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Evaluating the Readiness of Ships and Ports to Bunker and Use Alternative Fuels: A Brazil's Case Study

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Abstract: The International Maritime Organization (IMO) has recently revised its strategy for shipping decarbonization, deepening the ambition to reduce annual greenhouse gas emissions until 2050. The accomplishment of this strategy requires the large-scale deployment of alternative maritime fuels, whose diversity and technical characteristics impose transition challenges. While several studies address the production of these fuels, a notable gap lies in the analysis of the required adaptations in vessels and ports for their usage. This study aims to fill this gap through a comprehensive review of material compatibility, storage in ports/vessels, and bunkering technology. Firstly, we analyze key aspects of port/vessel adaptation: physical and chemical properties; energy conversion for propulsion; fuel feeding and storage; bunkering procedures. Then, we perform a maturity assessment, placing each studied fuel on the technological readiness scale, revealing the most promising options regarding infrastructure adaptability. Finally, we develop a case study for Brazil, whose economy is grounded on maritime exports. Findings indicate that multi-product ports may have potential to serve as multi-fuel hubs, while the remaining ports are inclined to specific fuels. In terms of vessel categories, we find that oil tankers, chemical ships and gas carriers are the most ready for conversion in the short-term.

Keywords: alternative fuels; port; ship; bunker; biofuels; LNG; ammonia; methanol

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1. Introduction

The Maritime Transport is a key sector to the global economy, accounting for approximately 90% of the global trade in mass basis [1,2]. Shipping is a fundamental mode of trade for consuming less fuel per mass transported and distance covered compared to alternatives modes. According to the Fourth IMO (International Maritime Organization) GHG (Greenhouse Gases) Study [3], shipping world fleet has consumed 13.6 exajoules (EJ) in 2018 and has emitted 1.056 billion tonnes of carbon dioxide equivalent (CO2eq), being responsible for nearly 3% of global greenhouse gas emissions. International shipping was responsible for 87% of total emissions. Smith et al. [4] suggest that in the absence of measures to reduce greenhouse gas emissions, these emissions could increase by 250% by the year of 2050. Among the available strategies to mitigate such emissions is to set speed, power, and fuel consumption limits [5]. Conversely, the vast diversity of ship types, with its associated challenges in construction and operation, has being a great barrier to standardization [6], in addition of the long lifetime of long-distance ships. Several studies have evidenced that the implementation of measures and technologies targeting reduction of greenhouse gases (GHG) holds the potential of curtailing emissions by up to 75% of current levels [7–9].

Regarding the imperative to mitigate pollutant gas emissions, IMO has established in 2023 a goal of achieving net zero GHG emissions[1] by 2050, accounting for the life cycle emissions of fuels, while a medium term goal entails achieving a minimum 20% reduction in GHG emissions from

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[1] Net zero emissions are achieved when human caused GHG emissions are balanced globally by human induced removals of CO2 on a global scale during a defined period [131].

International Shipping by 2030, as compared to emissions levels recorded in 2008 [10]. This new strategy exhibits a greater degree of firmness when contrasted with IMO's initial and also ambitious approach, which primarily focused on the reduction of shipping direct GHG emissions by a minimum of 50% in relation to 2008 levels [11]. Smith et al. [4] estimation indicates that the shipping sector emitted 921 million tonnes of carbon dioxide (CO2) by 2008. According to DNV GL [12], to achieve previous IMO 2050 goals, it was imperative that 40% of the energy supplied to shipping fleet is derived from fuels characterized by net zero emissions in ships. Faber et al [3] predict that without intervention, emissions could escalate to over 1300 million tonnes of CO2 by 2030 and surpass 2300 million tonnes by 2050. Consequently, in a comparison to a scenario with no actions to lessen the emissions, a decrease of more than 560 million tonnes of CO2 emitted would be necessary by 2030.

Therefore, to mitigate GHG emissions, which are mostly caused by carbon dioxide, methane and nitrous oxide [13], several measures can be employed, but the utilization of fuels with lower emissions levels or net zero emissions throughout their life cycle will be required [14]. The 2023 IMO guidelines removal of regulatory barriers concerning the blend of marine fuels with up to 30% of alternative fuels, specifically biofuels or synthetic fuels, encompasses a fundamental factor in promoting the entrance of these alternative fuels into the shipping market. The blends with alternative fuels are to be treated on par with regular fuels, implying that they can be utilized as long as they comply with NOx emission limits [15,16].

The investigation of alternative fuels for maritime transport has earned significant interest from both academic and professional community. Recently, there has been a substantial number of studies delving into the subject of biofuels [17–21], hydrogen and ammonia [22–26], liquefied natural gas [27–29], and methanol [30–33] for shipping. While a significant share of these studies focuses on the technical aspects of production, emissions mitigation, and their use in marine engines, few have given due attention to the necessary adaptations required in ships and ports to the operation of these alternative fuels. Actually, the implementation of alternative fuels in the maritime sector drives various adjustments within ships. These modifications encompass alterations in fuel tanks and engine locations, utilization of distinct material for storage tanks and pipelines, reinforcement of pipe structures, enhancement of ventilation systems to mitigate potential gas leakage [34] and changes in port infrastructure.

Therefore, the primary aim of this study is to assess the current progress of converting ships and ports to effectively use selected alternative fuels. By doing so, this analysis seeks to determine the technological readiness for the conversion of ports and ships to the storage, bunkering and use of the chosen fuels. Then, to validate and illustrate the assessment conducted in this study, a case study was carried out to assess the capacity of the Brazilian fleet and port infrastructure to adopt alternative fuels. The Brazilian case is emblematic since the country's economy heavily relies on marine routes [35] for exporting goods and sustaining its economics activities [36]. Additionally, Brazil has an impressive potential for alternative fuels production, particularly biofuels, given its abundant availability of biomass resources and established expertise in biofuels production [37]. For instance, according to Carvalho et al. [38], the comparative analysis encompassing Brazil, Europe, South Africa, and the USA illustrates that "biomass concentration in Brazil makes it the region with highest biobunker potential, which are mostly close to coastal areas and surpasses regional demand".

The next section outlines the methods and materials employed for the evaluation. In Section 3, the results of the analysis are presented, focusing on determining and comparing the readiness of each alternative fuel. Section 4 delves into a comprehensive discussion of the previous findings by applying them to a specific case study. Lastly, Section 5 provides the conclusions, along with recommendations and barriers identified in this study.

2. Materials and Methods

The primary objective of this study is to analyse the necessary adaptations in ships and ports for the proper storage, transfer, and utilization of alternative marine fuels. As such, it does not encompass fuels that can be classified as fully drop-in [39], such as Fischer-Tropsch liquids [40,41] from biomass or electric-derived hydrogen and CO_2. The deployment of these drop-in fuels can rely on existing ships and bunkering infrastructure, thereby enabling a direct replacement or blend with conventional fuels [42]. In contrast, most candidate alternative marine fuels require some level of adaptation in ships and ports. Some of them can be seen as partially drop-in, meaning that they only require minor adjustments and specific attention compared to conventional fuels to be used in the existing infrastructure. On the other hand, a second group (non-drop-in fuels) require substantial changes and investments in vessel technology and bunkering infrastructure. This study focuses on the assessment of specific fuels encompassed by these two categories, as shown in Table 1.

Table 1. Fuel grouping.

Partially drop-in[1]	Non-drop-in[1]
Biodiesel	Ammonia
Hydrotreated Pyrolysis Oil (HPO)	Liquefied Natural Gas (LNG)
Hydrotreated Vegetable Oil (HVO)	Methanol
Straight Vegetable Oil (SVO)	

[1] [18,43,44].

A comprehensive and thorough review of the technical literature was conducted, with a specific emphasis on the essential properties to be taken into consideration for achieving a successful adaptation in retrofitting both ships and ports to enable proper storage, transfer, and utilization of alternative fuels. Figure 1 provides a summary of the undertaken steps. This analytical study firstly undertook the examination of various aspects pertaining to selected alternative fuels. As a second step, considering the existing ships and bunkering infrastructure globally, along with regulatory frameworks and tests designed to assess fuels performance on ships, the analysed fuels were categorized into those that are partially or non-drop-in. This categorization was succeeded by an assessment of technology readiness based on the guidelines provided by the US Department of Energy [45].

