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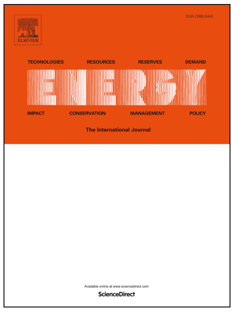

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Production of alternative marine fuels in Brazil: an IAM perspective

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Authors

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Abstract

This study aims to provide an Integrated Assessment Model (IAM) perspective of the production and distribution of alternative marine fuels in Brazilian ports, considering the International Maritime Organization (IMO) emission reduction target for 2050 (IMO2050). Although other mitigation measures are available, it is likely that alternative fuels will be required, implying additional costs and entailing relevant impacts on other energy chains and land use. Hence, the national IAM BLUES model is adapted to represent the relevant part of the international shipping sector. A set of scenarios is developed considering different fuel alternatives, demand assumptions and national mitigation targets. Findings show that taking into account emissions of CO_2 only or of all greenhouse gases (GHGs) within the IMO strategy significantly impacts the optimal technological portfolio. Furthermore, achieving the IMO2050 goal without considering a national decarbonization strategy may result in potential spillovers. The intense use of the energy sector could partially compromise the gains obtained by maritime decarbonization or even surpass it. Therefore, only an integrated mitigation strategy would lead to more effective decarbonization of the entire marine supply.

Keywords: international shipping, integrated assessment modelling, alternative fuels

1. Introduction

The shipping sector is an important contributor to global greenhouse gas (GHG) emissions, accounting for 1.06 $GtCO_2/yr$ (direct emissions), with 70-87%[1] of this amount associated with the international freight transport system [1]. Shipping GHG emissions (almost entirely composed of CO_2) originate from the use of fossil energy. Currently, heavy fuel oil (HFO) and marine gasoil (MGO) are the prevalent fuels in maritime operation, and accounted for approximately 95% of the sector's energy demand in 2018 [1]. In practice, marine fuels are often composed of a blend of these two types of petroleum products in varied proportions [2], [3]. In terms of energy conversion and carbon intensity, HFO and MGO are similar, with nearly equivalent specific consumption and emission factors [4]. As such, in this work, which provides a more aggregate view of the sector, these fuels are treated indistinctly under the designation "bunker".

In 2018, the International Maritime Organization (IMO), the United Nations body responsible for the regulation of international shipping, established a preliminary strategy to reduce the sector's

[1] A range is presented due to the different possibilities of emissions allocation. International shipping can be defined based on origins and destinations (voyage-based allocation) or on ship types (vessel-based allocation) [1].

contribution to climate change. This includes a 50% reduction of the total shipping-related GHG emissions by 2050 compared to 2008 (hereafter IMO2050) [5].

To fulfil IMO2050, several mitigation measures can be considered. For example, more efficient vessel design can provide efficiency gains through the use of lightweight materials, air lubrication or new hull shapes and sizes (Bouman et al., 2017; Lindstad et al., 2014). Operational measures, such as speed and voyage optimization, favored by the digitalization of freight transport, could also play an important role [7], [8]. Other measures, as the use of auxiliary propulsion devices and waste heat recovery, might help to further reduce the energy demanded by ships [7], [9]. Reductions in the demand for shipping, especially in fossil fuel transportation, might also play an important role [10].

Nevertheless, these measures are not sufficient to meet IMO2050. Hence, it is likely that the bulk of the decarbonization of shipping will rely on the adoption of alternative fuels [11], [12]. From a technical perspective, several low-carbon fuels could be considered, such as vegetable oils, synthetic biofuels, bio-LNG, bio-alcohols and electrofuels (e-fuels) [12]. In any case, the use of alternative fuels will imply extra costs and might have relevant impacts on other energy chains and land use. Although some studies have carefully assessed the decarbonization potential of renewable marine fuels [11]–[13], an integrated perspective of the different options is lacking.

Therefore, this study aims to provide an Integrated Assessment Model (IAM) perspective of the production and distribution of alternative marine fuels in Brazilian ports up to 2050, considering IMO emission reduction target. IAMs are modelling tools used to develop overall long-term mitigation strategies. They vary in terms of methodology and scope, but in general, it can be said that IAMs combine several strands of knowledge to explore the impacts of human development and societal choices in the natural world. They generally contain a detailed representation of a region's energy, land use, agricultural and climate systems, as well as their interlinkages [14]–[16].

The use of an IAM for the analysis to be performed here is an original proposal compared to the earlier mentioned studies. While the latter are based on sectoral models, exploring in detail specific aspects of international maritime transport routes and services, an IAM-based analysis is capable of providing a systemic view of the problem. Actually, one benefit of this approach is to provide better identification of existing and candidate marine fuel production routes.

Sectoral assessments usually do not include multi-product facilities, such as petroleum refineries and biorefineries. As of today, bunker fuels are produced mainly from heavy residues (low-value cuts) of the fractional distillation of oil [3], [17], [18]. This could still be the case for alternative renewable bunkers, which in the future might be co-produced in bio- and e-refineries (or facilitating the co-production of e-fuels and/or electro-based materials). Only technological-detailed and well-adjusted IAMs can test this hypothesis since these models seek to match not only the shipping fuel demand but also the whole energy service demand of a certain country, region or the world [19]–[21]. This also enables a comprehensive assessment of the impacts of the fuel switch on the entire energy system (e.g. modifications in oil refining, increase in the power sector demand due to the production of e-fuels, a shift of fuel oil use from internal combustion to electricity generation).

Moreover, an integrated system assessment allows investigating the implications of fuel switch in shipping on total GHG emissions. The use of IAMs can help identify whether sectoral emission reductions may lead to effective mitigation of climate change or to an increase in overall emissions. In other words, this kind of modeling analysis can reveal potential rebound effects due to increasing pressure on upstream activities. Furthermore, IAM results include information on direct and indirect changes in land use, which have impacts on non-energy GHG emissions, water balance and food production. Finally, in contrast with sectoral analyses, an integrated modelling analysis allows the quantification of the total costs of decarbonization (e.g. energy and land-use systems, including investment and operational costs and logistics), and not only the fuel production and ship acquisition costs.

Brazil was selected as the case study of this work in view of its foreign trade particularities that severely affect the country´s economy. Brazil's foreign trade is characterized by the export of low value-added commodities with a large discrepancy in terms of mass and value [22], [23]. Besides, Brazil's unfavorable geographical position when it comes to international trade entails longer travel times, in addition to higher fuel costs and carbon intensities [24]. On the other hand, the consolidated biofuel market may represent an advantage for the country to kick-off the production of new marine fuels. Finally, the existence of the BLUES model, an internationally recognized Brazilian IAM [25], [26], together with a national political will to address IMO2050 [27], reinforce the motivations of this study.

Following this introduction, an overview of potential alternative fuels for seaborne transport is provided. Subsequently, methods used to integrate the relevant shipping routes and fuel options into the BLUES model are detailed, as well as the design of scenarios. Next, results of the scenario analysis are presented and discussed. Finally, concluding remarks and suggestions for future studies are explored.

