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Decarbonization Alternatives for the Maritime Transport Sector in Brazil: 2024

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THE PRESENT REPORT IS THE RESULT OF A COLLABORATION BETWEEN CEBRI AND THE CONSULATE GENERAL OF NORWAY IN RIO DE JANEIRO

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SUMMARY

EXECUTIVE SUMMARY

Regarding Brazilian activity, approximately 1.3 billion tons of cargo passed through Brazilian ports and terminals in 2023, marking a 7% increase compared to the previous year. However, this growth contrasts with a slight decrease in the energy demand of Brazilian navigation in recent years, attributable to energy optimization measures implemented on vessels.

In terms of alternative fuel maturity, ethanol, ammonia, HVO, and hydrogen have advanced in their technological development, including successful use in ignition engines and an increasing demand for vessels equipped with engines compatible with these fuels. Additionally, regulatory aspects have generally facilitated the use of biofuels, making it increasingly feasible for the sector, the use of up to 30% biofuels in the blend of maritime fuel has been facilitated. In Brazil, the use of biodiesel in maritime fuel blends has been validated and approved by Brazilian authorities for commercialization in national ports and terminals. In contrast, uncertainties remain regarding the quantification of the life-cycle emissions of biomass-derived fuels, particularly those related to land-use changes, which are still under discussion within the IMO[1].

In line with the 2030 sustainable fuels target, the establishment of green corridors—an agenda highlighted during the United Nations Conference—has garnered increasing attention from the maritime community. This report presents the main green corridors under development, analyzing the stakeholders involved and the energy vectors considered, with a focus on corridors that include ports located in South America.

In Brazil, the "Fuels of the Future" bill, enacted in 2024, promotes the use of biofuels, hydrogen, and carbon capture technologies. The use of biodiesel in vessels has become viable, and the addition of 5% hydrotreated vegetable oil (HVO) in diesel blends is now commercially available. On the infrastructure side, several Brazilian ports, such as Pecém, Suape, and Açu[2], are conducting studies and attracting investments to adapt their infrastructure to enable alternative fuel supply.

In Norway, measures taken position the country as a leader in the use of alternative fuels. Half of the world's vessels equipped for low-emission fuels are Norwegian. The country boasts ports actively developing green corridors, ammonia refueling terminals, and vessels experimenting with hydrogen fuel cells, alongside investments in carbon capture technologies. Norwegian companies are advancing sustainable technologies, such as converting ships for ammonia use and adopting green hydrogen.

Collaboration between Brazil and Norway could facilitate the expansion of biofuels and hydrogen production and usage, as well as the electrification of Brazil's short- and medium-distance inland waterway transportation. Partnerships between companies from both countries in energy efficiency technologies, such as vessel consumption optimization, have already yielded results. Brazil can further explore green corridors and routes to Europe, which accounted for 17% of Brazilian exports and 26% of imports[3] in 2023. This collaboration would contribute to meeting global climate targets by 2030.

[1] Discussions during IMO meetings on emissions related to indirect land-use changes from biomass cultivation, cited in the organization's life-cycle analysis guidelines [71], have involved entities such as the Navy [20] and EMBRAPA [135].
[2] Ports like Pecém, Suape, and Açu stand out for initiatives related to hydrogen use as cargo and fuel, as well as active participation in decarbonization efforts [111,115–117].
[3] Export and import data refer to 2023, based on the monetary value of goods, according to MDIC [134].

1. INTRODUCTION

Maritime transport plays a significant role in the global economy, accounting for approximately 90% of global trade by volume [1,2]. This activity, essential to the global economy, continues to grow [3]. Cargo movement via maritime transport has increased not only in volume but also in financial terms. Between 1985 and 2023, the total volume of cargo transported by ships tripled, while the value of cargo rose more than tenfold. By 2022, the value of goods transported via maritime routes represented 60% of the global GDP, compared to less than 40% in 1985 [4].

This growth in seaborne cargo flows is justified by economic efficiency: the estimated direct cost of transporting one ton of cargo over 1,000 kilometers is $4 for maritime transport [5], compared to approximately $80 for rail, $300 for road, and $2,000 for air transport[4] [4]. According to UNCTAD [3], international trade via maritime transport grew by 2.4% compared to 2022, when approximately 12 million tons of cargo were transported.

In terms of transport services, measured in ton-miles, there was a 4.2% increase compared to the previous year, reaching approximately 63 billion ton-miles. This higher growth compared to transported volume is attributed to shifts in trade flows caused by the war in Ukraine, reduced water levels in the Panama Canal, and tensions in the Red Sea.

Regarding passenger transport, due to its lower energy and volume demand compared to cargo transport [3,6], data availability is limited. However, it is noteworthy that passenger transport accounted for approximately 4% of the maritime sector's energy demand in 2018 [6]. In Brazil, passenger navigation represented about 0.5% of passenger movement, measured in passenger-kilometers (pkm)[5], in 2017 [7].
Amid this context of increasing cargo flows and geopolitical challenges, it is crucial to emphasize the discussion on reducing emissions from maritime transport, which currently generates approximately 1.05 billion tons of carbon dioxide equivalents (CO2eq) annually.

It is important to highlight that greater energy efficiency makes maritime transport a priority for freight and passenger transportation, given its potential to reduce energy consumption, which strengthens its short-term role in driving decarbonization actions. Conversely, prioritizing the maritime mode promotes the growth of the sector's activity.

[4] Esses valores não levam em conta o custo de oportunidade relacionado à maior agilidade dos demais modais em relação ao modal marítimo, à infraestrutura necessária e às limitações dada a necessidade de vias marítimas para viabilizar o transporte.
[5] Passageiro-quilômetro é uma medida de movimentação de passageiros, calculada a partir do produto quantidade total de passageiros e da distância total percorrida.

Facing the challenge of decarbonizing a sector that is expanding both in cargo movement and fleet size, the IMO revised its 2018 greenhouse gas (GHG) emission reduction targets in 2023. While the initial goal was to achieve a 50% reduction in emissions by 2050, compared to 2008 levels [8], the new targets include short-, medium-, and long-term timelines. By 2030, the objective is to reduce GHG emissions by at least 20% compared to 2008 [9], when emissions totaled approximately 1.02 billion tons of CO_2-eq [10]. By 2040, the target is a minimum reduction of 70%. For 2050, the IMO aims for the sector to achieve net-zero GHG emissions, including an analysis of the full life cycle of the fuels used [9].

In addition to GHG emission reduction targets, the IMO has set a goal for 2030, requiring at least 5% of the maritime transport sector's energy demand to be met by zero- or near-zero-emission fuels. Another significant aspect of the IMO's new targets is the emphasis on a fair and inclusive transition. Developing countries, which in 2023 accounted for approximately 54% of global maritime cargo shipments and 53% of receipts [3], will also need to meet IMO demands [9].

The challenges of decarbonization—whether economic, social, or technological—must be addressed. The transition of the maritime sector should be planned as a collective effort, with all nations contributing proportionally to their resource capacities, ensuring that no region is excluded or left behind in the process.

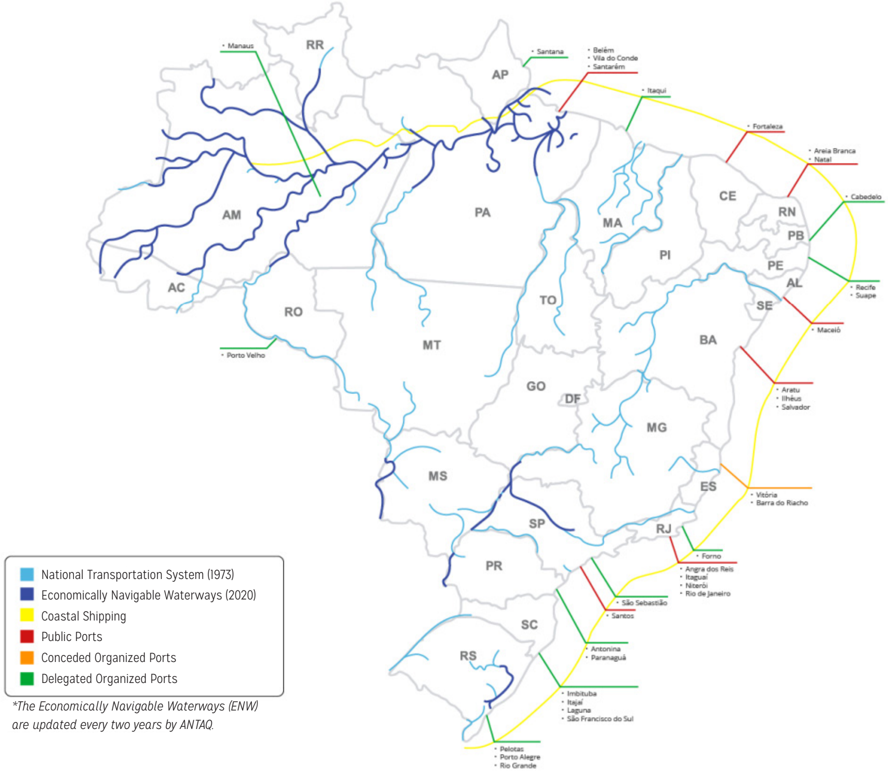
In this general context, this report aims to update possible pathways and measures for decarbonizing the Brazilian maritime sector, as well as opportunities for knowledge exchange with Norway. Following this brief introduction, the second chapter of the report provides updated data on Brazil's maritime transport sector. The third chapter examines advances in decarbonization options, particularly alternative fuels. The fourth chapter outlines the current status of the Brazilian maritime sector in terms of decarbonization actions, while the fifth chapter presents the Norwegian perspective. Finally, the sixth chapter offers the report's conclusions and highlights potential synergies for collaboration between the two nations to reduce sector emissions.

2. CHARACTERIZATION OF THE MARITIME SEGMENT IN BRAZIL

The Brazilian maritime sector recorded a total of 23,126[4] vessels in October 2024 [11], an increase of 31 vessels compared to the survey conducted in August 2023 [12]. These vessels operate not only in more than 380 ports and terminals across Brazilian territory [13] but also in international ports in the case of long-haul navigation. Figure 1 illustrates the layout of the main national routes and Brazilian ports.

Figure 1 shows the layout of the main national routes and Brazilian ports.

Figure 1: Major Brazilian Ports and Waterways.



Source: ANTAQ [14].