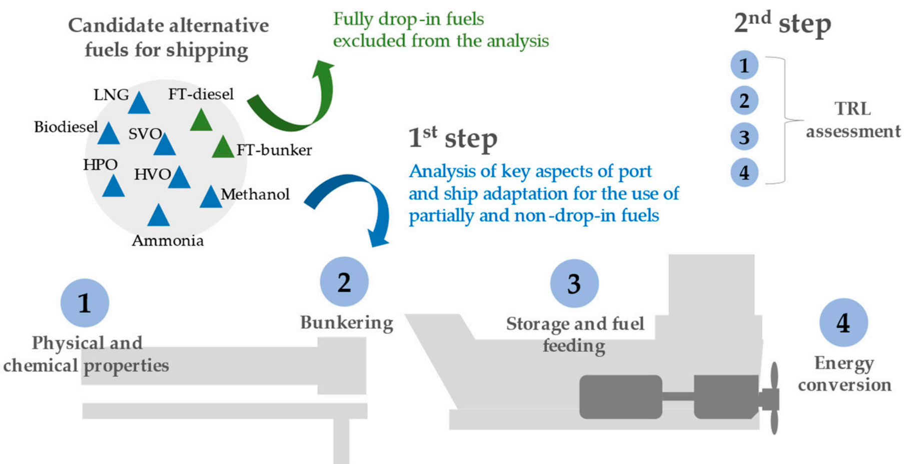

Figure 1. Methodological procedure.

As Figure 1 displays, the analysis of the first step encompasses the key aspects of port and ship conversion for the proper utilization of the selected alternative fuels. The first step was split into four main aspects, namely, physical and chemical characteristics properties, bunkering procedures, storage and fuel feeding systems, and energy conversion systems. Table 2 displays the main aspects analysed for each of the segments aforementioned.

Table 2. Main aspects analysed for each section concerning ships and ports adaptation to the use of partially and non-drop-in fuels.

Segment	Analysed aspects
Physical and chemical properties	Heating value
	Volumetric density
	Energy density
	Kinematic viscosity
	Acidity
	Flash point
	CCAI
	Other properties
Bunkering	Pressurization
	Liquefaction
	Tank shape
	Inertisation
	Ventilation
	Maintenance
Storage and fuel feeding	Pressurization
	Liquefaction
	Tank location
	Tank volume
	Inertisation
	Ventilation reinforcement
	Maintenance
	Need for double-wall
	Materials
	Drainage
	Preheating
	Filtering
Energy conversion	Converter type
	Need for pilot fuel
	Engine adjustments

As Table 2 illustrates, the initial analysis includes the review of the main properties of fuels, in comparison to conventional fossil bunker fuels. Heating value and volumetric density are both linked to energetic density, which represents the amount of energy per cubic meter. In shipping, greater energetic density is preferable as it allows for increased autonomy due to the higher energy demand of fuels. [46], as well as smaller losses of freight space [47]. High levels of kinematic viscosity directly impacts the spray and flow characteristics of fuel [48]. The acidity is associated to content of free fatty acids in the fuel. A high content of free fatty acids can result in engine deterioration, as well as degradation of engine feed [49]. Flash point refers to the minimum temperature at which gases ignite when exposed to a flame [50]. Hence, low flash point fuels are undesirable for shipping. Ellis and Tanneberger [30] underscored that low flash point trigger additional safety measures in order to prevent the fuel from being exposed to ignition sources. The Aromaticity Index, measured by the Calculated Carbon Aromaticity Index (CCAI), is adopted to assess fuel quality based on ignition delay. CCAI is calculated through evaluation of density and viscosity. For marine engines, it is

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recommended a CCAI below 870 [51]. Viscosity and CCAI values of LNG and ammonia are not evaluated in literature since they are equivalent or lower than those of traditional fuels. As a result, these factors were not considered, along with acidity levels of LNG, methanol, ammonia and HVO. Other properties, such as oxygen and water content, play a pivotal role in determining the requisite adjustments for utilizing theses fuels in current infrastructure.

Having addressed the fuels main properties, the study evaluated the necessary adjustments to the bunkering infrastructure to accommodate the usage of each selected fuels. As indicated in Table 2, certain aspects were examined, including the requirements for pressurization, liquefaction, different tank shapes, inertisation, ventilation reinforcement and increase in maintenance. This evaluation encompassed not only the bunkering process but also storage at ports.

Then, the study revised the challenges related to storage and fuel feeding in ships. The analysis carried out addressed significant modifications resulting from distinct properties of the chosen fuels, as opposed to conventional fossil bunker fuels. Aspects such as demands of pressurization and liquefaction during storage, different shapes, locations and volumes of tanks, double- wall and filtering were highlighted.

Finally, the energy conversion analysis addressed the available choices of energy converters for each fuel, with a specific emphasis on a potential pilot fuel demand and adjustments in engine to the proper use of the fuels. The analysed options of energy converters are diesel engine, dual-fuel engine and fuel cell. According to the Fourth GHG IMO Study [3], the conventional fossil bunker fuels, namely heavy fuel oil (HFO) and marine diesel oil (MDO), are the two primary fuels commonly used in marine industry, representing 66.0% and 30.5% of the world's consumption, respectively. Additionally, LNG accounted for roughly 3.4% of world consumption, whereas methanol represented a mere 0.05% of the overall shipping consumption. As a result, the predominant energy converter to propulsion in the vessel fleet is the two-stroke diesel engine. In 2018, slow, medium and high diesel engines accounted for over 98% of the global marine fleet, while dual-fuel LNG engines were installed in less than 0.5% of ships, and engines adopted to methanol were reported in less than 0.15% of the fleet [3]. Diesel engines designed for marine applications are available in two configurations: two and four-stroke variants. Larger ships typically opt for two-stroke engines due to their competence to achieve lower propulsion speeds effectively. In contrast, medium and high-speed engines predominantly employ four-stroke cycles to optimize operation of these vessels [52].

In relation to the conversion of diesel engines to dual-fuel engines, Tiwari [53] reported that the dual-fuel engine is essentially a diesel engine equipped with supplementary devices that enable the utilization of fuels such as LNG. Bhavani and Murugesan [54] further pointed out that the conversion from diesel to dual-fuel mode solely necessitates external modifications to the engine, while the internal components remain unchanged. Furthermore, the authors emphasized that the conversion process involves the addition of a set of retrofit components, including fuel supply systems, pilot and supplemental fuel inlet controllers, air and gas mixers, engine cooling systems, flameproof kits and gas detectors. Another viable energy converter option is the use of fuel cells, which is currently in the developmental phase for marine applications. Nevertheless, fuel cells present superior efficiency and emit fewer pollutants during the tank-to-wake, namely the use in ships, when compared to internal ignition and gas engines. In addition, a steam reformer can be incorporated into vessels to enable the use of hydrocarbons as an energy vector. Although this process does generate carbon dioxide emissions, they are significantly lower than those produced by conventional engines utilizing fossil fuels, and the emissions of other pollutants remain nearly negligible [55].

Having addressed all segments of the first step, the evaluation of TRL for each fuel was done. Figure 2 summarizes the assessment approach.

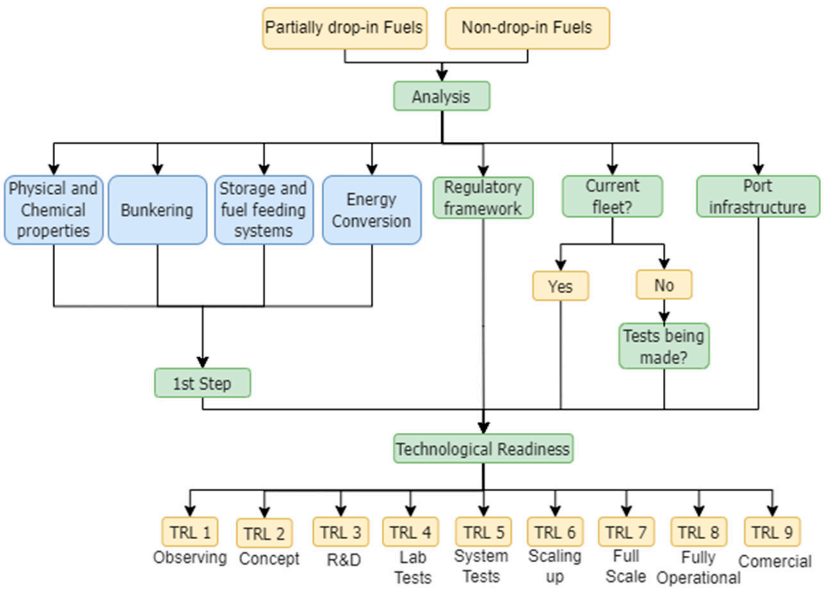

Figure 2. TRL evaluation of each fuel.

