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Decarbonization Alternatives for Brazil's Seaborne Transportation Industry

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1. INTRODUCTION

Seaborne transportation plays a significant role within the global economic sphere, representing around 90% of global trade transactions in terms of tonnage[1,2]. Seaborne transportation not only plays a crucial role in the international merchandise trade but also is more fuel-efficient than other modes of transportation when considering a certain mass carried for a certain distance[3]. In 2021, iron ore, seeds, oilseeds, fuels and distillation products answered for 45% of Brazil's total export revenue and for about 76% of total export tonnage[4,5]. As with other types of goods, seaborne transportation played a preponderant role in the shipment of those items, so that the maritime industry is key not only for the global economy but also for Brazil's.

At the same time, the growth in greenhouse gas emissions has raised concerns regarding the global climate scenario. The average temperature of the Earth's surface increased by 1.5°C between 2006 and 2015 compared to the period from 1850 to 1900[6]. That growing concern about the impacts of human activity on our planet, especially due to the emission of polluting substances, drives the effort to reduce emissions across all industrial sectors, including the maritime industry. The global energy demand of the vessel fleet was responsible for the consumption of 10.6 exajoules (EJ) in 2018[7]. The maritime industry emitted a significant volume of carbon dioxide (1.056 billion tonnes), corresponding to some 3% of world emissions. Seaborne transportation represented approximately 0.5% of Brazil's emissions in 2021. One strategy designed to reduce emissions was the creation of regulations to standardize parameters such as speed, power and fuel consumption limits. However, the great diversity in terms of vessel construction and operation raises substantial hurdles to that approach. Implementing the relevant standards may create disadvantages for vessels that use more environmentally-responsible operating practices[8].

In an effort to curb polluting gas emissions, the International Maritime Organization (IMO) has established an ambitious target for 2050: to neutralize greenhouse gas emissions by and/or around 2050[9]. Switching to low- or zero-emission fuels and enhancing energy efficiency are promising alternatives[10] to reduce the emissions of major greenhouse gases such as carbon dioxide, methane and nitrous oxide[11]. It is then not surprising that the use of alternative fuels is attracting great interest from the naval community.

Improved hull shapes and propulsion systems may optimize ship operations leading to better overall vessel energy efficiency. Any such optimization will be effective only if ships operate within their design specifications, that is, within the recommended speed range. Speed, consumption and emissions monitoring systems will greatly help the oversight and use of those technologies[14].

The technical and scientific community is working on seaborne transportation decarbonization actions and, among the countries that invest the most in said actions, Norway stands out as world leader in the effort to adopt low- or zero-emission carbon technologies[15].

This report aims to map promising decarbonization paths for Brazil's maritime industry, and each one's abatement potential, and to find potential opportunities to exchange experiences with Norway. Chapter two in this report describes Brazil's maritime transportation industry. Chapter three addresses various decarbonization options, focusing on alternative fuels. Chapter four provides an outlook of the current decarbonization efforts of Brazil's maritime industry. Chapter five gives an outlook of the decarbonization of Norway's maritime industry and, finally, chapter six shows how Brazil and Norway can cooperate in furtherance of the sustainability of seaborne transportation.

2. DESCRIPTION OF BRAZIL'S MARITIME INDUSTRY

Brazil's maritime industry encompasses a 2281-vessel fleet[4] and more than 380 ports or terminals[16].

Port activities are of paramount importance for Brazil's economy, representing approximately 14% of Brazil's GDP (Gross Domestic Product) [17]. Figure 1 shows Brazil's major domestic routes and ports.

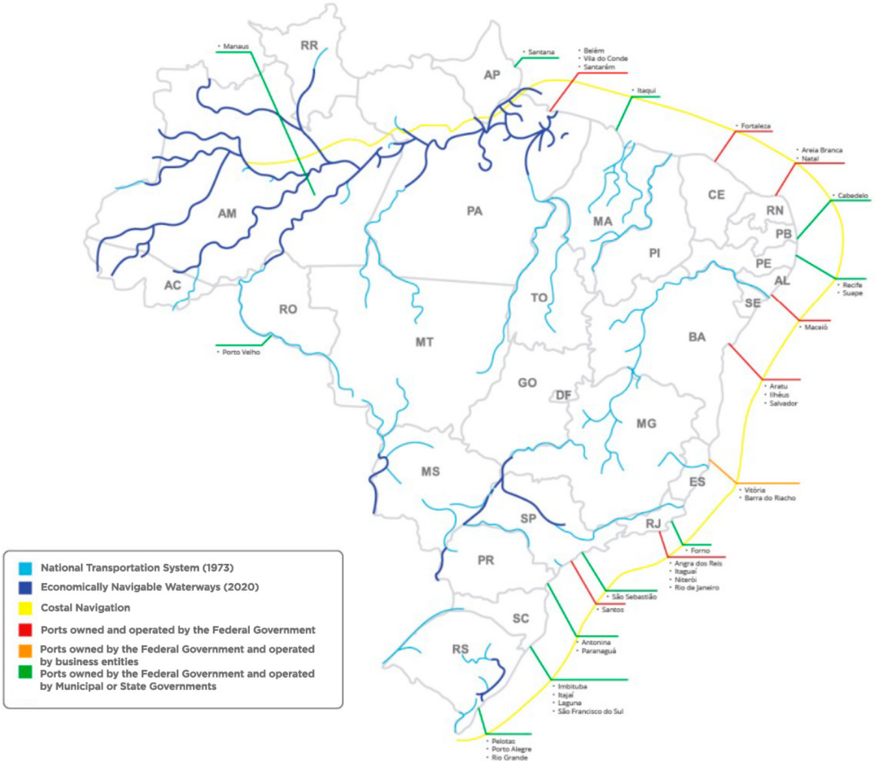

Figure 1: Main Brazilian ports and waterways. Source: ANTAQ[18].

According to ANTAQ (National Sea and Inland Waterway Transportation Agency), Brazilian ports and terminals handled in 2021 more than 1.2 billion tonnes of cargo in approximately 400,000 berthings[4]. The busiest cargo route connects Ponta da Madeira, in Maranhão, to the port of Qingdao, in China, and involves mainly iron ore. That route answered for approximately 130 million tonnes, corresponding to 18% of Brazil's total sea and inland waterway cargo tonnage in 2021. Most cargo falls into one of four categories: solid bulk, liquid and gas bulk, containers and general cargo. Figure 2 breaks down by type the cargo tonnage handled from 2011 to 2021, while Figure 3 shows the number of trips made by type of cargo from 2011 to 2021. Major solid bulks are iron and other ores, coal, grain, bauxite and phosphate, and oilseeds. Bulk cargo is usually carried on especially-designed ships and are loaded directly onto the ship, without any packaging[19]. Adding to about 707 million tonnes, that type of cargo represented 58% of the total cargo Brazilian ports handled in 2021.

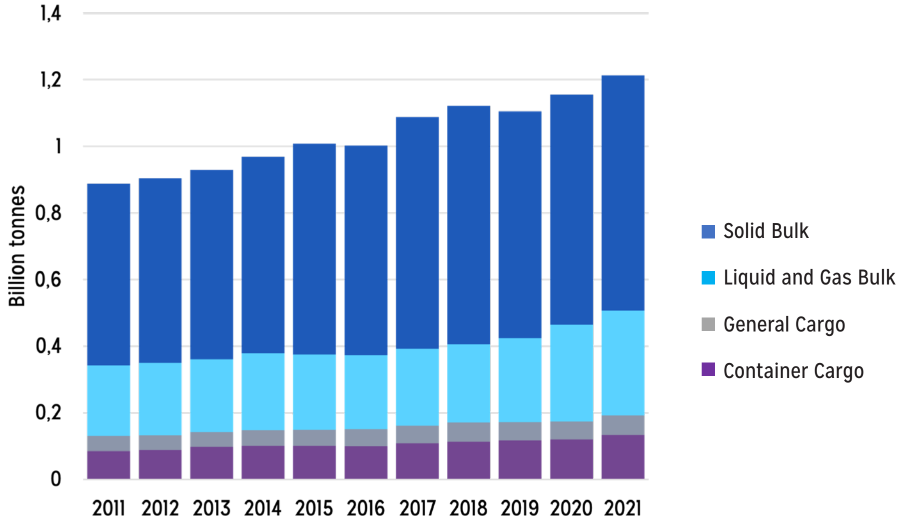

Figure 2: Tonnage handed in Brazilian ports from 2011 to 2021 by type of cargo. Source: adapted from ANTAQ[4].