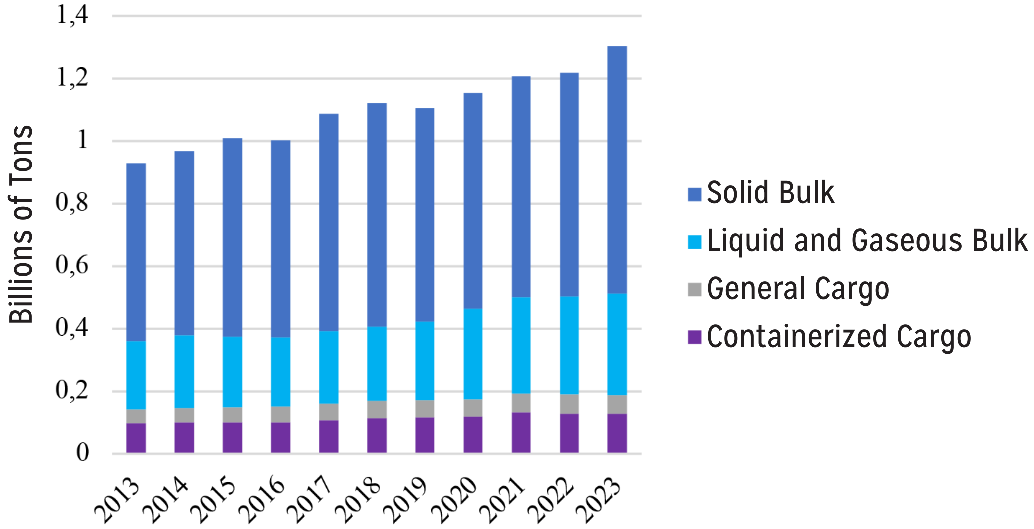
Data from ANTAQ (National Agency for Waterway Transportation) show that in 2023, national ports and terminals handled approximately 1.3 billion tons of cargo in about 193,000 trips. These figures represent a 7% and 3% increase, respectively, in cargo movement and trips compared to 2022 data [14].

The route with the highest cargo volume in 2023 was from Ponta da Madeira, in Maranhão, to the port of Qingdao, in

[6] Vessels flying the Brazilian flag.
[7] As stated in the previous report, the number of trips in the Brazilian maritime sector in 2021 was approximately 400,000. However, this figure was recently revised in the ANTAQ database, and the updated value for 2021 is approximately 194,000 trips. Docking figures for previous years were also revised [11].

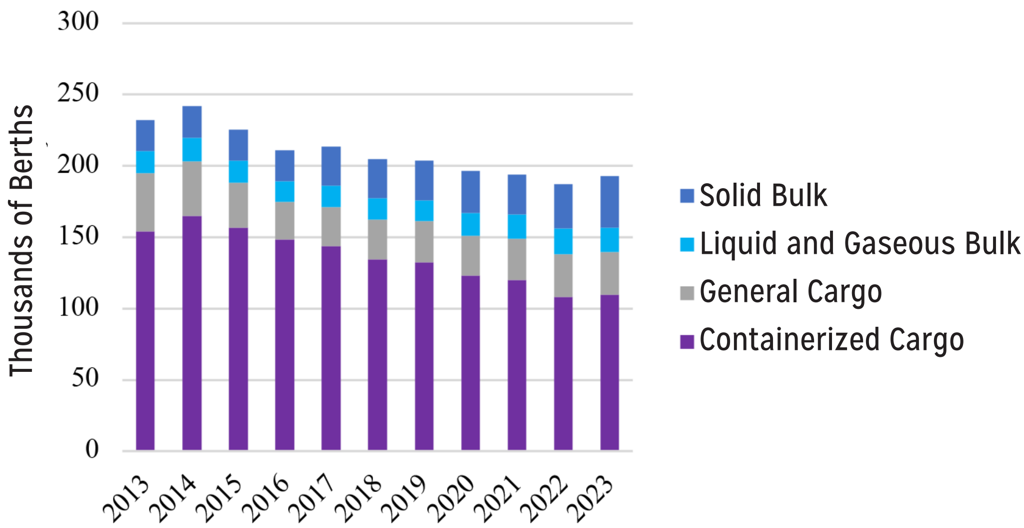
China, with approximately 130 million tons transported, equivalent to approximately 10% of the total cargo moved by the Brazilian maritime sector in the same year.

Figure 2: Total Cargo Movement by Type in Brazilian Ports from 2013 to 2023.



Source: Adapted from ANTAQ [11].

Figure 3: Number of Trips Originating from and/or Destined for Brazilian Ports by Cargo Type from 2013 to 2023.



Source: Adapted from ANTAQ [11].

Cargo movement in Brazil in 2022 and 2023 was dominated by solid bulk, which accounted for 59% and 61% of the total volume handled, with 715 and 790 million tons, respectively. Iron ore, corn, and soybeans were the primary products, representing 74% of the total in 2023. This type of cargo generated 31,000 and 36,000 dockings in these years, with the route between Porto Velho (RO) and Itacoatiara (AM) standing out, accounting for 11% of the segment's trips in 2023.

Liquid bulk, on the other hand, handled 314 and 325 million tons in 2022 and 2023, respectively, with focusing on the logistics of oil and derivatives, liquid bulk operations were concentrated in the terminals of São Sebastião (SP) and Angra dos Reis (RJ).

General cargo accounted for 62 and 60 million tons in 2022 and 2023, respectively, with pulp and iron as the primary products (74% of the total). Highlighted routes include iron exports from Rio de Janeiro (RJ) to the United States and the transport of chemical wood pulp to China and Rio Grande do Sul. Containerized cargo totaled 128 million tons in both years, representing only 10% of the total volume but accounting for 57% of maritime trips in 2023, with the port of Santos (SP) serving as a strategic hub.

Regarding navigation, volumes in 2023 followed the trend of 2021, with long-haul navigation (70%), coastal shipping (23%), and inland navigation (6%) dominating the total volume. In terms of dockings, long-haul navigation accounted for 56% of the trips, followed by inland navigation (25%) and coastal shipping (17%), reaffirming the importance of these modes in the national logistics landscape.Table 1 summarizes the data on maritime cargo movement in Brazil, highlighting the main types, products, and routes with the highest volume and frequency.

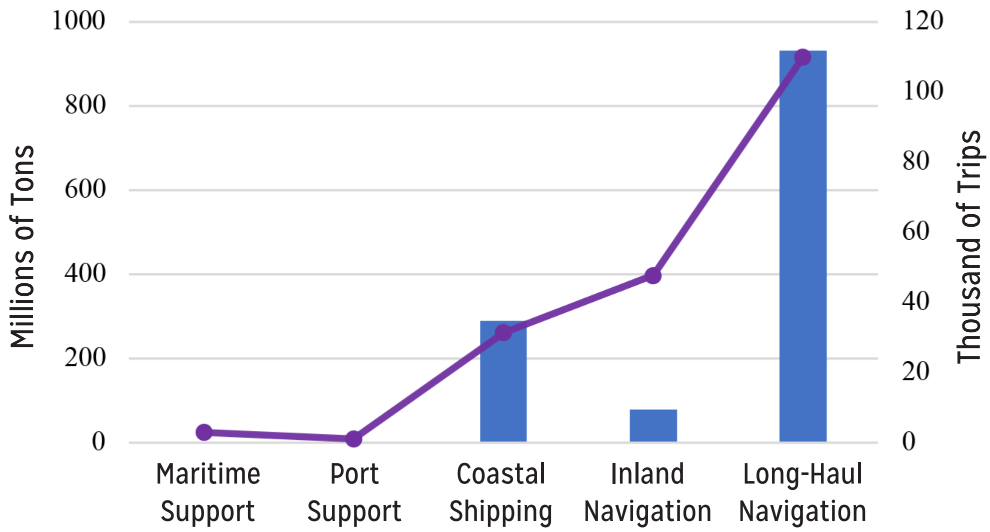
Table 1: Volume, in millions of tons, by type of cargo handled at Brazilian ports in 2022 and 2023

Cargo Type	Volume 2022 (Mt)	Volume 2023 (Mt)	% of Total (2023)	Main Products / Routes	Trips 2023
Solid Bulk	715	790	61%	Iron Ore (49%), Corn (16%), Soybeans (9%)	36,000 (19%)
Liquid Bulk	314	325	25%	Oil and Derivatives (20% on SP and RJ routes)	17,000 (9%)
General Cargo	62	60	5%	Pulp, Iron, and Steel (74%); RJ - USA Route (3.7 Mt)	30,000 (16%)
Containerized	128	128	10%	Santos - Singapore; Vitória - Santos	110,000 (57%)
Navigation	-	-	-	Long-Haul (70%), Coastal Shipping (23%), Inland Naviga-tion (6%)	Inland: 25%; Long Haul: 56%

Source: Adapted from ANTAQ [11].

Figure 4 shows the movement of cargo and the number of trips made by type of navigation with Brazilian ports as origin and/or destination in the year 2023.

Figure 4: Cargo Movement (in billions of tons) and Number of Trips Originating from and/or Destined for Brazilian Ports by Type of Navigation in 2023.



Source: Adapted from ANTAQ [11].

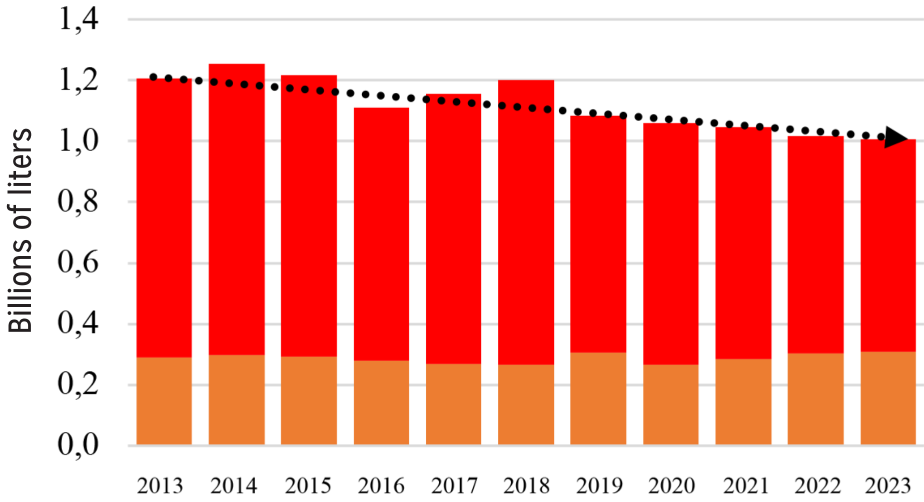
In 2023, long-haul navigation stood out for transporting iron ore, soybeans, containers, oil and derivatives, and corn. Iron ore export routes to Qingdao, China, originating from terminals such as Ponta da Madeira (MA) and Tubarão (ES), moved 207 million tons, representing 16% of the national total.

Container transport led in the number of trips, with nearly 12,000 trips involving the ports of Santos (SP) and Paranaguá (PR), reflecting the high added value of containerized cargo compared to bulk cargo. Container trips carried an average of 14,000 tons per trip, compared to 88,000 tons for iron ore.

In coastal shipping, oil and derivatives dominated, accounting for 67% of the 290 million tons transported in 2023 and 4,172 dockings, representing 13% of the total. Inland navigation focused on soybean and corn transport, with the Miritituba (PA) – Vila do Conde (PA) route standing out, moving 6 million tons of oilseeds and 4.6 million tons of grains. The Portochuelo (RO) – Hermasa (AM) route led in the number of trips, with 3,950 operations totaling 7 million tons of cargo. These data reinforce the importance of regional and intermodal routes in supporting national logistics.

Regarding energy consumption in Brazil's maritime transport sector, Figure 5 shows the energy demand, in billions of liters of fuel, for heavy fuel oil (in red) and marine diesel oil (in orange) from 2013 to 2023.