As Figure 2 illustrates, the determination of TRL for each fuel resulted from the analysis done, also considering the current regulatory and port infrastructure. A detailed exploratory review was done to assert the established standards, guidelines and whitepapers conducting the procedural aspects associated with the utilization of each designated fuel, thus enabling the assessment of the regulatory framework. Current infrastructure evaluation was also done by compiling data pertaining to vessels that already adopted the utilization of alternative bunker fuels. In the absence of ships using the fuel, a review encompassing not only vessels but also other modes of transportation was conducted. Furthermore, the evaluation of port infrastructure was conducted to identify existent port facilities offering bunkering services for each fuel. The required adjustment of each fuel to be used in maritime infrastructure facilities leads to the estimation of TRL. This ranges from observation of technology (TRL 1), passing through conceptualization (TRL 2), Research and Development or R&D (TRL 3), Laboratory Tests (TRL 4), Systems Tests in real conditions (TRL 5), Scaling Up in real conditions tests (TRL 6), Full Scale in real conditions tests (TRL 7), Fully Operational functioning (TRL 8) to reach commercial status (TRL 9) [45].

Finally, after conducting the comprehensive assessment of the obstacles and complexities involved in adapting the existing maritime infrastructure to accommodate alternative fuels, this research applied it to a case study as a representative example. The case study was based on Brazil, since its high economic dependency on maritime routes, from cabotage to national trade to long-haul distances for exportation [35,36], as well as its notably potential as a major future biobunker producer [38]. It followed a structured approach, involving the examination the current state of Brazilian shipping sector, including high priority ports given their cargo movement and initiatives to bunkering of alternative fuels, an analysis of potential multi fuel hubs, the progress and challenges made in converting ships for alternative fuels, the initiatives assumed by local governments and companies linked to the maritime sector to achieve decarbonization of Brazil's maritime transport, thermal stability of fuels in maritime routes, and the problem of loss of cargo space. The primary objective was to develop a coherent framework that would evaluate the potential of introducing alternative fuels in the country. This framework can serve as a first roadmap for assessing the feasibility of applying alternative fuels solutions in Brazil and potentially induce these findings to other countries and regions with similar characteristics.

3. Results

3.1. Physical and Chemical Properties

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Table 3 displays the main properties of the selected alternative fuels.

Table 3. Properties of marine fuels.

Fuel Property	**Heating Value**	**Volumetric density**	**Energy density**	**Viscosity at 40° C**	**Acidity**	**Flash Point**	**Aromaticity Index (CCAI)**
Unit	MJ/kg	kg/m³	MJ/m³	mm/s²	Mg KOH/g	°C	-
HFO	40.0[a]	991[a]	39,640	380[i]	2.5[i]	>60[i]	856.5[p]
MGO	42.0[a]	890[a]	37,380	3.5[i]	0.5[i]	>60[i]	808.1[p]
LNG	50.0[b]	415[b]	20,750	-	-	-188[b]	-
Biodiesel	37.1[c]	885[c]	32,833.5	4-6[j]	0.052-0.295[m]	>93[c]	822.6[p]
SVO	37-39.62[a]	900-930[a]	33,300-36,847	14-40[k]	0.02-20[n]	>400[K]	836.6-878.7[p]
HVO	44.1[d]	780[d]	34,398	3[d]	-	99[d]	738.4[p]
HPO	28.9[e]	1150[h]	33,235	9[h]	21.3-76.1[h]	53-101[h]	1076[p]
Ammonia	18.6[g]	758[g]	14,101	-	-	132[o]	-
Methanol	20.1[f]	798[f]	16,040	0.58[l]	-	12[f]	837.6[p]

* a - [50]; b – [56]; c – [17]; d – [57]; e - [58]; f - [59]; g - [60]; h - [61]; i - [62]; j - [63]; k - [64]; l - [30]; m - [65]; n - [66]; o - [43]; p - [67].

In a comparison between fossil fuels, LNG stands as the option for mitigation of sulphur oxides, nitrogenous oxides, and particulate matters emissions [68]. It is predominantly composed of methane, accompanied by minor proportions of other hydrocarbons such as ethane, propane, and butane [69]. Under atmospheric temperature and pressure, LNG is on gaseous phase and has low density. In order to optimize storage, natural gas is liquefied at a temperature of -162° C and atmospheric pressure, thereby reducing the required volume for storage [56].

The properties of biofuels may present variation depending on feedstock employed in production. Biodiesel, SVO, HVO and HPO have energy density levels close to HFO and MGO compared to the other assessed fuels, suggesting that those fuels have greater potential to provide increased autonomy or reduced storage space requirements. SVO is a biofuel that entails a straightforward production process in comparison to other fuels. The production steps involve biomass collection, low-temperature seed pressing, and filtration to remove sludge. The quality of the fuel is heavily influenced by the quality of the feedstock and the conditions during production and processing [70]. When contrasted with traditional marine fuels, SVO has a slightly lower energy density, higher flash point, viscosity, and acidity. These characteristics can potentially result in corrosion of engine feed pipelines [50]. Biodiesel (or FAME), widely regarded as one of the most promising biofuels, is repeatedly stated as a potential blend component for diesel in the road transport sector [71].

HVO is a fuel consisted of straight chains of paraffinic hydrocarbons, which undergo additional production steps in comparison to SVO. These steps include catalytic saturation (hydrogenation), hydrodeoxygenation, hydrodecarboxylation, and isomerization. HVO is distinguished by its exceedingly low sulphur content and minimal emission factors [57]. As a paraffinic compound, HVO exhibits a high cetane number, typically ranging from 75 to 95 [72].

Hydrotreated pyrolysis oil, also known bio-oil or even HPO [73], is derived from biomass, which undergoes a high-temperature process in the absence of oxygen. The biomass is subjected to a temperature of 500 °C for a brief duration [20]. Hydrogenation is the final step, transforming the pyrolysis oil into hydrotreated pyrolysis oil. Depending on the pyrolysis process, the water content in the bio-oil can reach up to 30%, which is sufficient to induce phase separation when stored at ambient temperature for six months [19]. Treatment of bio-oil can result in a compound with significant reduction of oxygen content and increase in light aromatic compounds.

In relation to viscosity, SVO and HPO entail elevated levels, imposing appropriated measures to viscosity decrease such as preheating. Moreover, these fuels are also notable for its high acidity levels. Biodiesel has a viscosity greater than traditional diesel yet not as high as SVO and HPO, therefore preheating is advisable [21]. HPO has a high and unstable viscosity, posing a challenge for both its use as a fuel and storage [74]. Notably, the low flash point of biodiesel limits its practical utilization in low air temperature conditions [75]. HVO has a flash point higher than traditional fuels [72].

The acidity level of SVO, as is the case for biodiesel, is associated with its specific feedstock, such is the case for biodiesel. While certain vegetable oils may present higher acidity levels compared to HFO, others exhibit relatively low acid values, exemplified by rapeseed oil, which has an acidity level below 2.5 mg KOH/g [70]. Despite undergoing a reduction of approximately 70% in acidity trough treatment, HPO resultant acidity level remains notably higher when compared to traditional marine fuels [61].

The majority of discussed fuels exhibit aromaticity index below the recommended limit. However, depending on the feedstock employed, the aromaticity index of SVO may exceed the suggested limit, as is the case for HPO. Ellis and Tanneberger [30] draw attention to the possibility of utilizing a lubricant oil to address the issue of low lubricity. In comparison to traditional fuels, biodiesel has superior lubricity and lower toxicity levels. However, it possesses a high oxygen content, typically ranging between 10 to 11%, and a low pour point [50,75,76]. To mitigate the risk of corrosion, the usage of a corrosion inhibitor know as tert-butylamine is advisable, with a recommended concentration of 250 ppm [76].

