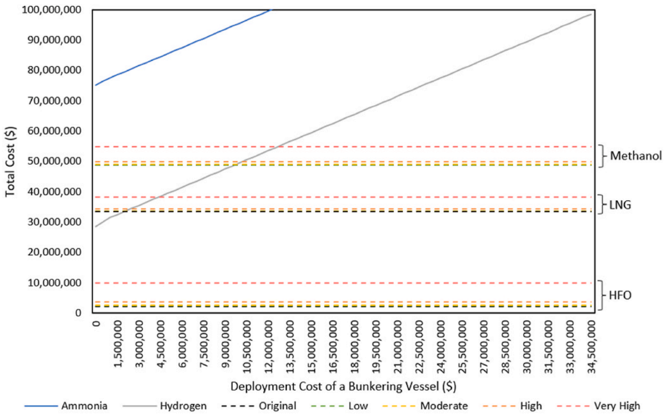

Fig. 7. Total Cost Assessment at Varying Deployment Costs of a Bunkering Vessel and Varying Carbon Taxes at a Sailing Speed of 22 knots

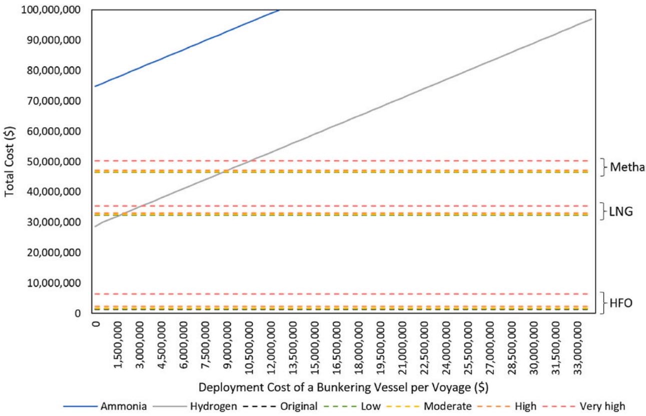

Fig. 8. Total Cost Assessment at Varying Deployment Costs of a Bunkering Vessel and Varying Carbon Taxes at a Sailing Speed of 18 knots

5.3. *Comparison to other similar frameworks*

The framework proposed in this paper presents an examination of the shift, from traditional fossil fuels to alternative fuel sources. It takes into account cost factors like opportunity costs and carbon emission taxes. What sets this framework apart from others is its emphasis on conducting a sensitivity analysis that assesses how changing carbon tax rates affect the cost effectiveness of fuel choices. This nuanced approach gives stakeholders an insight into the feasibility under different regulatory conditions. By adopting such a strategy decision makers are better equipped to promote the adoption of friendly shipping practices. Unlike frameworks this one focuses on the economic evaluation of transitioning to alternative fuels for a single voyage distinguishing it from broader scoped frameworks or those, with different objectives related to green shipping routes [92]. The framework suggested in the paper offers a viewpoint, on the feasibility of using hydrogen as an alternative fuel setting it apart from other frameworks. This detailed examination of hydrogen expenses taking into account factors like sailing speed sets it apart from existing frameworks that often overlook specifics and treat hydrogen generally. By presenting these findings the proposed framework gives stakeholders a grasp of the circumstances that make hydrogen a feasible and competitive fuel choice compared to well established options such, as LNG [53,55]. The proposed framework gives stakeholders an overview of the consequences in contrast, to other models that concentrate on fewer factors or lack detailed cost breakdowns.

The proposed framework thoroughly examines the costs associated with hydrogen especially when compared to heavy fuel oil (HFO). It sets cost thresholds, for deploying hydrogen showing that it remains the economical choice until the bunkering vessel costs reach around \$1,990,285 at a speed of 22 knots. At that point LNG becomes more cost effective regardless of variations in carbon taxes. Unlike frameworks this one provides insights into the cost dynamics of hydrogen versus HFO. Many existing frameworks simply view hydrogen as an option without specifying the conditions under which it becomes economically competitive [43,44,50]. This lack of analysis from other papers makes it challenging for stakeholders to make informed decisions, about transitioning fuels. However, this framework nuanced approach is valuable to decision makers by offering a more detailed view of the factors that determine hydrogens viability compared to HFO, LNG and Methanol.