Figure 5: Energy Consumption of Maritime Transport in Brazil from 2013 to 2023

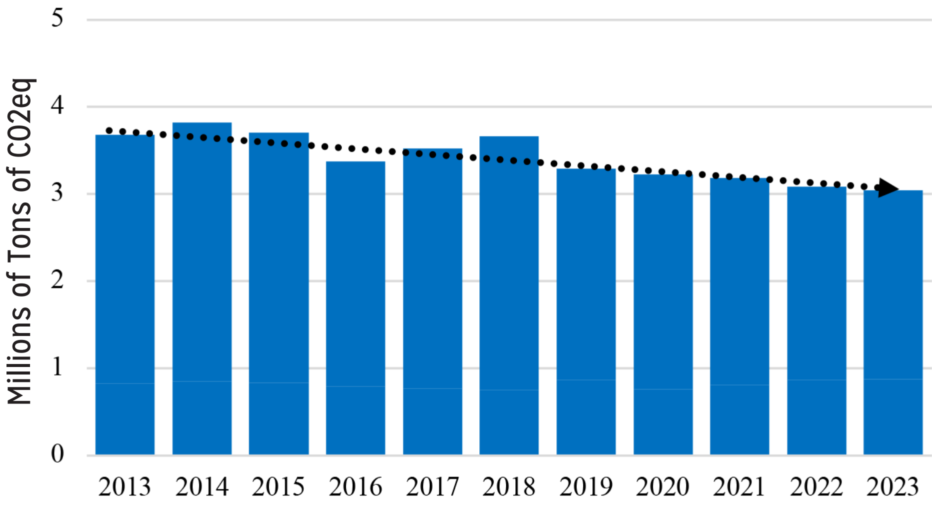


Source: EPE, 2024 [15].

As Figure 5 shows, the downward trend in energy consumption in the maritime sector, as noted in the previous report, continues. Between 2013 and 2023, the average energy consumption of maritime transport was 1.1 billion liters, and in 2023 the demand was 1 billion liters of fuel, with a cumulative drop in consumption since 2013 of 17%. In addition, marine diesel has been increasing its share in the energy demand of Brazilian vessels: in 2018, the fuel represented 22% of the sector's total energy supply, rising to 31% in 2023. This reduction in consumption may be caused by measures such as reducing speed or optimizing ship operations, through actions such as improvements in the shape of the hull or propulsion systems. In 2023, heavy fuel oil consumption was 697 million liters, while marine diesel consumption was approximately 309 million liters. This fuel consumption represented approximately 0.4% of the total energy demand consumed by the country and 1.2% of the demand of the entire national transport sector in 2023.

The end use of these fuels generated emissions of approximately 3 million tons of CO2eq, of which 2.2 came from the use of heavy fuel oil and 0.9 from the use of marine diesel. Figure 6 shows the estimated greenhouse gas emissions for the end use of marine fuels in Brazil for the years between 2013 and 2023, with the fuel emission factors based on Comer and Osipova [16].

Figure 6: Estimated Greenhouse Gas Emissions (in CO2eq) from the Final Use of Fuels in Brazilian Vessel Activities from 2013 to 2023.



Source: Own elaboration

The emission reduction, considering the final use of fuels in the maritime sector, can be observed in Figure 6. Comparing the estimated emissions between 2023 and 2013, a reduction of approximately 17% is noted. If compared to 2008, the baseline year for the IMO's short- and medium-term targets, with an energy demand of 1.3 million liters or 60.8 petajoules (PJ) [17], the emission reduction in 2023 amounts to 26%. It is important to highlight that this emission reduction is solely attributed to the decreased consumption of maritime fuels.

3. DECARBONIZATION OPTIONS FOR THE MARITIME SECTOR

This chapter is divided into three parts. The first addresses possible actions for each group of stakeholders in the maritime sector to promote decarbonization. The second part focuses on the production of alternative fuels. The third part evaluates alternative fuel options regarding their use in ships, emission reduction potential, technological maturity, fleet integration feasibility, and a discussion on green corridors, highlighting recent updates supporting the use of these fuels.

3.1. ACTIONS FOR DECARBONIZING THE MARITIME SECTOR

When addressing the issue of decarbonizing the transport sector, different perspectives must be considered to achieve a common solution. Thus, two opposing general viewpoints should be taken into account for the maritime industry: the perspective of regulators and government bodies, which focus on implementing actions to achieve established decarbonization targets, and the perspective of shipowners and maritime operators, who must find ways to comply with government decisions through short-term actions that will likely have long-term implications for their business operations [18].

The stakeholders in the maritime sector are divided into four main categories: government and regulatory entities, shipowners and operators, research institutions, and the naval and energy industries. Each group has potential actions to take to achieve pollutant emission reductions. Figure X illustrates a framework of the key actions envisioned for each stakeholder.

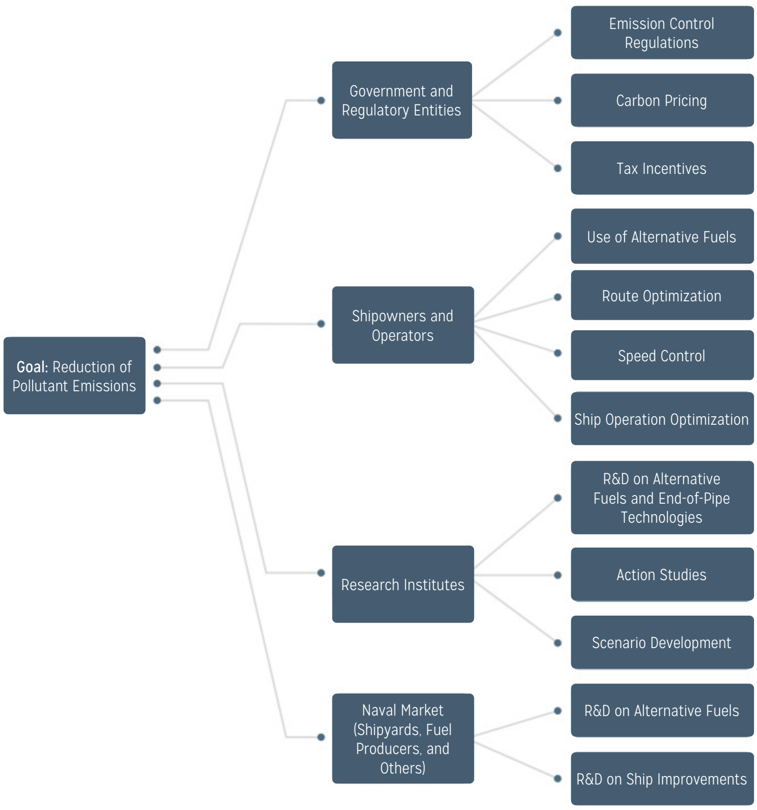


Figure 7: Potential Measures Each Stakeholder Group Can Take to Reduce Pollutant Emissions in the Maritime Sector.

Source: Own elaboration.

The measures are presented according to the stakeholder groups described in Figure 7, which will be further detailed and exemplified.

3.1.1. GOVERNMENT AND REGULATORY ENTITIES

This group includes national governments, government officials, ministries, and agencies related to transportation, energy, and the environment, as well as organizations like the United Nations, represented by the IMO. The policies and regulations imposed by these stakeholders are critical for facilitating the reduction of pollutant gases [19].

3.1.1.1. EMISSION CONTROL REGULATIONS

Emission control is a tool already in use in some regions of the world: in addition to decarbonization targets, the IMO has established Emission Control Areas (ECAs) for sulfur dioxide in the Baltic Sea, the North Sea, North America, and the U.S. Caribbean Sea [18]. Emission control targets and regulations are crucial to pressuring other stakeholders in the maritime sector to reduce emissions and encouraging investments in new technologies. Furthermore, pollution monitoring in the maritime sector is also expected to be intensified by countries to ensure compliance with these targets and regulations.

3.1.1.2. CARBON PRICING

The concept of pricing based on the pollutant emissions associated with a fuel is another important measure to be discussed by government bodies. In this case, shipowners and operators would pay a fixed fee based on fuel consumption, and part of this revenue could, for instance, be used to fund greenhouse gas emission reduction projects [18]. The adoption of carbon pricing was discussed during the Marine Environment Protection Committee (MEPC) meeting in October 2024 as a measure to be finalized by 2027 [20].

3.1.1.3. TAX INCENTIVES

Another way to encourage emission reductions is through tax incentives and subsidies granted by government entities. Subsidy policies can be used to reward vessels for reducing air pollution, as opposed to taxes or fees, which focus on penalties.These incentives may take the form of grants or loans to offset costs related to reducing pollutant emissions in the maritime industry, provided by the government or maritime authorities [21]. Other subsidy mechanisms include donations, reduced tax rates, bidding systems, carbon credit purchases, and other forms of financial assistance. An example of such an incentive was the Port of Hamburg, which for a time offered publicly funded discounts on port fees for ships that met certain emission criteria [22].

3.1.2. SHIPOWNERS AND OPERATORS

Shipowners are the owners of the vessels and may or may not choose to operate the vessels. The shipowner has the option of engaging shipping companies to operate the vessels. Thus, the vessel operator is not always the owner of the vessel [23].

3.1.2.1. USE OF ALTERNATIVE FUELS

To meet the new decarbonization targets set by the IMO, the large-scale use of fuels with zero or near-zero greenhouse gas emissions emerges as one of the most promising alternatives. The potential alternatives for maritime fuels are diverse, and identifying the best choice for the maritime sector's energy transition is no trivial task.

3.1.2.2. OTIMIZAÇÃO DE ROTA

The use of modern technologies enables highly accurate predictions of weather and sea conditions, allowing for the selection of routes that maximize the vessel's energy efficiency while avoiding those with poor conditions that may hinder optimal operation. Route optimization not only reduces operator costs but also leads to lower fuel consumption and, consequently, reduced pollutant emissions [18].

3.1.2.3. SPEED CONTROL

The relationship between fuel consumption and vessel speed is not linear but rather proportional to the cube of the ship's velocity. Thus, even a slight reduction in speed can significantly decrease fuel consumption [24]. This speed reduction can be achieved through both operational and technological measures. Operational speed reduction, commonly known as "slow steaming," involves adjusting the sailing pace, whereas the technological approach involves reducing the installed engine power [18].

3.1.2.4. SHIP OPERATION OPTIMIZATION

As mentioned in Chapter 1, ship operation optimizations include improvements in hull design, propulsion systems, and the vessel's energy efficiency. Hull design directly impacts ship performance, and its optimization can reduce fuel consumption and CO2 emissions by up to 15% for large vessels. It is important to note that this optimization is effective only if the ship operates within the design specifications, including the recommended speed range [25].

With the adoption of the EEDI and, more recently, the EEXI, the IMO now regulates maritime sector emissions based on estimated CO2 emissions per distance and ship size. These estimates are calculated using the installed engine power and the expected power at the vessel's optimal design speed range [18]. Monitoring operational data is therefore critical to optimizing vessel operational standards, with the potential to reduce fuel consumption by up to 20% [26,27].

3.1.3. RESEARCH INSTITUTES

Institutions responsible for providing studies and analyses for developing emission reduction measures for the maritime industry include academic institutions, think tanks, government agencies, and non-governmental organizations [28]. These entities play a key role in developing new technologies, actions, and perspectives for the maritime sector.

3.1.3.1. RESEARCH AND DEVELOPMENT OF ALTERNATIVE FUELS AND END-OF-PIPE TECHNOLOGIES

An important role of research institutes is to conduct studies on maritime fuels with low or zero pollutant emissions. Various studies [22,29–31] analyze the characteristics, technological maturity, production, compatibility with the fleet and existing infrastructure, life-cycle emissions, and other aspects of alternative fuels. The possibility of continuing to use current fuels alongside end-of-pipe technologies for emission mitigation is also explored by the scientific community [32,33].