2. Alternative fuels for shipping

Figure 1 provides an overview of conventional and potential alternative marine fuels, including fossil and renewable resources. Even though petroleum products are prevalent, natural gas is presently a relevant energy carrier in the shipping industry, having provided around 0.4 EJ to vessels in 2018 [1]. Even since before the set of IMO's targets, liquefied natural gas (LNG) has been gaining space due to the increasingly competitive gas prices [28] and stricter regulations regarding atmospheric pollution (Lindstad et al., 2020). Today, several ships, particularly a number of gas carriers, are equipped with dual-fuel engines, which can run with both bunker and LNG [1]. Despite its limited benefits in terms of climate mitigation, LNG is still seen by part of the industry as a transition fuel for the next decades [12], [30].

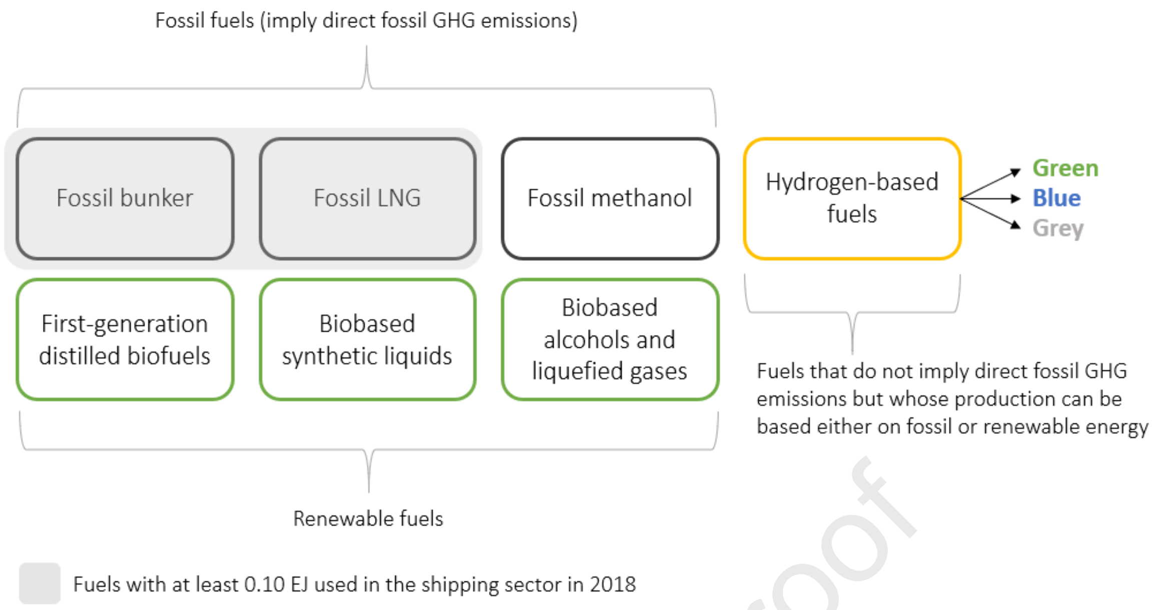


Figure 1: Conventional and alternative marine fuels

In terms of biobased options, fuels can be divided in three groups: first-generation distilled fuels, synthetic liquids and alcohols/liquefied gases. The first group is composed of biofuels obtained through extraction and treatment processes, such as straight vegetable oils (SVO), hydrotreated vegetable oils (HVO), and biodiesel (fatty acid methyl ester – FAME), typically associated with feedstocks like oilseeds and animal fats [31]. The second group includes advanced biofuels produced through thermochemical routes from forest and agro-industrial residues. This includes bio-oils, such as hydrotreated pyrolysis oils (HDPOs) [32] and Fischer-Tropsch (FT) liquids [33]. The FT process outputs multiple hydrocarbon fractions, similar to oil refineries. Most of its products (e.g. biojet, bio-ultra low sulphur diesel and FT-naphtha) have higher market value than fractions suited for use in vessels (FT-diesel and FT-gasoil). Thus, FT-marine fuels can be seen as coproducts. The third group corresponds to biobased gases and alcohols, including liquefied biomethane (bio-LNG), biomethanol (bio-CH_3OH) and bioethanol. Bio-LNG is produced from biogas, which is generated through anaerobic digestion and upgrading [34] Bio-CH_3OH can be produced from biogas or through a thermochemical route similar to the one presented in the second group. Finally, ethanol can be produced from sugar crops or through the enzymatic hydrolysis of lignocellulosic biomass [35].

Alternative energy carriers for shipping can also be based on hydrogen (H_2-fuels[2]). This includes not only hydrogen itself (H_2) but also ammonia (NH_3), produced through the Haber-Bosch process, and liquid organic hydrogen carriers (LOHCs) [12], [36], [37]. Hydrogen-based synthetic fuels can also be part of this group. In this case, hydrocarbons or alcohols are obtained through the FT process, similar to the biomass-to-liquids (BtL) route, but combining molecular hydrogen and captured carbon dioxide [38]. As indicated in Figure 1, even though hydrogen-based fuels (H_2-fuels) do never imply direct fossil GHG emissions, they can be fossil-based. In this sense, Figure 2 illustrates the possible H_2-fuels denominations according to the energy source used to produce hydrogen. Green H_2-fuels are defined as those relying on renewable-based processes, such as photovoltaic-powered

[2] In case these energy carriers are produced by storing electrical energy in their chemical structure, they are called e-fuels.

electrolysis. In contrast, blue and grey H_2-fuels are produced from fossil sources, such as natural gas (through steam methane reforming, SMR). Blue H_2-fuels differ from grey H_2-fuels for including a carbon capture and storage (CCS) plant in their production process.

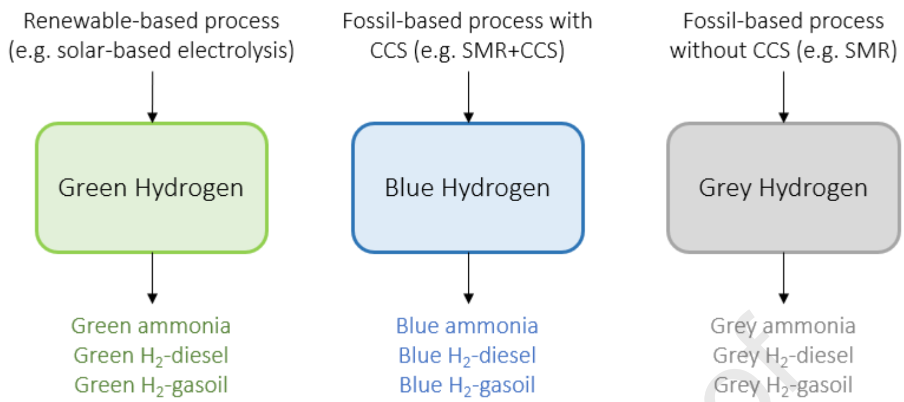


Figure 2: Green, blue and grey H_2-fuels

3. Methods

Figure 3 provides an overview of the methodology. To conduct the analysis, the Brazilian Land Use and Energy Systems (BLUES) model was applied. As shown in Figure 4, BLUES is a national IAM that represents the Brazilian energy, material, agriculture, and land use energy sectors and takes into account the interactions between these systems [39]. The model is an intertemporal optimization tool comprising the period between 2010 and 2050, used to perform scenario analyses of energy use, GHG emissions, petrochemicals fabrication, agricultural production, and land-use changes in Brazil [40], [41]. The detailed description of BLUES can be found in the common IAM documentation webpage [26].

