Are there synergies in the decarbonization of aviation and shipping? An integrated perspective for the case of Brazil

**Highlights**

- Renewable aviation fuel production routes have marine fuels as coproducts
- The decarbonization of aviation in Brazil could rely on the Biomass-to-Liquids route
- SVO, HVO, and biobunker seem the most interesting options for shipping
- Shipping and road transport have the most relevant synergy

**Scenario design**

| Scenario      | IATA2050 | IMO2050 | National policy |
|---------------|----------|---------|-----------------|
| IATA/ICAO     | Yes      | No      | No              |
| IMO           | No       | Yes     | No              |
| IATA/ICAO IMO | Yes      | Yes     | No              |
| B2C           | Yes      | Yes     | Yes             |

**BLUES model (national IAM)**

- Agriculture and land use
- Energy systems
- Materials

**Yearly fuel demand in Brazil (PJ/yr)**

| Year  | Aviation (PJ) | Shipping (PJ) |
|-------|---------------|---------------|
| 2020  | 95            | 200           |
| 2030  | 230           | 460           |

**With a climate policy only for aviation...**

- 84% of the jet market supplied by the Biomass-to-Liquids route
- Some coproduction of biobunker

**With a climate policy only for shipping...**

- Oleo-fuels are the main options for the marine fuel mix
- Aviation almost entirely based on fossil kerosene

**With climate policies for both...**

- Aviation and shipping follow independent decarbonization pathways with limited synergies between the two sectors associated with the HVO route
- With Brazil compatible with a world well below 2°C...

The energy mix of both sectors is dominated by biofuels produced in combination with CCS, producing large-scale CDR. Due to a difference of scale, only limited synergies are observed between aviation and shipping.

**A different synergy...**

- Particularly, most of the bioenergy used in the shipping sector is a by-product from road diesel plants, not kerosene plants

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Are there synergies in the decarbonization of aviation and shipping? An integrated perspective for the case of Brazil

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SUMMARY
Aviation and shipping account for 22% of total transport-related CO2 emissions. Low-carbon fuels (such as biofuels and e-fuels) are the most promising alternatives to deeply decarbonize air and maritime transport. A number of technological routes focused on the production of renewable jet fuel can coproduce marine fuels, emulating the economies of scope of crude oil refineries. This work aims to investigate possible synergies in the decarbonization of aviation and shipping in Brazil, selected as an interesting case study. An Integrated Assessment Model (IAM) of national scope is used to explore different combinations of sectoral and national climate targets. This IAM represents not only the energy supply and transport systems but also the agricultural and land-use systems. In the absence of a deep mitigation policy for Brazil, results indicate synergies related to oilseed- and lignocellulosic-based biofuels production routes. Imposing a strict carbon budget to the Brazilian economy compatible with a world well below 2°C, the portfolio of aviation and shipping fuels changes significantly with the need for carbon dioxide removal strategies based on bioenergy. In such a scenario, synergies between the two sectors still exist, but most renewable marine energy supply is a by-product of synthetic diesel produced for road transport, revealing a synergy different from the one originally investigated by this work.

INTRODUCTION
The Glasgow Climate Pact reached at COP26 strengthened climate mitigation ambition, recognizing that the impacts of climate change will be much lower with a temperature anomaly of 1.5°C compared with 2.0°C (UNFCCC 2022). The transport sector is a major CO2 emissions source, accounting for some 8.5 GtCO2 in 2019 (i.e., around 25% of the total energy-related CO2 emissions that year) (IEA 2020a, 2021a). Moreover, the demand for transport will likely increase in the coming decades. Without mitigation measures, this will imply higher annual CO2 emissions from this sector (Yeh et al., 2017; Sharmina et al., 2021; ITF 2021; Jaramillo et al., 2022). Most transport-related CO2 emissions come from light (45%) and heavy (30%) road vehicles. Aviation and shipping come next, with 11% each. Rail, pipeline, and non-specified modes represent only 3% of transport emissions (IEA 2019) (Figure 1).