3.1.3.2. ACTION STUDIES

Researchers in the maritime sector can also study potential actions needed to achieve IMO-imposed targets and identify the stakeholders responsible for them. Numerous scientific studies [18,19,22,34] highlight specific actions to reduce emissions, many of which are referenced in this report.

3.1.3.3. SCENARIO ANALYSIS

Researchers can use scenario methodologies to evaluate quantitative and qualitative variables often involved in complex and dynamic systems. Unlike projections, scenario analysis provides insights into differing perspectives and values related to specific situations. Scenarios explore various "futures," contrasting traditional viewpoints and fostering debate [35]. Some studies [36,37] build scenarios for different regions within the maritime sector, enabling the analysis of actions taken and their impacts, as well as comparative studies between integrated models emphasizing the maritime industry [38]. Government institutions such as the IMO [39] and maritime companies like DNV [40] also employ scenario methodologies for maritime transportation.

3.1.4. NAVAL MARKET

This group includes shipbuilders, maritime fuel producers, and companies interacting with the maritime sector, such as classification societies, maintenance firms, and engine and propulsion system suppliers.

3.1.4.1. RESEARCH AND DEVELOPMENT OF ALTERNATIVE FUELS

Like research institutes, companies within the naval market play a fundamental role in researching and developing low- or zero-emission fuels. Production and development of these fuels are already underway by companies like Neste [41], BP, Repsol, Galp, Total, Cespa, Honeywell BTG-BTL, TechnipFMC, Fortum, and Valmet [42], with other companies, such as Petrobras [43], planning to begin production.

3.1.4.2. RESEARCH AND DEVELOPMENT OF INFRASTRUCTURE IMPROVEMENTS

Manufacturers of maritime engines are conducting analyses and tests to identify optimal propulsion systems for alternative fuels. Companies such as Caterpillar, MAN Diesel, and Wartsila are testing and adapting diesel engines—the traditional engines for vessels—for biofuel use [44]. Alternative propulsion technologies, such as wind or solar-based systems, as well as electrification through fuel cells and batteries, are also being explored [18].

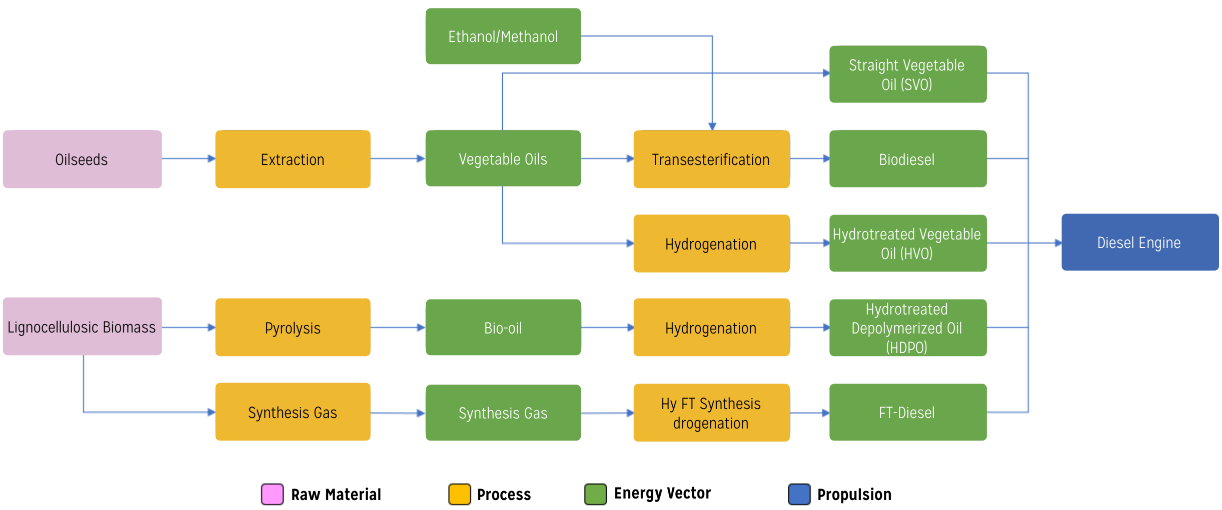
Fuel cell usage guidelines have already been established by DNV GL, a classification society, detailing installation designs and safe refueling procedures for certain alternative fuels with lower flash points or toxic characteristics [45].

3.2. PRODUCTION OF ALTERNATIVE FUELS

From a strictly technological perspective, a variety of options exist for producing alternative fuels, ranging from the direct use of vegetable oils to the creation of synthetic fuels via hydrogen and recycled carbon dioxide (CO2) conversion [46]. However, it is essential to also incorporate economic, environmental, and operational factors when assessing the feasibility of alternative fuels for maritime navigation within the timeframe defined by the sector's 2050 targets.

Figures 8, 9, and 10 illustrate the production routes for various alternative fuels, which can be divided into three groups as presented in the study by Carvalho et al. [47]. The first group includes distilled fuels, the second group consists of alcohols and liquefied gases, and the third group includes hydrogen, ammonia, and electrofuels, which are synthetic fuels derived from hydrogen.

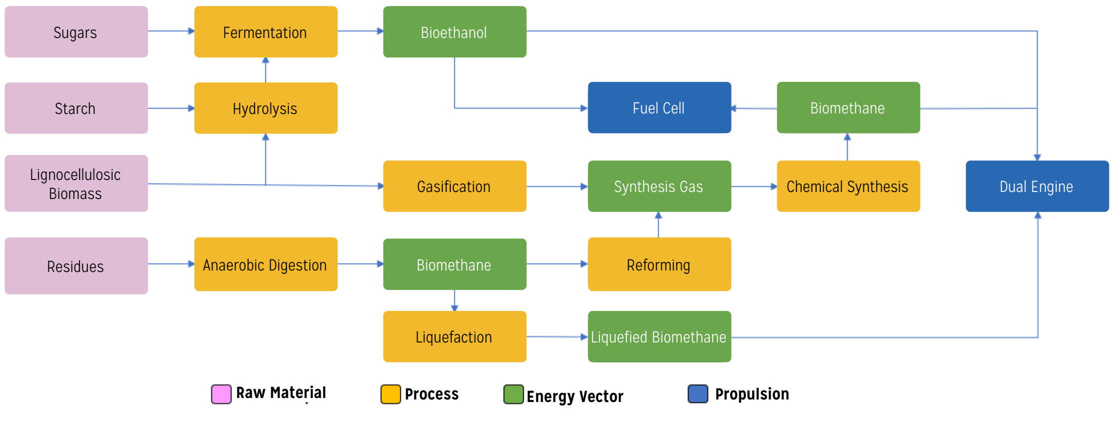
Figure 8: Distilled Fuels, Potentially Carbon-Neutral Alternative Fuels for the Maritime Sector.



Source: Carvalho et al [47].

Liquid distilled biofuels fall under the category of drop-in[8] (or near drop-in[9]) fuels, derived from vegetable oils, lignocellulosic biomass (including agricultural and forestry residues), or bio-alcohols. Biofuels originating from vegetable oils include straight vegetable oils (SVO) and hydrotreated vegetable oils (HVO), while those derived from lignocellulosic biomass and bio-alcohols include hydrotreated pyrolysis oil (HDPO), Fischer-Tropsch diesel (FT-diesel), and alcohol-based diesel (ATD), respectively.

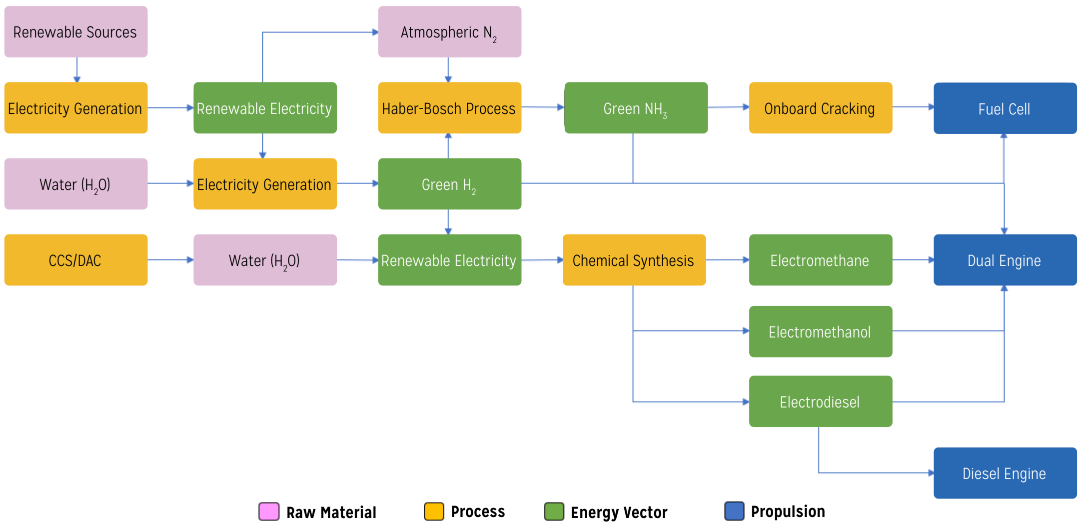
Figure 9: Alcohols and Liquefied Gases, Potentially Carbon-Neutral Alternative Fuels for the Maritime Sector.



Source: Carvalho et al [47].

Alcohol and liquefied gases form the second group of fuels, representing options that are not ideal for directly replacing conventional maritime fuels, i.e., non-drop-in fuels. However, their application can be attractive, mainly due to their increased use of dual-fuel engines, which use a pilot fuel to initiate ignition and a primary fuel to complete combustion, in the maritime fleet. Fuels in this group include liquefied biomethane, as well as methanol and ethanol derived from biomass (biomethanol and bioethanol, respectively).

Figure 10: Hydrogen, Ammonia, and Electrofuels, Potentially Carbon-Neutral Alternative Fuels for the Maritime Sector.



Source: Carvalho et al [47].