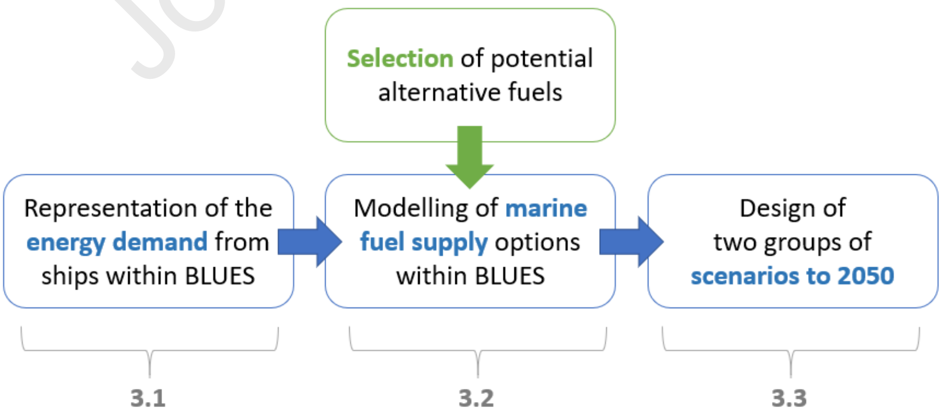


Figure 3: Overview of the methodology

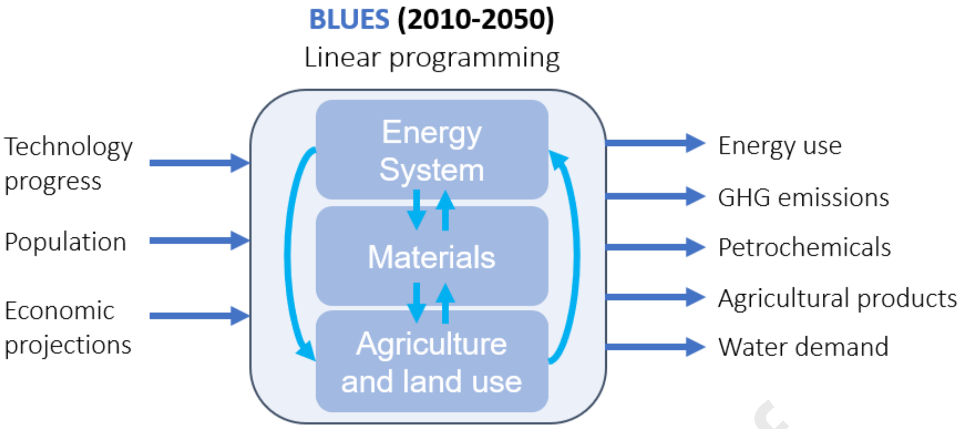


Figure 4: Structure of the BLUES model

3.1. Energy demand

Originally, international trade was not represented[3] in BLUES, given that it is a national model. As such, an important part of the methodology here is the incorporation of shipping fuel demand into BLUES (Figure 5).

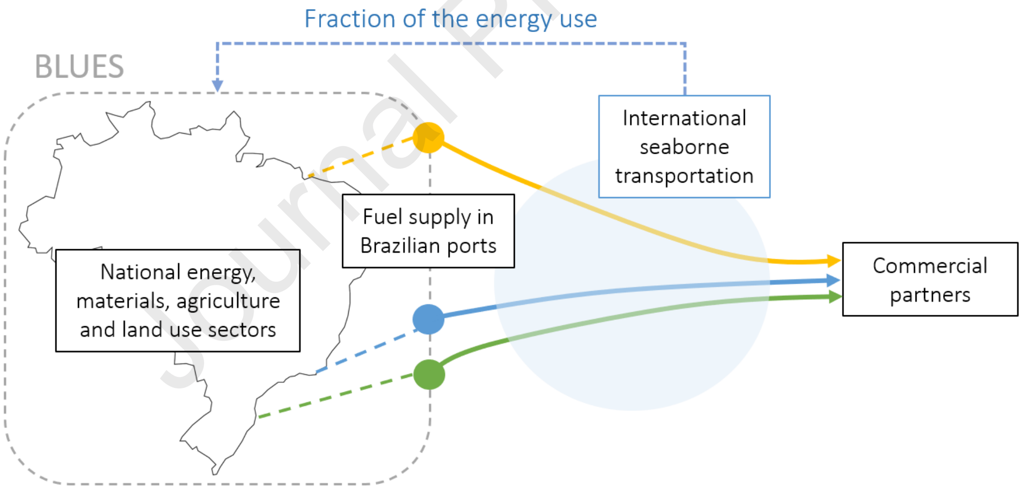


Figure 5: Adaptation of the BLUES model to represent international seaborne trade

This integration was performed based on the assumption that only a fraction of the energy demanded by Brazil's international trade is provided by national ports. The remaining part is supplied by ports of the commercial partners (*i.e.* China, Singapore, Europe, etc.) or even along the shipping routes.

In terms of mass, Brazil's exports are way higher than its imports. Hence, while imports are treated as a single category, exports are divided into five categories that represent the country's main export products: iron ore, crude oil, soybean, sugar, and others [22]. Also, iron ore is divided into two categories, reflecting the two different kinds of ships used to transport this commodity [24]. Coastal

[3] The trade itself is represented for several products in BLUES, but the energy demand linked to this trade is not modelled, given that it is not directly associated to the country.

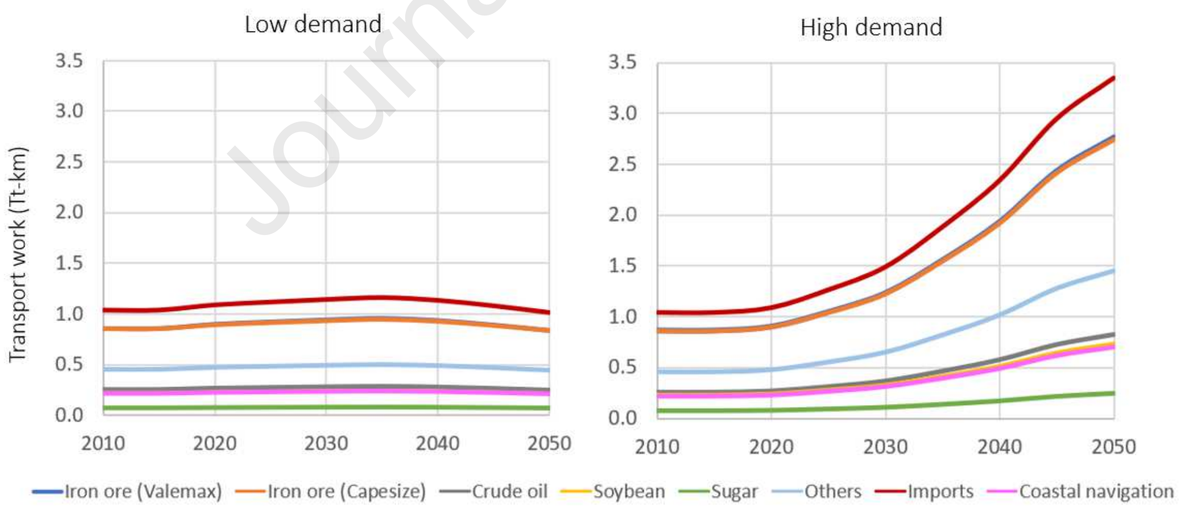
navigation, which is a small part of fuel demand, is also modelled. Even though coastal navigation is not in the scope of IMO's target, it is assumed that it will follow the trends of long-haul shipping.