Table 17
Impact of carbon tax on carbon emissions tax cost and total cost for HFO, LNG, and methanol.

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

6. Sensitivity analysis

A sensitivity analysis was performed to assess each fuel type's economic feasibility. This analysis will help to determine if changes in the parameters of each fuel type will alter the preferred fuel choice for the transition to greener fuels. Five different sensitivity analyses were performed, varying different factors. For these analyses, the equation considered to calculate the total cost for each alternative fuel is detailed bellow:

Total Cost (TC) ($) = $C^{C} + C^{CO2} + C^{F} + C^{O} + C^{D}$

a) Sensitivity analysis for the deployment cost of a bunkering vessel ($\boldsymbol{C^{D}}$).

A sensitivity analysis of the deployment costs of bunkering vessels was performed to assess how they affect the total costs of each alternative fuel.

From the base case and considering 22 knots of sailing speed, different assumptions were taken.

1. Costs for **Ammonia** ($): $\mathbf{C^{C}}$ = 70,000,000; $\mathbf{C^{CO2}}$ = 0; $\mathbf{C^{F}}$ = 4,595,288.23; $\mathbf{C^{O}}$ = 615,870.28 (for 5 bunkering stops); $\mathbf{C^{D}}$ = Not specified
2. Costs for **Hydrogen** ($): $\mathbf{C^{C}}$ = 23,553,482; $\mathbf{C^{CO2}}$ = 0; $\mathbf{C^{F}}$ = 4,004,996.79; $\mathbf{C^{O}}$ = 1,912,481.78 (for 2 bunkering stops); $\mathbf{C^{D}}$ = Not specified
3. Costs for **LNG** ($): $\mathbf{C^{C}}$ = 30,000,000; $\mathbf{C^{CO2}}$ = 481,537.68; $\mathbf{C^{F}}$ = 2,423,447.82; $\mathbf{C^{O}}$ = 306,544.62; $\mathbf{C^{D}}$ = 240,000
4. Cost for **Methanol** ($): $\mathbf{C^{C}}$ = 42,000,000; $\mathbf{C^{CO2}}$ = 605,805.47; $\mathbf{C^{F}}$ = 5,665,933.33; $\mathbf{C^{O}}$ = 410,602.11; $\mathbf{C^{D}}$ = 36,000
5. **Ammonia**: 3 vessels, base case: $\mathbf{C^{D}}$ = 900,000 (300,000 per vessel); **Hydrogen**: 2 vessels,: $\mathbf{C^{D}}$ = 600,000 (300,000 per vessel);

For this sensitivity analysis, five different scenarios are considered in which the deployment cost (C^{D}) varies: a decrease of 25% and 50%, and an increase of 25%, 50% and 100%. The results are presented in Table 18.

These results highlight that of all alternative fuels, Hydrogen is the most sensitive to changes in the deployment cost. Even though

Table 18
Sensitivity analysis results of deployment costs for Ammonia, Hydrogen, LNG and Methanol.

Fuel Type	% change in deployment cost	Deployment cost (C^{D}) ($)	Total Cost ($)
Ammonia	**(−) 50%**	450,000	75,661,158.51
	(−) 25%	675,000	75,886,158.51
	0% (Base case)	900,000	76,111,158.51
	(+) 25%	1,125,000	76,336,158.51
	(+) 50%	1,350,000	76,561,158.51
	(+) 100%	1,800,000	77,011,158.51
Hydrogen	**(−) 50%**	300,000	29,770,960.57
	(−) 25%	450,000	29,920,960.57
	0% (Base case)	600,000	30,070,960.57
	(+) 25%	750,000	30,220,960.57
	(+) 50%	900,000	30,370,960.57
	(+) 100%	1,200,000	30,670,960.57
LNG	**(−) 50%**	120,000	33,331,530.12
	(−) 25%	180,000	33,391,530.12
	0% (Base case)	240,000	33,451,530.12
	(+) 25%	300,000	33,511,530.12
	(+) 50%	360,000	33,571,530.12
	(+) 100%	480,000	33,691,530.12
Methanol	**(−) 50%**	18,000	48,700,340.91
	(−) 25%	27,000	48,709,340.91
	0% (Base case)	36,000	48,718,340.91
	(+) 25%	45,000	48,727,340.91
	(+) 50%	54,000	48,736,340.91
	(+) 100%	72,000	48,754,340.91