With the rise of electric vehicles (EVs), electrification is increasingly regarded as key to decarbonize passenger road transport. EVs could strongly reduce the carbon intensity of the transport sector; however, without proper power supply decarbonization, transport electrification could increase overall energy emissions (Zhang and Fujimori 2020). Furthermore, EVs could become an important option for road freight, mainly in short-haul routes (Longden 2014; Pitzcsera et al., 2014; Luderer et al., 2018; Zhang et al., 2018; Hill et al., 2019; Zhang and Fujimori 2020; Ferrara et al., 2021; IEA 2021b). In the case of air and maritime transport, the full electrification of powertrains is unlikely to be the most competitive option due to energy density issues (see Figure 2). The low energy density of batteries (even the most advanced ones) implies either an enormous range reduction or an unrealistic extra weight onboard (Gray et al., 2021; IEA 2021b).

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As such, aviation and shipping are part of the hard-to-abate sectors, defined as sectors associated with energy services/industrial processes that are particularly difficult to provide without adding CO₂ to the atmosphere (Davis et al., 2018; Gota et al., 2019; Shell 2020; Paltsev et al., 2021; Sharmina et al., 2021; IEA 2021b). Still, rapidly reducing CO₂ emissions from aircrafts and ships is essential to keep the 1.5°C warming limit within reach. In the Working Group III contribution to the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC), scenario categories are defined by their likelihood of exceeding global warming levels. From the eight existing categories, C1 (limit global warming to 1.5°C with no or low overshoot) and C2 (return to 1.5°C after a high overshoot) represent the lowest warming scenarios (Riahi et al., 2022). In scenarios falling into this categories, aviation emissions typically equal 0.3–1.0 GtCO₂/year in 2050 (compared with 1.0 GtCO₂ in 2019) (Byers et al., 2022; IEA 2019). For the same warming categories, shipping emissions decline to 0.3–0.7 GtCO₂/year in 2050 (from 1.0 GtCO₂/year in 2018) (Faber et al., 2021; Jaramillo et al., 2022).

Both the International Civil Aviation Organization (ICAO) and the International Air Transport Association (IATA) have goals and measures focused on achieving carbon neutrality (including out-of-sector options) by 2050, including a 50% reduction in annual aviation emissions by 2050 compared with 2005 (hereinafter IATA2050) (ICAO 2010, 2013, 2019; IATA 2021a, 2021b). Similarly, the shipping sector has recently started to incorporate the climate dimension into its long-term planning. In 2018, the International Maritime Organization (IMO) set a preliminary strategy to reduce shipping-related greenhouse gas (GHG) emissions, which includes a 50% cutback in total emissions by 2050 compared with 2008 (hereinafter 2050) (IMO 2019; Faber et al., 2021).

If applied strictly to sectoral direct emissions, both IATA2050 (which means 0.35 GtCO₂/year in 2050) and IMO2050 (which means 0.50 GtCO₂/year in 2050) can be seen as in line with global scenarios that limit global warming to 1.5°C (C1) or return to 1.5°C after a significant overshoot (C2). This is especially true if the 50% cutback targets are complemented with upfront emission reductions (Riahi et al., 2022; Byers et al., 2022; Jaramillo et al., 2022). In this context, low-carbon fuels (i.e., fuels having renewable resources as their main feedstock, e.g., biofuels and e-fuels) are front runners in the mitigation strategies of both sectors since the energy efficiency mitigation potential is intrinsically limited (strictly speaking, in addition to renewable-based fuels, low-carbon fuels could include energy carriers produced from fossil resources with carbon capture or even nuclear energy. For simplicity, low-carbon fuels and renewable fuels are treated as synonyms over the text. They include conventional/advanced biofuels and renewable hydrogen-based fuels) (Carvalho et al., 2021a). This limitation refers to the whole set of potential mitigation measures that can help lower aviation and shipping energy intensities, including constructive and operational measures (e.g., improvements in hull and aircraft design, wind assistance, slow steaming, weather routing) (Bouman et al., 2017). Depending on the perspective, all of these can be considered energy efficiency measures (contrary to fuel switch). Moreover, the annual global demand for international transport is expected to increase significantly over the next decades (Muller-Casseres et al., 2021b; Faber et al., 2021; IEA 2021b).