Table 1 shows the estimation of the transport work related to Brazilian exports, imports, and coastal navigation (*MDIC 2019; Sea Distance 2020*). The proportion of the fuel supplied by Brazilian ports is similar for all products[4] (around 31%). Estimates derivate from the comparison of the results of the modelling with historical data for the base year (5.3 million tonnes of bunker in 2018) [43].

Table 1: Estimation of transport work associated with fuel supplied in Brazilian ports in 2018

	Mass traded (Mt)	**Typical distance** (nm)	**Total transport work** (Tt-km)	**Transport work fueled by Brazil** (Tt-km)
Iron ore (Valemax)	195	8,943	2.99	0.93
Iron ore (Capesize)	195	8,943	2.99	0.93
Crude oil	58	7,165	0.71	0.22
Soybeans	84	9,039	0.84	0.26
Sugar	21	8,382	0.25	0.08
Others	153	8,382	1.52	0.48
Imports	151	8,382	3.50	1.09
Coastal navigation	229	780	0.23	0.23

Two demand scenarios are developed based on the literature on global shipping forecasts (Figure 6). The low demand scenario is based on the activity growth reported in DNV's maritime forecast[5] [44], while the high demand scenario is based on the Business as Usual (BAU) scenario of IMO's third GHG study [45]. It is assumed that the exported products do not change over the period of analysis.



[4] Except for coastal navigation, whose fuel supply is 100% provided by Brazilian ports.
[5] The adopted literature scenarios are based on secondary energy, not transport work (useful energy). In the case of the high demand scenario, which considers the maintenance of efficiencies base year conversion rates, this is not significant. In the case of the scenario with the lowest consumption, however, there is a lag between the profile of the energy curve and that of demand, given the premises related to efficiency. However, for simplicity and data limitation, the final energy is directly used as a proxy for the growth of the projected tonne-kilometers. This implies, in the worst-case scenario, a range of slightly wider demand.

Figure 6: Demand for transport work associated with fuel supplied in Brazilian ports in high and low demand scenarios

The energy associated with Brazilian transport work in each scenario is determined using a simplified energy model and is calibrated with historical data for 2010-2018. The model estimates the demand for main engines (used for propulsion), auxiliary engines (electricity generation), and auxiliary boilers (heat production).

The propulsion energy demand is estimated through simplified hydrodynamic equations [7], [46]. The total hull resistance R_T and the associated brake power P_B are presented in equations 1 and 2, respectively.

$$R_T = \frac{1}{2}\rho C_T S v^2 \tag{1}$$

$$P_B = \frac{(1+m)R_T v}{\eta_T} \tag{2}$$

In equations 1 and 2, ρ is the seawater density, C_T is the total resistance coefficient, S is the wetted surface, m is the sea margin, v is the speed of the ship and η_T is the total propulsion efficiency. These parameters are estimated based on ship sizes and categories. Table 1 shows the vessels considered for each product, as well as their deadweight tonnage.

Auxiliary engines and boilers energy demand estimation follows IMO (2015). It considers typical loads for different vessel categories, sizes and operational mods (at-berth, at-anchorage, maneuvering and at-sea) [47]–[54] (Table 2):

Table 2: Ships types and categories

Product	Ship type	Ship category	Deadweight (dwt)
Iron ore (Valemax)	Bulk carrier	Valemax	400,000
Iron ore (Capesize)	Bulk carrier	Capesize	150,000
Crude oil	Oil tanker	Suezmax	150,000
Soybean	Bulk carrier	Panamax	60,000
Sugar	Bulk carrier	Panamax	60,000
Other	Bulk carrier	Panamax	60,000
Import	Oil tanker	Panamax	60,000
Coastal navigation	Oil tanker	Panamax	75,000

In terms of fuel use, three different powertrains are considered: conventional 2-stroke diesel engines, dual-fuel engines, and solid oxide fuel cells (SOFCs) used in combination with electric motors. Table 3 shows the fuels suited to each one of these configurations. The literature indicates that fuels with lower energy density, such as methanol, LNG and ammonia, might reduce the space available for cargo. Therefore, a volume loss of approximately 5% is considered for dual-fuel engines and solid oxide fuel cells [55]. Differences in investment costs are also considered [55]–[57]. As shown in Table 4, depending on the motorization, significant increases in the total CAPEX are observed, especially for the case of fuel cells. However, some drop-in[6] alternative fuels need only minor changes of the ship and bunkering to be directly used.

Table 3: Technology options regarding the powertrain

Powertrain	Abbreviation	Extra cost (2010 USD/kW)	Volume loss (%)	Suitable fuels
Two-stroke diesel engine	2S-D	0	0	Bunker, drop-in fuels
Dual-fuel engine	DF	242	5	LNG, methanol, bunker, drop-in fuels
Solid oxide fuel cell	SOFC	4675	5	Ammonia

Table 4: Investment costs for the vessels considered in the modelling

Ship	Powertrain	CAPEX (2010 kUSD)
Bulk - Valemax	2S-D	81,000
Bulk - Valemax	DF	87,000
Bulk - Valemax	SOFC	198,000
Bulk - Capesize	2S-D	38,000
Bulk - Capesize	DF	42,000
Bulk - Capesize	SOFC	108,000
Bulk - Panamax	2S-D	30,000
Bulk - Panamax	DF	32,000
Bulk - Panamax	SOFC	67,000
Tanker - Suezmax	2S-D	49,000
Tanker - Suezmax	DF	53,000
Tanker - Suezmax	SOFC	119,000

As shown in Table 5, specific fuel consumption (SFC) varies according to the fuel used [45], [55], [58].

Table 5: Main engine specific fuel consumption

Fuel	SFC (g/kWh)
Fossil/synthetic bunker	179
SVO	170
HVO	190
LNG	150
Methanol	381
Ammonia	319

Efficiency gains are also modelled, since this is expected to be a major aspect contributing to the reduction of the energy demand from international shipping. Consistently with the projections of the literature [7], [59] and with the Energy Efficiency Design Index [60], when compared to 2010, new vessels are taken to be 20% more efficient in 2030 and 30% in 2050.

3.2. Fuel supply

[6] Fuels that can be used in marine diesel engines with no or small adaptation.

As explained in section 2, several alternative fuels can be considered for shipping. In this study, the most promising alternatives from each group are selected for integrated modelling. The fuel alternatives are summarized in Figure 7.

In the first generation biofuels group, SVO and HVO stand out as the most promising alternatives, with mature production technologies, good applicability and reasonable costs [61]. Usually, these fuels are associated with sustainability concerns on land-use change [62]–[64]. This is addressed in this study since integrated modelling is performed in an energy-land-use system model.

Regarding thermochemical routes, biobased FT-liquids are selected for the analysis, given their high mitigation potential, good applicability and especially its economies of scope. This includes FT-diesel and FT-gasoil, potential coproducts of higher market value fractions that can be used in different proportions to formulate FT-bunkers.