Hydrogen remains the most cost-effective alternative fuel, even with an increase of 100% in the deployment costs, the analysis shows that LNG has potential to improve its competitiveness with Hydrogen. If LNG deployment costs decrease while Hydrogen deployment costs increase, LNG will likely become more competitive. Furthermore, LNG and Methanol show the lowest sensitivity to changes in deployment costs, with Methanol being less advantageous than LNG for all ranges. Ammonia, even though it is the second most sensitive fuel to changes in the deployment cost, is the least cost-effective alternative in all scenarios.

b) Sensitivity analysis for fuel prices $\left(\boldsymbol{C^F}\right)$

A sensitivity analysis of fuel prices is critical, considering their volatility and the significant impact on each fuel's total cost. The fuel cost is calculated through the equation that follows:

$$\mathbf{C^F} = \text{Fuel consumption } (\text{FC}) * \text{Days of operation per year } (\mathbf{D}) * \text{Price of fuel}(\mathbf{P})$$

Considering the base case scenario for each fuel type, the following assumptions were made.

1. **HFO**: **FC** = 50 ton/day; **P** = 2500 \$/ton; $\mathbf{C^F}$ = 37,500,000 (\$)
2. **Ammonia**: **FC** = 100 ton/day; **P** = 539.3 \$/ton; $\mathbf{C^F}$ = 16,179,000 (\$)
3. **Hydrogen**: **FC** = 20 ton/day; **P** = 2738.20 \$/ton; $\mathbf{C^F}$ = 116,429,000 (\$)
4. **LNG**: **FC** = 60 ton/day; **P** = 692 \$/ton; $\mathbf{C^F}$ = 12,456,000 (\$)
5. **Methanol**: **FC** = 90 ton/day; **P** = 643 \$/ton; $\mathbf{C^F}$ = 17,361,000 (\$)
6. Days of operation consider: 300
7. For the base case scenario: **HFO** Total Cost (\$) = 2,179,255.02; **LNG** Total Cost (\$) = 33,451,530.12; **Methanol** Total Cost (\$) = 48,718,340.91; for Ammonia and Hydrogen, the total cost is obtained by the sum of C^C + C^F: **Ammonia** Total Cost (\$) = 74,595.288.23; **Hydrogen** Total Cost (\$) = 27,558,478.79

To carry out the sensitivity analysis, the fuel prices will vary in four different scenarios, where these costs increase or decrease by 10% and 20%, considering a 22 knots speed of sailing. The main results are detailed in Table 19.

Table 19
Sensitivity analysis results of deployment costs for Ammonia, Hydrogen, LNG and Methanol.

Fuel Type	% change in fuel prices (C^F)	Fuel Cost (C^F) (\$)	Total Cost (\$)
HFO	**(−) 20%**	30,000,000	−5,320,744.98
	(−) 10%	33,750,000	−1,570,744.98
	0% (Base Case)	37,500,000	2,179,255.02
	(+) 10%	41,250,000	5,929,255.02
	(+) 20%	45,000,000	9,679,255.02
Ammonia	**(−) 20%**	12,943,200	71,359,488.23
	(−) 10%	14,561,100	72,977,388.23
	Base Case	16,179,000	74,595,288.23
	(+) 10%	17,796,900	76,213,188.23
	(+) 20%	19,414,800	77,831,088.23
Hydrogen	**(−) 20%**	13,143,360	24,272,638.79
	(−) 10%	14,786,280	25,915,558.79
	Base Case	16,429,200	27,558,478.79
	(+) 10%	18,072,120	29,201,398.79
	(+) 20%	19,715,040	30,844,318.79
LNG	**(−) 20%**	9,964,800	30,960,330.12
	(−) 10%	11,210,400	32,205,930.12
	Base Case	12,456,000	33,451,530.12
	(+) 10%	13,701,600	34,697,130.12
	(+) 20%	14,947,200	35,942,730.12
Methanol	**(−) 20%**	13,888,800	45,246,140.91
	(−) 10%	15,624,900	46,982,240.91
	Base Case	17,361,000	48,718,340.91
	(+) 10%	19,097,100	50,454,440.91
	(+) 20%	20,833,200	52,190,540.91