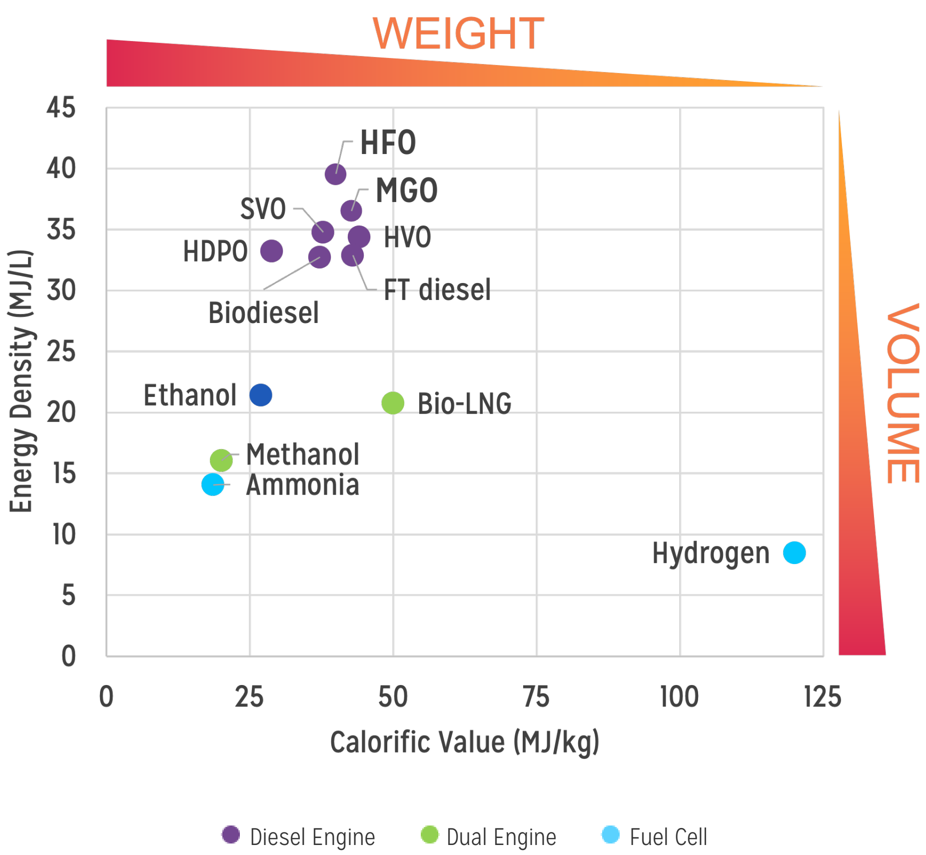
[8] Drop-in fuels can be used in existing ship engines and refueling infrastructure, allowing them to directly replace or be blended with traditional maritime fuels.
[9] Near drop-in fuels are those that require modifications to the fuel supply infrastructure and refueling systems but do not necessitate a different type of energy converter than those traditionally used in the maritime industry.
[10] Pilot fuel is a fuel with properties suitable for initiating ignition under high pressure, used in cases where the primary fuel is a gas or liquid that does not have optimal ignition characteristics under pressure. Typically, diesel is used as the pilot fuel, and this configuration is applied in dual-fuel engines, where combustion is initiated by diesel and sustained by the primary fuel.

Lastly, the third group comprises hydrogen-based fuels, including not only pure hydrogen (H_2) but also ammonia (NH_3) and synthetic fuels. These synthetic fuels, known as electrodiesel, electromethane, and electromethanol, are produced using hydrogen generated through electrolysis and captured CO_2

3.2.2. GENERAL CHARACTERISTICS OF ALTERNATIVE FUELS

Figure 11 presents a comparison between traditional fuels (HFO – heavy fuel oil and MGO – marine gas oil, similar to marine diesel) and some of the alternative fuels mentioned earlier in terms of energy density and calorific value. The lower the calorific value, the higher the weight. Conversely, the lower the density, the more storage space required.

Figure 11: Comparison of Energy Density and Calorific Value Between Traditional and Alternative Fuels



Source: adapted from DNV GL [46]

The liquefied biomethane emerges as an alternative to reduce emissions of sulfur oxides, nitrogen oxides, and particulates [48]. It is a fuel similar to liquefied natural gas (LNG), but its production route is based on biomass [47]. Under atmospheric temperature and pressure conditions, the fuel is in a gaseous state and has low density. To optimize storage, natural gas must be liquefied at a temperature of -162°C and atmospheric pressure, resulting in a significant reduction in the required storage volume [49].

Bioethanol, also referred to as ethanol, is an alcohol largely produced through the fermentation and distillation of biomass containing sugar or starch, such as corn, sugarcane, and wheat [50]. It is highly flammable due to its extremely low flash point, lower energy density compared to traditional fuels, and high carbon content [51].

The characteristics of biofuels can vary according to the raw materials used in their production. Biodiesel, SVO, HVO, HPO, and FT diesel exhibit energy density levels close to those of HFO and MGO when compared to other discussed fuels, suggesting greater potential for enhanced range or reduced storage space requirements. SVO is a biofuel that involves a direct production process compared to other fuels. The production stages include biomass collection, low-temperature seed pressing, and filtration to remove impurities. The fuel quality is significantly influenced by the quality of the raw material and the conditions during production and processing [52].

Compared to traditional maritime fuels, SVO has a slightly lower energy density but higher flash point, viscosity, and acidity levels. These characteristics could potentially lead to corrosion in the engine fuel supply pipelines [53]. Biodiesel, often considered one of the most promising biofuels, is frequently highlighted as a possible substitute for diesel in the road transport sector [34].

HVO is a fuel composed of linear chains of paraffinic hydrocarbons and undergoes additional production steps compared to SVO. HVO stands out for its extremely low sulfur content and minimal emissions [54]. As a paraffinic compound, HVO has a high cetane number, typically ranging from 75 to 95 [55]. Pyrolysis oil, also known as bio-oil or even HDPO, is derived from biomass through a high-temperature process in the absence of oxygen. Depending on the pyrolysis process, HDPO's water content can reach up to 30%, which is sufficient to induce phase separation when stored at room temperature for six months [56].

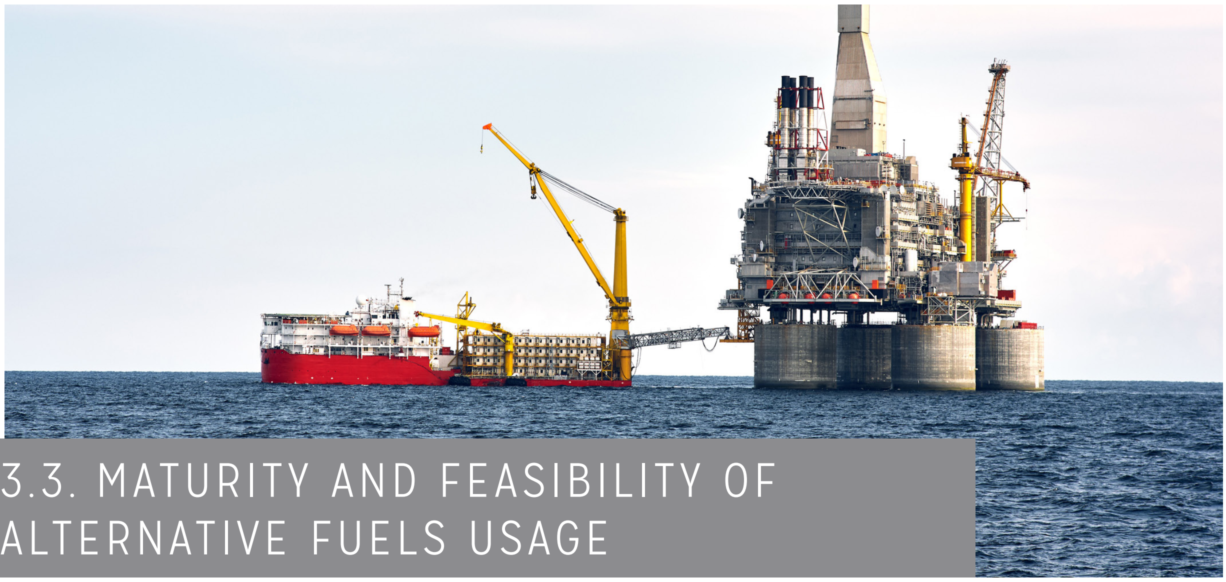
Finally, FT diesel is a drop-in fuel, meaning it can be used directly in diesel engines without requiring modifications to the engines or fueling infrastructure. Additionally, the fuel has a slightly lower density than conventional fuels. In terms of viscosity, both SVO and HDPO exhibit high levels, necessitating adequate measures such as preheating to reduce viscosity. Furthermore, these fuels are also notable for their high acidity levels. Biodiesel has a higher viscosity than traditional diesel, though not as high as SVO or HDPO, hence the recommendation for preheating [57]. HDPO has remarkably high and unstable viscosity, posing challenges for its use as a fuel and its storage [58]. The low flash point of biodiesel limits its practical application in low ambient air temperature conditions [59]. In contrast, HVO has a higher flash point than traditional fuels [55]. FT diesel shows viscosity within the same range as fossil fuels and a higher cetane number, indicating superior performance [60].

The acidity level of SVO, like biodiesel, is linked to its specific raw material, as is the case with biodiesel. While certain vegetable oils may exhibit higher acidity levels compared to HFO, others, such as canola oil, demonstrate relatively low acid values, with an acidity level below 2.5 mg KOH/g [52]. Despite undergoing treatment that reduces acidity by approximately 70%, HPO retains a significantly higher acidity level compared to traditional maritime fuels [58].

Methanol [61] and ammonia [62] are widely used as raw materials in the chemical industry. Due to their high toxicity, safety measures are imperative to prevent leaks and human exposure. Ammonia has been proposed as a potential sustainable hydrogen energy carrier due to its composition of three hydrogen atoms per ammonia molecule (NH_3) [63]. Additionally, the storage of liquid hydrogen requires extremely low temperatures, specifically -253°C [64]. Hydrogen is recognized as a promising maritime fuel, with ongoing tests aimed at advancing its use in the shipping industry. However, as reported by ABS [65], hydrogen currently offers very limited energy output, accompanied by significant costs and restricted production. Moreover, hydrogen storage on vessels presents substantial challenges that the maritime community still needs to overcome.

Ammonia has an energy content 1.7 times greater than hydrogen [66], along with a 50% higher hydrogen content by volume [67], resulting in reduced fuel storage volume requirements. Methanol, which is liquid under atmospheric conditions [68], requires pressurization. Like LNG, ammonia also requires lower temperatures and pressurization to maintain its liquid state during storage. Ammonia can be stored at 25°C under 10 bar pressure, while under atmospheric pressure, the required storage temperature is -33.4°C [66]. Methanol and LNG are both low-flash-point fuels, making them highly flammable. Methanol is flammable and has lower lubrication compared to conventional maritime fuels [53]. Despite its high flash point, ammonia has a lower flame speed compared to conventional fuels. Additionally, ammonia is characterized by its high toxicity [69]. High concentrations of ammonia pose health risks and can be lethal within certain concentration ranges and exposure durations [62]. Finally, ethanol is characterized by a low cetane number, which can result in significant ignition delay, making it unsuitable for use in compression ignition engines [70].

Biodiesel is being tested in ships as a blend with traditional fuels, with established standards; Methanol and LNG are already used in vessels, though sustainable production of these fuels remains in its infancy. HVO and FT diesel, while competing with the aviation and road transport sectors, require fewer adaptations to port infrastructure due to their similarity to maritime diesel. SVO and HDPO require preheating, as does HFO. HDPO requires treatment to reduce acidity and improve stability during storage.



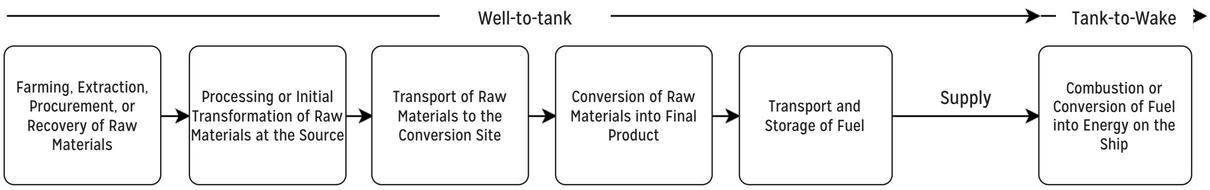
3.3. MATURITY AND FEASIBILITY OF ALTERNATIVE FUELS USAGE

This section provides a discussion on the main alternative fuel options for vessels. It begins by addressing the technological maturity and feasibility of application, followed by an analysis of the potential emission reductions associated with the use of these fuels.