From the third group, which corresponds to biobased gases and alcohols, biomethanol is selected rather than LNG. Despite its drop-in characteristic relatively to fossil LNG, bio-LNG faces technical challenges, such as feedstock heterogeneity, geographical dispersion, and the need for cryogenic storage. Biomethanol would benefit from the existing infrastructure of fossil methanol and, despite not being a drop-in fuel, it has good applicability to the global fleet, once its use requires minor modifications on existing marine dual-fuel engines [65].

Finally, regarding hydrogen-based fuels, ammonia and synthetic hydrocarbons are selected rather than pure hydrogen. In spite of their direct emission reduction potential, both hydrogen and ammonia have very low applicability to the existing fleet, requiring preferably electrochemical-based motorization, which is not a mature technology yet [55], [66]. On the other hand, ammonia has better energy density and is more easily stored when compared to hydrogen, which can be an advantage [37]. Amongst the H_2-based hydrocarbons, H_2-diesel and H_2-gasoil are a natural option, since they are fully compatible with existing marine engines. It is worth noting that the model is free to choose between grey, blue and green H_2-fuels according to its optimization strategy.

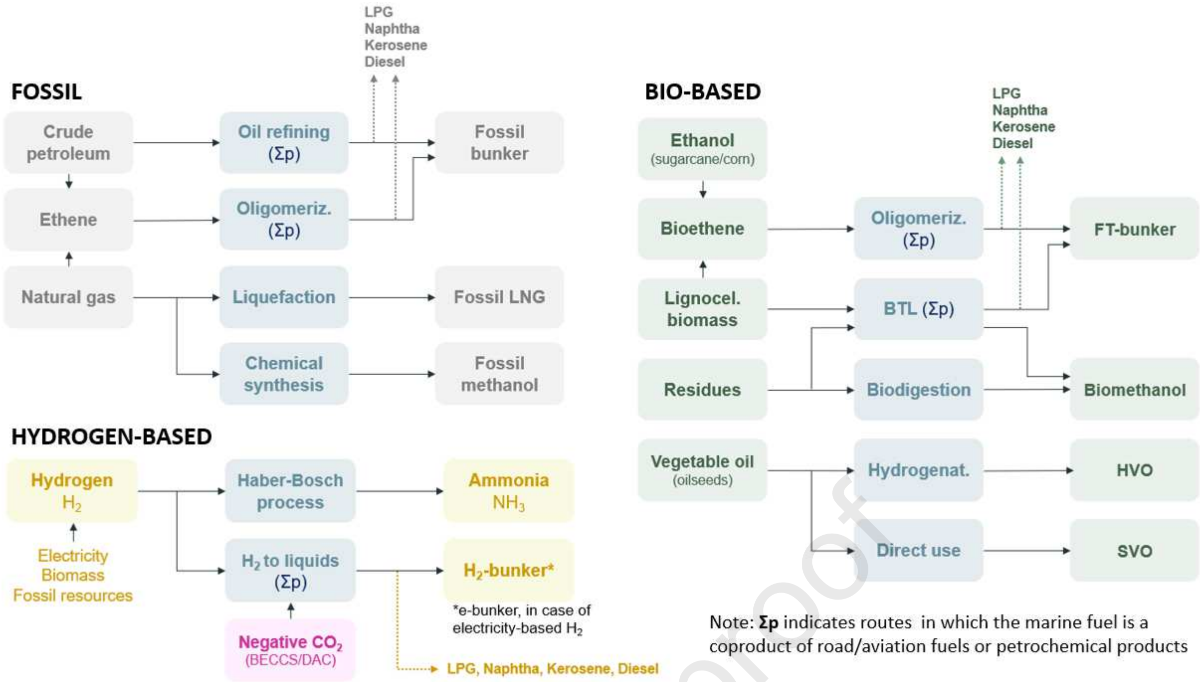


Figure 7: Marine fuel options represented in BLUES

3.3. Design of scenarios

With the alternative fuels for shipping represented within BLUES, eight scenarios are developed combining different assumptions. These scenarios are divided into two groups: portfolio and individual fuel scenarios. The idea is to explore a set of possible pathways in terms of freight demand and decarbonization scenarios of the Brazilian maritime transport sector. By exploring these scenarios, this study shows how an integrated assessment can indicate technological choices, and trade-offs, between emissions in ships and emissions in the upstream energy and land-use sectors. Clearly, various scenarios could also be explored, but for the sake of simplicity, this study aims at highlighting the relevance of using IAMs for studying the IMO target by deepening a set of threshold scenarios.

Portfolio scenarios (group 1) present no restrictions on fuel choice. Therefore, based on costs and carbon intensities, the model finds the least-cost combination of fuels. The portfolio scenarios premises are presented in Table 6.

Table 6: Scenarios' design (group 1, portfolio)

Scenario	Carbon metric	IMO2050	National target	Fuel restrictions
Baseline	-	No	No	None
IMO CO_2	CO_2	Yes	No	None
IMO GHG	CO_2eq	Yes	No	None
Brazil B2C	CO_2eq	Yes	Yes	None

The ***Baseline*** scenario represents a current policy view, admitting that announced mid-term policies are adopted and implemented. In ***IMO CO_2*** scenarios, the model is forced to halve the CO_2 emissions associated with the Brazilian foreign trade in 2050, consistently with the IMO2050 target. ***IMO GHG*** scenarios are similar to the latter but use CO_2eq instead of only CO_2 as a carbon metric. The idea is to capture the effect of all GHG emissions and not only carbon dioxide. Finally, ***Brazil B2C*** scenarios include emissions restriction not only to maritime transport but also to the whole Brazilian agriculture, land-use, and energy systems. As in Rochedo et al. (2018), the Brazilian budget is provided by a global model (Computable Framework for Energy and the Environment - COFFEE). This model, also an IAM, has Brazil as one of its 18 regions. Considering a global budget compatible with warming well below 2^{o}C, COFFEE outputs emissions trajectories for all the modelled regions, including Brazil. This value is then used as an input in ***Brazil B2C*** scenarios.

Individual fuel scenarios (group 2) are those in which only one fuel (or group of fuels) is selected as a mitigation alternative. The idea behind these scenarios is to analyze the impacts of choosing a single technological option to decarbonize the maritime sector. The individual fuel scenarios are presented in Table 7. Again, each scenario follows two trends over the evaluated period: low and high demands for maritime transportation.

In ***IMO drop-in*** scenarios, in addition to bunker, the model can choose any fuel that is a drop-in or nearly drop-in alternative. This includes SVO[7], HVO, and synthetic residual fuels coming from the Fischer-Tropsch process (FT-gasoil, in the case of a bio-based fuel or H_2-gasoil, in the case of a hydrogen-based fuel).

In **IMO *H_2-bunker*** scenarios, the model is restricted to fossil and hydrogen-based bunker (H_2-bunker). H_2-bunker is formed by the blend of H_2-diesel and H_2-gasoil, produced from hydrogen and carbon dioxide through the FT process. Carbon dioxide can only come from bioenergy with carbon capture (BECC) or direct air capture (DAC).

In ***IMO CH_3OH*** scenarios, in addition to fossil bunker, the model can use methanol (from fossil sources) or biomethanol (produced from anaerobic digestion or biomass gasification).

Finally, in ***IMO NH_3*** scenarios, the model is restricted to ammonia and fossil bunker. There is no restriction on the type of hydrogen used to produce ammonia and thus, the model can choose between fossil- and renewable-based hydrogen.