Methanol [77] and ammonia [78] are widely employed as feedstocks in the chemical industry. Given their high toxicity, it is essential to implement safety measures to prevent leaks and human exposure to these substances. Ammonia has been proposed as a potential sustainable energy carrier of hydrogen due to its composition of three hydrogen atoms per ammonia molecule (NH_3) [79]. In addition, the storage of liquid hydrogen requires extremely low temperatures, specifically -253°C [80]. Hydrogen is recognized as a promising marine fuel, with ongoing tests aimed at advancing its utilization in the shipping industry. However, as reported by ABS [81], hydrogen, currently offers a very limited power output, associated with substantial costs and limited production. Additionality, hydrogen storage in vessels address significant problems that marine community have yet to overcome. Kim et al. [60] also highlighted that ammonia possesses 1.7 times higher energy content compared to hydrogen, along with a 50% greater hydrogen content by volume [25], leading to a reduced volume requirement of fuel storage. Methanol, liquid under atmospheric conditions [82], requires pressurization. Alongside LNG, ammonia also necessitates lower temperatures and pressurization to maintain its liquid state during storage. Ammonia can be stored at 25°C when pressurized at 10 bar, whereas under atmospheric pressure, the required storage temperature is -33.4°C [60]. Methanol and LNG are low flashpoint fuels, turning them highly flammable. Methanol is flammable and exhibits lower lubricity compared to conventional marine fuels [30]. Regardless of its high flash point, ammonia has lower flame velocity compared to conventional fuels [78]. Moreover, ammonia is characterized by its high toxicity [78]. According to Hansson et al. [26], the presence of high concentrations of ammonia poses health risks and can prove lethal within certain concentrations and exposure durations.

3.2. Bunkering

The bunkering of conventional fuels can be carried out using tank trucks (Truck to Ship Transfer or TTS), bunker vessels (Ship to Ship or STS), as well as shore tanks or pipelines (Shore Tank to Ship or TPS) [83]. Regarding alternative fuels, the three aforementioned methods can be applied for bunkering, with specific protocols designed to each fuel type based on its distinct characteristics.

For LNG bunkering, a security protocol must be followed to avoid leakages of the fuel under cryogenic conditions. If materials such as steel come into contact with LNG, they tend to become fragile and may experience cracking. The procedures to leak prevention are as follows: checking the connection of the supply pipeline, inertization of the pipeline with nitrogen gas, cleaning the interior of the pipeline with vapor from liquefied natural gas at cryogenic temperatures, bunkering, cleaning the remaining LNG inside the pipeline with vapor from natural gas at cryogenic temperatures, inertization of the pipeline with nitrogen and disconnection of the supply pipeline [84].

To ensure the appropriate bunkering of biofuels, it is imperative to modify storage tanks in accordance with the specific fuel properties [85]. Ideally, the tanks should possess a narrow shape, aiming to reduce the retention of oil and fats during the cleaning process. Furthermore, the tank bottoms should be tapered to facilitate effective drainage [86]. The fuelling processes for SVO [50] and HVO [87] are comparable to those already established for HFO and marine diesel, respectively. However, as Kesieme et al. [50] stated, certain adjustments are necessary to safeguard against corrosion and water contamination. Additionally, the authors recommend that maintenance procedures should be reinforced to ensure prolonged use. Regarding HPO, the complete supply chain must be developed, including the development of suitable bunkering infrastructure to accommodate the unique fuelling requirements of bio-oil [88].

All fuelling methods applicable to LNG can be employed for methanol as well. However, additional requirements must be met, specifically, the filling station must be equipped with appropriate ventilation, either through natural means or by employing machinery. Additionally, the piping system must be self-draining and composed of inert materials [89]. In order to ensure the appropriate bunkering of ammonia and prevent the release of the substance, it is imperative, as emphasized by Duong et al. [90], to develop a comprehensive strategy aimed at minimizing ammonia leakage during the bunkering process.

3.3. Storage and Fuel Feeding

Due to the low temperatures observed during storage, specific tanks become necessary when utilizing LNG in ships. Several options for storage tanks are available: IMO Type A, which resembles the ones commonly used for standard marine fuel [91], Type C, designed as pressure vessels, and membrane tanks. Additionally, there exists a category called Type B, encompassing all tanks that are neither Type A, Type C, nor membrane tanks. Between the mentioned tank types, Type A and Type B are the most suitable for larger vessels due to their generally prismatic shape [92]. However, an obstacle to the effective utilization of LNG as fuel is the occurrence of methane slip [68], which involves gas leakage during both storage and engine operation. This issue can be mitigated if the leaked gas is reclaimed and reused by other ship machinery, such as in gas combustion units [91].

The utilization of biofuels, such as biodiesel, imposes the adoption of appropriate materials for tanks and pipelines. It is recommended that stainless steel, as a material, be employed for this purpose. However, when the blends comprise no more than 20% biodiesel in the overall volume, conventional materials can be used if adequately coated with zinc. The construction of feed pipelines using mild steel is permissible, provided that filters are installed to ensure the smooth operation of the system [93]. Moreover, to maintain the integrity of the biofuel infrastructure and prevent any potential water contamination, regular and careful inspections, maintenance activities, and constant cleaning of tanks and piping are essential [86].

The coexistence of water within the fuel blend poses a significant risk of degrading fuel filter cartridges, potentially leading to cavitation [50]. To mitigate such hazards, the use of stainless steel is recommended as the material of choice for constructing pipelines and tanks to ensure optimal safety. Alternatively, mild steel can be considered for tank and pipeline construction if suitably coated with an inert material. However, it is imperative to conduct regular inspections of the tanks to assess the condition of the coatings and ensure their integrity is preserved. Furthermore, it is of utmost importance that all materials utilized in tanks and auxiliary machinery, including heating units, must be inert to vegetable oils [86].

HVO exhibits a great level of resemblance to conventional diesel-based fuels, rendering it compatible with the materials already employed in marine infrastructure for pipelines, tanks, feed systems, and engines. Nevertheless, it is recommended to take on maintenance and cleaning procedures for storage tanks before fuelling to ensure optimal performance. Additionally, strict supervision is advised to prevent any contact between HVO and water within the tanks and feed system, as this could lead to detrimental effects. Remarkably, HVO sets itself apart from other biofuels by displaying a unique resistance to corrode the materials commonly utilized in the naval industry's infrastructure. This exceptional property contributes to enhanced durability and safety in marine operations involving HVO usage [87].

The high viscosity characteristic of HPO leads to an increase in engine deposits, which subsequently forces more energy for pumping and results in accelerated wear on fuel pump components and injectors. To mitigate these effects, preheating the fuel is essential as it effectively reduces the viscosity level. For the engine feed system, it is imperative to construct it using corrosion-resistant materials to withstand the high acidity of the oil. Copper can be considered as a viable material option for tank storage and pipelines; however, it is recommended to utilize stainless steel for tanks and pipes. The high acidity of HPO poses limitations on the use of carbon steel in pumps, fuel lines, or burners. These components must be made of materials that can resist the corrosive nature of the fuel. Furthermore, due to the presence of solid particles with high energy density, filtering them is not considered desirable. Nevertheless, careful design of the fuel supply piping is essential to prevent any blockages resulting from the solid particles material. Moreover, both pumping and atomizing processes should be equipped with suitable filtration mechanisms to ensure smooth and efficient operation [88].

When utilizing fuels with high acidity and/or flammability in ships, it is imperative that fuel storage tanks in ships adhere to a double-walled construction for enhanced safety measures. These tanks can be positioned either at the main deck, offering a more economical and less complex installation, or at lower decks, as long as they are sufficiently distanced and detached from accommodation and machinery spaces. To minimize the risk of gas leakages, stringent preventive measures must be employed. These include the implementation of inert systems, reinforcement of ventilation, and the utilization of specialized materials such as aluminium or, preferably, stainless steel for storage, feed, and engine components [69]. Furthermore, it is crucial to ensure that the pressure within the feed system does not exceed 10 bar [94] to maintain operational safety. By sticking to these guidelines, the potential hazards associated with fuel storage and usage in ships can be effectively mitigated.