From these results, several facts can be highlighted. Fuels with higher consumption rates are more sensitive to price fluctuations. HFO's economic advantage is sensitive to price changes. Substantial increases in HFO prices will have a significant impact on its total cost and are likely to affect its economic advantage. If HFO price increases could make it less competitive compared with other alternative greener fuels. HFO shows a negative total cost at lower fuel prices due to the base case scenario, where the total cost is lower than the calculated C^F.

On the other hand, while price variations can affect Ammonia's total cost, Ammonia is likely to remain the least cost-effective option (especially due to its high conversion costs). Considering Hydrogen, it is evident that variations in the price would significantly impact its competitiveness with LNG – as a decrease in Hydrogen prices and an increase in LNG would extend the range of bunkering vessel deployment costs where Hydrogen is preferable. Thus, LNG, as the third most cost-effective option in the base case, evidences that changes in its price would affect the point at which it becomes more economical than Hydrogen. For Methanol, it is possible to conclude that even though price variations would affect the fuel's total cost. Methanol is likely to remain less competitive than Hydrogen and LNG.

c) Sensitivity analysis for carbon tax $\left(\boldsymbol{C^{CO_2}}\right)$

A more granular sensitivity analysis on carbon tax scenarios was developed to identify potential triggering points where fuel choices might change. As Ammonia and Hydrogen do not emit CO_2 when combusted, these are not included in the analysis. In the base case scenario, the initial carbon tax was 50 \$/ton of CO_2 emitted. Nine different scenarios of increase in the carbon tax were analyzed: 20%, 50%, 100%, 200%, 400%, 600%, 800%, and 1000%.

The analysis includes the total costs at both 22 knots and 18 knots of sailing speed. The results are provided in Table 20.

From the results, it is possible to retrieve some conclusions and insights. Of all fuels, HFO is the most sensitive to carbon tax increases, which can be explained by its higher CO_2 emissions. The total cost for HFO increases 361%, at both 22 and 18 knots, when the carbon tax increases from 50 to 550 \$/ton of CO_2 emitted. On the other hand, LNG is less sensitive to carbon tax increases compared to HFO, as the total cost for LNG can increase by 14.4% at 22 knots and 9.46% at 18 knots, for the same carbon tax range. Methanol shows a similar sensitivity to LNG. The difference in the total cost between LNG and Methanol decreases when carbon tax increases; however, Methanol remains a more expensive option. The carbon tax would need to increase significantly for LNG or Methanol to become more expensive than HFO. Furthermore, as expected the impact of carbon tax is more pronounced at higher sailing speeds due to the increase in fuel consumption and emissions.

This analysis also allows to conclude about the potential triggering points for fuel changes, that were identified as follows.

- HFO *versus* LNG: At 22 knots, HFO remains cheaper than LNG even at the highest carbon tax scenario. At 18 knots, HFO becomes more expensive than LNG when the carbon tax exceeds approximately 520 \$/ton of CO_2.
- HFO *versus* Methanol: HFO remains cheaper than Methanol across all examined scenarios for both speeds.
- LNG *versus* Methanol: The carbon tax increase doesn't change their relative positions; LNG remains cheaper than Methanol across all scenarios.
- Hydrogen and Ammonia: As zero-emission fuels, they become relatively more attractive as the carbon tax increases, but their competitiveness depends more on their fuel prices and infrastructure costs.

Figs. 9 and 10 represent how the costs of the different fuel types vary according to the carbon tax, both for 22 and 18 knots of sailing speed.

Table 20
Sensitivity analysis results for carbon tax.