Table 7: Scenarios' design (group 2, individual fuels)

Scenario	Carbon metric	IMO2050	National target	Fuel restrictions
IMO drop-in	CO_2eq	Yes	No	Only drop-in[1]
IMO H_2-bunker	CO_2eq	Yes	No	Only H_2-bunker[2]
IMO CH_3OH	CO_2eq	Yes	No	Only methanol[3]
IMO NH_3	CO_2eq	Yes	No	Only ammonia[4]

[1]Drop-in fuels: SVO, HVO, FT-gasoil (residual fuel from FT-synthesis), or H_2-gasoil.
[2]Blend of H_2-diesel and H_2-gasoil.
[3]Fossil methanol and biomethanol.
[4]Fossil-based and renewable-based ammonia.

In terms of energy demand (subsection 3.2), each scenario follows two trends for maritime transportation activity: low and high demand.

4. Results

[7] SVO is considered as a nearly drop-in alternative, given concerns regarding its viscosity and oxidative and thermal stability [72].

4.1. Portfolio scenarios

Figure 8 shows fuel consumption for group 1 scenarios. In the absence of a national climate target, results indicate that LNG, SVO, and HVO are the preferable fuels to decarbonize maritime emissions (***IMO CO_2*** scenarios). In these scenarios, LNG figures as the least-cost choice, reducing CO_2 emissions compared to conventional fossil bunker, but still responsible for part of the emissions. On the other hand, an extra effort is needed to achieve IMO2050 and, therefore, carbon-neutral fuels play an important role. Hence, SVO (from soybeans) arises as a choice in the ***IMO CO_2 (Low)***[8] scenario, followed by HVO in the ***IMO CO_2 (High)*** scenario, replacing all traditional bunker in 2050 in the latter.

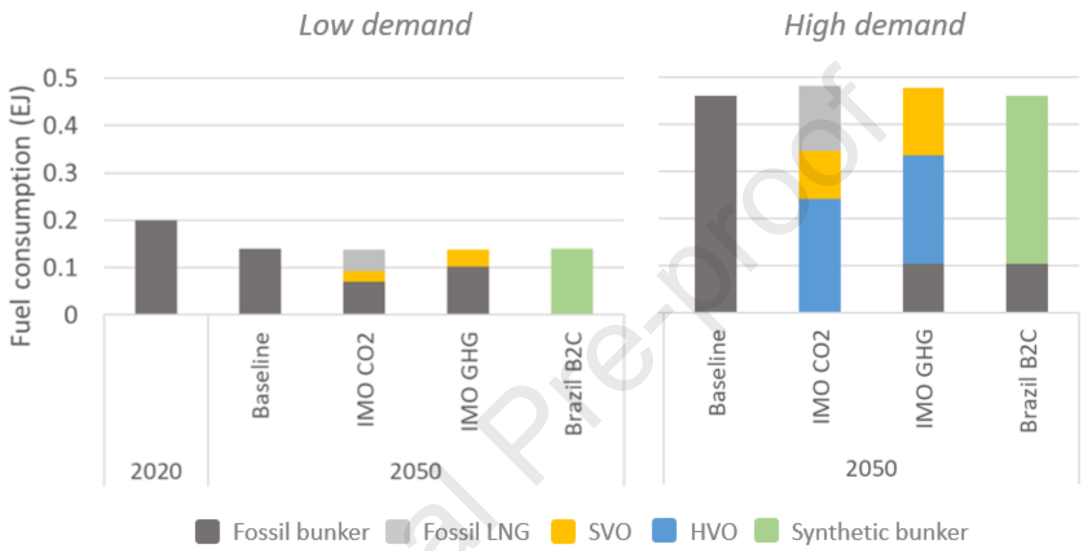


Figure 8: Fuels consumption in low and high demand portfolio scenarios

When restricting all GHG emissions (***IMO GHG*** scenarios), CH_4 emissions from LNG are taken into account and the fuel is replaced by fossil bunker and SVO. The latter is produced from soybeans, doubling soybean oil production in ***IMO CO_2 (High)*** and ***IMO GHG (High)*** scenarios in 2050, compared to the ***Baseline (High)*** scenario.

Despite the area expansion required for crops in these scenarios (around 9 Mha in each one), deforestation would not increase under a purely technical-economic evaluation. In Brazil, deforestation is not proportional to agricultural production, but rather mostly related to land grabbing [40], [67]–[71]. For SVO production, degraded pasture areas can be converted into crop areas, with no pure technical reasons to increase deforestation rates.

The inclusion of a carbon budget for Brazil´s national GHG emissions on top of IMO2050 (***Brazil B2C*** scenarios) shows a synergy between the whole country and international shipping decarbonization efforts. In a *well-below* 2°C world, advanced biofuels are produced in Brazil to replace part of the fossil kerosene and diesel. These technological routes are also able to supply heavy hydrocarbon fractions as a coproduct, which could be used as synthetic bio-based bunker fuels (biobunkers). In this sense, it can be stated that the decarbonization of the maritime freight transport needed to

[8] In this section, we use "*High*" or "*Low*" between parenthesis to differentiate high demand and low demand scenarios.

meet IMO requirements would be included in a deep mitigation pathway in Brazil compatible with a *well-below* 2°C world.

The cumulative land-use change from 2020 to 2050 is presented in Figure 9. Results show a small increase in crop area to produce soybeans for SVO and HVO in ***IMO CO_2 (High)*** and ***IMO GHG (High)*** scenarios. In a *well-below* 2°C world (***Brazil B2C*** scenarios), land use largely contributes to mitigation in Brazil through reforestation and pasture recovery, resulting in a significant land-use change in a horizon up to 2050.

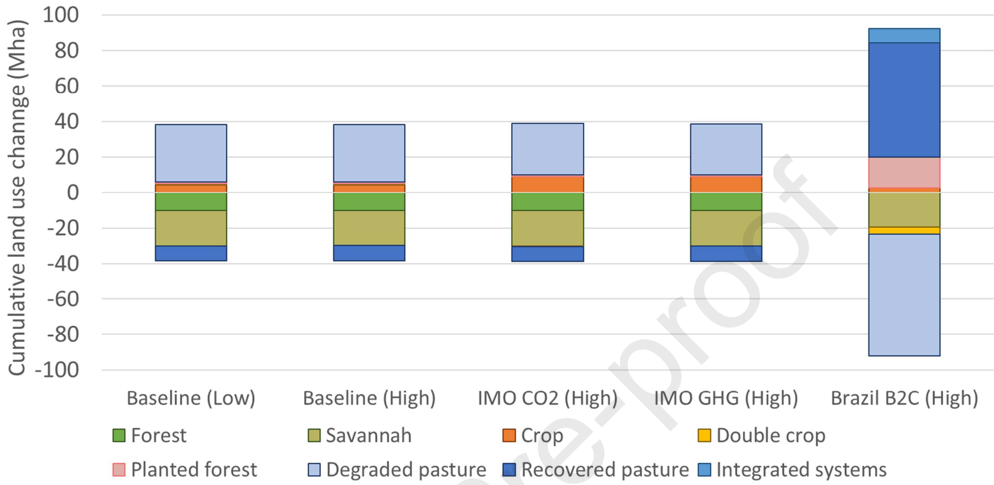


Figure 9: Cumulative land-use change between 2020 and 2050

4.2. Individual fuel scenarios

Figure 10 shows the results of group 2 scenarios, in which only one fuel category competes with fossil bunker, meaning that Brazil chooses a single technology or group of technologies to achieve IMO2050.