In 2020, IMO [89] issued a comprehensive set of guidelines regarding the utilization of methanol and ethanol in vessels, encompassing fuelling procedures and safety practices. Some of these practices were already disseminated by DNV GL. The recommended safety measures include the implementation of double-walled feed pipelines and storage tanks constructed from stainless steel or austenitic steel, the incorporation of inert gas purging devices to facilitate the controlled release of gas, the installation of service tanks with the capacity to power operational loads for a minimum of eight hours, and the use of high-pressure pumps with a minimum pressure of 10 bar to facilitate the fuel feed to engines [95]. It is preferable to position the service tank on the main deck, while the pilot fuel tank may be situated at the engine room [33]. Due to the highly toxic nature of methanol, all areas containing pipelines or tanks are required to have adequate ventilation reinforcement. Specifically, normal spaces require a minimum of 15 air renovations per hour, while spaces more susceptible to fuel leakage necessitate 30 air renovations per hour [30].

Regarding the utilization of ammonia in vessels, the required tanks for storing ammonia should be pressurized, with a minimum pressure of 8.6 bar, while the recommended pressure level stands at 17 bar [96]. For optimal cost-effectiveness, the type C tank has demonstrated its superiority and versatility, as it can be conveniently installed on the main deck and seamlessly integrated into the majority of existing ships [97]. To ensure the safe handling of ammonia, the feed pipelines must be constructed using durable materials such as carbon and stainless steel [24]. These pipelines should be displayed in a double-walled configuration to mitigate the risks of leakage [95]. Additionally, it is mandatory to equip all spaces associated with the fuel storage system with a comprehensive ventilation system. This measure is indispensable in preventing any potential ammonia leakages [96], thereby enhancing overall safety and minimizing the associated hazards.

3.4. Energy Converters

The analysed fuels are applicable for one or more of the 3 energy converters considered by this study. With appropriate adjustments to adapt feed and combustion requirements, all fuels can be effectively applied in existing marine engines. Biodiesel [75], SVO [50], HVO [57] and HPO [74] demand relatively minor modifications to the existing marine diesel engines and feed infrastructure. On the other hand, methanol and LNG, due to their high ignition temperature and consequently low cetane number, face ignition complications. To tackle this issue, dual-fuel engines can be employed, in which a pilot fuel, such as marine diesel, is injected to start ignition [69].

Regarding SVO, to achieve the desirable viscosity levels, fuel preheating is imperative. The recommended heating temperature is within the range of 67 to 78°C, which is comparatively lower than temperatures required to preheat HFO [49]. Similarly, to a proper use of HPO in diesel engines, preheating within the temperature range of 40 to 80°C is required [88]. It is crucial to be cautious of potential impurities in vegetable oils, since their presence may lead to engine failure or damage while using it as marine fuel [50]. Combustion properties of HVO are alike to those of conventional fuels, such as marine diesel, even though with lower density. Therefore, it is advisable to make adjustment in order to enable longer fuel injections for engine optimization, thereby increasing efficiency and fuel savings [57].

According to Dincer and Siddiqui [98], the use of ammonia in diesel engines presents drawbacks, notably its limited flammability range and low kinetic rate. Ammonia's combustion properties demand modifications to conventional combustion engines, as well as blending with fuels exhibiting superior combustion properties [99]. Burning ammonia may have the potential of more NOx emissions than regular fuels [100], potentially also releasing N_2O, a much stronger greenhouse gas than CO_2 [101]. Another alternative for ammonia is the adoption of fuel cells [98]. Kim et al. [60] compare the use of polymer electrolyte membrane fuel cell (PEMFC), a low-cost alternative, and solid-oxide fuel cell (SOFC), for ammonia chemical energy conversion, indicating that the latter is a simpler and more optimized operation, for an ammonia fuelled 2500 TEU container ship. SOFC used 12% less fuel in volumetric basis.

3.5. Technology Readiness

The analysis of El-Gohary [102] demonstrated that the utilization of LNG as the primary fuel instead of conventional marine fuels has the potential to reach a notable reduction in annual expenses associated with fuel and maintenance, ranging from 30% to 40%. The implementation of LNG as the primary fuel for ships is rapidly becoming a reality. As of July 2023, a substantial portion of the global fleet, specifically 403 ships, has already adopted the use of LNG as fuel, and 275 terminals worldwide have equipped bunkering facilities for these vessels [103]. Consequently, the infrastructure for LNG bunkering has been firmly established, and all requisite fuels procedures have been meticulously documented by classification societies, with a particular emphasis on Tanker ships [94]. This thorough development and documentation have led to the classification of LNG's practical use as commercially available, indicated by a TRL of 9.

Among all the analysed fuels in this study, only biodiesel was mentioned in standards until 2022, allowing its use in marine fuel blends. Specifically, ISO 8217:2017 enables the utilization of up to 7% v/v of biofuel in such blend [104]. Mohd et al. [105] demonstrated that the direct use of biofuel in ships could potentially compromise current power supply systems, decrease efficiency and consequently, increase specific consumption. However, Mohd et al. also pointed out that certain engine manufacturers, such as MAN, Wärtsilä, and Caterpillar, have conducted tests showing satisfactory performance without necessitating modifications if the blend contains up to 30% v/v of biofuel. Additionally, Ogunkunle and Ahmed [106] reported that blends containing 30% biofuel (B30) and diesel do not result in engine alterations, although there is an increase in specific consumption. Countless marine engine manufacturers have undertaken research and testing to enhance the implementation of biofuels in vessels. Despite this progress, biofuel bunkering process in ships still requires further development, even though minor adjustments may be necessary [17]. Consequently, as a marine fuel, biofuel is still in the full scale testing phase, awaiting validation under real operating conditions, characterized as TRL 7.

Kesieme et al. [50] asserted that, although SVO and HFO share some similarities, it is improbable that a blend of these two types of fuels would be compatible. Consequently, the most practical and viable solution would be a complete replacement from HFO to SVO. The usage of SVO in marine applications is still under research, both as a drop-in replacement and as a blend with traditional fuels. It has been observed that if the blend contains no more than 20% v/v of SVO with diesel, no changes in the fuel feeding systems of engines are necessary [107]. Furthermore, No [108] reported that a blend containing 20% v/v of SVO and diesel does not require any alterations to the marine engine systems. Additionally, it was found that pre-heating SVO at temperatures ranging from 55 to 85°C allows for an increase in the percentage of SVO in the blend to 30% to 60% v/v without requiring changes in engine structures. Blin et al. [66] proposed that for drop-in usage of SVO in ships, a dual injection system should be employed, where diesel would be injected at the start of the engine, and once it is warmed up, SVO would be injected. The implementation of SVO as a marine fuel demands the development of bunkering infrastructure [50], as well as further testing and refinement, leading to an assumed TRL regarding the use of the biofuel of 5.

HVO exhibits the potential to serve as a viable substitute for marine diesel, owing to its similar characteristics and compatibility with conventional ignition engines [109]. Currently, HVO is undergoing tests in the transport sector. Notably, numerous experiments have been conducted involving trucks and cars utilizing HVO either as a drop-in fuel or as a component in the fuel blend. These tests have been carried out in diverse countries, including Germany, Canada, United States, Finland and Sweden. One particularly significant test took place in the city of Alberta, Canara, demonstrating HVO's capability to function efficiently even in extremely cold temperatures reaching as low as -44°C. However, despite investigations in road transportation, there was no documented record of HVO being tested in ships until the year of 2022 [87]. Therefore, HVO emerges as the alternative marine fuel in this study, imposing the least modifications for its implementation in existing fleet and bunkering infrastructure. However, there exist certain barriers to the widespread adoption of HVO in the maritime sector, such as limited production capacity and high pricing, along with competition from the road and air sector [20]. To overcome these challenges and establish HVO as a viable marine fuel, further comprehensive studies and research are vital, assuring an assumed TRL of 5.

Concerning its utilization in marine engines, Chong and Bridgewater [73] stated that the blend of HPO with diesel and alcohol should not exceed 40% v/v. There is an emerging prospect that HPO may serve as a replacement for heavy oil in the future. However, its widespread adoption requires further research and comprehensive testing [88]. As a result of its early stage of development, HPO has been classified as having a low maturity level, specifically TRL 2.