Carbon Tax	C^{CO_2} (22 knots)	**Total Cost** (22 knots)	C^{CO_2} (18 knots)	**Total Cost** (18 knots)
HFO				
50 \$/ton CO_2	786,755.02	2,179,255.02	500,827.85	1,387,257.25
60 \$/ton CO_2	944,106.03	2,336,606.03	600,993.42	1,487,422.82
75 \$/ton CO_2	1,180,132.54	2,572,632.54	751,241.78	1,637,671.17
100 \$/ton CO_2	1,573,510.05	2,966,010.05	1,001,655.70	1,888,085.09
150 \$/ton CO_2	2,360,265.07	3,752,765.07	1,502,483.55	2,388,912.95
250 \$/ton CO_2	3,933,775.12	5,326,275.12	2,504,139.25	3,390,568.65
350 \$/ton CO_2	5,507,285.17	6,899,785.17	3,505,794.95	4,392,224.35
450 \$/ton CO_2	7,080,795.22	8,473,295.22	4,507,450.65	5,393,880.05
550 \$/ton CO_2	8,654,305.26	10,046,805.26	5,509,106.36	6,395,535.76
LNG Carbon Tax	C^{CO_2} (22 knots)	**Total Cost** (22 knots)	C^{CO_2} (18 knots)	**Total Cost** (18 knots)
50 \$/ton CO_2	481,537.68	33,451,530.12	306,534.40	32,395,783.07
60 \$/ton CO_2	577,845.22	33,547,837.66	367,841.28	32,457,089.95
75 \$/ton CO_2	722,306.52	33,692,298.96	459,801.60	32,549,050.28
100 \$/ton CO_2	963,075.36	33,933,067.80	613,068.80	32,702,317.48
150 \$/ton CO_2	1,444,613.04	34,414,605.48	919,603.21	33,008,851.88
250 \$/ton CO_2	2,407,688.40	35,377,680.84	1,532,672.01	33,621,920.68
350 \$/ton CO_2	3,370,763.76	36,340,756.20	2,145,740.81	34,234,989.48
450 \$/ton CO_2	4,333,839.12	37,303,831.56	2,758,809.61	34,848,058.28
550 \$/ton CO_2	5,296,914.49	38,266,906.93	3,371,878.44	35,461,127.11
Methanol Carbon Tax	C^{CO_2} (22 knots)	**Total Cost** (22 knots)	C^{CO_2} (18 knots)	**Total Cost** (18 knots)
50 \$/ton CO_2	605,805.47	48,718,340.91	385,640.06	46,439,028.43
60 \$/ton CO_2	726,966.56	48,839,502.01	462,768.07	46,516,156.44
75 \$/ton CO_2	908,708.20	49,021,243.65	578,460.08	46,631,848.46
100 \$/ton CO_2	1,211,610.94	49,324,146.38	771,280.11	46,824,668.49
150 \$/ton CO_2	1,817,416.41	49,929,951.85	1,156,920.17	47,210,308.54
250 \$/ton CO_2	3,029,027.35	51,141,562.79	1,928,200.28	47,981,588.65
350 \$/ton CO_2	4,240,638.29	52,353,173.73	2,699,480.39	48,752,868.76
450 \$/ton CO_2	5,452,249.23	53,564,784.67	3,470,760.50	49,524,148.87
550 \$/ton CO_2	6,663,860.16	54,776,395.61	4,242,040.61	50,295,428.99

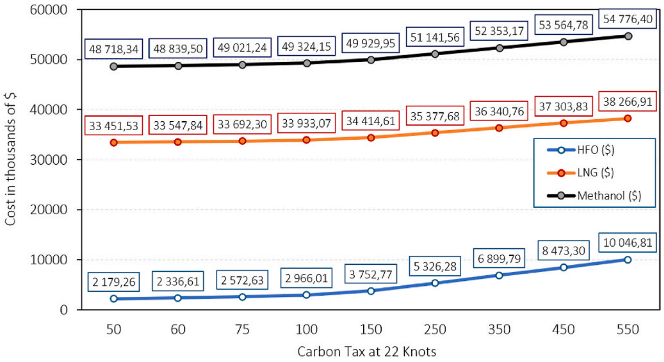

Fig. 9. Variation of carbon tax at 22 knots of sailing speed for HFO, LNG and Methanol