In oil refineries, aviation fuels have strict specifications in terms of chemical properties, whereas marine fuels (bunkers) require high energy density at low costs (to deal with the type of energy service required by shipping—long-haul transport, usually of lower value-added goods). Thus, aviation fuels often make
up the margin of oil refineries (as “premium” fuels), whereas bunkers are normally produced from residual fractions, seeking to meet the compromise between quality and price (Szklo et al., 2008).

Similarly, several technological routes focused on the production of renewable aviation fuels coproduce fractions suited to the formulation of renewable marine fuels. As such, the economies of scope observed today in oil refineries could also be present in low-carbon energy systems. In this case, renewable-based bunker would be a by-product of renewable-based kerosene. This would represent a synergy between the sectors, making the mitigation of aviation and shipping more efficient, potentially minimizing impacts on land-use change (Carvalho et al., 2019).

This study aims to evaluate this theoretical synergy for a practical case study in Brazil, given its relevant foreign trade specificities. The country’s economy is highly dependent on the exports of low value-added products (implying high energy consumption per unit of exported value) (ITC 2022), and its maritime trade routes typically involve distances longer than 8,000 nautical miles. The country is therefore exposed to significant risks in terms of freight costs. Furthermore, the Brazilian aviation market is the seventh largest in the world (CIRIUM 2022). Another reason that justifies the choice of Brazil is its leading role in bioenergy production and use (Daioglou et al., 2020).

Figure 2. Energy density—liquid hydrocarbons versus batteries

(A) Red: ratio between full-tank fuel weight and total ICE-based vehicle weight. Green: ratio between battery weight and total electric vehicle weight considering an amount of batteries equivalent to the energy stored in the fuel tank of an ICE-based vehicle.

(B) Red: ICE-based vehicle range. Green: electric vehicle range considering an amount of batteries equivalent to the mass contained in the fuel tank of an ICE-based vehicle. The blue arrow represents the range of a typical electric car (Chevrolet Bolt). Pure electric cars make up the low energy density of batteries by adding a large battery while making the rest of the car as light as possible. Still, they tend to be heavier than ICE vehicles. Source: Own elaboration, based on Kamal and Chang (2022).
As detailed over the course of the article, the Brazilian Land Use and Energy System (BLUES) model is an Integrated Assessment Model (IAM) representing not only the aviation and shipping sectors but also the whole energy, agriculture, and land-use systems of Brazil (Rochedo et al., 2018; IAMC 2020). BLUES simultaneously represents the food and energy supply-demand balances, therefore taking aspects such as food security into account. IAMs have been broadly used to explore the consequences of various long-term climate change mitigation strategies. They contain a detailed representation of the world’s energy, land use, agricultural, and climate systems, as well as their inter-linkages (Gambhir et al., 2017; Grubler et al., 2018; Rogelj et al., 2018; IPCC, 2022). In this work, an integrated assessment perspective is used to analyze the possible developments of the aviation and shipping sectors under specific climate targets, with a special focus on the upstream connections between these two sectors. In short, the research question of this work can be summarized as “Several renewable fuel production routes can output both aviation and maritime fuels. Given that aviation fuels typically have higher value-added, is it possible that the decarbonization of the Brazilian jet fuel market engenders a low-cost renewable energy surplus capable of meeting a significant share of the country’s maritime fuel demand, thereby lowering the mitigation effort of the shipping sector?”