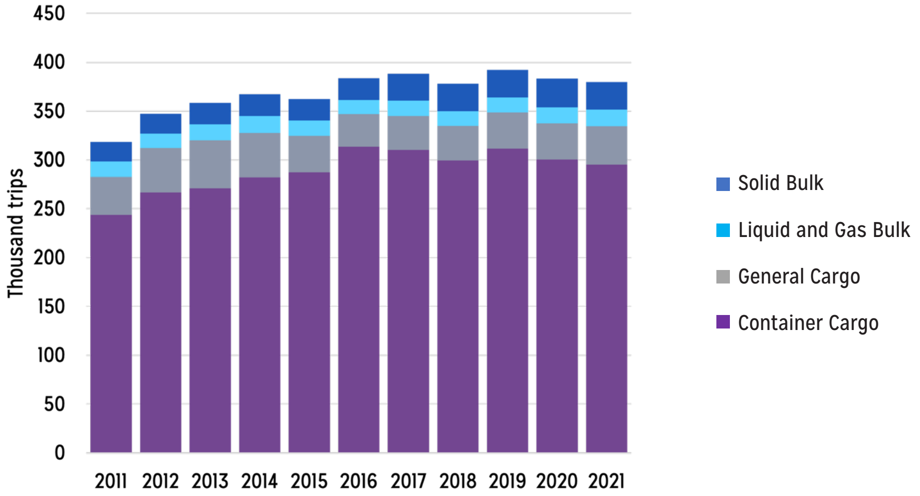

Figure 3: Number of trips to and/or from Brazilian ports by type of cargo carried from 2011 to 2021. Source: adapted from ANTAQ[4].

Iron ore, corn and soybeans stand out, accounting respectively for 52%, 16% and 4% of the total tonnage handled. As to the number of berthings, this type of cargo was responsible for more than 28,000 berthings in 2021, representing 7% of total berthings in Brazilian ports. More than 10% of them occurred on the route connecting Portochuelo Terminal, located in Porto Velho, state of Rondônia (RO), to Hermasa Terminal, located in the city of Itacoatiara, state of Amazonas (AM), used for corn and soybeans.

Liquid and gas bulk can be divided into two main categories: vegetable oils (edible or not) and petroleum oils and gases (Khan et al. 2016). Much of that type of cargo is concentrated on routes from oil production fields to the Brazilian coast, mainly to the ports of Angra dos Reis and Açu, in Rio de Janeiro (RJ), and São Sebastião, in São Paulo. Those routes answered for about 26% of the total liquid and gas bulk tonnage Brazilian ports handled in 2021. The vast majority of the almost 17,000 berthings for liquid and gas bulk cargo occurred in 2021 involved oil and oil products. The busiest routes were those from Ilha D'Água Terminal to Guanabara Bay Terminal, in Rio de Janeiro, and from Terminais Fluviais do Brasil, in Itacoatiara (AM), to Manaus (AM). Those two routes involved more than 600 berthings each, and together they represent 8% of berthings for that type of cargo.

The term "general cargo" encompasses products ranging from goods stored in sacks, boxes, crates and drums to large-size machinery parts or vehicles. General cargo requires careful storage because it comes in different sizes and shapes. Approximately 60 million tonnes of that type of cargo were handled in 2021. Chemical wood pulp and semi-manufactured iron or steel products represented respectively 33% (more than 19 million tonnes) and 14% (more than 8 million tonnes) of the total tonnage of this type of cargo handled in Brazilian ports and terminals.

The busiest route for chemical wood pastes connects Guaíba to Rio Grande, both in the state of Rio Grande do Sul, with more than 3.1 million tonnes carried. In relation to semi-manufactured iron or steel products, the route from the Thyssenkrupp terminal, in the city of Rio de Janeiro (RJ), to Brownsville, in the United States, was the one of the busiest, with around 1.9 million tonnes carried in 2021. In relation to berthings, this type of cargo involved some 39,000 trips in 2021, and the route from Belém to Manaus was the busiest (5127 trips).

Finally, containers are unitized cargoa measured in TEU (twenty-feet equivalent unit, corresponding to a length of 6.1 meters). The containers that passed through Brazilian ports in 2021 added to more than 133 million tonnes, with no concentration in any one route. The busiest route connects Vitória, in the state of Espírito Santo (ES), to Santos, in São Paulo, with approximately 2.2 million tonnes, corresponding to approximately 1.7% of total container traffic in the country in that year. As to the number of berthings, container handling dominated seaborne transportation, with more than 295,000 trips in 2021, equivalent to 78% of all trips. Major routes included Santos to Pecém, the latter in the state of Ceará, with 1957 berthings, Suape, in Bahia, to Santos, with 1649 berthings, and Pecém to Santos, with 1541 berthings.

There are 5 types of navigation: maritime support, port support, coastal, inland navigation and long-distance navigation. Figure 4 shows the cargo handled and the number of trips to and/or from Brazilian ports by type of navigation in 2021. Support navigation, both maritime and port, represented a minuscule volume of cargo handled and number of berthings for the years in focus. On the other hand, inland, coastal and long-distance navigation represented in 2021 respectively 5%, 24% and 70% of total cargo handled, and 15%, 20% and 64% of total trips to and from Brazilian ports and terminals.

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[a] Cargo unitization is the process of reorganizing and grouping goods to reduce handling work so as to optimize the cargo handling process. Its purpose is to arrange cargo as "units" that can be placed onto a base, usually a pallet, that can be more efficiently lifted and carried by mechanical handling equipment.

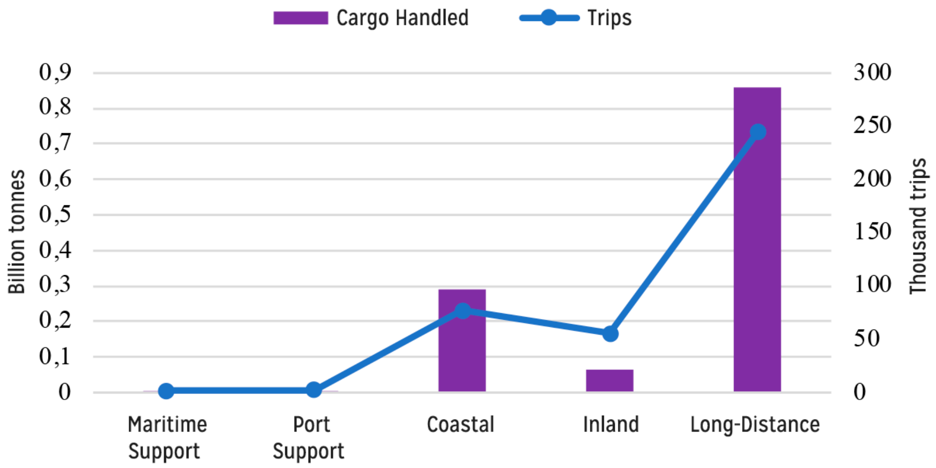


Figure 4: Cargo handled, in billion tonnes, and number of trips to and/or from Brazilian ports in 2021 by type of navigation. Source: adapted from ANTAQ[4].

Long-distance navigation connects Brazilian and foreign ports [17]. Much of the long-distance cargo goes to the port of Qingdao from the ports of Ponta da Madeira (MA), Ilha da Guaíba (RJ), Itaguaí (RJ), Tubarão (ES) and Angra dos Reis (RJ), which in 2021 handled more than 193 million tonnes, largely iron ore, representing 23% of long-distance cargo and 15% of total cargo handled in Brazilian ports and terminals. Regarding the number of trips, the container route connecting Shanghai, China, to Santos (SP) is the busiest one, with 1423 trips in 2021. The contrast between the routes with the largest cargo tonnage and those with the greatest number of trips stems from the added value of the relevant goods: low-added-value iron ore is carried in greater volumes and fewer trips, with an average load of approximately 27,000 tonnes per trip, while containers carry high-added-value goods and for that very reason are shipped in lesser volumes and in more trips, so as to make shipment more efficient, with an average load of approximately 364 tonnes per trip. In addition to iron ore, soybeans and oil and oil products also have a heavy presence in this type of navigation. Together the 3 types of product represent more than 60% of the long-distance cargo carried between 2011 and 2021.

Coastal navigation connects ports or points in Brazilian territory by sea or inland waterway[17]. Some routes in that type of navigation can be very busy, such as the route between Santos, in the state of São Paulo, and Pecém, in the state of Ceará, used mainly for containers. However, that type of navigation involves approximately one third the cargo tonnage and the number of trips of long-distance navigation.

Inland navigation takes place on domestic or international inland waterways[17]. The busiest such route connects Belém and Manaus and is used mainly to carry machinery and vehicles. The Porto Velho-Itaituba (PA) route is also significant and is used to carry large volumes of corn and soybeans.

As to the energy consumption of Brazil's maritime industry, Figure 5 shows its energy demand, in billion liters of fuel, either heavy fuel oil (in red) or marine diesel oil (in orange), for 2009-2021.