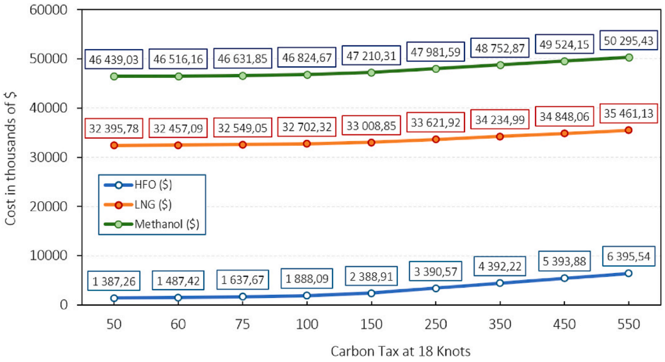

Fig. 10. Variation of carbon tax at 18 knots of sailing speed for HFO, LNG and Methanol

d) Sensitivity analysis for vessel conversion costs ($\boldsymbol{C^C}$).

Considering the base case results, the vessel conversion costs for each fuel type corresponded to.

1. Ammonia: 70$ million
2. Hydrogen: 23,55$ million
3. LNG: 28$ million
4. Methanol: 42$ million

To carry out the sensitivity analysis, the vessel conversion costs will vary in ten different scenarios, where these costs increase or decrease by 50% in 10% increments. The main results are presented considering 22knots of sailing speed and are detailed in Table 21.

Conclusions can be drawn from these results. Considering ammonia, it is highlighted that even with a 50% decrease in the vessel's conversion costs, this remains the least cost-effective fuel type. Ammonia is the most

Table 21

Sensitivity analysis results of vessel conversion costs.

% change in conversion cost (C^C)	Ammonia Total Cost ($)	Hydrogen Total Cost ($)	LNG Total Cost ($)	Methanol Total Cost ($)
(−) 50%	40,211,158.51	21,673,048.13	17,451,530.12	27,718,340.91
(−) 40%	47,211,158.51	24,028,048.13	20,251,530.12	31,918,340.91
(−) 30%	54,211,158.51	26,383,048.13	23,051,530.12	36,118,340.91
(−) 20%	61,211,158.51	28,738,048.13	25,851,530.12	40,318,340.91
(−) 10%	68,211,158.51	31,093,048.13	28,651,530.12	44,518,340.91
Base Case	75,211,158.51	33,448,048.13	31,451,530.12	48,718,340.91
(+) 10%	82,211,158.51	35,803,048.13	34,251,530.12	52,918,340.91
(+) 20%	89,211,158.51	38,158,048.13	37,051,530.12	57,118,340.91
(+) 30%	96,211,158.51	40,513,048.13	39,851,530.12	61,318,340.91
(+) 40%	103,211,158.51	42,868,048.13	42,651,530.12	65,518,340.91
(+) 50%	110,211,158.51	45,223,048.13	45,451,530.12	69,718,340.91

sensitive to changes in the vessel's conversion costs. However, on the other hand, changes in Hydrogen conversion costs could likely impact its competitiveness with LNG. If Hydrogen conversion costs decrease, while LNG's increase, Hydrogen might become more attractive. In the base case, LNG is considered to be the second most cost-effective option, and from the sensitivity analysis, it can be concluded that changes in LNG's conversion costs could affect the point at which it becomes more economical than Hydrogen. Finally, concerning to Methanol, it is evident that changes in the conversion costs would affect its total cost but overall, Methanol is likely to remain less competitive than Hydrogen or LNG.

For this sensitivity analysis, HFO was not included because it has no conversion costs. Thus, increasing the conversion costs of greener fuels would only strengthen HFO's economic advantage. Fig. 11 presents a visual comparison between the total cost of the different alternative fuels when the conversion costs vary.

e) Sensitivity analysis for sailing speed

The final analysis includes variations in the sailing speed of the vessels. Seven scenarios were created in which the speeds range from 14 to 26 knots in 2-knot increments. There is a need to make some assumptions, namely.