The novelty of this study can be summarized in the following points:

- Analysis of the role of aviation and shipping in deep mitigation scenarios using a national IAM;
- Assessment of the decarbonization of the two sectors beyond the sectoral perspective, considering the inter-linkages between energy, agriculture, and land use;
- Modeling and optimization of marine and aviation renewable fuel production routes with high detail, including economies of scale and scope; and
- Pioneer reflection on the possibility of a combined decarbonization supply strategy for the aviation and shipping sectors in Brazil.

Despite the focus on the linkage aviation-shipping, another notable synergy indicated by this work involves the road transport sector. Just as kerosene, the production of fossil or renewable diesel has heavy fractions as a by-product. As such, in deep mitigation scenarios, for which the BLUES model indicates bio-based diesel (such as the one produced from biomass gasification and Fischer-Tropsch [FT] synthesis) as the optimal alternative to decarbonize the large Brazilian diesel market, significant amounts of biobunker are coproduced.

Coproduction of renewable aviation and marine fuels

Figure 3 summarizes the main technologies capable of producing renewable-based aviation fuels, with marine fuels as by-products. As shown in Table 1, four technologies are assessed: synthetic kerosene from
Hydrotreated esters and fatty acids (biokerosene, HEFA/HVO), synthetic kerosene from the oligomerization of alcohols (biokerosene, AtJ), synthetic kerosene from lignocellulosic biomass (biokerosene, BtL), and synthetic kerosene from electrolytic hydrogen (e-kerosene). All of these fuels are fully drop-in alternatives, both in case of aviation and shipping.

The HEFA/HVO, AtJ, and BtL routes are certified biokerosene production routes, approved for blends up to 50% with conventional jet fuel (IATA 2019). However, among all certified technologies, only HEFA/HVO has reached the commercialization status (TRL 9), as shown in Table 2. Currently, ten HEFA/HVO plants are in operation and produce 5 billion liters of fuel (mostly renewable diesel) annually (McMillan and Saddler 2019). In their turn, BtL and AtJ reached TRL 7, which means that processes have been demonstrated in an operational environment. Contrastingly, e-kerosene is still in validation stages (TRL 5) (IEA 2020b).

In terms of costs, all pathways register values above current jet fuel prices. As illustrated by Figure 4, the average price of fossil kerosene was around 15 USD/GJ in 2018, while the production costs of low-carbon fuels vary between 18 and 510 USD/GJ, according to the literature (Diederichs et al., 2016; Geleynse et al., 2018; Bonomi et al., 2019; Cervi et al., 2020, 2021; Fonte 2021; Carvalho et al., 2019). Among biofuels, price levels are approximately within the same ranges. The AtJ route registers both the lowest (18 USD/GJ) and the highest (93 USD/GJ) levelized costs, which is explained by feedstock cost variation and intermediate alcohol production technology. For e-kerosene, LCOF is almost 10 times higher than the average cost of biokerosene and at least 15 times higher than the price of conventional jet fuel. This is mainly due to high costs associated with low-maturity level technologies that are needed in the production pathway of this kind of fuel, such as carbon capture. Generally, low-carbon fuel costs are highly dependent on feedstock, inputs, and technology specificities.

In addition, the use of biomass to obtain renewable fuels can also occur through the coprocessing of biomass-derived oils in existing oil refineries. This solution uses infrastructure and labor that are already available and, thus, can be readily applied without significant additional investments. Although refining units capable of processing biomass-derived oils are not usually focused on the production of jet fuel, this strategy is also assessed by this work because these units produce heavy oil fractions suitable to shipping (Karatzos et al., 2014). The most common biomass-derived oils proposed for coprocessing include Straight Vegetable Oils (SVOs) and Pyrolysis Oil (POs, also known as bio-ols [Al-Sabawi and Chen 2012]). While SVOs are suitable for coprocessing in Fluid Catalytic Cracking (FCC) and Hydrotreatment (HDT) units, POs can be fed mainly to FCC units (van Dyk et al., 2019), although some studies also tested its processing in thermal cracking and de-asphalting units (Sousa-Aguiar et al., 2018). In all cases, the products obtained in the end of the refining process contain a bio-carbon content. SVO coprocessing shows higher maturity level when compared with PO coprocessing. Many refineries, including some from companies such as BP, Repsol, and Shell, already operate this kind of process (Vertz and Sayal 2020). Usually, low investment costs are required due to the application of existing infrastructure. Operation and maintenance (O&M) costs are mainly influenced by biomass acquisition costs. In the case of hydrotreatment operations, O&M costs tend to be higher due to high steam reformed or electrolyzed hydrogen consumption and, in some cases, by the need for more expensive catalysts (Yañez et al., 2021; Al-Sabawi and Chen 2012).