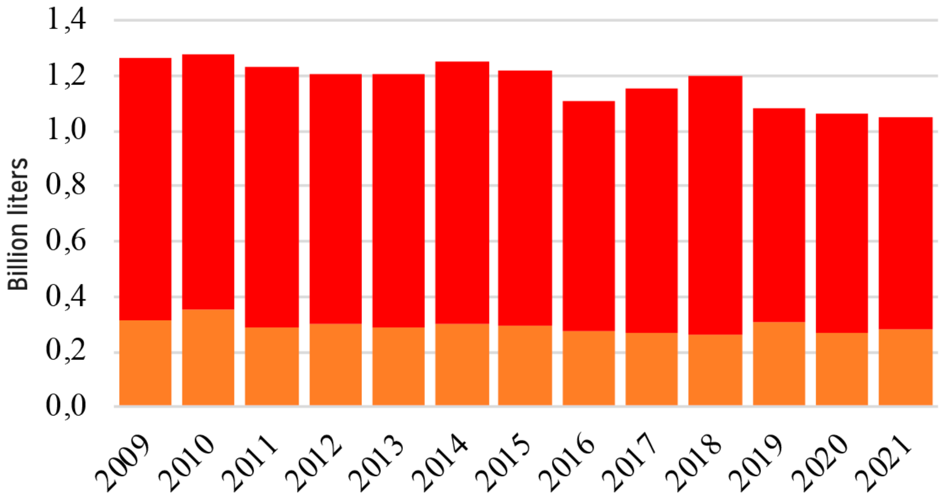


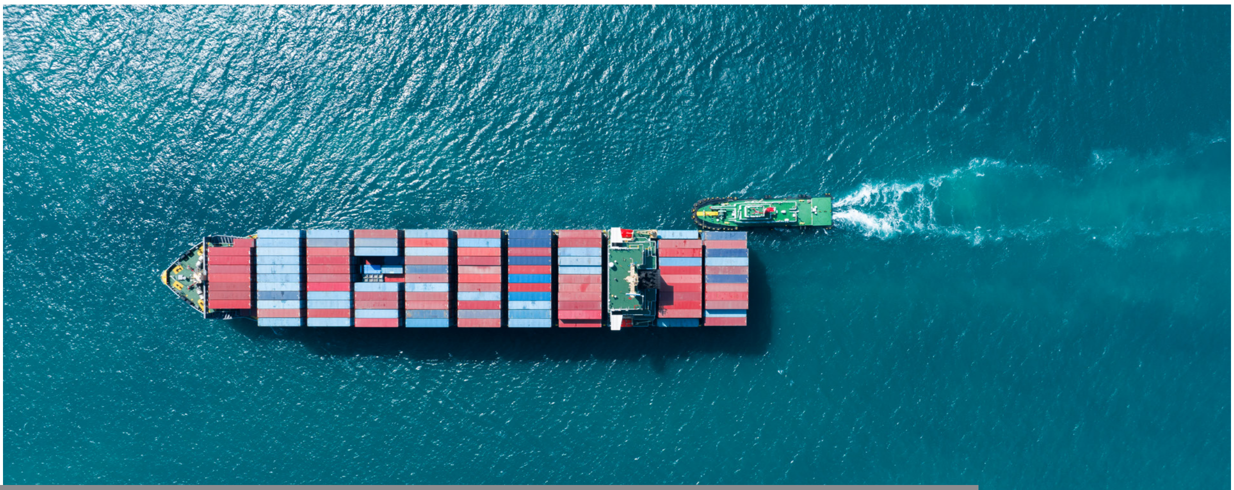
Figure 5: Energy consumption of Brazil's seaborne transportation from 2009 to 2021. Source: EPE[20].

Annual consumption during that timeframe averaged some 1.2 billion liters, showing a downward trend of approximately 1.5% p.a. In 2021, the most recent year for EPE data, consumption amounted to 1.047 billion liters, of which 762 million liters of fuel oil and 285 million liters of diesel. That consumption caused the direct emission of 2.4 million tonnes of carbon dioxide equivalent (CO2eq) for fuel oil and 0.8 million tonnes of CO2eq for diesel consumed, so that the total for seaborne transportation was 3.2 million tonnes CO2eq. Ships powered with fuel oil are mostly large, ply longer routes and are equipped with 2-stroke engines, used by 72% of ships in the world fleet. Smaller vessels, such as maritime support ships and tugboats, opt for 4-stroke engines, present in 26% of the world fleet according to IMO data for 2018[7].

The energy demand of vessels operating in Brazilian waters in 2021 corresponded to 1.3% of the transportation industry's total demand and to 0.7% of the country's overall energy demand [20], which shows that sea and waterway transportation is an energy-efficient mode to carry both freight and passengers. Sea and inland waterway transportation can greatly contribute to optimize the energy consumption of Brazil's transportation industry. That transportation mode generated 1.8% of the industry's emissions and only 0.2% of Brazil's total emissions in 2021 but carried a small proportion of freight and passenger traffic when compared to highway transportation. That said, the fuels currently used are hard to replace and Brazil's naval community must find alternatives to curb the industry's emissions in alignment with the IMO's targets.

3. DECARBONIZATION OPTIONS FOR THE MARITIME INDUSTRY

This chapter is divided into four parts. The first discusses the potential decarbonization actions each group of players in the maritime industry can develop. The second part focuses on the production of alternative fuels. The third part looks at the technological maturity of alternative fuels and at the feasibility of their widespread use on ships. Finally, the fourth part addresses the emission reduction potential of alternative fuels.



3.1. ACTIONS TO DECARBONIZE THE MARITIME INDUSTRY

Different perspectives must be considered to find a common solution to decarbonize the transportation industry, involving two opposing approaches for the maritime industry: the perspective of government and regulatory entities, which focus on actions to achieve decarbonization goals, 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 repercussions on their businesses[21].

We have here divided maritime industry players into four main categories: government and regulatory entities, shipowners and operators, research institutions and shipbuilders and energy industry. Each such group can take different paths to curb pollutant emissions. Figure 6 shows key potential actions for each group of players.

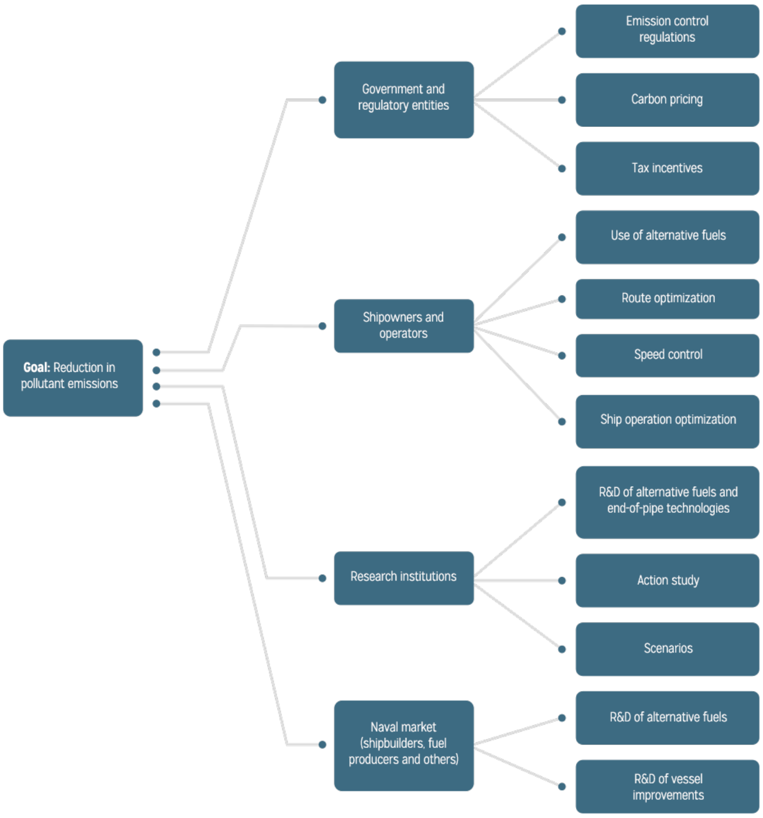


Figure 6: Potential actions that each group of players can take to reduce the maritime industry's pollutant emissions.

Those actions are presented according to the pertinent group of players shown in Figure 6 and will be better described below.

3.1.1. GOVERNMENT AND REGULATORY ENTITIES

This group includes national governments, government members, transportation, energy and environmental ministries and agencies, as well as organizations such as the United Nations represented by the IMO. The policies and regulations established by those players are important to facilitate the reduction in the emission of polluting gases[22].

3.1.1.1. EMISSION CONTROL REGULATIONS

Emission control is a tool already used in some parts of the world: in addition to decarbonization targets, the IMO has established Emission Control Areas (ECA) for sulfur dioxide in the Baltic Sea, in the North Sea and the US portion of the Caribbean Sea [21]. Emission control targets and regulations are important to put pressure on other maritime industry players to reduce their emissions and to invest in new technologies. Furthermore, national governments tend to use a more stringent oversight of maritime industry pollution as a means to achieve targets and to comply with regulations.