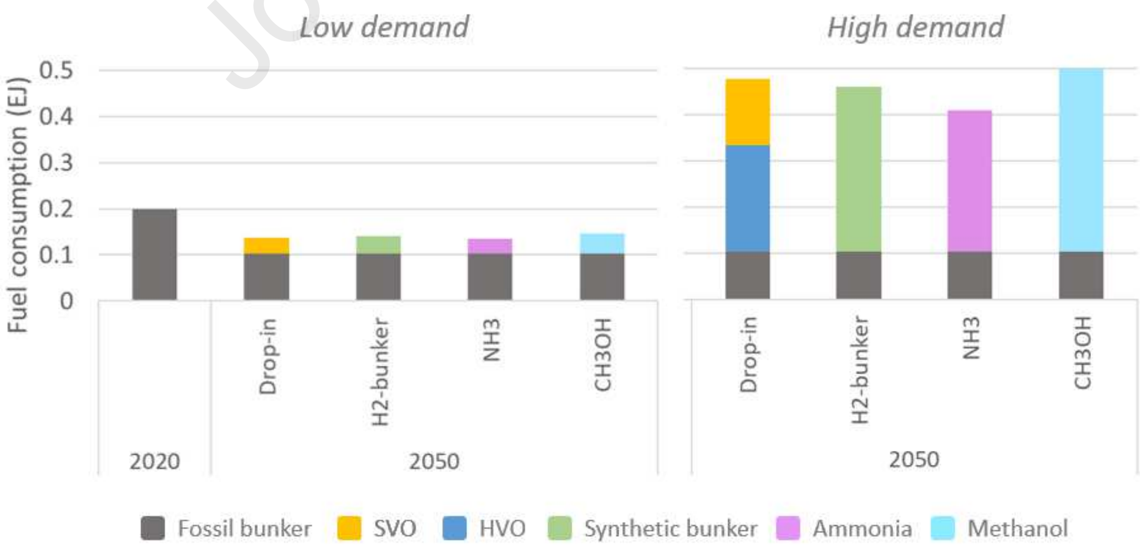


Figure 10: Fuels consumption in low and high demand individual scenarios

In ***IMO drop-in*** scenarios, the same result as ***IMO GHG*** is reached, since the use of drop-in fuels represents the least-cost option. Due to its lower costs, SVO is again the preferred alternative, followed by HVO.

In ***IMO H_2-bunker*** scenarios, the synthetic fuel is produced from both fossil-based hydrogen – from hydrogen production units (HPUs) in oil refineries –, due to its lower cost, and renewable hydrogen. HPU capacities must increase 20 times between 2020 to 2050 to produce the required amounts of hydrogen, which is unlikely to occur. Also, a large quantity of CO_2 is required for the FT process, which is supplied by carbon capture coming from different types of bioenergy plants (ethanol, FT-diesel, and bio-based hydrogen production).

For this reason, ethanol production increases around 30% in the ***IMO H_2-bunker (High)*** scenario compared to the ***Baseline (High)*** scenario. Part of this surplus is used to produce advanced kerosene through ethanol dehydration and subsequent ethene oligomerization.

A similar effect is observed in ***IMO NH_3*** scenarios, with ammonia being produced entirely from fossil-based hydrogen due to its lower production cost. In the ***IMO NH_3 (High)*** scenario, a 12-time increase is observed in HPU capacity until 2050. With respect to the fleet, in the ***IMO NH_3 (Low)*** scenario, 127 ammonia-based vessels would be required up to 2050, whilst in the ***IMO NH_3 (High)*** scenario this quantity would be 1,077, which represents an 8.5-time increase. As fossil-based ammonia does not produce direct emissions in ships, no incentive to produce clean hydrogen is observed.

In contrast, in ***IMO CH_3OH*** scenarios, in which the use of fossil methanol would imply direct CO_2 emissions in ships, only biomethanol is used.

4.3. Emissions spill over and cost increase

Figure 11 presents, for the high demand scenarios, a relation between the national emissions and the mitigation (CO_2eq abated) on maritime transportation associated with Brazilian foreign trade, attained as a result of IMO2050. It states that the decarbonization of the navigation sector implies a spill over on Brazilian emissions due to an increase in energy sector activities.

Figure 11 shows, for some of the individual pathway scenarios, that the spill over exceeds the mitigation achieved for seaborne transport; thus, representing an increase in total emissions. Even in ***IMO CO_2***, ***IMO GHG,*** and ***IMO CH_3OH*** high demand scenarios, around half of the emissions avoided by switching to low-carbon maritime fuels would be additionally emitted by the Brazilian energy system, partially compromising the gains obtained by maritime decarbonization efforts.

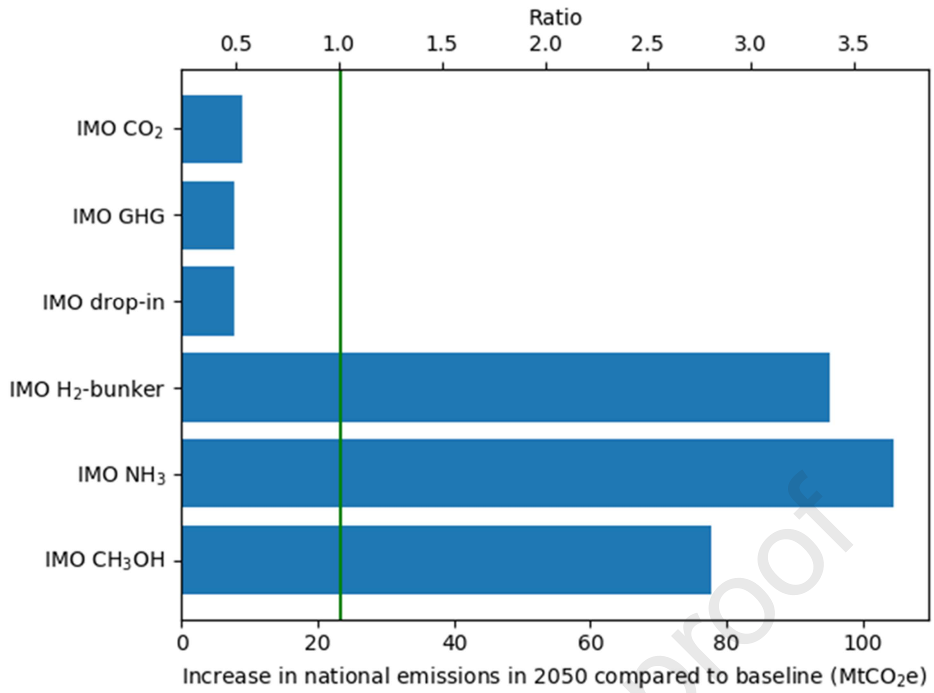


Figure 11: Increase in national emissions in different high demand scenarios. The green line represents the level at which an increase in national emissions equal to decrease observed in the maritime emissions. In Brazil B2C (High) scenario, there is significant reduction in national emissions that can not be associated with IMO's target. As such, this scenario is not presented in the figure.