### Table 1. Renewable drop-in aviation and marine fuels

| Aviation fuel | ASTM name | Marine fuel | Short process description |
|---------------|-----------|-------------|---------------------------|
| Biokerosene, HEFA/HVO | HEFA-SPK | Biobunker, HEFA/HVO | Hydrosprocessing of fatty acids and esters |
| Biokerosene, AtJ | ATJ-SPK | Biobunker, AtJ | Oligomerization + hydrogenation of alcohols |
| Biokerosene, BtL | FT-SPK | Biobunker, BtL | Biomass gasification + FT synthesis |
| E-kerosene | FT-SPK | E-bunker | Electrolysis/co-electrolysis + FT synthesis |

HEFA, Hydroprocessed Ester and Fatty Acids; HVO, Hydrotreated Vegetable Oil; AtJ, Alcohol-to-Jet; BtL, Biomass-to-Liquids; ASTM, American Society for Testing and Materials.

*Taking into consideration that the same aircraft can be fueled in different countries, international specifications have been adopted for jet fuels. The standard regulating the technical certification of SAF is ASTM D7566. Upon release from blending the fuel is certified to ASTM D1655 and from this point is regarded as conventional Jet A or Jet A1 kerosene (IATA 2020).

*According to ASTM, FT-SPK is defined as a bio-based fuel. However, considering that Fischer-Tropsch synthesis can also be used in electricity-based pathways to produce synthetic kerosene, we assume that the name FT-SPK is also applicable to this case.

In this column, we use the term “bunker” in a broad sense, including both light and heavy gasoil.
The BLUES model

The analysis conducted in this study uses the BLUES model, an IAM of national scope. BLUES is a partial equilibrium, intertemporal, and least-cost optimization tool representing the Brazilian energy, agriculture, land-use, and materials sectors, along with their multiple inter-linkages (Figure 5). With inputs related to population growth, macroeconomic assumptions, and technology progress, the model seeks to find the minimum cost solution for the expansion and development of the represented sectors, outputting variables such as energy use, GHG emissions, agricultural production, water use, and atmospheric pollution. This modeling framework is particularly suited to long-term analyses of the energy and land-use systems under specific conditions through the development of scenarios. The detailed description of the BLUES model can be found in the Integrated Assessment Modeling Consortium (IAMC) documentation webpage (Köberle 2018; IAMC 2020).

It is worth noting that the BLUES model depicts the whole energy and land systems, including food chains, from primary resources to the final consumption. Historical capacities, investment and operational costs, efficiency/yield coefficients, and energy inputs are attributed to all activities/technologies. Furthermore, CO₂ emission factors are attributed to every energy source. These emission factors derive from the carbon content of each fuel and from the IPCC TFI tier 1/2/3 methodological framework (Eggleston et al., 2006). Since the BLUES model follows an integrated approach, overall CO₂ emissions include all steps of supply chains.