3.1.1.2. CARBON PRICING

Another alternative open to government entities is to put a price on the pollutants a certain fuel emits. In this alternative, shipowners and operators will pay a fixed fee based on fuel consumption and part of the proceeds can be used to, for example, fund greenhouse gas emission reduction projects[21].

3.1.1.3. TAX INCENTIVES

Tax incentives and subsidies given by government entities are another form of emissions-related stimulus. The reduction of vessel air pollution can be fostered through subsidies instead of charges or taxes that operate as penalties. Those incentives can be made through concessions or loans given by government entities or maritime authorities to reduce the cost of curbing maritime industry pollutant emissions[23]. Other subsidy mechanisms are donations, lower tax rates, bidding systems, purchase of carbon credits and other types of financial aid. The Port of Hamburg, for example, for a certain time used public funds to reduce port fees for ships that met certain emission criteria[24].

3.1.2. SHIPOWNERS AND OPERATORS

Shipowners may or may not choose to operate the ships they own. They can engage shipping companies to operate their ships, so that the operator of a certain vessel is not always its owner[25].

3.1.2.1. USE OF ALTERNATIVE FUELS

The large-scale use of carbon-neutral fuels is one of the most promising alternatives to meet the IMO's new decarbonization and desulfurization targets. There are numerous potential alternative maritime fuels and finding the ideal one for the energy transition is no easy task.

3.1.2.2. ROUTE OPTIMIZATION

Thanks to current high-accuracy weather and sea conditions forecast technologies, operators can choose the most energy-efficient routes by plotting courses that avoid areas with poor sailing conditions. Route optimization not only reduces the operator's costs but also reduces fuel consumption and thus causes lower pollutant emissions[21].

3.1.2.3. SPEED CONTROL

The relationship between fuel consumption and sailing speed is not linear, but rather proportional to the cube of vessel speed. Thus, a small decrease in speed can lead to a significant reduction in fuel consumption[26]. Speed can be decreased through operating or technological actions. The former is commonly referred to as "slow steaming", while the latter is achieved by reducing vessel installed power[21].

3.1.2.4. OPTIMIZATION OF SHIP OPERATION

As mentioned in Chapter 1, ship operation can be optimized through improved hull shapes and propulsion systems or through better overall vessel energy efficiency. The shape of the hull directly affects ship performance, and its optimization can reduce fuel consumption and CO2 emissions by up to 15% for large vessels. Any such optimization will be effective only if ships operate within their design specifications, that is, within the recommended speed range[27].

With the adoption of EEDI and, recently, of EEXI, the IMO began using carbon dioxide emission estimates associated with distance and ship size to regulate maritime emissions. Those estimates are calculated based on the installed power of a vessel's engine and on the expected power at its optimal design speed range (Serra and Fancello 2020). Monitoring ship operation data is vital to successfully optimize vessel operating standards, which can potentially reduce fuel consumption by up to 20%[14].

3.1.3. RESEARCH INSTITUTIONS

The institutions that provide the studies and reports the maritime industry uses to develop emission reduction efforts are academic institutions, think tanks, government entities and non-governmental organizations[28]. Those players develop new technologies, actions and visions for the maritime industry.

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

An important action by research institutions is to develop studies on low- or zero-pollutant emission marine fuels. Several studies[24,29,30] have investigated the characteristics, technological maturity, production and life-cycle emissions of alternative fuels and how easily they fit the existing fleet and infrastructure. The scientific community is also investigating if current fuels can be used alongside end-of-pipe technologies to mitigate emissions[31,32].

3.1.3.2. ACTION DESIGN

Maritime industry researchers can also design actions to achieve IMO goals and indicate who should implement those actions. This report mentions several scientific studies [21,22,24,33] presenting some actions that can be taken to reduce emissions.

3.1.3.3. SCENARIOS

Researchers can use the scenario methodology to examine quantitative and qualitative variables in systems that usually are complex and dynamic. This methodology does not create projections, but rather seeks to find different approaches and values for certain circumstances. Scenarios are different “futures” associated with different approaches and values and operate as counterpoint to the traditional view so as to foster debate[34]. Some studies[11,35] construct different scenarios for different regions for the maritime industry in order to review the actions that were taken and the consequences of those actions. Government institutions such as the IMO[7] and some businesses close to the naval sector such as DNV[36] also use the scenario methodology to study seaborne transportation.

3.1.4. THE NAVAL MARKET

This group of players includes shipbuilders, marine fuel producers and businesses that interact with the maritime industry such as classification organizations and providers of maintenance services and of engines and propellers.

3.1.4.1. RESEARCH AND DEVELOPMENT OF ALTERNATIVE FUELS

Similarly to research institutions, businesses that operate in the naval market play a key role in the research and development of low- or zero-pollutant emission fuels. Companies such as Neste[37], BP, Repsol, Galp, Total, Cespa, Honeywell BTG-BTL, TechnipFMC, Fortum and Valmet[38] already produce those fuels and others such as Petrobras[39] plan to do so.

3.1.4.2. RESEARCH AND DEVELOPMENT OF INFRASTRUCTURE IMPROVEMENTS

Marine engine manufacturers are also looking for an optimal propulsion system for alternative fuels. Companies such as Caterpillar, MAN Diesel and Wartsila are working to adapt diesel engines, which are the usual propulsion system for ships, to use biofuels[40]. Another option is to change the propulsion technology, using wind or solar systems to power vessels or using fuel cells and batteries to electrify their propulsion[21]. Classification organization DNV GL has created guidelines on where and how to install fuel cells and procedures for the safe bunkering of some alternative fuels with lower flash points than traditional fuels or that are toxic[41].

3.2. PRODUCTION OF ALTERNATIVE FUELS

From a strictly technological perspective, there are a number of alternative fuels to consider, ranging from the direct use of vegetable oils to the manufacture of synthetic fuels through the conversion of hydrogen and recycled carbon dioxide (CO2)[42]. It is crucial to include economic, environmental and operating factors when analyzing the feasibility of fuel alternatives for vessel use in view of the maritime industry's targets for 2050. Figures 7, 8 and 9 show the production routes of several alternative fuels, which can be divided into three groups, as described in Carvalho et al[43]. The first group encompasses distillate fuels, which can be used in current ignition engines with minor tweaks. The second group includes alcohols and liquefied gases, which can also be used in current ignition engines with certain changes. Finally, the third group comprises hydrogen, ammonia and electrofuels, which are synthetic fuels made from hydrogen.

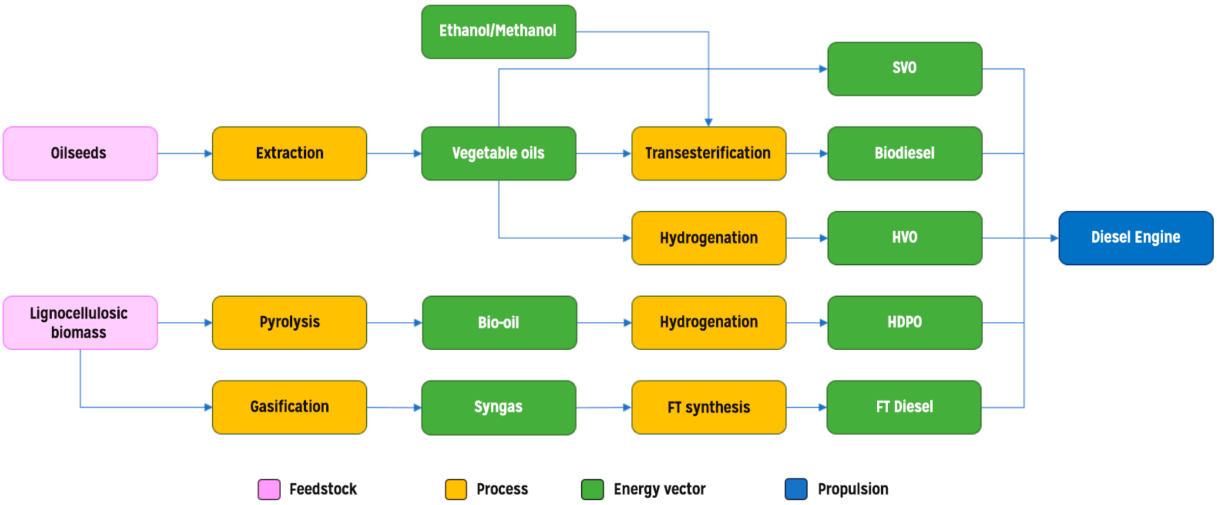


Figure 7: Potentially carbon-neutral alternative fuels for the maritime industry: distillates. Source: Carvalho et al[43].

Liquid distillate biofuels fall into the category of drop-in (or near-drop-in) fuels, derived from vegetable oils, lignocellulosic biomass (including agricultural and forestry residues) or bio-alcohols. Biofuels sourced from vegetable oils include pure 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.