In July 2023, methanol had already become the fuel for 25 ships worldwide, and 127 terminals were successfully supplying ships with this fuel [103]. As previously mentioned, the technologies and procedures for using methanol as a marine fuel and for bunkering applications have been established and regulated by the IMO and classification societies. According to the report from the ABS [31], methanol-burning engines utilizing high-pressure diesel combustion processes have been made available by manufacturers MAN and Wärtsilä. Moreover, methanol has been transported in chemical carriers for several decades and is also utilized by Offshore Support Vessels (OSV) and Platform Supply Vessels (PSV) for offshore industry [31], facilitating its widespread adoption as a marine fuel. Due to these favourable factors and the potential for rapid integration into the marine fleet, methanol was estimated to possess high potential for widespread use in the short term. As a result, the technological readiness level assigned to methanol as a marine fuel is TRL 8, indicating an advanced stage of technological development and readiness for practical implementation.

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Ammonia currently benefits from an established supply chain network primarily catered to its use in the chemical industry [60], with efficient transportation via ships worldwide. The MAN dual fuel engine, originally designed to operate with methanol and diesel, can also be adapted to use ammonia as an alternative fuel, provided certain modifications are made to the feed system's pressure [22]. As a result, the technologies, materials, and procedures necessary for its application are well-known within the industry. Nonetheless, further adaptation and development are required to utilize ammonia as a marine fuel [97]. The use of the fuel would face competition from the chemical sector and encounters challenges such as high toxicity and the technology's premature stage for integration into engines and fuel cells. Consequently, in order for ammonia to attain full commercial viability in the long term, it necessitates further technological advancement, and as a result, the assumed TRL for ammonia is 5.

3.6. Summary of results

In Table 4, the comparison between fuels is summarized by topics: energy density compared to HFO, bunkering readiness, material compatibility, storage tanks, engine feed, engine option, safety, and TRL.

Table 4. Summary of comparison between fuels.

Criteria	LNG	Biodiesel	SVO	HVO	HPO	Methanol	Ammonia
Energy density HFO/fuel	1.91	1.21	1.19-1.08	1.15	1.19	2.47	2.81
Bunkering readiness	Already worldwide stablished	Adaptation to biodiesel properties, narrow shaped tanks, constant cleaning	Procedures are similar from HFO bunkering	Procedures are similar from MDO bunkering	Urge of development all bunkering process	Under establishment, ventilation reinforcement	Ammonia bunkering is already done to chemical industry
Material Compatibility	Aluminium and stainless steel	Stainless steel or zinc reinforcement	Stainless or mild steel if coated with zinc silicate	No changes are needed	Stainless steel	Stainless or austenitic manganese steel	Stainless steel
Storage tanks	Double walled, cryogenic storage (-162°), 10 bar pressure, inert	Isolated from machinery	Isolated from machinery, coated with vegetable oil inert material	Constant Maintenance to avoid water contamination	Isolated from machinery, coated with biomass oil inert material	Double walled, detection system to leakages	Double walled, isolated from machinery, pressure of 8.6 bar
Engine Feed	Double walled, Ventilation reinforcement, 10 bar feed pressure	Filtering, constant maintenance	Pre-heating (67 to 78°C), filtering, constant maintenance	No changes are needed	Pre-heating, piping designed to do not block solid particles, filtering	Double walled, ventilation reinforcement, pressure of 10 bar	Double walled, ventilation reinforcement
Engine Option	Dual fuel	Diesel Engine	Diesel Engine	Diesel Engine	Diesel Engine	Dual fuel	Fuel Cell
Safety	Flammable	Low temperature use restricted due to low pour point, low toxic	Low toxicity	Low toxicity	Low toxicity	Highly toxic and flammable	Highly toxic and flammable
TRL	9	7	5	5	2	8	5

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4. Case Study

It is worth applying the previous results to a specific case, in order to see if the adaptations required by each fuel can undermine their use in a practical case. As mentioned before, given the relevance of maritime transportation to its international trade and its biofuel production potential, Brazil was selected as a case study. The Brazilian maritime sector has a fleet of approximately 2,700 vessels [35] and more than 380 ports or terminals [110]. According to ANTAQ (Agência Nacional de Transportes Aquaviários) [35], long-haul navigation accounts for the highest cargo and travel movement, indicating the significant flow of Brazilian trade goods with foreign countries. Cabotage has some heavily travelled routes, such as Santos to Pecém, which is mainly focused on container transportation. However, this type of freight represents roughly one-third of the cargo and travel compared to deep-sea navigation. Concerning the energy transition of maritime sector, the Brazilian Ministry of Mines and Energy (MME) initiated a program in 2012 aimed at the deliberation and advancement of sustainable technologies applicable to all modes of transportation, particularly marine transport [111].

4.1. Main Ports profile and future hubs

Brazilian port facilities exhibiting higher activity rates, as determined by 2021 cargo movement data, namely Ponta da Madeira, Santos, Tubarão, Angra dos Reis, São Sebastião, Paranaguá, Açu, Itaguaí, Itaqui, and Ilha da Guaíba [35], can be identified as primary hotspots for the transition of the Brazilian maritime transportation sector. Furthermore, ports and terminals with registered bunkering or movement of alternative fuels as cargo, meaning there is an infrastructure in place to handle the loading or unloading of selected fuels, should also be accounted for. Finally, there are also ports that exhibit planned implementation of infrastructure dedicated to bunkering of alternative fuels. **Error! Reference source not found.**Figure 3 summarizes Brazilian ports information, classified according to the previous mentioned criteria.

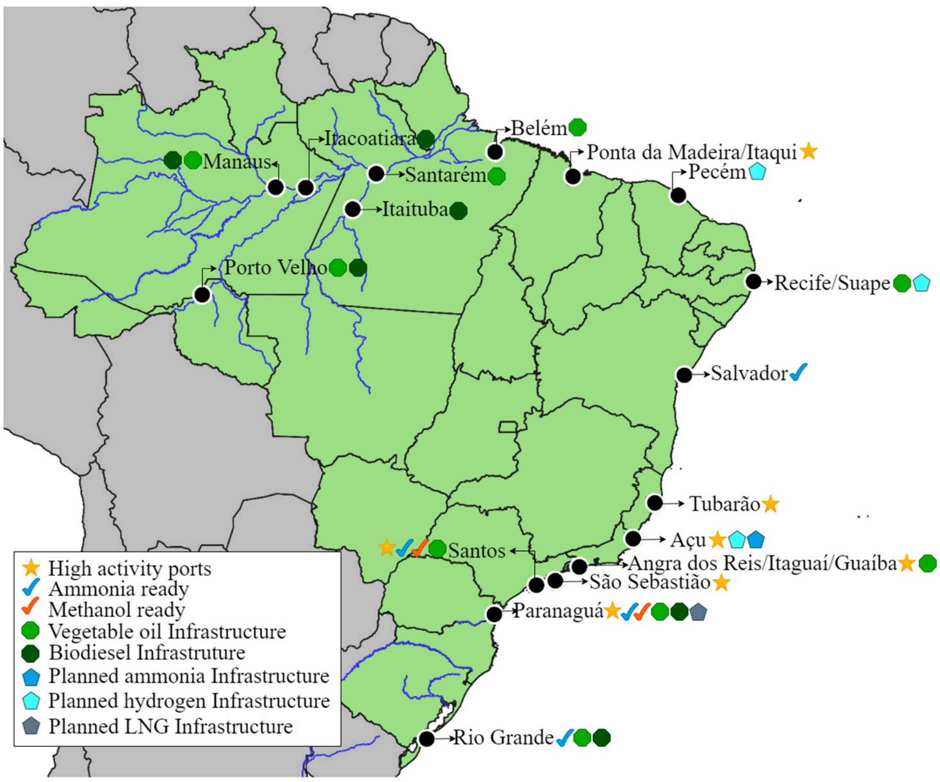

Figure 3. High activity and alternative fuels ready, available handling infrastructure, and planned ports and terminals.

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Regarding bunkering, in July 2023, an agreement was concluded with ports and companies within the Brazilian maritime sector, with the primary objective of promoting the utilization of alternative fuels in ships [112]. Given the limited number of Brazilian ports equipped with the necessary infrastructure for bunkering non-conventional fuels, such initiatives are of utmost importance in stimulating the transformation of Brazil's maritime infrastructure. As exposed in **Error! Reference source not found.**, notably, the ports located in Santos, Rio Grande, Paranaguá and Salvador possess the infrastructure for ammonia bunkering, whereas the facilities in Santos and Paranaguá are additionally equipped for methanol bunkering [103].