1. Fuel consumption increases approximately quadratically with speed
2. Carbon emissions are directly proportional to fuel consumption
3. Operating costs (C^O) remain constant across speeds for simplicity
4. The cost of converting the vessel (C^C) remains constant across speeds.
5. For Hydrogen, the break-even deployment cost scenario was used to make a fair comparison.

The results from the analysis are presented in Table 22.

The results highlight that from an economic perspective, even though operating at lower speeds significantly reduces costs for all fuel types, HFO remains the most cost-effective fuel across all speeds that were considered. This is aligned with earlier conclusions that a higher carbon tax might be required to make alternative fuels more economically competitive compared to HFO. On the other hand, the cost difference between HFO and the alternative fuels, LNG and Hydrogen, decreases as the sailing speed increases. This might suggest that alternative fuels might become more competitive at an even higher speed rate. Finally, Methanol and Ammonia are the most expensive options due to their high conversion costs.

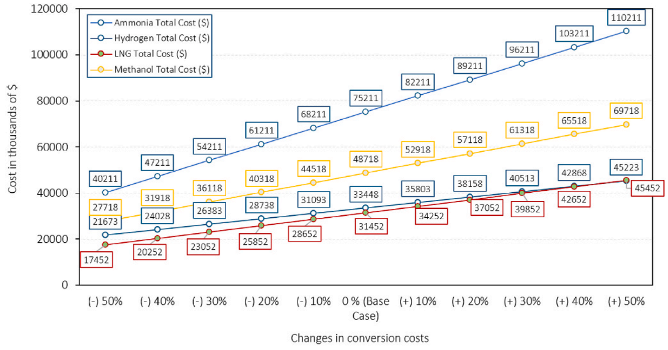

Fig. 11. Variation of conversion costs in the total cost of Ammonia, Hydrogen, LNG and Methanol

Figs. 12 and 13 illustrate the comparison between the results obtained for each fuel type.

The optimization results from the base case identified Hydrogen and LNG as the most cost-effective alternative fuels, depending on the deployment cost of bunkering vessels. The sensitivity analysis reinforces and expands upon these findings. The effect of variations in different parameters, namely, deployment costs, fuel prices, carbon tax, vessel conversion costs and sailing speed, on the total cost of the different fuel options was explored. The analysis revealed that Hydrogen remains the most economical choice when the deployment costs of bunkering vessels are below 1,990,285$. Above these limits, LNG becomes more economically advantageous. Moreover, the sensitivity analysis to an increase in carbon tax highlights that HFO remains the cheapest option, even under a 1000% tax increase. However, the cost gap between HFO and alternative fuels narrows significantly with an increase in carbon tax. It implies that by pairing a carbon tax, with policies and laws there is a chance to tilt the economic scale in favor of more environmentally friendly fuels. Furthermore the sensitivity analysis reveals how the speed at which ships sail affects the competitiveness of fuel options indicating that the cost gap, between HFO and alternative fuels narrows as speeds increase.

7. Conclusion

This study addressed the pertinent topic of GHG emissions and their contribution to global warming, focusing on the shipping industry. The literature review enabled the consolidation of insightful information about GHG emissions, and the measures being implemented to minimize them. This review brought to light a gap in the literature: the absence of a tool to guide stakeholders involved in green shipping corridor initiatives in determining and minimizing the costs of transitioning from fossil fuels to alternative fuels, in order to obtain the costs for different alternatives and choose the most economical one. This motivated the definition of the research objective: the proposal of a framework to find out and minimize the costs of transitioning from fossil fuel to different alternative fuels. This approach stands out from others because it centers on examining the implications of shifting to fuels for a specific journey as opposed to broader perspectives or varied goals concerning environmentally friendly shipping routes. To fulfill this objective, a comprehensive framework was presented, and its effectiveness was validated through a case study.

During the application of the framework to the case study, all the

Table 22
Sensitivity analysis results for sailing speed.