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*Drop-in fuels can be used in ship engines and in the current bunkering infrastructure and thus can directly replace traditional marine fuels or be blended with them.

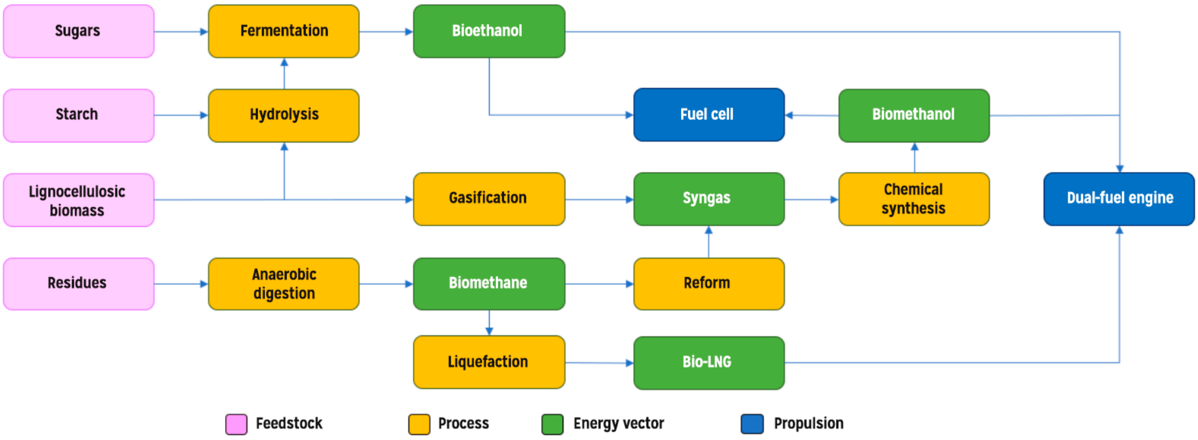

Figure 8: Potentially carbon-neutral alternative fuels for the maritime industry: alcohols and liquefied gases.
Source: Carvalho et al[43].

The second fuel group includes alcohol and liquefied gases, which are not ideal direct substitutes for conventional marine fuels, i.e., they are not "drop-in". But they may become attractive as dual-fuel engines grow more common in the maritime fleet. Those engines use a pilot fuel to spark ignition and a main fuel to complete combustion. Fuels in this group are liquefied biomethane (Bio-LNG), as well as biomass-derived methanol and ethanol (biomethanol and bioethanol, respectively).

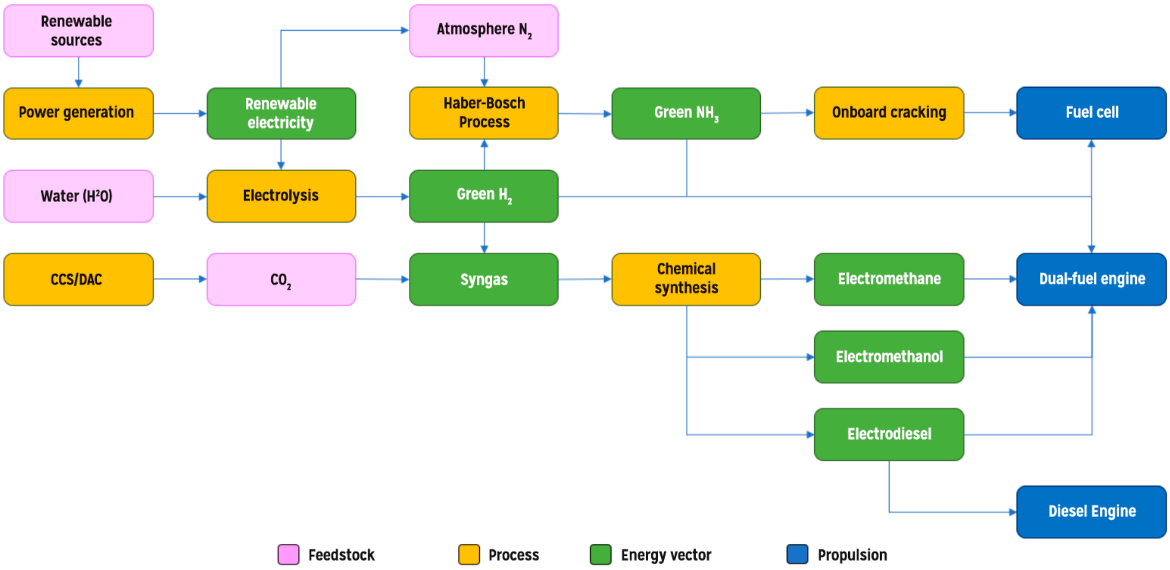

Figure 9: Potentially carbon-neutral alternative fuels for the marine industry: hydrogen, ammonia and electrofuels.
Source: Carvalho et al[43].

Finally, the third group comprises hydrogen-based fuels, not only pure hydrogen (H2) but also ammonia (NH3) and synthetic fuels produced from hydrogen generated by electrolysis and from captured CO2, called electrodiesel, electromethane and electromethanol.

3.3. FEASIBILITY OF USING ALTERNATIVE FUELS

This section focuses on the major alternative fuel options for vessels, initially presenting their general characteristics and then reviewing their technological maturity, the feasibility of their use and their emission reduction potential.

3.3.1. GENERAL CHARACTERISTICS

Figure 10 compares the energy density and calorific value of traditional fuels (HFO - heavy fuel oil and MGO - marine gasoil, similar to marine diesel) and some of the alternative fuels mentioned above. The lower the calorific value, the greater the weight. On the other hand, the lower the density, the more space required for storage.

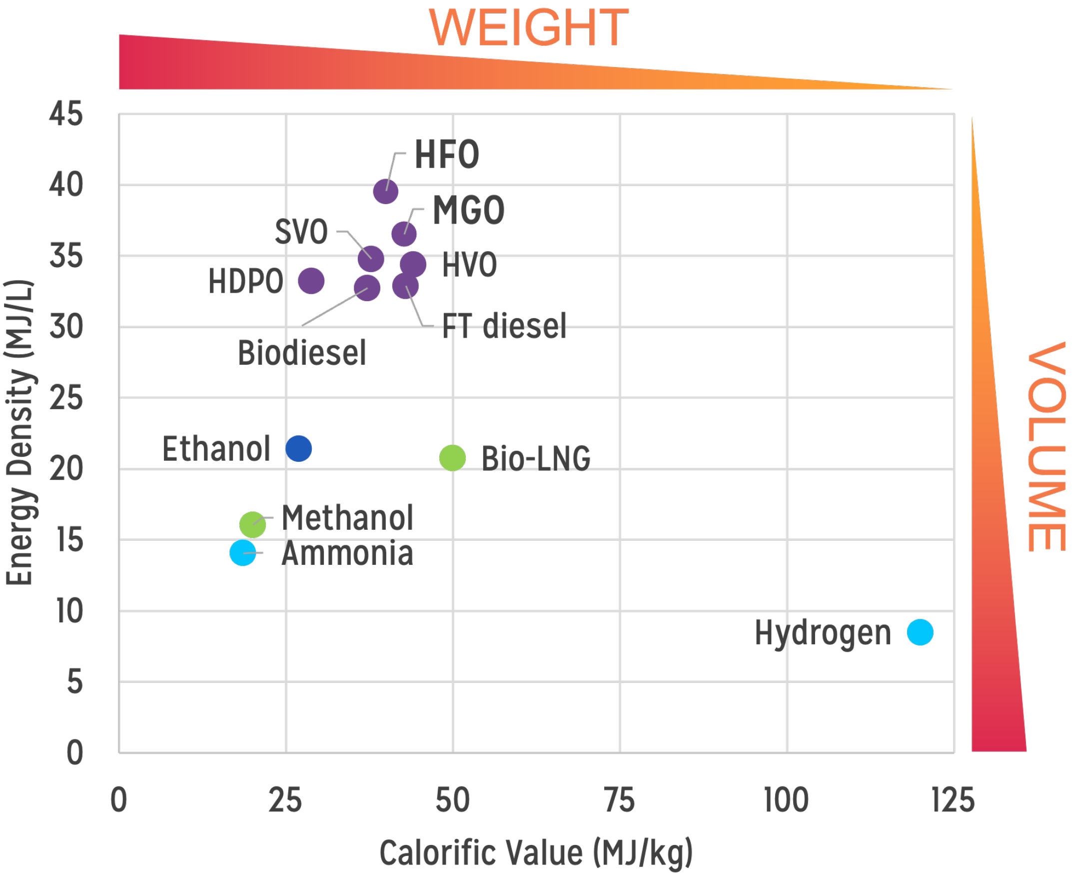

Figure 10: Comparison of the energy density and of the calorific value of traditional and alternative fuels.
Source: adapted from DNV GL[42].