Error! Reference source not found. also shows ports and terminals that have infrastructure to handle SVO and biodiesel. Since 2013, biodiesel has been transported by ships departing from various ports in Brazil, namely Belém, Itacoatiara, Itaituba, Manaus, Paranaguá, Porto Velho and Rio Grande [35]. Additionally, ANTAQ [35] displays the transportation of vegetable oils (specifically, palm and soybean) using specific Brazilian ports, including Barcarena, Belém, Manaus, Paranaguá, Porto Velho, Santos, Recife, Rio de Janeiro, Rio Grande and Santarém. This indicates the existence of adequate infrastructure to handle vegetable oils and its derivatives bunkering at major ports throughout Brazil.

Furthermore, with regards to forthcoming adaptations, the Paranaguá port has undertaken plans to construct infrastructure to facilitate LNG bunkering, with the projected beginning of operations in 2025 [113]. Simultaneously, the port is also actively investigating the implementation of a biodigester plant dedicated to the production of biomethane, which can be liquefied and turned into a green alternative to LNG [114]. In a parallel, the Pecém port has created in 2021 a proposal for the establishment of a hydrogen hub in its facilities [115]. This strategic move holds the potential to equip the ports with a dedicated infrastructure for the transportation and handling of hydrogen. As outlined earlier, hydrogen handling demands liquefaction and pressurization to optimize storage, along with precise conditions for loading and unloading operations [116]. Consequently, the procedures governing the handling of hydrogen closely mirror those already employed for LNG and ammonia, rendering the port susceptible to the bunkering procedures of the aforementioned fuels.

The port of Açu also has plans to enable the bunkering of not only hydrogen but also ammonia. In partnership with the oil company Shell, the port authority is arranging the establishment of a facility dedicated to the production of the aforementioned fuels, along with the development of the necessary supply infrastructure [117]. Similarly, the port of Suape is also engaged in ongoing projects for the production of green hydrogen and ammonia [118].

The selected ports were also examined in terms of cargo movement, main products handled and destinations. Table 5 displays their main compiled data.

Table 5. Total cargo movement (in millions of metric-ton) in 2021, main products and destinations departing from each analysed port.

Port	Cargo Movement (10^6 metric-ton)	Main Products	Main Destinations
Açu	39.0	Oil and derivatives, containers, cooper, Iron and Steel	Suape, Madre de Deus, Santos, Rio de Janeiro, Vitória
Angra dos Reis	29.3	Iron and Steel, Oil and derivatives	Alexandria (Egipt), Mersin (Turkey), Kabil (Indonesia), Qingdao (China), Aratu
Belém	2.6	Containers, Oil and derivatives, Corn, General Cargo	Manaus, Barcarena, Fortaleza, Madre de Deus, Santarém
Guaíba	26.3	Iron Ore, Wood, Cellulose Pulp	Rio de Janeiro, Rio Grande, Port Talbot (Wales), Ijmuiden and Rotterdam (Netherlands)

Itacoatiara	7.0	Soy, Soy Oil, Ethanol, Fossil Fuels, Oil and derivatives	Fortaleza, Manaus, Itaqui
Itaguaí	46.9	Containers	Santos, Imbituba, Suape, Callao (Peru), Rotterdam (Netherlands)
Itaituba	6.1	Oil and derivatives, Corn, Soy	Belém, Manaus, Porto Velho, Santarém, Santana
Itaqui	20.3	Oil and derivatives, Containers, Ethanol, Chemical products	Belém, Aratu, Fortaleza, Santos, Suape
Manaus	6.0	Oil and derivatives, Containers, General Cargo	Belém, Fortaleza, Santos, Suape, Itacoatiara
Paranaguá	32.6	Containers, Oil and derivatives, Chemical Products, Wheat	Belém, Fortaleza, Santos, Suape, Itaguaí
Pecém	10.4	Containers, Iron and Steel, Oil and derivatives, Manganese	Los Angeles (USA), Manaus, Cubatão, Brownsville (USA), Santos
Ponta da Madeira	186.6	Iron Ore	Qingdao (China), Labuan (Malaysia), Kwangyang (Korea), Sohrar (Oman), Pecém
Porto Velho	14.2	Soy, Corn, Containers, General Cargo	Santarém, Itacoatiara, Belém, Long Beach (USA), Montoir De Bretagne (France)
Recife	0.3	Sugar, Salt, Oil and derivatives, Fossil fuels	Dubai (UAE), Fernando de Noronha, Baltimore (USA), Barra Do Riacho, Douala (Cameroon)
Rio Grande	20.0	Soy, Containers, Wood, Fertilizers	Tanger (Morocco), Pecém, Antwerpen (Belgiun), Porto Alegre, Dafeng (China)
São Sebastião	12.6	Oil and derivatives, Sugar	Singapore, Qingdao (China), Manaus, Itaqui, Itacoatiara
Salvador	4.5	Oil and derivatives, Cellulose Pulp, Containers	Vila do Conde, Belém, São Sebastião, Changshu (China), Santos
Santarém	6.5	Oil and derivatives, Soy, Corn, Fertilizers	Itaituba, Algete and Barcelona (Spain), Belém, Rotterdam (Netherlands)
Santos	99.1	Soy, Oil and derivatives, Soy Oil, Containers	Anshan, Koh Sichang (China), Bandar Khomeini (Iran), Singapore, São Sebastião
Suape	11.8	Oil and derivatives, Containers, Sugar, Ethanol	Singapore, Manaus, Fortaleza, Itaqui, Santos
Tubarão	62.7	Iron Ore, Soy	Tangshan, Qingdao and Rizhao (China), Labuan (Malaysia), Rio de Janeiro

* Data from ANTAQ [35].

One important outlook of the analysis of main Brazilian ports is that shipping is focused on bulk and container products. Routes are diverse, yet most of cargo movement are concentrated in international destinations, confirming the importance of long-haul navigation to Brazil's economy. China is the busiest destination of Brazilian exports, mainly due to iron ore, soy, corn, oil, and containers [35]. Another output is the high activity in the Brazilian North region, mostly in the Legal Amazon Area. Ports such as Ponta da Madeira, Manaus, Belém, Porto Velho and Santarém heavily contributes for local shipping.

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Considering the cargo movement and the potential of conversion of ports to the bunkering of alternative fuels, it can be concluded that ports characterized by high cargo movement - herein presumed as ports sustaining an annual cargo movement greater than 10 million tonnes - alongside a diverse products flow, encompassing a minimum of four distinct products categories, and consequently having a varied array of types of ships docked, are more acceptable to an implementation as a multi-fuel hub. The ports satisfying these criteria, as listed in **Error! Reference source not found.**, encompass Açu, Itaqui, Paranaguá, Porto Velho, Rio Grande, Santos and Suape.

Additionally, ports that envision the integration of infrastructure designed to enable the provision of two or more alternative fuels bunkering exhibit a heightened precedence in relation to the establishment of multi-fuel hubs. Ports that have handled any of the analysed fuels as cargo also meet this criterion. Specifically, as **Error! Reference source not found.** shows, the ports are Açu, Manaus, Paranaguá, Porto Velho, Santos, Suape, and Rio Grande.

Taken into account the two above-mentioned criteria, our analysis delineates the following ports as possessing the potential to serve as a multi-fuel hub: Açu, Paranaguá, Porto Velho, Rio Grande, Santos, and Suape.

Conversely, ports such as Ponta da Madeira, Itaguaí, and Tubarão, distinguished by substantial cargo movement although with a concentrated product range, have been assessed to be more prone to experiencing a more restricted bunkering of alternative fuels. In other words, these ports are better suited to the bunkering of a particular alternative fuel, considering factors such as the final destinations of the product's fuel availability, and even the local production disposal of alternative fuels.

4.2. Fleet and cargo profile: challenges and progress in conversion to alternative fuels use

In 2023, the Brazilian ship fleet recorded an average age of approximately 19.5 years. Support vessels, despite being smaller, stand out due to their significant quantity, representing 90% of the fleet. Port support vessels account for 73% of this total, while maritime support vessels represent 27% [35]. Among the ships with the highest gross tonnage, bulk carriers and container ships are highlighted. Based on ANTAQ [35], Table 6 displays the products transported, age and average Deadweight Tonnage (DWT), along with the quantity of ships, for the types of vessels with the highest average DWT in the Brazilian fleet.