3.3.1. REDUCTION IN POLLUTANT EMISSIONS

With the IMO's new target for 2050, the scope of greenhouse gas emissions analysis for the maritime sector has shifted to a full life-cycle approach. This encompasses the entire process, from the production of the energy carrier to its end-use. This analysis, referred to in the maritime sector as "well-to-wake," must quantify all stages of production, logistics, and fuel usage, as illustrated in Figure 12.

Figure 12: Life Cycle of Maritime Fuel.



Source: IMO, 2023 [71].

In July 2023, the IMO released the Life Cycle Assessment (LCA) guide with the Fuel Lifecycle Label (FLL), standardizing information such as type, raw materials, emissions, and sustainability. The FLL evaluates the entire lifecycle from production to usage, including carbon credits and the full environmental impact. With five parts, it addresses production ("well-to-tank"), usage ("tank-to-wake"), total emissions, and sustainable performance, considering GHG, natural resources, and biodiversity. The goal is to standardize data and production pathways while respecting regional specificities [71].

The LCA methodology, based on ISO 14044:2006, employs an attributional approach, and emission quantification uses the Global Warming Potential index (GWP) over a 100-year time horizon, based on the Fifth Assessment Report of

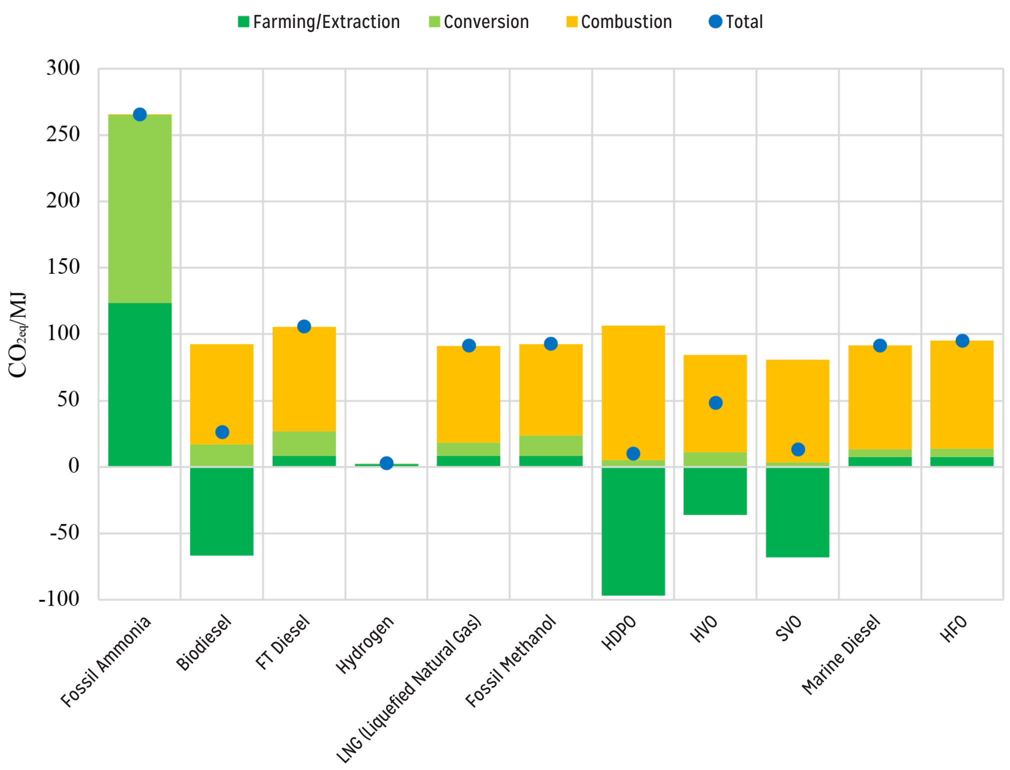
[11] The attributional life cycle assessment (LCA) accounts for the direct environmental impacts of using a specific product. In contrast, the consequential life cycle assessment evaluates not only the direct environmental impacts of the product but also the indirect impacts of its use, making it a more complex analysis [136].
[12] The Global Warming Potential (GWP) measures the radiative forcing following the emission of a unit mass of the main greenhouse gases over a chosen time horizon, relative to the reference substance, carbon dioxide (CO_2). Thus, the GWP represents the combined effect of the different atmospheric lifetimes of these substances and their efficiency in causing radiative forcing [72].

the IPCC. For this index, the 100-year GWP of CO2, CH4, and N2O is such that 1 gram of CH4 and 1 gram of N2O are considered equivalent to 28 grams and 265 grams of CO2, respectively. The GWP unit is expressed in grams of CO2 equivalent (CO2-eq) [72].

The attributional approach considers the entire production chain and fuel use but can be expanded to include Indirect Land Use Change (ILUC), analyzed through a risk perspective on sustainability aspects, with IMO citing biofuel production as an example [71].

As noted in the previous report, the lifecycle emissions of a fuel depend on the production process [12]. This is illustrated in Figure 13, which shows the LCA for various fuels produced in the United States [73], highlighting emissions during raw material cultivation and/or extraction, conversion, combustion, and total net emissions.

Figure 13: Lifecycle Emissions of Selected Maritime Fuels.



Source: Zincir e Arslanoglu [73].

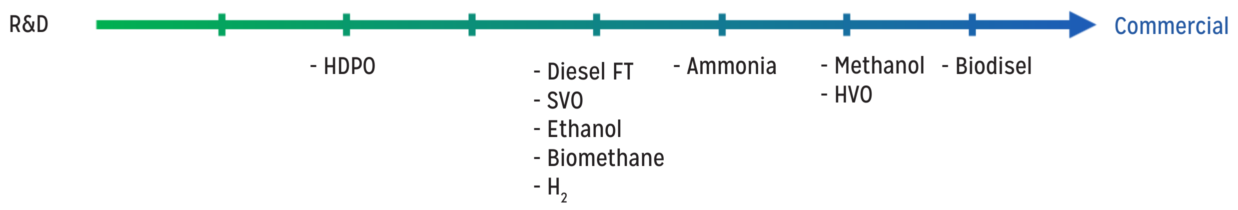
As presented in Figure 13, some alternative fuels are considered to have fossil origins: ammonia, FT diesel, and methanol. Hydrogen emissions are based on an electrolysis production pathway using renewable electricity.

In the study by Zincir and Arslanoglu [73], these fuels are produced from natural gas, which explains why their full life-cycle emission factors are similar to those of traditional fuels. In the case of fossil ammonia, this index is 2.8 times higher than that of HFO. This example highlights that for fuel certification, it is essential to analyze the production process, the region of production, and the raw materials used.

3.3.2. TECHNOLOGICAL MATURITY

In general, the applicability of fuels, considering the production stage and port and vessel infrastructure, has undergone some changes compared to what was presented in the previous report. Figure 14 illustrates the stage of technological maturity for fuels in the context of the Brazilian maritime sector.

Figure 14: Current Stage of Technological Maturity of Alternative Fuels in the Brazilian Context.



Source: Own elaboration.

3.3.2.1. BIODIESEL

Regarding biodiesel, the IMO adopted a directive removing regulatory barriers for blends containing up to 30% by volume of biomass-derived fuels in marine fuel mixtures [74,75]. This directive replaces ISO 8217:2017, which permitted up to 7% v/v of biofuel in such blends [76], allowing a higher proportion of this type of fuel to be used in vessels. The new biofuel blending limit aligns with tests conducted by marine engine manufacturers, which had already tested and approved fuel blends containing 30% biofuels [59]. Thus, from a regulatory perspective, biofuels have seen progress. For biodiesel, tests conducted by Petrobras with up to 24% biodiesel in blends were successful.

In July 2024, the company was authorized by the ANP (Brazilian National Agency of Petroleum, Natural Gas, and Biofuels) to commercialize a marine fuel blend comprising 24% second-generation biodiesel and the remainder low-sulfur heavy fuel oil [77]. Furthermore, the ANP also approved the use of biodiesel as a standalone fuel—referred to as B100—for vessels operated by Hermasa on the route between Porto Velho (RO) and Itacoatiara (AM), starting in April 2024 [78]. Therefore, regulatory advancements have been made concerning biofuels in general, and for biodiesel in particular, within the Brazilian context. Since biodiesel was already considered at a commercial use stage in the previous report, its maturity level remains unchanged.

3.3.2.2. METANOL

As of October 2024, 31 vessels in the global fleet were already using methanol as fuel, with 130 terminals equipped to refuel these ships [79]. This alternative fuel has garnered significant interest among shipowners, and in 2024, approximately 10% of new ship orders by tonnage were for vessels compatible with methanol use [27]. Considering both existing fleets and orders, around 300 methanol-powered ships are in use or on order, including 170 container ships, 50 chemical tankers, and 10 bulk carriers [4]. In terms of technological maturity, despite the growing methanol fleet and increased interest, its maturity level remains unchanged from 2023 due to the continued need for further development of green methanol production.

3.3.2.3. HVO

HVO is a potential substitute for marine diesel due to its compatibility with conventional engines [80]. Tests conducted on trucks and cars in countries such as Germany, Canada, the USA, Finland, and Sweden demonstrated its efficiency, even in extreme conditions, such as in Alberta, Canada, at temperatures as low as -44°C [41]. However, as of 2023, there were no recorded tests on ships [31]. The adoption of HVO in the maritime sector faces challenges, such as limited production, high costs, and competition with the road and aviation sectors [81]. Nevertheless, in February 2024, Petrobras began marketing a blend of fossil diesel containing 5% HVO. Thus, given its production, commercial availability in blends, and high compatibility with maritime infrastructure, HVO is now considered to have reached a high level of technological maturity.

3.3.2.4. AMMONIA

Ammonia currently benefits from an established supply chain network primarily oriented toward its use in the chemical industry [66], with efficient transport by ships worldwide. Advances have been made in using ammonia in ignition engines, including four-stroke engines used in small vessels developed by Wärtsilä [82]. The use of ammonia as a fuel in two-stroke engines has also been announced by major marine engine manufacturers. As of August 2024, 20 ammonia-powered vessels were under construction, including 10 bulk carriers, 9 liquefied gas carriers, 2 oil tankers, and 1 container ship [4]. Thus, compared to 2023, there has been an increase in the technological maturity of ammonia, attributed to the establishment of compatible engines.

3.3.2.5. FT DIESEL

Although FT diesel is identical to its fossil counterpart in physicochemical properties and usability, the integration of the processes involved in producing a fuel via this route remains in development [83]. Furthermore, Fischer-Tropsch processes have yet to be scaled to operational levels, with several demonstration projects in Europe canceled [84]. As such, FT diesel is rated as having a medium level of technological maturity.