Bio-LNG can reduce the emissions of sulfur oxides, nitrogen oxides and particulates[44]. Bio-LNG is a low-density gas at atmospheric temperature and pressure conditions. Natural gas is cooled to -162°C so that it liquifies at atmospheric pressure, which reduces its volume and optimizes storage[45].

Bioethanol is an alcohol produced largely from the fermentation and distillation of sugar- or starch-rich biomasses such as corn, sugarcane, and wheat[46]. It is a highly flammable (extremely low flash point) and carbon-rich compound whose energy density is lower than that of traditional fuels[47].

Biofuel characteristics may vary depending on the feedstock used to produce them. The energy density of biodiesel, SVO, HVO, HDPO and FT is similar to that of HFO and MGO and exceeds that of the other fuels discussed, so that they offer greater sailing range or require less storage space. SVO is a biofuel that involves a direct production process in contrast to other fuels. Production steps include biomass collection, low-temperature seed pressing, and filtration to remove impurities. Fuel quality is greatly influenced by feedstock quality and by production and processing conditions[48]. Compared to traditional marine fuels, SVO has a slightly lower energy density but higher flash point, viscosity and acidity. Those characteristics can potentially result in corrosion in engine feed tubes[49]. Biodiesel, often considered one of the most promising biofuels, is often mentioned as a potential substitute for diesel in road transportation[33].

HVO is composed of linear paraffinic hydrocarbon and goes through additional production steps in relation to SVO. HVO stands out for its extremely low sulfur content and for its minimal emissions[50]. As a paraffinic compound, HVO has a high cetane number, generally ranging from 75 to 95[51]. Pyrolysis oil, also known as bio-oil or as HDPO, is derived from biomass and goes through a high-temperature process in the absence of oxygen. Depending on the pyrolysis process, HDPO can be up to 30% water, which is enough to induce phase separation when stored at room temperature for six months[52]. Finally, FT diesel is a drop-in fuel, which means that it can be employed directly in diesel engines without any change to the engine or to the bunkering infrastructure, and it has a slightly lower density than conventional fuels.

Both SVO and HDPO, which are highly acidic, require appropriate measures to reduce their high viscosity, such as preheating. Biodiesel is more viscous than traditional diesel, although not as much as SVO and HDPO, hence the recommendation for preheating[53]. HPO's remarkably high and unstable viscosity poses challenges both for its use as fuel and for its storage[54].

Biodiesel's low flash point restricts its practical application at low air temperatures[55]. On the other hand, HVO has a higher flash point than traditional fuels[51]. FT diesel's viscosity, within the same range as fossil fuels, and its higher cetane number make it a high-performance fuel[56].

In similarity to biodiesel, SVO's acidity level is associated with its specific feedstock. While certain vegetable oils may be more acidic than HFO, others have relatively low acid values, such as canola oil, whose acidity level is under 2.5 mg

KOH/g[48]. Despite going through treatment that reduces acidity by approximately 70%, HPO remains significantly more acidic than traditional marine fuels[54].

Methanol[57] and ammonia[58] are widely used as feedstock in the chemical industry. Those substances are highly toxic and require safety measures to prevent leaks and human exposure. Ammonia has been proposed as a potential sustainable energy carrier for hydrogen because each ammonia molecule (NH_3) has three hydrogen atoms[59]. Furthermore, liquid hydrogen storage requires extremely low temperatures, specifically -253°C[60]. Hydrogen is recognized as a promising marine fuel, with trials underway to foster its use in seaborne transportation. However, as reported by ABS[61], hydrogen currently offers very limited energy output and involves significant costs and its production is limited. In addition, hydrogen storage on vessels presents significant challenges that the maritime community has yet to overcome. Ammonia's energy content is 1.7 times greater than hydrogen's[62] and its hydrogen content by volume is 50% higher[63], resulting in reduced fuel storage requirements. Methanol, which is liquid under atmospheric conditions[64], 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 at 10 bar pressure, while the required storage temperature at atmospheric pressure is -33.4°C[62]. Both Methanol and LNG are low-flash point fuels, making them highly flammable. Methanol is flammable and has lower lubricity than conventional marine fuels[49]. Despite its high flash point, ammonia has a lower flame velocity than conventional fuels and is highly toxic[65]. Ammonia is a health hazard at high concentrations and can be lethal at certain concentration ranges and exposure times[58]. Finally, bioethanol's low cetane number can greatly delay ignition[66], making it unfeasible for use in compression ignition engines.

Biodiesel is being tested on vessels blended with traditional fuels under established standards: Methanol and LNG are used on ships, but sustainable production of those fuels remains in its infancy; HVO and FT Diesel suffer competition from the airborne and highway transportation modes and require fewer adaptations to port structure in general as they are similar to marine diesel; SVO and HDPO require preheating, as does HFO. HDPO requires treatment to reduce acidity and to improve stability during storage.

3.3.2. TECHNOLOGICAL MATURITY AND FEASIBILITY

Fuels with an already established production chain tend to have greater technological maturity for use on vessels. Figure 11 shows the current fuel technological maturity based on their general applicability in the Brazilian maritime industry.

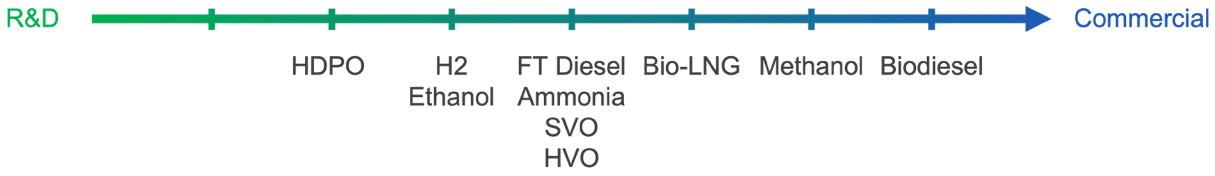

Figure 11: Current technological maturity of alternative fuels.

LNG use as primary fuel for ships is rapidly becoming a reality. By July 2023, a substantial part of the global fleet, specifically 403 ships, was LNG-powered and 275 terminals worldwide had bunkering facilities for such vessels[67]. It is then fair to say that the LNG bunkering infrastructure is firmly established and that all necessary procedures have been meticulously documented by classification organizations, with particular emphasis on oil tankers[68]. Bio-LNG production remains incipient despite its great potential in Brazil. Bio-LNG's maturity level was considered intermediate because its offer is limited despite its growing use as vessel fuel.

Although ethanol production is already a reality and Brazil is a major producer of this biofuel[69], its use on vessels requires further research and development and is expected to occur in the long term, mainly for fuel cells. This fuel's technological maturity for the maritime industry is therefore low.

Of all fuels discussed, only biodiesel can be used in marine fuel blends because it was the only one mentioned in any standard until 2022. Specifically, ISO 8217:2017 allows up to 7% v/v biofuel blends[70]. The direct use of biofuel on ships may compromise current energy supply systems, reduce efficiency and, consequently, increase specific consumption. However, certain engine manufacturers such as MAN, Wärtsilä and Caterpillar have run tests showing that up to 30% v/v biofuel blends can perform satisfactorily in unmodified engines[55]. In addition, 30% biofuel and diesel blends (B30) cause no change to engines, although they do increase specific consumption. Numerous marine engine manufacturers have conducted research and tests to foster the use of biofuels on vessels[71]. Despite that progress, the biofuel bunkering process requires further development, although minor adjustments may suffice[72]. Biofuel continues to be tested in order to be validated as marine fuel in real operating conditions, but its production is well established in Brazil and its technological maturity may be considered close to commercial use.

Although SVO and HFO share some similarities, blends of those two fuels are unlikely to be feasible. The most practical and feasible solution therefore is to fully replace HFO with SVO. SVO use in the maritime industry, both in direct replacement of conventional fuels and blended with them, remains under research. Diesel blends with no more than 20% v/v SVO do not require changes to engine fuel feed systems[73]. And if the SVO is preheated to temperatures between 55 and 85°C, the SVO content in the blend can go as high as 30% to 60% v/v without changes to engine structure[74]. SVO's success as marine fuel requires the development of bunkering infrastructure, as well as additional testing and improvements, so that its technological maturity is considered intermediate.

HVO's similarities to marine diesel and compatibility with conventional ignition engines make it a viable potential substitute for marine diesel. HVO is now being tested for use in the transportation industry. Numerous experiments have been made in several countries, such as Germany, Canada, the United States, Finland and Sweden, using HVO both as direct fuel and in fuel blends for trucks and cars. A particularly significant test took place in Alberta, Canada, where HVO was shown to operate efficiently even at extremely low temperatures, as low as -44°C. But if experiments were made with trucks and cars, no ship test was reported until 2022[37]. Widespread HVO use in the maritime industry faces some hurdles such as its limited production capacity and high prices and competition from road and airborne transportation modes. Further comprehensive studies and research are key for HVO to overcome those hurdles and to become a viable marine fuel, so that its technological maturity is considered intermediate.