Speed (knots)	Total Cost HFO ($)	Total Cost LNG ($)	Total Cost Hydrogen ($)	Total Cost Methanol ($)	Total Cost Ammonia ($)
14	1,012,897	31,859,604	28,304,721	43,569,202.01	71,188,621.78
16	1,188,818	32,116,435	28,876,582	44,530,619.63	71,915,613.60
18	1,387,257	32,395,783	29,470,961	46,004,617.33	73,758,654.50
20	1,608,214	32,697,648	30,087,858	47,128,940.46	73,758,654.50
22	1,851,690	33,022,030	30,727,273	48,271,738.80	75,431,300.10
24	2,117,684	33,368,929	31,389,206	49,416,488.57	76,399,882.48
26	2,406,196	33,737,345	32,073,657	50,461,016.59	76,399,882.48

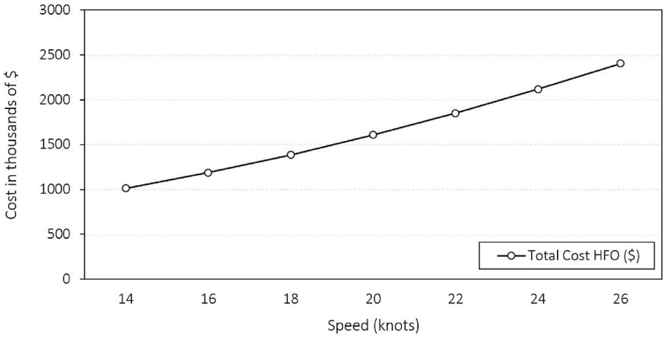

Fig. 12. Variation of speed sailing for HFO

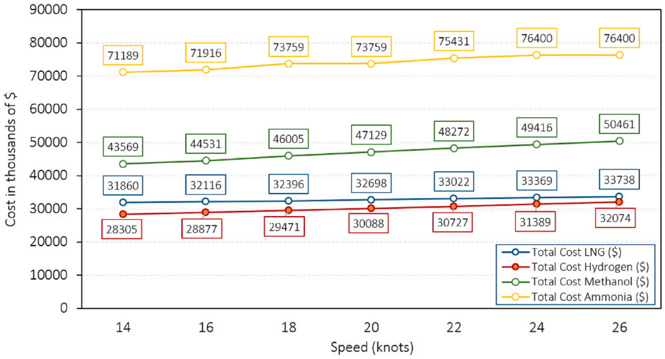

Fig. 13. Variation of speed sailing for LNG, Hydrogen, Methanol and Ammonia

steps that a stakeholder takes to determine which fuel is the most cost-effective were traversed, making it easier for interested parties to replicate the framework's application.

The assessment of the total cost of the different alternative fuels under study led to the conclusion that the most cost-advantageous alternative fuel is hydrogen for a deployment cost per bunkering vessel per voyage equal to or lower than 1,990,284,78 $ for a sailing speed of 22 knots and 2,190,171,09 $ for a sailing speed of 18 knots. For a deployment cost above this value, LNG becomes the most cost-advantageous option.

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

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

Limitations and future work

Since bunkering vessels for ammonia and hydrogen are still under development, the prices of these bunkering facilities have not yet been published, making the results of applying the framework in the case study more subjective. Furthermore, the considered costs corresponded to the costs applied within the time of the study. It was not possible to provide an exact answer regarding which alternative fuel was more advantageous in terms of costs because the deployment cost of a bunkering vessel for ammonia and hydrogen is still uncertain. Since ammonia and hydrogen are included in the majority of the long-term fuel mix projections and bunkering vessels for these fuels are already being developed, their deployment cost is expected to be known in the future. When this happens, it will be possible to apply this framework to obtain an exact answer that guides the stakeholders involved in the fuel transition in a more precise direction.

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

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

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

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

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CRediT authorship contribution statement

Beatriz Jesus: Formal analysis, Software, Writing – original draft. **Inês Abreu Ferreira:** Data curation, Formal analysis, Validation, Visualization, Writing – review & editing. **Augusto Carreira:** Data curation, Formal analysis, Methodology. **Stein Ove Erikstad:** Conceptualization, Methodology, Supervision, Validation. **Radu Godina:** Investigation, Resources, Supervision, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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