3.3.2.6. SVO (STRAIGHT VEGETABLE OIL)

Regarding the direct utilization of vegetable oils, which share some usage similarities with HFO, it is unlikely that blends of these two fuel types would be compatible. Therefore, the most practical and viable solution would be the complete replacement of HFO with SVO. SVO's use in maritime applications is still under investigation, both as a direct substitute and as a blend with conventional fuels [53]. It has been observed that blends containing up to 20% v/v of SVO with diesel do not require changes to engine fuel systems [85]. Additionally, preheating SVO to temperatures between 55°C and 85°C allows for blending proportions of 30% to 60% v/v without requiring modifications to engine structures [86]. Despite regulatory advances common to all biofuels, no recent significant changes targeting its use in maritime engines have been detected. Thus, SVO's technological maturity level remains at an intermediate stage.

3.3.2.7. ETHANOL

Recent advances in ethanol use include its direct application in fuel cells[13], enhancing the energy density capacity of this type of energy converter [87]. Additionally, ethanol production is already well-established, with Brazil being one of the largest biofuel producers globally [88]. Tests on ignition engines for vessels have been conducted by Wärtsilä in partnership with Raízen [89,90], which produces first- and second-generation ethanol[14]. Furthermore, Wärtsilä has signed an agreement with Compagnie Maritime Monégasque (CMM) to supply such engines for the construction of 10 offshore support vessels [91]. Therefore, concerning technological maturity, ethanol has shown growth, reaching an intermediate level.

3.3.2.8. BIOMETANO LIQUEFEITO

The implementation of LNG as a primary fuel for ships is rapidly becoming a commercial reality. By October 2024, 526 vessels were already using natural gas as fuel, and 280 terminals worldwide had refueling facilities for these vessels [79]. Consequently, the LNG refueling infrastructure is firmly established, with all necessary procedures meticulously documented by classification societies, particularly for tanker ships [92]. Thus, LNG operates on a consolidated commercial scale, with increasing use in the maritime sector, driven by its technical viability and robust infrastructure for ships and ports.

In contrast, biomethane, although still at an intermediate technological maturity level (mid TRL), shows significant growth potential. In 2023, global biomethane production surpassed 9 billion cubic meters, a modest volume compared to global demand but representing a significant advance, with production doubling since 2019. It is believed that as biomethane supply evolves, it will be possible to integrate it into the maritime market using the existing LNG infrastructure, given that both can be liquefied and stored similarly. This synergy between fuels could accelerate biomethane adoption, increasing its relevance in the maritime context and contributing to sector decarbonization, although its competitiveness depends on technological and production scale advancements [93].

3.3.2.9. HDPO (ÓLEO DE PIRÓLISE HIDROTRATADO DO INGLÊS *HYDROTREATED PYROLYSIS OIL*)

Regarding its use in maritime engines, HDPO blends with diesel and alcohol should not exceed 40% v/v. There is potential for HDPO to serve as a heavy oil substitute in the future [94]. However, its widespread adoption requires further research and extensive testing [87]. Thus, its development level is in the early stages, and the fuel is rated as having low technological maturity.

[13] Direct Ethanol Fuel Cells use alcohol due to its thermodynamic instability, which makes them, in principle, more easily oxidized, and therefore have a reduction potential close to hydrogen [137].
[14] First-generation biofuels are produced from food crops such as corn and sugarcane, generating conflicts between food and energy production and presenting limited environmental impacts. Second-generation biofuels use non-edible lignocellulosic biomass, such as agricultural and forestry residues, thus avoiding food safety issues. In addition, technological advances allow greater efficiency in the conversion of cellulose into fuels [138].

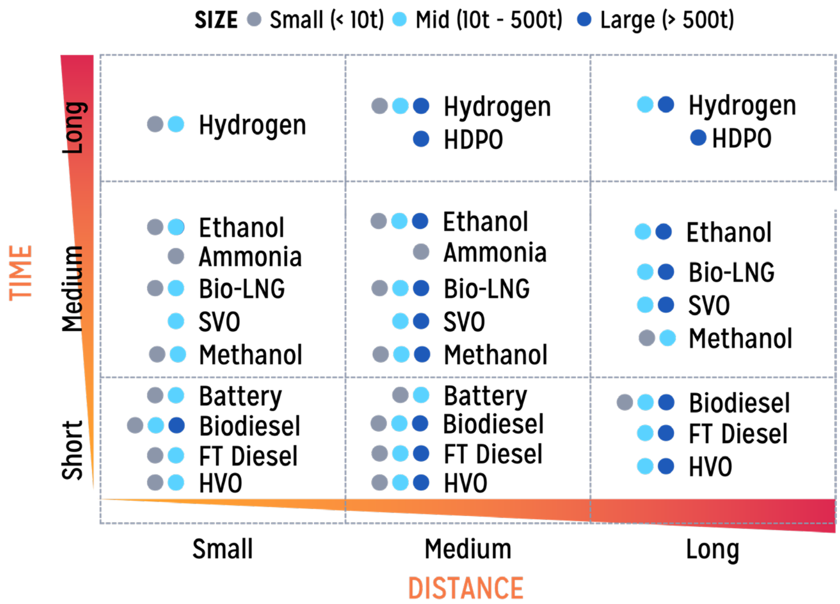
3.3.2.10. HYDROGEN

For hydrogen, advancements include tests using the fuel in ignition engines for small vessels [95], agreements for testing on medium-sized vessels [96], and some small vessels using fuel cells for short distances [4]. However, Amoni et al. [97] emphasize the need for additional research to implement hydrogen refueling in Brazilian ports. Additionally, sustainable hydrogen production remains nascent, its costs are high [65], and the most efficient propulsion system (fuel cells) is still under development. Considering the progress made, hydrogen is now deemed to have reached an intermediate level of technological maturity, especially concerning combustion in ignition engines.

3.3.3. FEASIBILITY OF ALTERNATIVE FUELS AND EMISSION REDUCTION TECHNOLOGIES FOR THE MARITIME SECTOR

The feasibility evaluation for incorporating alternative fuels and technologies was conducted considering fuel properties, the stage of technological development, and relevant economic aspects. Three criteria were used for categorization: vessel route distance, ship size, and time horizon. In general, the feasibility panorama for fuels regarding their full establishment timeline, travel distances[15], and ship sizes[16] is presented in Figure 15.

Figure 15: Feasibility Analysis of Fuels and Emission Reduction Technologies for the Maritime Sector in 2024



Source: Own elaboration.

[15] Routes of up to 100 kilometers, such as those crossing rivers, between nearby cities and between nearby locations, can be considered short-distance routes. Routes of up to 1,000 kilometers, connecting intercity or even interstate locations, are considered medium-distance routes. Transport over distances greater than 1,000 kilometers is considered long-distance.
[16] Small vessels are those that carry up to 10 tons; examples are most boats that transport passengers, such as canoes, yachts, speedboats, schooners, among others. Medium-sized vessels cover the range between 10 and 500 tons transported, such as ships that transport passengers with greater capacity and some ships that transport cargo. Large vessels are those that carry more than 500 tons.

3.3.3.1. SMALL-SCALE VESSELS

For small-scale vessels, these are generally more suited for shorter distances, here considered to be under 1,000 kilometers. This is due to the fact that smaller vessels focus more on passenger crossings or mixed operations between nearby locations. Regarding battery use, as of October 2024, Energy Storage Systems (ESS) were already employed in 324 vessels [79]. Compared to 2023, a significant development is the adoption of biodiesel as a viable short-term fuel, considering the approval for blends with up to 24% biodiesel v/v and its commercialization. Additionally, HVO is emerging as a viable short-term option due to its similarity to current fossil fuels, allowing relatively simple adaptation of existing propulsion systems for its use, similar to FT diesel.

In the medium term, as propulsion systems compatible with biomass-derived methanol and liquefied biomethane become more widespread and these fuels are produced at greater scales, they also become viable options for medium-sized vessels. For liquefied biomethane, infrastructure development for refueling remains necessary within the country. Additionally, ethanol has seen an increase in maturity, shifting from a long-term option to a medium-term one, given the recent tests and the beginning of vessel construction with compatible infrastructure for this fuel. Finally, ammonia also appears as a medium-term option, given ongoing tests and the construction of vessels with ignition engines compatible with this fuel.

In the long term, there are expectations for widespread adoption of fuel cell technology and reductions in hydrogen prices, alongside production viability aligned with demand competition in other sectors. This could make hydrogen a suitable option for small vessels by 2040–2050.

3.3.3.2. MEDIUM-SCALE VESSELS

For medium-scale vessels, the assessment for short- and medium-distance crossings is similar to that for small vessels. However, in the medium term, SVO (Straight Vegetable Oil) becomes a viable option, as medium-sized vessels can accommodate the fuel heating systems necessary for its use. For long-distance routes, batteries are no longer viable, leaving HVO as an alternative. The fuel options for medium and long-term applications are similar to those for small vessels, including SVO, liquefied biomethane, ammonia, and ethanol for the medium term, and hydrogen for the long term, potentially using fuel cells.

3.3.3.3. LARGE-SCALE VESSELS

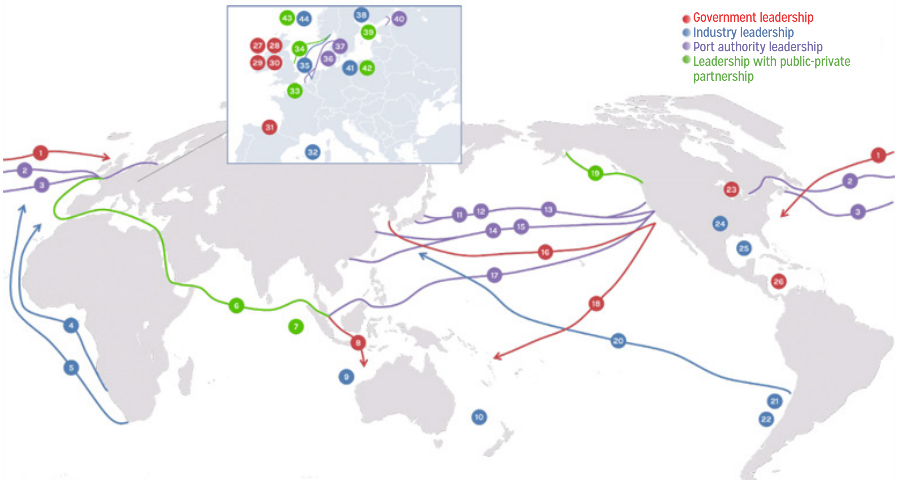
For large-scale vessels, predominantly used for medium- and long-distance cargo transport, batteries are not considered viable due to the size of the vessels and the longer distances involved. In the short term, the use of HVO and FT Diesel is a viable option, providing a reduction in carbon dioxide equivalent emissions, with economic concerns highlighted due to the high cost of these fuels. In the medium and long term, fuel options are similar to those for medium-sized vessels, including biodiesel, SVO, liquefied biomethane, methanol, hydrogen, ammonia, and ethanol, with potential applications for fuel cells in the long term.

3.3.4. GREEN CORRIDORS

Green corridors are maritime routes between two or more ports where greenhouse gas emissions are eliminated through the use of zero-emission or near-zero-emission energy sources. These corridors have gained prominence recently within the naval community and among global leaders. Given the IMO's 2030 demand for zero- or near-zero-emission technologies or fuels, this strategy becomes a potential catalyst to facilitate the dissemination of alternative fuels and, consequently, achieve short-term goals. During the November 2021 Conference of the Parties (COP), the objective was set to create at least six green corridors by 2025 [98]. To achieve this, involved ports must ensure the availability of sustainable fuels, and all stakeholders in the routes must commit to allocating resources for the decarbonization of these corridors [99].