Blends of HDPO with diesel and alcohol must not exceed 40% v/v to be useful in marine engines. HPVO may come to replace heavy oil in the future[76] but its widespread use requires further research and comprehensive testing[87]. Given its early stage of development, HDPO's maturity level is considered low.

Although the individual components of the Fischer-Tropsch process are well known and have been demonstrated at industrial scales, process integration and operation demonstration are still far from reaching the commercial stage[77]. To date, the Fischer-Tropsch process has been demonstrated in pilot plants and no large-scale plant has yet come online. Several industrial-scale demonstration projects have been recently canceled in Europe[78] but other initiatives remain underway. Given that context, FT-diesel's technological maturity is considered intermediate.

As of July 2023, 25 ships worldwide used methanol as fuel and 127 terminals had methanol bunkering facilities[67]. As said earlier, both the IMO and classification organizations have regulated and established technologies and procedures for methanol use as marine fuel and for methanol bunkering. According to an ABS report[79], manufacturers MAN and Wärtsilä provide methanol-fired engines using high-pressure diesel combustion processes. In view of those favorable factors and of its potentially rapid integration into the maritime fleet, methanol is considered to have a high potential for widespread use in the short term. As a result, methanol's technological readiness is considered high although methanol production from biomass sources requires further development.

Ammonia currently benefits from an established supply chain network focused primarily on its use in the chemical industry[62], with efficient ship transportation networks around the world. The MAN dual-fuel engine, originally designed to operate with methanol and diesel, can be adapted to use ammonia as an alternative fuel, provided that certain modifications are made to the pressure fuel feed system[80]. As a result, the technologies, materials and procedures required for its application are well-known within the industry. However, further adaptations and development are needed for ammonia to become a useful marine fuel[81]. Its use as fuel would face competition from the chemical industry and would face challenges such as high toxicity and difficulties to integrate that technology into engines and fuel cells. Additional technological advances are required for ammonia to achieve full long-term commercial viability, so that its technological maturity is considered intermediate.

In similarity to ammonia regarding the practical aspects of naval infrastructure, the production of hydrogen via sustainable routes is still in its infancy, its cost is high[61] and its use with the most efficient propulsion system (fuel cells) remains in development. The widespread use of this fuel is expected to be in the distant future and its technological maturity is considered low.

The feasibility of alternative fuels and technologies was assessed taking into account each fuel's properties, technological development and economic aspects. Three criteria were used for categorization: route distance, ship size and time horizon. Routes were categorized based on distance taking Brazil's territory as a reference. Routes up to 100 kilometers long, such as river crossings, trips between nearby cities and locations, are considered short-distance. Intercity or interstate routes up to 1000 kilometers long are considered medium-distance. Routes more than 1000 kilometers long are considered long-distance. Ships were categorized based on their size.

Small vessels are those that carry up to 10 tonnes, encompassing most passenger boats such as canoes, yachts, speedboats, schooners, among others. Mid-size vessels carry from 10 to 500 tonnes, encompassing larger passenger ships and some cargo ships. Finally, large ships are those that carry more than 500 tonnes. This category includes most cargo ships. Finally, the time horizon is defined based on the classification mentioned above: short term (until 2030), medium term (between 2030 and 2040) and long term (between 2040 and 2050). Figure 12 shows a summary of the analysis according to the 3 variables mentioned.

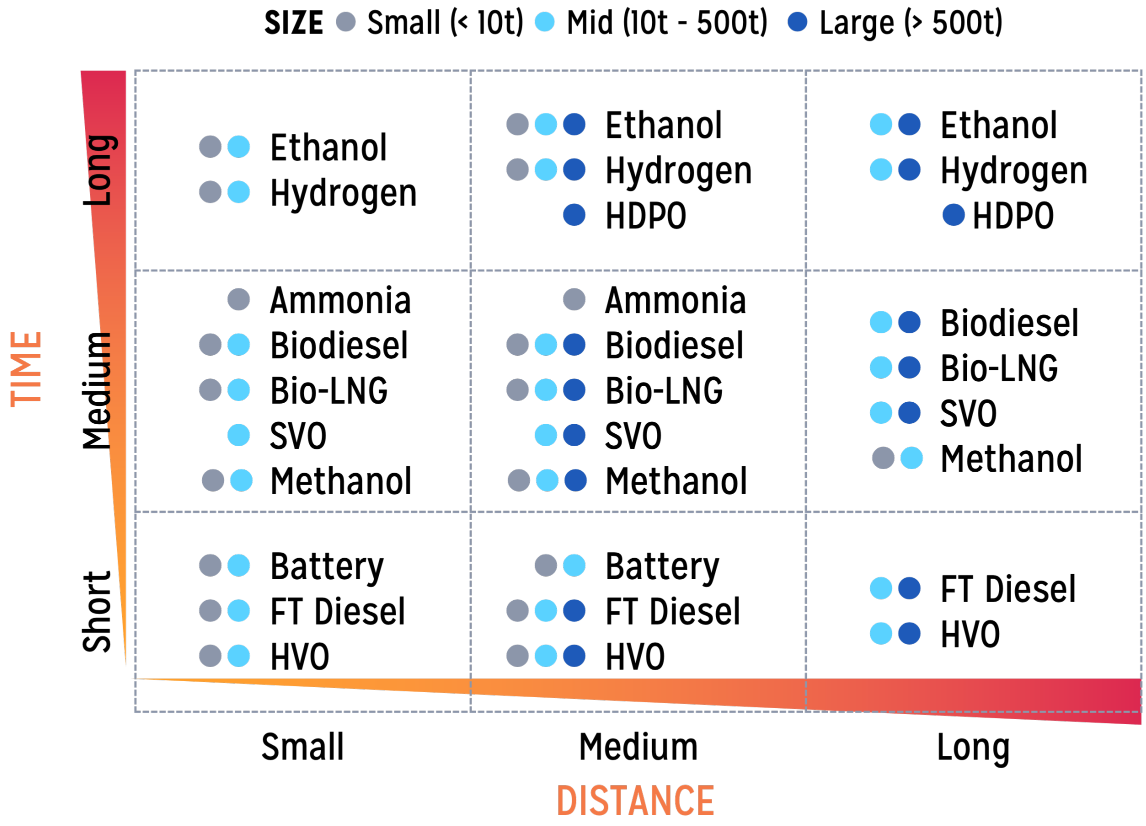

Figure 12: Analysis of the viability of alternative fuels and technologies for the maritime industry.

Small vessels are considered more suitable for shorter distances (less than 1000 kilometers), carrying passengers or passengers and cargo between nearby locations. Electricity batteries may in the short term prove viable for shorter distances, especially if used in hybrid systems. Energy storage systems (ESS) are already in operation on ships [82]. As of 2023, 324 vessels made full or partial use of batteries as energy source [67]. HVO may also prove viable in the short term because current engine systems require only minor changes to use HVO thanks to its similarity to current fossil fuels.

In the medium term, as propulsion conversion systems compatible with biodiesel, biomass methanol and bio-LNG become more common and as the production of those fuels gains scale, they will also become viable options for mid-size vessels. The widespread use of fuel cell technology and the reduction in the price of fuels such as hydrogen, ammonia and ethanol expected for the long term (2040-2050) can make those options suitable for use on small vessels. Despite its limited technological maturity, HDPO too may be viable in the long term both for mid- and large-size vessels.

The same rationale used for small-size vessels applies to mid-size ones employed in short- and medium-distance crossings. The difference is that SVO may become viable in the medium term because mid-size vessels can accommodate the required fuel heating systems. Battery systems are not viable for long-distance routes, so that HVO is the only alternative. The medium- and long-term fuel options available are similar to those for small vessels: biodiesel, SVO and bio-LNG in the medium term and methanol, hydrogen, ammonia and ethanol in the long term, possibly alongside fuel cells.

Batteries are not considered viable for large vessels, which are predominantly used in medium- and long-distance cargo routes, because of vessel size and of the greater distances involved. HVO and FT Diesel are viable short-term options that can reduce carbon dioxide equivalent emissions. The medium- and long-term fuel options available are similar to those for mid-size vessels: biodiesel, SVO, bio-LNG, methanol, hydrogen, ammonia and ethanol and possibly fuel cells in the long term.

3.4. REDUCTION IN POLLUTANT EMISSIONS

Net pollutant emissions, that is, total emissions from fuel production to its final use, are directly dependent on the production process. Figure 13 shows the full life-cycle emission rates of fuels when used on ships.