Regarding costs (Table 8), the objective function of the model accounts for all the expenses of the energy system and land use, including investment and operational costs, as well as the costs associated with energy demand (e.g. new final energy consumption devices). Therefore, it reflects the cost increment of the energy systems to produce the fuels needed to achieve IMO2050 targets, as well as the costs for new vessel acquisition. For instance, it includes the cost of HPU expansion in oil refineries and in cropland technologies for enhancing soybean production for SVO and HVO. This clearly shows the relevance of using IAMs to assess the IMO target.

Table 8: Relative cost increase in high and low demand scenarios

	Relative cost increase[1,4]	
	Low demand	**High demand**
IMO CO_2	1.0[2]	1.0[3]
IMO GHG	1.6	1.1
IMO drop-in	1.6	1.1
IMO H_2-bunker	4.9	2.4
IMO NH_3	7.1	3.0
IMO CH_3OH	12.5	5.9

[1]Cost increment due to the whole energy and land use system, including investment and operational costs, demand, transformation, logistics, vessel acquisition, and others.

[2]Cumulative cost increase: 91 MUSD

[3]Cumulative cost increase: 1,900 MUSD

[4]***Brazil B2C*** scenarios' cost represents the system's decarbonization to attain

global climate targets and not only IMO2050. In this scenario, biobunker is a residue of synthetic biofuels routes already used to comply with a well-below 2°C world, focusing on diesel, jet fuel, and naphtha. As such, marine residual fuels have a null shadow price. As transportation costs to reach Brazilian ports are small compared to the full cost cycle, they can be neglected. Therefore, ***Brazil B2C*** scenarios can be seen as a non-regret policy to IMO's target.

The individual pathways scenarios required a large expansion of the fuels supply chain capacities. As aforementioned, HPU capacity would need to increase 20 times in the ***IMO H_2-bunker (High)*** scenario and approximately 950 extra ammonia-based vessels would be required in the ***IMO NH_3 (High)*** scenario, compared to the ***IMO NH_3 (Low)*** scenario. On the other hand, low demand scenarios do not strongly stress the energy and land-use systems. They offer plausible solutions, respecting reasonable industrial developments that could be a feasible pathway for the future.

5. Discussion

In case large amounts of low-carbon fuels are required to achieve IMO2050, relevant impacts could be observed on a national level, especially if it focuses on direct emissions, disregarding second-order effects. From a strictly technical point of view, our results indicate that Brazil can follow any low-carbon fuel strategy. However, second-order effects associated with the different scenarios, as well as their cost-effectiveness, vary widely.

In the case of group 1 (portfolio scenarios), a clear distinction is observed between scenarios assuming the coexistence of the IMO2050 strategy and a national climate target and scenarios in which IMO2050 is the only climate target. In the latter, LNG, SVO and HVO have to be produced exclusively because of shipping, while in the presence of a national climate target, ships are fuelled by bio-based bunker, generated as a coproduct of higher value synthetic hydrocarbons.

As expected, results from individual fuel scenarios are less cost-effective, as the optimization was forced to focus on technologies such as fuel cell-based ships, biodigestion and hydrogen production units. In the case of scenarios based on hydrogen-derived fuels, unrealistic increases in HPU capacities and fleet expansion were observed.

Furthermore, all individual fuel scenarios implied significant spill over effects, with GHG emissions reductions from shipping being way lower than the corresponding increase in national emissions. This is well illustrated by the results of the ***IMO NH_3 (High)*** scenario, in which the use of ammonia causes an increase of approximately 105 $MtCO_2e$ in national emissions in 2050 compared to the baseline, whereas navigation's emissions reduction would achieve around 28 $MtCO_2e$. This effect is partially due to the fact that, regardless of its origin, ammonia is a carbon free fuel in terms of direct emissions. As such, and given the lower cost of the fossil production route, IMO2050 is met at the expense of a higher carbon intensity in the supply chain.

The carbon leakage observed in this modelling exercise draws our attention to the need for a certification of alternative fuels. So far, IMO2050 refers exclusively to direct emissions [5]. Therefore, if ammonia or even hydrogen emerges as a marine fuel in the next decades, it is likely that increases in national emissions will take place all over the world. Nevertheless, this can be avoided through rigorous control of the origin of the fuel, including the possibility of producing blue ammonia.

Although the results of this study do not point to a similar effect for the case of methanol, there is a similar risk regarding this fuel. Unlike fossil-based ammonia, methanol obtained from natural gas, oil or coal is by definition a fossil resource. As such, its combustion is seen by the model as a source of extra direct GHG emissions. This is why the use of the fuel is very limited in ***IMO CH_3OH*** scenarios, dominated by biomethanol. This distinction prevents high spill over effects and, in methanol scenarios, the reduction in shipping emissions is indeed higher than the increase in national emissions. However, considering that biomethanol is chemically identical to fossil methanol, it can be said that, in the absence of adequate control of the supply chain, the shipping sector is exposed to the same risk described for the case of ammonia.

For biofuels, results indicate that it is technically and economically feasible to produce bio-based bunker fuels in Brazil without deforestation, but this does not guarantee that there will be no deforestation in the country. In this sense, the production of biofuels should be certified to avoid land speculation [69], [70]. Also, the model indicates the possibility of co-producing biomass-based marine fuels with higher value-added products, such as diesel, naphtha and biomaterials.

6. Final remarks

The set of IMO2050 has brought the climate mitigation discussion into the global maritime transportation sector. Achieving this goal can be challenging depending on the technological evolution of ships, and specially on the development of the demand for shipping, which is a function of the trade of products like coal, oil, grains, iron ore, chemicals and containerized cargo. With the expectation that the maritime activity will remain approximately constant over the next 30 years, constructive and operational efficiency gains in ships might promote most of the abatement of emissions required to comply with IMO2050 strategy. On the other hand, a future increase in maritime activity, which is consistent with the recent historic trend, will make IMO2050 strategy much harder to attain. In this case, low-carbon fuels might make a significant contribution, given that the impact of energy efficiency on emissions reduction is limited.

Brazil has some advantages to kick off the production of low-emissions alternative fuels for the maritime sector considering its experience in producing and implementing alternative transportation fuels. From an IAM point of view, the optimal portfolio of alternative fuels can vary depending on demand assumptions and mitigation targets. LNG, for example, stands out as a promising alternative in case only CO_2 emissions are accounted for within IMO goals, while it is replaced by SVO and HVO, when considering total GHG emissions.

Scenarios with a national decarbonization effort (***Brazil B2C***) show that drop-in renewable bunker fuels, produced mostly from technologies coupled with CCS, represent the most of fuel consumption and synthetic bunker is coproduced with higher value-added products, such as synthetic diesel and naphtha. These results highlight the synergies between both efforts, indicating that the achievement of IMO goals would be implicit in a national decarbonization strategy.

While it is possible to attain IMO2050 in Brazil with plants dedicated to the production of maritime fuels, achieving IMO2050 goal from a direct emission perspective may result in potential spill overs due to the intense use of the energy sector. In short, only an integrated national mitigation strategy could lead to effective decarbonization of the entire Brazilian marine fuel supply.

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Production of alternative marine fuels in Brazil: an integrated assessment perspective

Highlights

- There is no single optimal portfolio of alternative fuels for shipping
- Brazil can fulfil any low-carbon marine fuel strategy
- Marine fuels should be part of all national decarbonization strategies
- The decarbonization of shipping should be part of Brazil’s deep mitigation pathways

Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: