

# PROSPECTS FOR CARBON-NEUTRAL MARITIME FUEL PRODUCTION IN BRAZIL

EXECUTIVE SUMMARY - FINAL REPORT



# PROSPECTS FOR CARBON- NEUTRAL MARITIME FUEL PRODUCTION IN BRAZIL

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## INTRODUCTION

The project “Prospects for Carbon Neutral Maritime Fuel Production in Brazil” performs an analysis of decarbonization alternatives for the international shipping sector based on renewable fuels. This study, which has the International Maritime Organization (IMO) climate mitigation targets for 2050 as a background, aims to support Brazilian authorities to define the best alternatives for the shipping sector to meet these targets and, at the same time, ensure the positive effects of a low-carbon economy. Thus, this project’s objective is to compare, from an environmental, technical and economic point of view, different renewable fuels that could be selected for the decarbonization of long-distance maritime transport. To do so, an integrated analysis has been performed using the Brazil Land-Use and Energy Systems (BLUES) model, developed at the Centre for Energy and Environmental Studies (CENERGIA) laboratory, of the Energy Planning Program (PPE), COPPE, of the Universidade Federal do Rio de Janeiro (UFRJ), over the past 20 years.

The project included three phases. In the first phase of the project, different possibilities of renewable energy vectors for large vessels were investigated, as well as their technological applications. Then, a qualitative comparison between the different options was performed according to a set of criteria.

In the second phase, the five best performing fuels were studied in more detail. For each of them, a georeferenced analysis was developed to map the national production potential and to identify production hotspots. Additionally, emissions of greenhouse gases (GHGs) associated with the life cycle of these fuels were estimated.

The third and final phase of the project performed an economic analysis and an integrated assessment of these fuels.

## PHASE 1: COMPARATIVE ANALYSIS

The first phase of this project presented different pathways for producing renewable fuels for maritime transportation and their technological applications. A qualitative comparison between the alternatives was performed according to a set of criteria/indicators with scores ranging from 1 to 5, where 1 means “Very Bad” and 5 “Very Good” performance. Different weights were attributed to each indicator. Weight 3 was attributed to global sustainability, which is the main aspect of this work. The technical criteria (availability, applicability, energy density and technological maturity), were assigned weight 2, as they are prerequisites for the technical potential. Other criteria (economy, local sustainability, standardization and security) have weight 1.

The evaluated fuels were divided into three groups. Group 1 encompasses distillate fuels suitable for diesel (compression ignition) engines: straight vegetable oil (SVO), biodiesel (FAME<sup>1</sup> or FAEE<sup>2</sup>), hydrotreated vegetable oil (HVO), hydrotreated pyrolysis oil (HDPO) and Fischer-Tropsch diesel (FT-diesel). Group 2 comprises alcohols and liquefied gases suitable for spark ignition or dual-fuel engines: liquefied biomethane (Bio-LNG), biomass-derived methanol (biomethanol) and biomass-derived ethanol (bioethanol). Group 3 includes renewable-based hydrogen, ammonia and hydrogen-based synthetic fuels (e-fuels). Table 1 presents the evaluation of the fuels in each criterion.

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<sup>1</sup> Fatty Acids Methyl Esters. Biodiesel produced via transesterification with methanol

<sup>2</sup> Fatty Acid Ethyl Esters. Biodiesel produced via transesterification with ethanol

Table 1: Evaluation of fuel alternatives according to the criteria and defined weights (very good = 5, very bad = 1)

	SVO	Biodiesel	HVO	HDPO	FT-diesel	Bio-LNG	Biomethanol	Bioethanol	Green H <sub>2</sub>	Green NH <sub>3</sub>	e-diesel	e-LNG	e-methanol
Availability (2)	2	2	2	3	4	2	4	3	3	3	1	1	1
Applicability (2)	4	3	5	5	5	3	4	2	1	2	5	3	4
Technology readiness (2)	5	5	5	2	3	5	4	3	3	2	3	2	2
Energy density (2)	5	5	5	5	5	3	2	3	1	2	5	3	2
Economic (1)	4	4	4	3	3	4	5	3	1	2	1	1	1
Safety (2)	5	5	5	3	5	3	3	4	2	2	5	3	3
Standards (1)	3	3	4	4	4	4	5	5	1	1	4	4	5
Local sustainability (1)	4	4	4	4	5	5	4	4	3	3	3	3	3
Global sustainability (3)	3	3	3	4	5	3	4	2	5	5	5	4	5
<b>Total</b>	62	60	65	59	71	54	60	48	40	43	61	44	48
<b>Ranking</b>	3	5	2	7	1	8	5	9	13	12	4	11	9

The top five<sup>3</sup> alternatives were selected for further analysis: straight vegetable oil (SVO); hydrotreated vegetable oil (HVO); Fischer-Tropsch synthetic diesel produced from biomass (FT-diesel); biomethanol (bio-CH<sub>3</sub>OH); Fischer-Tropsch synthetic diesel produced from renewable hydrogen and carbon dioxide from Direct Air Capture (DAC) (electrodiesel or e-diesel).<sup>4</sup>

<sup>3</sup> Both biomethanol and biodiesel presented the same final score. Considering that HVO and SVO, which were already selected in the ranking, are based on the same production chain as biodiesel, the authors opted to include biomethanol, whose production is based on another type of raw material and technology.

<sup>4</sup> In this analysis, FT-diesel and e-diesel include both diesel and the residual fuel from the synthesis (heavy gasoil pool).

## PHASE 2: GEOREFERENCED AND LIFE CYCLE ANALYSIS

The second phase of this project assessed the five selected fuels according to two different analyses: georeferenced modeling and life cycle assessment (LCA). The purpose of the georeferenced analysis is to identify fuel production hotspots in Brazil, according to the supply of resources and their geographic distribution throughout the country. The LCA aims to quantify the emissions throughout the entire chain of a product or activity and, in the case of alternative renewable fuels, to assess their mitigation potential throughout the entire production chain in an integrated approach. Figure 1 and Figure 2 summarize the hotspots defined in the georeferenced analysis and the fuel production potential. Figure 3 compares the life cycle emissions of the evaluated fuels with conventional fossil bunker fuels.

*Figure 1: Fuel hotspots and the principal ports that handle Brazilian main export products*

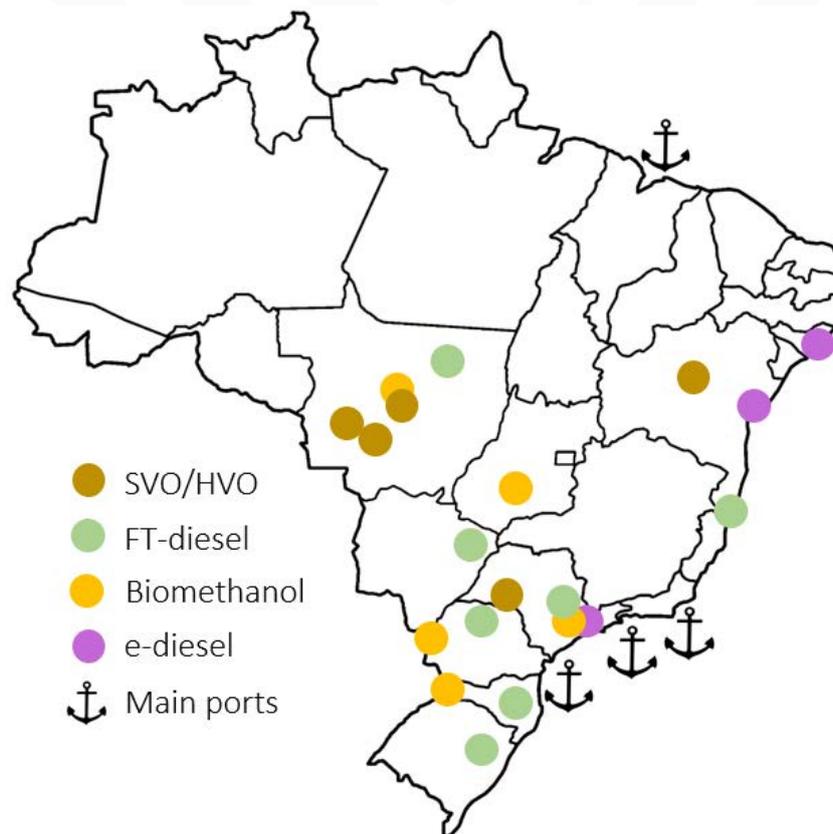
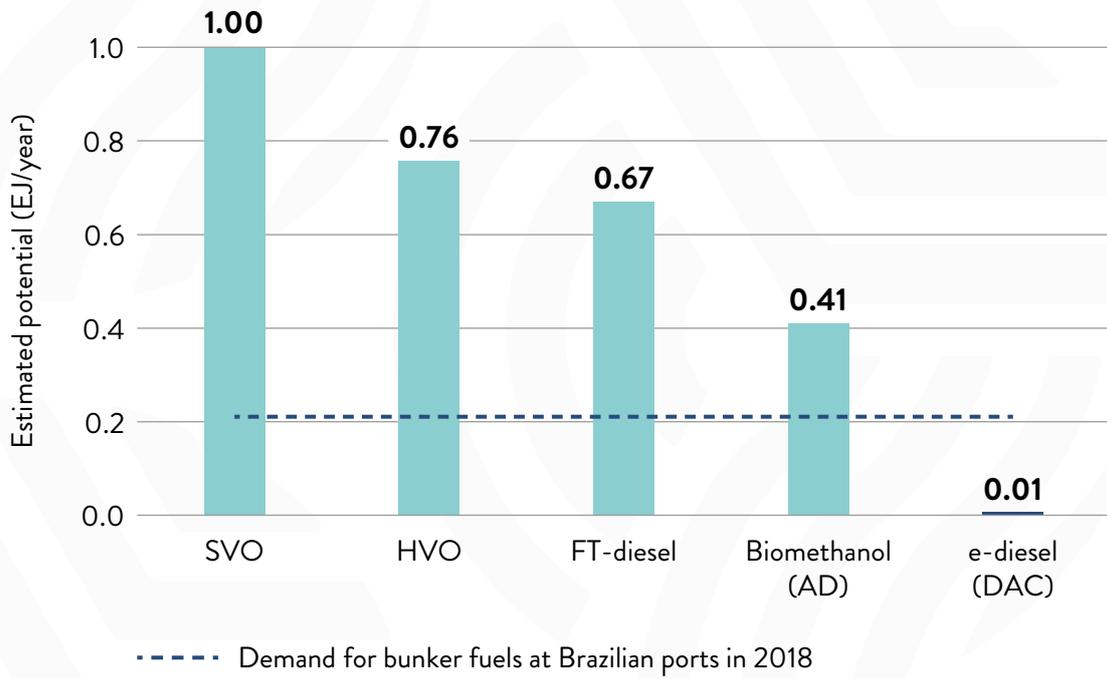
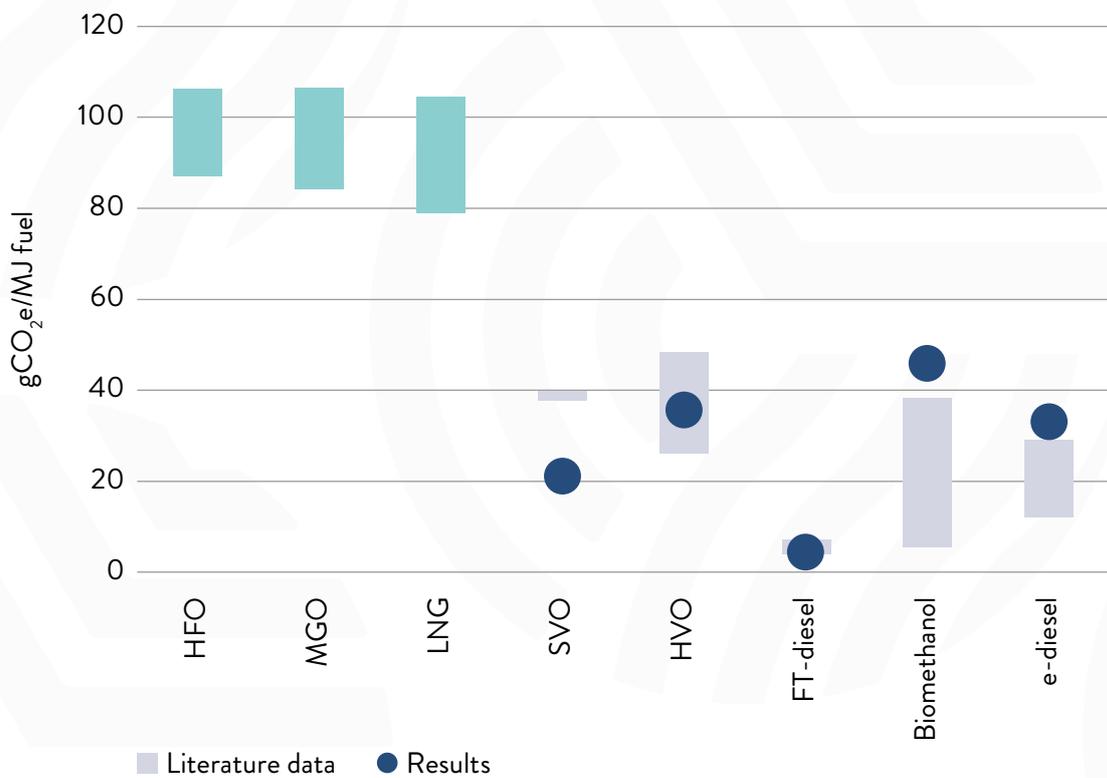


Figure 2: Fuel production potential.



Note: Biomethanol (AD) is produced via anaerobic digestion.

Figure 3: Results of the life cycle assessment. SVO/HVO results do not include possible indirect LUC (land use change) emissions



# PHASE 3: TECHNOECONOMIC ANALYSIS AND IAM

## 1) TECHNOECONOMIC ANALYSIS

The techno-economic analysis of the selected fuels<sup>5</sup> aimed to determine the capital and operation and maintenance costs for newly built facilities according to different plant scales (as defined by the hotspots in the georeferenced analysis) and the levelized costs (LCOF or LCOE).<sup>6</sup> Also, the cost analysis identified economies of scale for different plant sizes and the increased costs for pioneer plants (*First of a Kind* - FOAK) compared to mature plants (*N<sup>th</sup> of a Kind*, NOAK).

The analysis was applied using the same baseline assumptions. The economic lifetime of 30 years was chosen for the plants to comply with the time horizon of the IMO2050 goals and a discount rate of 5% per year was considered. The capital costs of the conversion plants were converted to 2019 values using the Chemical Engineering Plant Cost Index (CEPCI) and all costs were reported in 2019 US dollars (USD<sub>2019</sub>).

Figure 4 shows the LCOE for the evaluated fuels. E-diesel registered the highest LCOE (43.7 USD/GJ) followed by biomethanol (40.0 USD/GJ) and FT-diesel (34.2 USD/GJ). HVO registered the lowest LCOE among the alternative fuels (23.8 USD/GJ). In the FOAK plants, the costs of e-diesel and FT-diesel are even higher, totaling 68.0 USD/GJ and 58.7 USD/GJ, respectively.

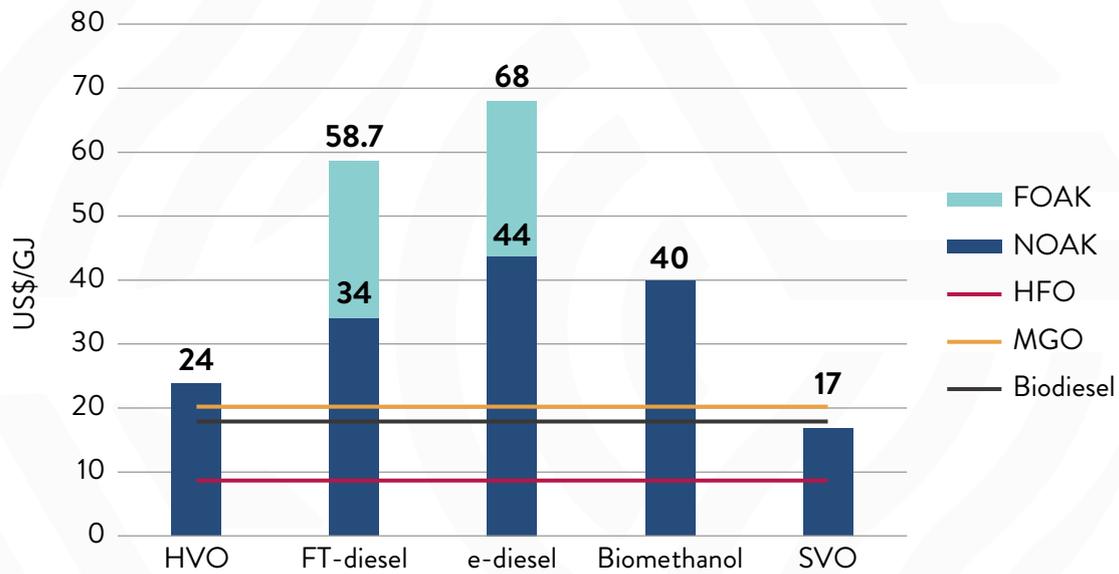
Figure 4 also compares the LCOE for the evaluated fuels with the prices of conventional bunker fuels (Heavy Fuel Oil, HFO and Marine Gas Oil, MGO) and biodiesel. The LCOE values of the alternative fuels are far higher than conventional bunker fuels. In relation to HFO prices, the costs of alternative fuels are up to four times higher. Compared with MGO prices, the worst case is for e-diesel with LCOE almost two times higher.

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<sup>5</sup> SVO are widely produced commodities and traded worldwide. Therefore, an economic analysis was not performed for this fuel alternative.

<sup>6</sup> Levelized cost of fuel - LCOF  
Levelized cost of energy - LCOE

Figure 4: LCOE for the evaluated fuels and literature estimates.



## 2) INTEGRATED ASSESSMENT

This study provided an integrated assessment of the production and distribution of alternative marine fuels in Brazilian ports between 2020 and 2050, considering IMO emission reduction targets. To achieve this, the Brazilian Land Use and Energy System (BLUES) model was used.

Integrated Assessment Models (IAMs) are useful tools for policy and future scenario development that assess the integration between GHG mitigation measures and long-term transformations across energy, land use and agriculture and other economy sectors (Huppmann et al. 2018; Kriegler et al. 2018; Angelkorte 2019). Currently, IAMs have a wide range of applications and levels of complexity, from the evaluation of new policy implementations in climate change mitigation to assessing impacts of dietary changes and regional food security in different global warming scenarios (Hasegawa et al. 2018; Köberle 2018).

The modelling of production and distribution of alternative fuels in the context of IMO2050 in the BLUES model followed four steps: (i) developing shipping demand (transport work) vectors, (ii) modelling energy conversion in ships associated with Brazilian international trade, (iii) representing different technological routes to produce and distribute marine fuels and (iv) elaborating scenarios to comply with IMO2050.

The creation of transport work vectors was based on literature scenarios (IMO 2015; DNV GL 2018) for the activity of international shipping. From these projections and considering the historic bunker fuel supply at Brazilian ports (EPE 2019), typical export products and associated trade routes, two transport work vectors (in t-km) were generated: low and high demand. These tonne-kilometers were disaggregated in terms of the international trade associated with Brazilian ports (exports of iron ore, crude oil, soybeans, sugar and others; imports, treated as an aggregated category). The transport work of the national coastal navigation was also included.

Shipping modelling followed the product disaggregation, in order to consider different vessel types and sizes. Furthermore, the conversion efficiencies of the fuels selected in the first report<sup>7</sup> were included. Regarding fossil options, in addition to conventional maritime bunker, liquefied natural gas (LNG), which has been gaining strength in the context of IMO's regulations for atmospheric pollution (Lindstad et al. 2020), fossil-derived methanol and ammonia, seen as a promising hydrogen carrier, were considered. It is important to mention that, even though this study focuses on zero emission fuels for shipping, fossil based alternatives were included in order to investigate the impacts of IMO2050 in an integrated perspective. In this sense, all the fuel options were considered, so that the impacts in the energy, land use, agriculture and other sectors of the economy could be observed. Also, given that BLUES is a cost-optimization model, and that IMO goals still allow a limited level of emissions in 2050, the authors considered plausible to examine all possible alternatives fuels.

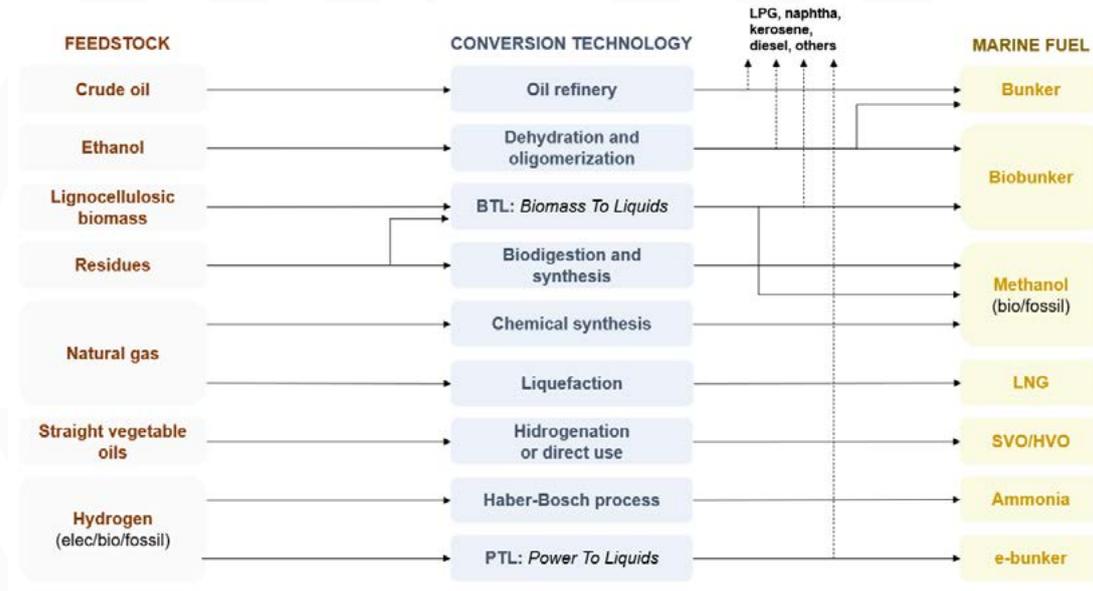
The modelling of fuel production and distribution in the BLUES model is illustrated in Figure 5, which presents the different technological options to produce the marine fuels listed above. It is worth noting that, in some cases (e.g., BTL<sup>8</sup>), marine fuel is not the main output of the process.

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<sup>7</sup> See the first part of this executive summary.

<sup>8</sup> Biomass-to-liquids, or BTL, also known as Fischer-Tropsch synthesis, converts biomass into bioliquids similar to oil products.

Figure 5: Technology fuel production pathways in BLUES.



After including the energy conversion of the maritime transport and the supply chain of the associated fuels within BLUES, a set of 16 scenarios was developed, considering the different combinations of global greenhouse gas (GHG) emission targets, fuel use restrictions and demand projections (estimate based on two literature scenarios for the shipping sector as a whole (IMO 2015; DNV GL 2018)).

The baseline scenario considers Brazil’s current policy trend, including the NDC<sup>9</sup> target. Also, three climate target scenarios were simulated, two accounting only for IMO2050 goals and one including both constraints on shipping emissions and Brazil’s energy system emissions, considering a “well-below 2 °C” world. Finally, individual scenarios were designed, in which only one fuel category replaces fossil bunker to achieve IMO2050 targets. The scenario assumptions are summarized in Figure 6 and Table 2. Demand projection is detailed in Figure 7.

<sup>9</sup> National Determined Contribution. Represents the country’s commitment to reduce GHG emissions.

Figure 6: Scenario design.

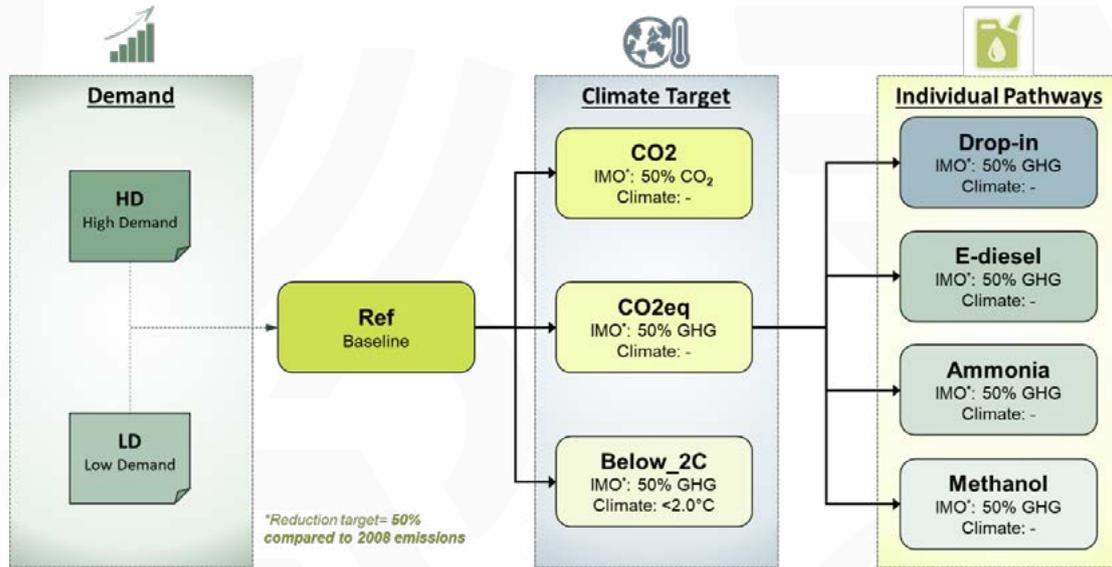


Figure 7: Low demand (LD) and high demand (HD)

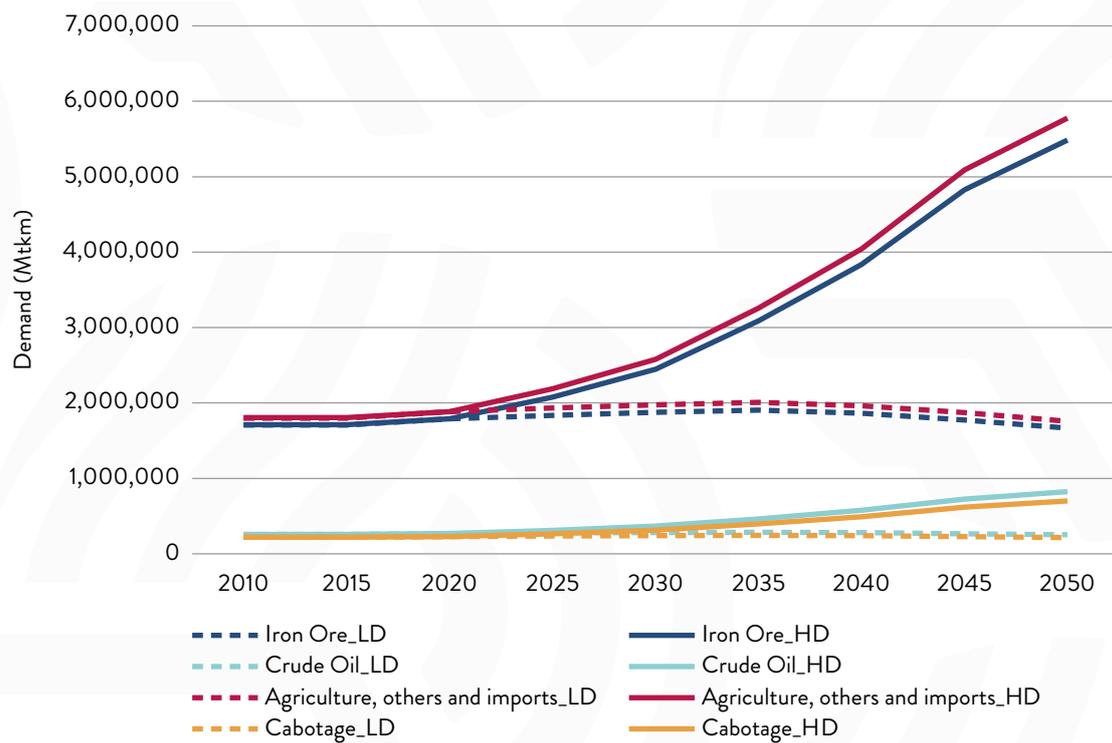


Table 2: Scenario design

Scenario	Fuel demand	Emission targets	Fuel choice restrictions
Baseline_LD	Low	Unlimited	None
Baseline_HD	High	Unlimited	
CO2_LD	Low	IMO2050 CO <sub>2</sub>	None
CO2_HD	High	IMO2050 CO <sub>2</sub>	
CO2eq_LD	Low	IMO2050 CO <sub>2</sub> eq	
CO2eq_HD	High	IMO2050 CO <sub>2</sub> eq	
Below_2C_LD	Low	IMO2050 CO <sub>2</sub> + well-below 2 °C	
Below_2C_HD	High	IMO2050 CO <sub>2</sub> + well-below 2 °C	
Drop-in_LD	Low	IMO2050 CO <sub>2</sub> eq	Only drop-in fuels used to meet the goal
Drop-in_HD	High	IMO2050 CO <sub>2</sub> eq	
E-diesel_LD	Low	IMO2050 CO <sub>2</sub> eq	Only e-diesel used to meet the goal
E-diesel_HD	High	IMO2050 CO <sub>2</sub> eq	
Methanol_LD	Low	IMO2050 CO <sub>2</sub> eq	Only methanol used to meet the goal
Methanol_HD	High	IMO2050 CO <sub>2</sub> eq	
Ammonia_LD	Low	IMO2050 CO <sub>2</sub> eq	Only ammonia used to meet the goal
Ammonia_HD	High	IMO2050 CO <sub>2</sub> eq	

Notes:

Drop-in fuels: SVO, HVO, FT-bunker (only the residual fuel from FT-synthesis), e-bunker (only the residual fuel from e-fuel synthesis)

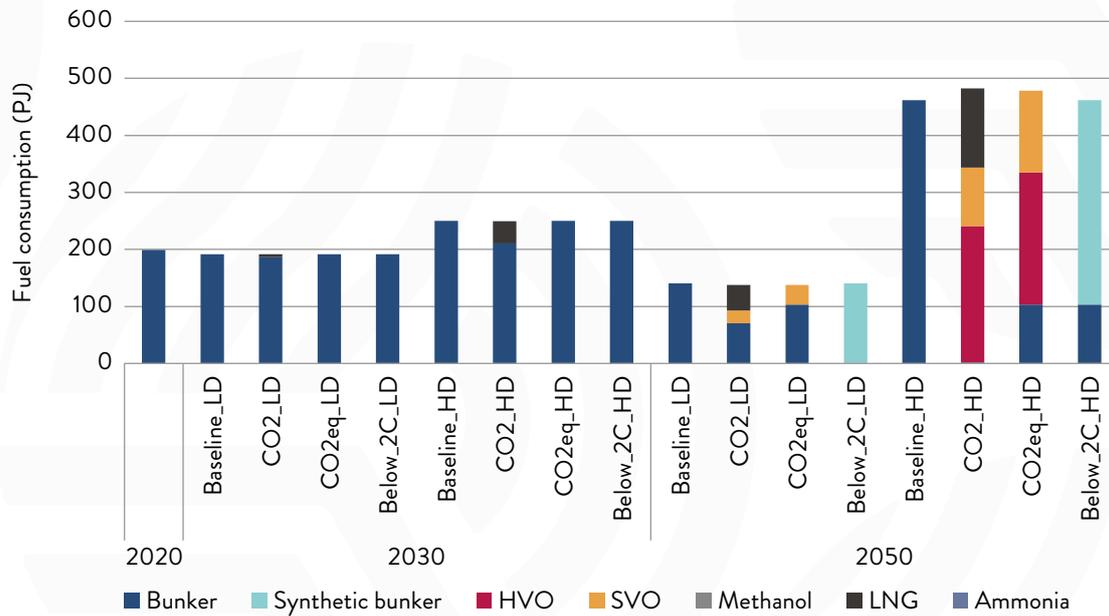
E-diesel: Blend of e-diesel and e-bunker

Ammonia: Fossil- and renewable-based ammonia

Methanol: Fossil- and renewable-based methanol

Figure 8 shows the fuel consumption for the reference scenario and climate target scenarios, as presented in Figure 6. The model results indicated that LNG, SVO and HVO would be the preferable fuels to decarbonize maritime emissions in the absence of a national climate target and considering only CO<sub>2</sub> emissions in IMO targets. However, LNG utilization can lead to methane emissions, a GHG with global warming potential (GWP) 28 times higher than CO<sub>2</sub>. Also, the use of LNG would reduce CO<sub>2</sub> compared to traditional bunkering, but LNG would still be responsible for part of the CO<sub>2</sub> emissions. In order to achieve IMO2050 targets, zero emission fuels play an important role, hence SVO arises as a choice in the CO<sub>2</sub>\_LD scenario, followed by HVO in the CO<sub>2</sub>\_HD scenario, eventually replacing all traditional bunker in 2050 in the latter. On the other hand, LNG would be the minimum cost choice.

Figure 8: Fuel consumption for each scenario.



Note: Synthetic bunker includes FT-bunker, e-bunker and oligomerization bunker (see Figure 5).

When also accounting for  $\text{CH}_4$  emissions from LNG (CO2eq scenarios), LNG is penalized and not chosen anymore. As methane has GWP 28 times higher than  $\text{CO}_2$ , it is substituted by additional bunker fuel and SVO. The latter is produced from soybean oil, doubling its production in CO2\_HD and CO2eq\_HD scenarios in 2050, compared to the Baseline\_HD. Despite the area expansion required for crops in these scenarios (around 9 Mha in each one), deforestation would not need to increase, under a pure technical economic evaluation. In Brazil, deforestation is more closely related to land grabbing (Rochedo et al. 2018). For SVO production, the model indicates that degraded pasture areas could be converted into crop areas, thus not necessarily resulting in higher deforestation rates.

The inclusion of a carbon budget on top of the IMO2050 target shows a synergy between both objectives. In a “well-below 2 °C” world, the model shows that advanced biomass biofuels (synthetic bunker) could be produced in Brazil to replace part of the fossil kerosene (jet fuel) and diesel. These technological routes are also able to supply biobunker<sup>10</sup> as a co-product. In this regard, the model results indicate that

<sup>10</sup> Residual fuel produced in biorefineries.

the decarbonization of the shipping sector needed to meet IMO2050 requirements would be included in a “well-below 2 °C” pathway to Brazil. In this case, an integrated approach of GHG mitigation, that considers all sectors of the economy, is crucial to achieve both IMO2050 and Paris Agreement decarbonization targets.

The cumulative land use change from 2020 to 2050 is presented in Figure 9. Amongst the IMO2050 target scenarios, there is a small increase in crop area to produce soybeans for SVO and HVO, in the CO<sub>2</sub>\_HD and CO<sub>2</sub>eq\_HD scenarios. In a “well-below 2 °C” world, land use plays an important role for mitigation through reforestation and pasture recovery, which results in a significant land use change in a horizon up to 2050.

Figure 9: Cumulative land use change from 2020 to 2050 (in Mha).

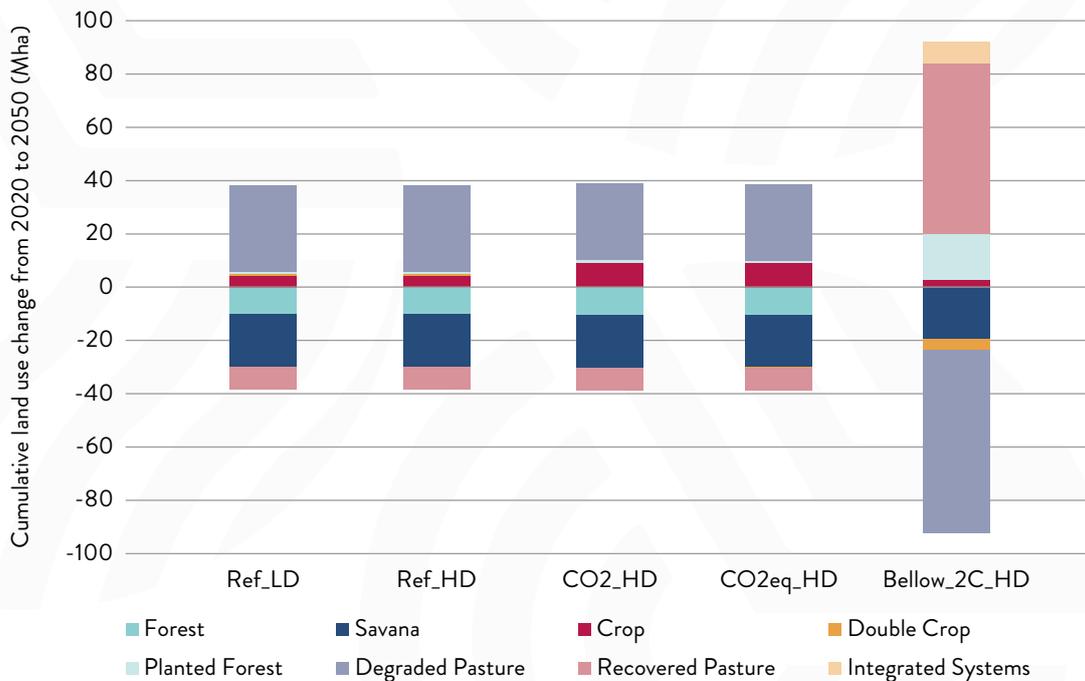


Figure 10 shows the results for the individual pathway scenarios, in which only one fuel category replaces fossil bunker to achieve the IMO2050 targets, meaning that the country chooses a mono-technological strategy to deal with the IMO target. In drop-in scenarios, the same results as CO<sub>2</sub>eq scenarios are reached, because the least cost option for both are indeed the use of drop-in fuels. Therefore, SVO is the preferred fuel alternative, due to its lower relative costs, followed by HVO. Again, under a pure technical economic analysis, the model shows an increase in land use for

soybean production, but considering that it could occur in degraded pasture areas, this production would not directly result in further deforestation. In e-diesel scenarios, the fuel is produced from both fossil-based hydrogen (from HGU<sup>11</sup>) and renewable hydrogen. A large quantity of CO<sub>2</sub> is needed as feedstock for the electro-diesel technology, which is supplied by carbon capture technology applied to ethanol, FT-diesel and bio-based hydrogen production. Because of that, ethanol production increases around 30% compared to the Baseline\_HD scenario and part of that (approximately 7 billion liters) is used to produce advanced kerosene through ethanol dehydration and subsequent ethene oligomerization. Still in the e-diesel\_HD scenario, the HGU capacities must increase 20 times from 2020 to 2050 to produce the required amounts of hydrogen in high demand scenarios, which is challenging.

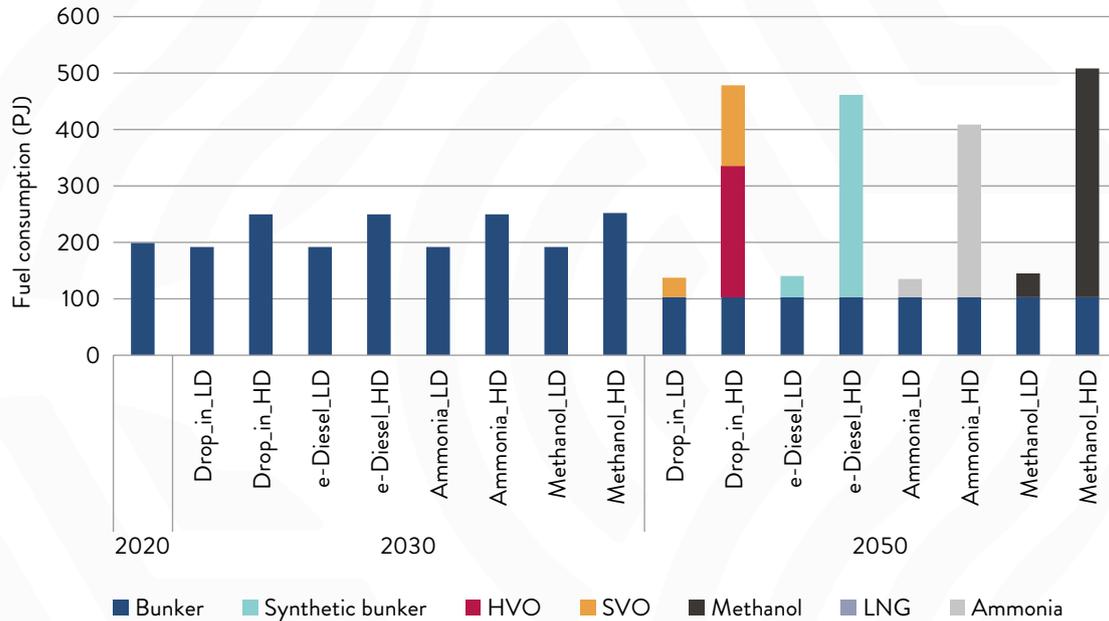
The same is observed in ammonia scenarios, because the model chooses the option of producing ammonia entirely from fossil-based hydrogen and a 12 time increase in HGU capacity from 2020 to 2050 is observed in the high demand scenario. In both the e-diesel and ammonia scenarios, the model's choice for fossil hydrogen is based on the lowest cost for producing it. As electrolysis costs are currently very high, the model does not choose renewable-based hydrogen production. Even though BLUES model considers the technological improvements and cost reductions for novel technologies over the years, they are not sufficient for the model to choose them as an alternative.

Also, the increase in HGU capacities observed in both scenarios could raise fuel lifecycle GHG emissions, which represents a trade-off between the maritime and energy sector emissions. Even though ammonia does not imply direct emissions in ships, its production through fossil sources increases the energy sector emissions. Finally, in methanol scenarios, in which the use of a fossil fuel would contribute to maritime emissions, there is a choice for biomethanol. Unlike the ammonia scenario, in which there are no emissions associated with the navigation sector, there is no incentive to produce clean hydrogen. As a result, large amounts of fossil hydrogen are produced in this scenario. This means that a scenario favoring ammonia must trace the origin of this fuel, which does not emit GHG in the ship but can emit GHG by being produced from fossil fuel.

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<sup>11</sup> HGU – Hydrogen generation unit in oil refineries

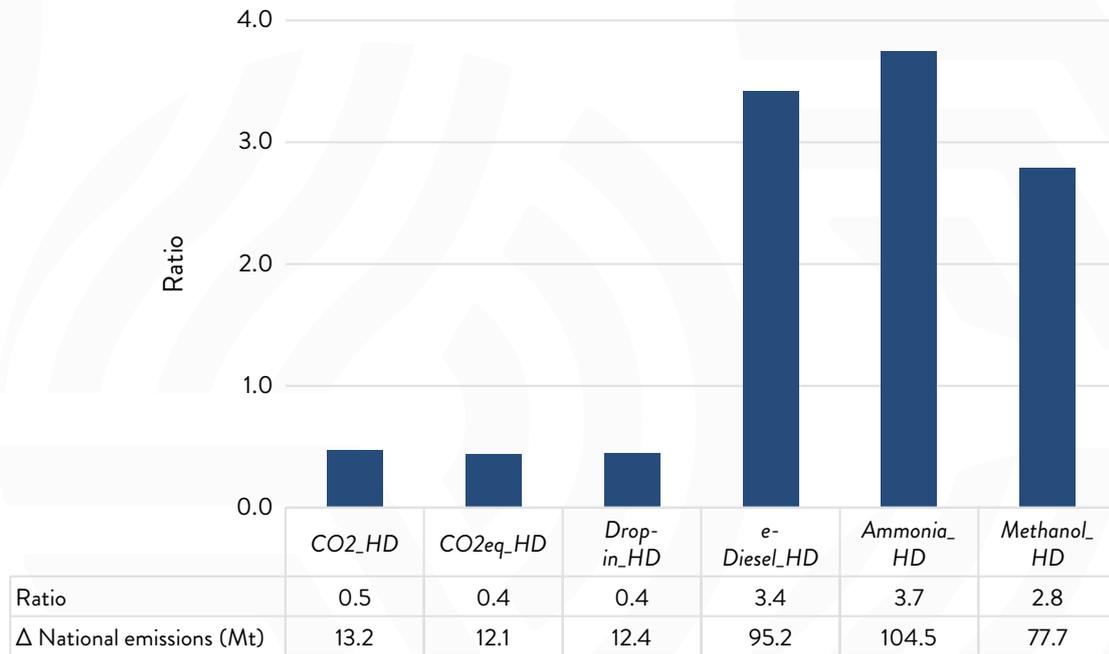
Figure 10: Fuel consumption for individual pathway scenarios



Note: In methanol scenarios, biomethanol is the fuel needed to meet the IMO2050 target

An interesting finding is presented in Figure 11, which indicates a relationship between the national emissions and the mitigation in the maritime sector, attained as a result of the IMO2050 targets. Particularly in the individual pathway scenarios, the model results show that the decarbonization of the navigation sector could imply a spillover onto Brazilian emissions, due to the higher activities in the energy sector if fuels life cycle emissions are not taken into account in the measures to reduce GHG from the maritime sector. However, even in the CO<sub>2</sub>, CO<sub>2</sub>eq and drop-in scenarios, results show that around half of the emissions avoided when switching to low carbon maritime fuels would be emitted by the Brazilian energy system, partially compromising the gains obtained in international maritime transportation. Such results emphasize the need to account for life cycle emissions of alternative fuels and to certify their production chain.

Figure 11: Increased national emissions compared to shipping emissions in 2050.



Notes:

Shipping emission reduction in 2050 for high demand scenarios is 28 MtCO<sub>2</sub> relative to the Baseline\_HD scenario.

Below\_2 °C scenario emissions represent mainly the system’s decarbonization to attain the global climate targets.

There is a significant reduction in national emissions that cannot be associated with IMO2050 targets and, therefore, it is not presented in the graph.

Regarding costs, 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 when producing the fuels needed to meet the IMO2050 targets, as well as the costs for the acquisition of new vessels. For instance, it includes costs of HGU expansion for hydrogen production and cropland technologies for enhancing soybean production for SVO and HVO. Table 3 presents the relative cost increase, which was normalized to the IMO CO<sub>2</sub> scenario. In the CO<sub>2</sub>\_LD scenario, there is a cumulative cost increase of US\$ 91 million, relative to the baseline\_LD scenario, due to the model’s option for the LNG and SVO production. In the CO<sub>2</sub>\_HD it corresponds to US\$ 1,900 million, relative to the baseline\_HD scenario, reflecting the costs associated with the HVO production needed to supply a higher demand. Therefore, it is important to highlight that the relative costs of the scenarios should only be compared with the same demand (HD or LD) and not between them, because they do not start from the same basis. With respect to the IMO2050 target scenarios, the methanol scenarios present the

highest costs, mainly associated with the large production of biomethanol. For the e-diesel and ammonia scenarios, if hydrogen from electrolysis were considered instead of fossil hydrogen, the costs would be even greater than the ones presented in Table 3. Even though technology advances may reduce electrolysis costs in the medium to long term, they are currently far higher than conventional hydrogen production technologies<sup>12</sup>. However, the benefit of the GHG reduction provided by the green hydrogen derived fuels is much higher when compared to fossil fuels.

Table 3: Cost increase for shipping mitigation scenarios.

	Relative cost increase <sup>a, d</sup>	
	LD	HD
<b>CO2</b>	1.0 <sup>b</sup>	1.0 <sup>c</sup>
<b>CO2eq</b>	1.6	1.1
<b>Drop_in</b>	1.6	1.1
<b>e-diesel</b>	4.9	2.4
<b>Ammonia</b>	7.1	3.0
<b>Methanol</b>	12.5	5.9
<b>Below_2 °C</b>	d	

Notes:

<sup>a</sup> This represents the cost increment due to the whole energy and land use system, including investment and operational costs, demand, transformation, logistics, shipping acquisition and others.

<sup>b</sup> Cumulative cost increase for the CO2\_LD scenario: US\$ 91 million.

<sup>c</sup> Cumulative cost increase for the CO2\_HD scenario: US\$ 1,900 million.

<sup>d</sup> Below\_2 °C scenario cost represents mainly the decarbonization of the system to attain the global climate targets and not only to meet the IMO2050 targets. In this scenario, biobunker is a residue of the synthetic biofuel routes already used to comply with a “well-below 2 °C” world, focusing mostly on diesel and jet fuel (and sometimes on naphtha). As such, bunker as a residual fuel has a zero shadow price. As transportation costs to reach Brazilian ports are small compared to the full cost cycle, they can be neglected. Therefore, below 2 °C scenarios can be seen as a no-regret policy to the IMO2050 targets.

The individual pathway scenarios required a large expansion in the capacity of the supply chain of the desirable fuels. HGU capacity would need to increase 20 times in the drop\_in\_HD scenario and several extra vessels for ammonia would be required in the ammonia\_HD scenarios, which is unlikely to occur. On the other hand, low demand scenarios do not affect the energy and land use systems that much. They offer plausible solutions, respecting reasonable industrial developments that could be a possible pathway for the future.

<sup>12</sup> Costs for hydrogen produced from natural gas range from US\$ 1-2/kg, while hydrogen produced from electrolysis using renewable electricity range from US\$ 3-7/kg (IRENA, 2019) (IEA, 2019).

## CONCLUSION

Considering the IMO2050 decarbonization target, this project aimed to compare different maritime renewable fuels in terms of environmental, technical and economic impacts. In the first phase of the project, different possibilities of renewable energy vectors for large vessels were qualitatively compared according to a set of criteria. As a result, the five best performing fuels, HVO, SVO, FT-diesel, biomethanol and e-diesel were studied in more detail in the second phase, which included a georeferenced analysis and life cycle emission estimation.

The results revealed that Brazil has some advantages to foster the production of low-emission alternative fuels for maritime transportation. Except for e-diesel, all the renewable fuels registered a production potential higher than bunker fuel demand in the Brazilian ports. However, logistics could be challenging as the estimated hotspots are mainly concentrated in countryside areas.

In terms of GHG emissions, alternative fuels show significant reductions (on average, 75%). Among the alternatives, FT-diesel shows the best performance in terms of life cycle GHG emissions, with 97% emission reduction in comparison with HFO.

These results were inputs for the third and last phase of this research project, which sought to determine the levelized costs of the selected fuels and to evaluate how they would contribute to the maritime sector decarbonization in the perspective of IAMs.

The technical and economic analysis indicate that the alternative fuels are yet to be competitive with conventional fossil marine fuels, as they presented higher levelized costs than the conventional fuel prices. SVO and HVO are the less costly solution, followed by FT-diesel, biomethanol and e-diesel. E-diesel costs are almost four times higher than HFO prices.

The integrated assessment findings show that considering only CO<sub>2</sub> emissions or all GHG within IMO strategy expressively impacts the results. When only CO<sub>2</sub> emissions are accounted for in the IMO goals, the model chooses LNG, which would represent

around 30% of global fuel consumption both in high and low demand scenarios. However, LNG utilization may increase methane emissions, which has higher impacts in global warming than CO<sub>2</sub>. Considering total GHG emissions, however, the model chooses to replace LNG by SVO and HVO, which together represent around 80% of fuel consumption in 2050 in a high demand scenario. In all the relevant scenarios, the model shows that SVO and HVO utilization would not necessarily have a direct impact on land use and deforestation, as the model assumes that the soybean production expansion occurs through the conversion of degraded pasture areas into crop areas, under a pure technical and economic evaluation. However, deforestation in Brazil is a sensitive issue and other aspects, such as specific land use policies and other important concerns should be evaluated in further work.

The results for a “well-below 2 °C” scenario, which represents not only the IMO goals but also an entire national decarbonization effort, reveal different fuel portfolios. In this scenario, drop-in renewable bunker fuels, produced mostly from technologies coupled with carbon capture and storage (CCS), would replace all fossil bunker demand in 2050 in the low demand scenario and represent most fuel consumption in the high demand scenario. It is important to note that, in this case, synthetic bunker is produced as a byproduct of higher value goods, such as synthetic diesel and naphtha, used in sectors other than maritime transportation. These results highlight the synergies between both efforts, indicating that the fulfillment of IMO goals would be implicit in a national decarbonization strategy.

Individual pathway scenarios show that considering only one fuel category to replace fossil bunker is still feasible but challenging due to high costs and increased demand for hydrogen production and CCS technologies. The intense use of the energy sector leads to an increase of national emissions, in order to achieve the IMO2050 targets.

In short, the results of the integrated assessment indicate that, while it is possible to achieve IMO2050 in Brazil with plants dedicated to the production of maritime fuels, only an integrated national mitigation strategy could lead to an effective decarbonization of the entire Brazilian marine fuel supply.

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