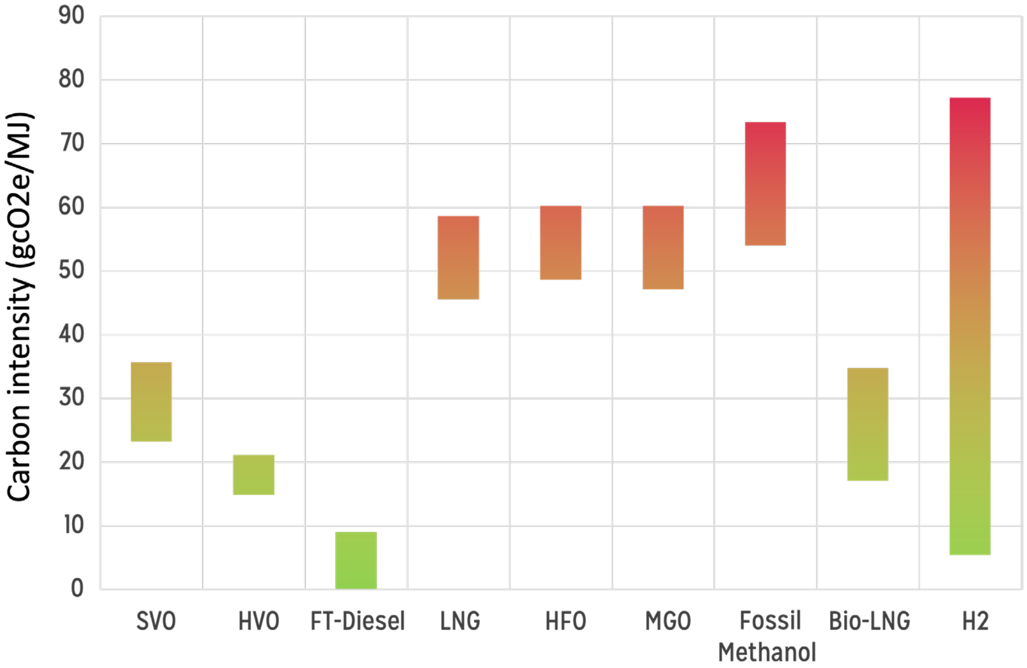

Figure 13: Full life-cycle emissions of marine fuels.
Source: adapted from Schaeffer et al[83], Balcombe et al[24] and Brynolf[29].

Biofuels are carbon-neutral in the combustion phase, that is, the CO2 amount emitted during combustion is similar to the carbon amount captured during biomass growth. The carbon intensities shown in Figure 13 for SVO, HVO and FT diesel considered their use in Brazilian routes and biomass as their feedstock[83]. Ammonia and hydrogen emit zero carbon during combustion because they have no carbon atom in their composition, so that their carbon intensity essentially comes from their production processes[84]. Hydrogen's wide carbon intensity range in the figure above is due to the different production routes available, which can use high-emission fossil sources or low-emission sustainable sources. As expected, fossil-origin fuels will have higher emission rates than fuels originated from biomass, which corroborates the use of sustainable fuels in the maritime industry.

4. OUTLOOK OF THE CURRENT DECARBONIZATION EFFORTS IN BRAZIL'S MARITIME INDUSTRY

Bearing in mind the context of the decarbonization options described in the preceding chapter, the maritime industry's energy transition may be driven by the adoption not of a single alternative fuel but of a basket of fuels depending on ship category, on the maritime infrastructure available and on local production. Despite the growing debate, the energy transition of Brazil's maritime industry requires further research and far-reaching efforts to gain traction.

In 2021, Brazil's Ministry of Mines and Energy (MME) initiated a program to promote the research and development of sustainable technologies applicable to all means of transportation, including seaborne transportation. The Brazilian government, in cooperation with the Navy and with other significant stakeholders, regularly organizes meetings to debate and to implement actions to reduce the carbon emissions of the country's maritime industry. The topics discussed include, among others, the identification of alternative marine fuels, promising technological routes, the production potential for alternative fuels, the feasibility of their production and distribution options and actions to encourage the use of alternative fuels[85].

As to the actual use of sustainable fuels, in 2022 Bunker One and the Federal University of Rio Grande do Norte (UFRN) ran joint tests at the port of Rio de Janeiro with two tugboats powered by a 7% v/v biodiesel blend with HFO[86] to gauge the performance of the blend in real operating conditions.

Petrobras also ran tests with a 90% HFO and 10% biodiesel v/v blend on the "Darcy Ribeiro", a tanker that carries liquefied petroleum gas (LPG). The primary purpose of those tests was to measure performance and to identify any potential logistical challenges. Petrobras research labs tested and evaluated that blend in January 2023 and found that its use requires no change to the existing maritime infrastructure[87]. In July 2023, Petrobras announced new tests using a 24% v/v biodiesel blend[88]. Furthermore, Petrobras is investing to equip its refineries with large-scale HVO production capabilities[89].

Because they involve larger cargo tonnages and a greater number of trips, as seen further above, long-distance, coastal and inland navigation should be the primary focus to kick off the energy transition of Brazil's maritime industry through the implementation of sustainable fuels. Investments to adapt infrastructure and production should focus on busy ports that handle large tonnages such as Belém, Ilha da Guaíba, Pecém, Ponta da Madeira and Santos. Companies should channel their investments to those types of navigation and ports that carry and handle the most significant cargo such as iron ore, oil and oil products and containers. The Statutorily Defined Amazon Region (Statutory Amazonia) also comes to mind as an important starting point. As reported in "Nova Economia da Amazônia"[90], the region is heavily dependent on vessels for passenger and cargo transportation and concentrates more than 50% of the energy demand of Brazil's maritime industry. As discussed in section 3.3.2 above, a large part of the region's transportation activities involves small- and medium-distance routes plied by small vessels. In this specific region, then, investments should focus on the electrification of small vessels, which can better store energy in batteries.

5. DECARBONIZATION ACTIONS IN NORWAY'S MARITIME INDUSTRY

Boasting the world's largest fleet under its flag and a leading position in maritime technology innovation, Norway is a heavyweight in international seaborne transportation[91]. Norway is also a leader in sustainability efforts and has pioneered several actions to decarbonize seaborne transportation. Reportedly 40% of the world's battery-powered vessels operated in the country in 2021. Passenger and vehicle ferries for short-distance routes and ships that serve the offshore industry represented much of that electrified fleet[92].

Again showing Norway's pioneering spirit, the world's first ship using a hydrogen-powered fuel cell as converter for propulsion began operating there in March 2023. The MF Hydra can carry up to 300 passengers and 80 cars and is equipped with two 200-kilowatt fuel cells[93]. In addition, Norway was one of the first countries to introduce carbon taxation, in 1991, and plans to increase taxation by 5% by 2025[15].

Norway's great heft on vessel sustainability initiatives stems from its plans and actions to encourage the production and use of neutral fuels seeking to cut emissions by 50% by 2030 in relation to 2008 levels. Norway has also introduced a mandatory biofuel percentage on vessels operating in the country, focusing on advanced biofuels made from biomass or urban waste. The use of alternative fuels on Norwegian-flagged vessels contributes toward achieving the target, as the Norwegian government offers cheaper electricity for national vessels. Finally, both government and business entities such as Enova, Innovation Norway and the Research Council of Norway offer funding to promote alternative fuels[15].

6. OPPORTUNITIES FOR COOPERATION BETWEEN BRAZIL AND NORWAY

As seen in this report, both Brazil and Norway rely heavily on the maritime industry in activities ranging from passenger and cargo transportation to offshore oil production. Brazil can benefit from Norwegian expertise in building up the sustainability of seaborne transportation by using Norway's knowledge base and practical experience as a reference to design its energy transition initiatives.

The production and use of alternative fuels can be encouraged through actions similar to those taken by the Norwegian government such as introducing a bold emission reduction target and mandating the use of biofuels in marine fuel blends. Brazil's great potential for the production of sustainable fuels and energy vectors, mainly from biomass, and expertise in the production of biofuels[94] provide a stepping stone to boost the production of neutral fuels by both countries.

To give but one example of potential cooperation, Norway's expertise in the electrification of small- and mid-size vessels can help Brazil do the same in the small- and medium-distance routes along the rivers of Statutory Amazonia. Brazil can also benefit from Norway's experience with carbon pricing and with incentives to foster the use of alternative fuels.

Business entities can also engage in that cooperation focusing not only on using alternative fuels but also on improving energy efficiency, which will help curb energy consumption. A case in point is the partnership between Vale and Kongsberg to meticulously monitor vessel fuel consumption so as to optimize operating efficiency[95].

Finally, an option that has been gaining traction recently is the creation of green corridors, which are specific trade routes interconnecting major port networks. The feasibility of using zero-emission fuels in those port networks must be shown and industry players and government entities must allocate resources to strategies that can reduce maritime trade's carbon emissions in each specific route. Researchers have been focusing on some of the world's major trade routes such as the iron ore routes between Brazil and China and between Australia and China and the container route between Australia and Europe[96]. Routes connecting ports in the same country or ports that are significant for trade between the two countries such as the port of Santos, in Brazil, and the port of Oslo, in Norway, can operate as catalysts for change in the energy mix.

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