Table 6. Products transported, average age and deadweight tonnage, and number of ships of main Brazilian ship types.

Ship Type	Products transported	Average age (2023)	Average DWT	Fleet size
Tanker	Crude oil and derivatives	10	89,054	54
Bulk	Dry Bulk	15	57,007	21
Container	Container	13	45,009	33
Chemical Tanker	Chemical products	18	26,234	8
Pipe Laying Support Vessel (PLSV)	Offshore Pipes	9	10,661	8
Subsea Equipment Support Vessel	Subsea Equipment	15	7,570	2
LPG Tanker	Liquefied petroleum gas	11	5,481	8
Liquefied Gas Tanker	Liquefied gases	13	5,455	11

* [35].

Given that the typical lifespan of a ship is 30 years [47], it can be concluded that the highlighted type of vessels exhibits a residual lifespan of no less than 12 years, a scenario particularly applicable to the chemical tanker fleet. Therefore, the replacement of the existing fleet due to end of lifetime remains an impractical course of action for short period. In this regard, a priority arises to optimize the ship retrofits required for the adoption of alternative fuels.

LPG and liquefied gas tanker are notably suited to embrace the utilization of liquefied and pressurized fuels, namely LNG, ammonia, and methanol. This advantage stems from the existing infrastructure designed for the storage and management of these fuels, which leads to a simplified conversion than other vessels.

Chemical tankers are also more suitable for ammonia and methanol. These fuels are flammable, demanding ships to be meticulously constructed and operated, with intensified attention to potential incidents concerning the cargo [119]. This condition particularly applies to chemical ships, easing the adaptation to the use of the aforesaid fuels.

Tanker ships also exhibit a notable advantage in terms of adaptability due to their operation with fuel as cargo. However, changes in the entire infrastructure, encompassing storage tanks, fuel feeding and engines, is imperative. Given their intrinsic lack of operational experience with liquefaction and extreme pressurization, these vessels are better suited for a conversion for the utilization of other fuels preferably having higher readiness level, such as biodiesel, SVO and HVO. The analogous circumstance applies to the remaining selected types of vessels, given their inherent limitation of lacking experience in the handling of fuel as cargo.

Concerning the current stage of fuels usage, in 2022, Bunker One, a Danish bunkering company actively engaged in operations along the Brazilian coast, has entered into a collaborative partnership with Federal University of Rio Grande do Norte to conduct experimental trials on a fuel blend composed of HFO and 7% v/v biodiesel. These trials are specifically focused on tugboats operating within the area of the Port of Rio de Janeiro, with the aim of gathering valuable data on the performance and suitability of this mixture in the maritime context [120]. Petrobras has undertaken the implementation of a fuel blend consisting of 90% HFO and 10% biodiesel in a LPG tanker, with the primary objective of conducting a comprehensive analysis of its performance characteristics and identifying any potential logistics challenges that may arise. The dedicated Research Laboratories at Petrobras have conducted testing and assessment of this fuel mixture in January 2023, observing that its integration necessitates no modifications to the existing maritime infrastructure [121]. In July 2023, the company made an announcement regarding its plans to conduct additional tests on vessels using a blend of 24% v/v of biodiesel [122]. Additionally, the company is actively investing in and establishing the development of large-scale production of HVO within its refineries [123].

As aforementioned, companies linked to the maritime and energy sectors have taken the lead on the effort to introduce alternative fuels into vessels. Apart from these companies, governmental and regulatory bodies must be prepared to assume a pivotal role in facilitating the transition of the maritime sector [7]. Their contribution encompasses measures targeted not only in facilitating fuel production but also at proposing the conversion of marine fleet and port infrastructure. The actions of governments, such as Norway's actions, ranging from setting more ambitious targets relative to those defined by IMO, directing mandatory percentages of biofuels within maritime fuel blends, to instituting fiscal incentives for enterprises that champion the utilization of alternative fuels [124], present examples that Brazil could consider to follow.

4.3. Thermal Stability of fuels in the main routes

In terms of thermal stability of the selected fuels, as highlighted in section 3.1 and 3.6, biodiesel exhibits a low pour point compared to traditional marine fuels and the other alternative fuels. This particular property restricts its widespread usage in regions characterized by low temperatures or during cold seasons [75]. Given the routes departing from the main Brazilian ports, displayed in **Error! Reference source not found.**, and global historical average temperatures across various regions [125], it can be concluded that international routes transiting through South Africa, Europe,

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United States, and North Asia demand the use of distinct fuels from biodiesel during periods of low temperature.

4.4. Fleet profile: loss of cargo space

Shipping companies, particularly those specialized in long-haul navigation, are continuously in the search of strategies to optimize the allocation of cargo freight, aiming to maximize its utilization during a voyage. This pursuit explains the quest for achieving economies of scale in bulk shipping [126], whose vessels are progressively with larger cargo capacities. For instance, standard dry bulk carriers have reached a capacity of 400,000 DWT through the deployment of Valemax vessels, the regular ships for the Ponta da Madeira to Qingdao iron ore route [127]. As clarified in Section 3, the adoption of alternative fuels brings a consequential requirement for increased storage tank volume due to the relatively lower energy density in contrast to conventional fuels. This decrease in space availability, particularly seen in the cases of LNG, ammonia, and methanol, is set to decrease the allocation of cargo space [128]. Given the substantial reliance on bulk shipping in the Brazilian context, this loss of cargo space emerges as a considerable barrier to the effective use of alternative fuels. In response to this challenge, Lindstad et al. [129] have proposed some initiatives aimed at mitigating the loss of cargo space, including the increasement of maximum draught and length of vessels. In the short term, however, this loss of space tends to be solved with more ships [130].

5. Conclusions

This study reviewed and summarized the major changes required for ports and ships to store, feed and use alternative fuels. These changes derive from: (i) the low energy density of fuels compared to HFO, particularly LNG, ammonia, and methanol, leading to loss in cargo space; (ii) the necessity for liquefaction (LNG) and/or pressurization (ammonia and methanol) of fuels to optimize storage or facilitate proper fuel feeding; (iii) the utilization of different materials such stainless steel and mild steel in storage tanks and fuel feeding systems; (iv) the requirement for double-walled in both storage tanks and fuel feeding systems, as observed in the cases of LNG, ammonia, and methanol; (v) the need for enhanced precautions to prevent water contamination, particularly to biofuels usage; (vi) high toxicity of fuels, notably ammonia and methanol, which require extra ventilation inside ships; (vii) thermal stability issues impacting biodiesel utilization, particularly in extreme low temperatures; (ix) modifications in engine fuel feeding and ignition (biofuels), adjustments for dual-fuel (LNG and methanol), or substitution for fuel cell (ammonia).

While the demand for alternatives fuels is increasing, further advancement is necessary to significantly broaden the array of options. While certain fuels like LNG and methanol are already in operation on specific vessels, others such as HPO and SVO remain in the experimental stage, which has indeed complicated the process of reviewing technical and scientific literature for these fuels. The conducted case study underscored the feasibility of single or multi fuel bunkering within the main Brazilian ports by indicating the main products, routes, and the prospective development of alternative bunkering infrastructure within each port studied. Ports such as Açu, Paranaguá, Porto Velho, Rio Grande, Santos, and Suape exhibit potential for accommodating multi-fuel bunkering, while Ponta da Madeira, Itaguaí, and Tubarão tend to single-fuel bunkering.

Concerning the Brazilian fleet, given the limited number of alternative fuels trials within the country, the analysis was conducted by evaluating vessel types requiring fewer adaptations to the utilization of alternative fuels. Given the operational characteristics of the ships, LPG and liquefied gas tankers are ahead in terms of conversion for utilizing fuels like LNG, ammonia, and methanol. A similar trend is observed for chemical vessels, more suitable to conversion for ammonia and methanol, as well as tanker ships, which hold potential for the use of fuels such as biodiesel, SVO, and HVO. In the pursuit of establishing a fleet powered by alternative fuels, stakeholders may adopt diverse strategies, including the establishment of more ambitious targets, mandatory incorporation of biofuels in blends, and fiscal incentives promoting the integration of alternative fuels in their fleets. The analysis of these different strategies should be deepened in further studies.

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