According to the Getting to Zero Coalition [100], as of October 2023, 44 green corridors were either under analysis or implementation, with the highest concentration in Europe, Asia, and North America. The industry is directly involved in 14 of these corridors, while governments and port authorities lead 11 each. Public-private partnerships are engaged in 8 corridors. Figure 16 shows the planned routes and their respective leaderships.

Figura 16: Green corridors under study or implementation in 2023.



Source: adapted from Getting to Zero Coalition [100].

In Figure 16, it is possible to observe that there are three corridors originating from South America, all departing from Chile and focusing on the following products: copper concentrate, aquaculture, and sulfuric acid. Therefore, among the cited corridors, none include Brazilian ports or terminals. In a preliminary report from 2021, the mention of an iron ore route departing from Brazilian ports and destined for Asian countries, primarily China, is noted. However, despite the corridor's high potential for reducing emissions in the maritime sector, the segment was deemed low feasibility for conversion to the use of low or zero-emission fuels due to high costs [99].

Regarding sustainable fuels for these routes, methanol stands out as the primary energy option in 14 corridors, followed by ammonia, hydrogen, electricity, and second-generation biofuels, discussed in 9, 6, 4, and 2 corridors, respectively. Many corridors do not yet have a specific type of vessel defined, although container ships, ferries, roll-on/roll-off[17] vessels (Ro-Ro), bulk carriers, and tankers are the predominant vessel types in 11, 8, 6, and 3 of the analyzed corridors, respectively.

[17] Vessels dedicated to cargo transportation, where the cargo is loaded and unloaded with the assistance of vehicles or as rolling cargo through ramps [139].

4. CURRENT PANORAMA OF THE BRAZILIAN MARITIME SECTOR'S DECARBONIZATION

The decarbonization of Brazil's maritime transportation sector, as well as its transportation sector in general, is underway through industry efforts, government initiatives, and strategic partnerships. The energy transition in this mode of transport should not rely on a single alternative fuel but rather on the adoption of a mix of fuels suited to vessel characteristics, infrastructure availability, and local production. Despite needing more development and dissemination within the Brazilian community, the topic of energy transition for Brazilian vessels has gained more traction, with several initiatives standing out.

A significant first step dates back to 2021, when Brazil's Ministry of Mines and Energy (MME) initiated a program to promote the analysis and development of sustainable technologies applicable across all modes of transport, including maritime transport. The Brazilian government, in collaboration with the Navy and other relevant stakeholders, regularly organizes meetings to discuss and implement measures that favor carbon emissions reduction in the country's maritime sector [101].

The "Fuels of the Future" bill, announced in 2023, encompasses several actions aimed at decarbonizing transport. These include increasing the proportion of ethanol and biodiesel in gasoline and diesel blends, respectively; regulating synthetic fuels; gradually introducing green diesel; implementing geological carbon capture and storage; and progressively incorporating bio-jet fuel into aviation fuel blends [102]. This bill was enacted in October 2024 [103], emphasizing incentives for green diesel, biomethane, and carbon capture production, which could serve as pillars to catalyze measures for reducing emissions in Brazil's maritime sector. Additionally, discussions about investments and incentives for producing lower-emission fuels [104], alongside regulations [105] and incentives [106] for hydrogen production as fuel, have emerged.

On the other hand, as cited in section 3.3.2, the new IMO target has driven efforts to quantify the life cycle emissions of energy carriers used by ships. This has led to debates about indirect emissions, particularly indirect land use change (ILUC), heavily associated with biofuel production. Quantifying emissions linked to land-use changes for biomass production is fraught with uncertainties since ILUC emission factors reported in the literature vary widely [107]. At the October 2024 MEPC meeting, Brazilian representatives advocated that the country has areas previously used for pastures, which are moderately to severely degraded and could be used for agricultural production [20]. Biomass production in these areas would reduce competition between food and fuel production, thereby lowering ILUC emissions [108].

From the industry perspective, the successful tests of fuel blends containing 24% biodiesel by volume, alongside the commercialization of this fuel (referenced in section 3.3.3), highlight the progress in using lower-emission resources in national vessels. Additionally, the commercialization of diesel with a 5% HVO blend [109] is noteworthy. Regarding the supply of such fuels at Brazilian ports and terminals, an agreement was reached in July 2023 between Brazilian ports and maritime industry companies to promote alternative fuel use [110]. In September 2024, these organizations released a guide with recommendations for decarbonizing Brazilian ports and vessels, detailing the electrification of port equipment and vessels, alternative fuels use, and green corridors [111]. Given the limited number of Brazilian ports with infrastructure for alternative fuel supply, these initiatives are considered essential to modernize the country's maritime infrastructure [31].

Regarding current infrastructure, ports in Santos, Rio Grande, Paranaguá, and Salvador have the capacity to supply ammonia. Ports capable of supplying methanol are located in Santos and Paranaguá [79]. As for biodiesel, since 2013, this fuel has been transported by ships departing from ports such as Belém, Itacoatiara, Itaituba, Manaus, Paranaguá, Porto Velho, and Rio Grande. Additionally, the transport of vegetable oils (soybean and palm) is already carried out through terminals and ports in cities like Barcarena, Belém, Manaus, Paranaguá, Porto Velho, Santos, Recife, Rio de Janeiro, Rio Grande, and Santarém [11]. This indicates that these terminals and ports already have infrastructure for handling vegetable oils and their derivatives.

Furthermore, Itaqui Port (MA) partnered with Transpetro in March 2024 to enable diesel with HVO blends supply and the adoption of sustainable fuels for the port's fleet and equipment [112]. Paranaguá Port plans to begin LNG operations in 2025 [113] and is evaluating the installation of a biodigestion plant to produce biomethane [114]. Pecém Port proposed creating a hydrogen hub in 2021 [115], adapting its infrastructure for fuel transport and handling with processes similar to LNG and ammonia. Similarly, Açu Port, in partnership with Shell, plans to produce and supply hydrogen and ammonia [116], while Suape Port is developing projects for using these fuels [117].

Lastly, the Amazon region could also become a significant starting point. According to the New Amazon Economy report [118], the region heavily relies on vessels for passenger and cargo transportation. Moreover, the area accounts for over 50% of Brazil's maritime transport sector's energy demand. Much of this transport involves short-to-medium distances and small vessels. Therefore, investments in electrifying small vessels, which are more adaptable to battery energy storage, could be a strategic focus for this specific region.

5. NORWEGIAN MARITIME DECARBONIZATION EFFORTS

Regarding Norway, a country with significant influence in international maritime transport, it boasts the largest fleet of ships under its flag and stands as a global leader in maritime technology innovation [119]. Norway also plays a key role in sustainability, being a pioneer in adopting decarbonization measures for maritime transport. Although projections indicate that, in 2023, Norway's overall measures may not be sufficient to meet its national short- and long-term emission reduction targets, the transportation sector stands out for aligning with the objectives set for this area [120]. In this context, the country's maritime transport sector is a global leader in adopting strategies that combine energy efficiency measures with lower-emission fuels. While the global fleet comprises approximately 2% of ships using or compatible with alternative fuels, around 50% of these ships are registered under the Norwegian flag [121].

Regarding green corridors, of the 44 routes announced as of November 2023, five include Norwegian ports or terminals [100]. In this scope, in March 2024, the construction of the first low-emission ammonia refueling terminal was approved in the Norwegian city of Florø. This terminal will feature a barge with a capacity of 650 tons of ammonia [122]. Investments in vessels capable of accommodating low-carbon energy vectors have been growing. In June 2024, the Norwegian state-owned company ENOVA SF announced a $113 million investment to fund 15 sustainable navigation projects, including nine focused on hydrogen and six on ammonia, aiming to reduce cost differences between alternative and traditional fuels [123].

Beyond government actions to decarbonize Norway's maritime sector, companies have also made significant advances in this area. One example is the Viking Energy, a ship owned by the Norwegian company Eidesvik and operating for Equinor, which will be converted to use ammonia by 2026 [124]. Additionally, the Norwegian shipyard Myklebust Verft announced the construction of two ferries powered by green hydrogen that will operate on a 278 km route in the Arctic Circle. The plan is for these ferries to use green hydrogen as fuel for at least 85% of their operations, with biodiesel as an alternative. Each ferry is being designed with a length of 117 meters, capacity for up to 120 cars, and the potential to reduce up to 26,500 tons of CO_2 annually [125].

Lastly, it is worth highlighting the inauguration of a large-scale Carbon Capture and Storage (CCS) plant in the Norwegian city of Øygarden, with an initial capacity to store approximately 1.5 million tons of CO_2 annually [126].

6. OPPORTUNITIES FOR COLLABORATION BETWEEN BRAZIL AND NORWAY

Despite their different contexts, both Brazil and Norway maintain investments in initiatives aimed at reducing emissions in the maritime sector. Brazil has heavily invested in solutions related to biomass, while Norway focuses on the use of green hydrogen and ammonia. Norway holds a prominent position in the decarbonization landscape of maritime transport, being a pioneer in employing hydrogen fuel cells and establishing a green ammonia terminal.

Investments in biomass-derived fuels, which are crucial for meeting the IMO's short-term goals and establishing the sector's long-term energy transition, represent a significant opportunity for Brazil's maritime sector. The debate surrounding life cycle assessment methodologies, particularly concerning indirect emissions linked to land use, must be emphasized and intensified. As highlighted in this report, uncertainties due to the wide variability of emission factors can significantly impact not only decision-making for meeting the maritime sector's energy demands but also the entire global logistics chain. Parallel to this, investments in the production of alternative fuels like hydrogen and ammonia in Brazil [127] align with Norway's example of investing in such fuels, as discussed in Chapter 5.

A synergy between the two nations lies in Norway's investments in the Amazon Fund, which primarily aims to combat deforestation in the Amazon rainforest [128]. In alignment with this initiative, a potential action could involve sharing Norway's expertise in electrifying small and medium-sized vessels with Brazil, particularly for use in the Amazon region. This area heavily relies on waterways for passenger and cargo transportation, mainly for short- and medium-distance routes. Additionally, cooperation based on Norway's experience with carbon pricing policies and incentives for alternative fuels could be adapted to the Brazilian context.

From the perspective of energy efficiency technologies, partnerships between Brazilian and Norwegian companies are expanding. For example, as mentioned earlier, the partnership between Vale and Kongsberg for monitoring vessel consumption rates to optimize operations [129]. Similarly, Brazilian companies such as Posidonia [130] and Locar [131] have also adopted Kongsberg technology to optimize their fleet's fuel consumption.

Finally, considering the IMO's requirement to use at least 5% fuels with zero or near-zero emission levels by 2030, the establishment of green corridors is a promising alternative. As seen in Chapter 5, five routes announced include Norwegian ports or terminals. However, no routes with origin or destination in Brazil have been announced. Despite this, studies have addressed routes such as those for iron ore [132] and soybeans between Brazil and China [133], which have high energy demand and economic importance for the country. Efforts could also explore potential routes to Europe, including Norway, which receives key Brazilian exports such as aluminum, oil and derivatives, and soybeans [134].

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