Over the past 5 years, the BLUES model has been extensively used in studies related to climate mitigation. For example, Rochedo et al. (2018) analyzed the impact of the weakening of deforestation governance on the mitigation effort needed in other sectors of the Brazilian economy. Besides, de Oliveira et al. (2021) developed an integrated analysis of the role of bio-based petrochemicals in deep mitigation scenarios. Also, Müller-Casseres et al. (2021a) explored the possible developments of the Brazilian marine energy

Table 2. Technology Readiness Level (TRL) of low-carbon fuel production pathways

| TRL | Production Route | Companies |
|-----|------------------|-----------|
| Basic principles reported (1) | – | – |
| Concept formulated (2) | – | – |
| Proof of concept (3) | – | – |
| Preliminary evaluation (4) | – | – |
| Process validation (5) | E-kerosene | Carbon Engineering, Norsk e-fuel, Zenid |
| Full-scale technical evaluation (6) | – | – |
| Fuel approval (7) | BTL, ATJ | Byogy, Comsyn, LanzaTech, Red Rock Biofuels, Total, Velocys |
| Commercialization validated (8) | – | – |
| Production capability established (9) | HVO/HEFA | Eni, Honeywell, Omega Green, Neste Oil |

Figure 4. Levelized cost of fuel for low-carbon jet fuel production technologies (Diederichs et al., 2016; Geleyse et al., 2018; Bonomi et al., 2019; Carvalho et al., 2019; Cervi et al., 2020, 2021)

The dashed line represents the average price of conventional jet fuel in 2018 (15 USD/GJ) (Index Mundi, 2019).
supply and their potential impacts on the national energy and land-use system. As a last and more recent example, Baptista et al. (2022) used eleven well-established IAMs of national scope (including BLUES) to list out good practice policies that may allow bridging the emissions gap in key countries. The representation of energy alternatives for aviation and shipping in BLUES is summarized in Figure 6.

**Scenario design**

Several scenarios could be explored considering the possible combinations of aviation and shipping sectoral mitigation targets and national mitigation goals. For simplicity, this study focuses on four main scenarios (Table 3).

The *IATA/ICAO scenario* represents a current policies view of the Brazilian energy system combined with IATA and ICAO mitigation pledges (particularly with IATA2050). Similarly, the *IMO scenario* reflects Brazilian current policies combined with IMO mitigation pledged by 2050. The *IATA/ICAO IMO scenario* is a merger of the first two (i.e., it addresses simultaneously the mitigation strategies in aviation and shipping sectors). Finally, the *B2C scenario* includes emissions restrictions not only to aviation and shipping but also to the whole Brazilian agriculture, energy, and land-use systems aligned with the Paris Agreement goals. This deep mitigation scenario is based on the results of the COFFEE model (IAMC 2019), an IAM of global scope that includes Brazil as one of its 18 regions. In this specific run, the global carbon budget inputted to COFFEE was 600 GtCO₂ (Riahi et al., 2021) implying a carbon budget of 15.4 GtCO₂ for Brazil over the period 2010-2050.

Figure 5. Basic structure of the BLUES model

Figure 6. Aviation and shipping fuel options represented in the BLUES model
In addition, three sensitivity scenarios are explored, as shown in Table 4. The Small BtL scenarios are variations of the IATA/ICAO IMO and B2C scenarios that have different cost assumptions for the BtL technology. Climate mitigation scenarios from the BLUES model typically show a large increase in BtL technologies between 2020 and 2050 (Rochedo et al., 2018; de Oliveira et al., 2021; Müller-Casseres et al., 2021a). This is partly due to cost assumptions for these technologies (e.g., the standard plant capacity in the model is 1.6 ML/day, with considerable gains of scale). Small BtL scenarios seek to reflect a future energy system in which the development of BtL technologies is slower, relying mostly on small pioneer plants, with higher costs (de Jong et al., 2015; Carvalho et al., 2021b). As such, in these scenarios, the standard plant capacity is 0.13 ML/day. Small BtL scenarios also reflect the uncertainty associated with Carbon Capture and Storage (CCS). The potential combination with CCS is one of the key advantages of BtL routes, but optimistic cost assumptions can overlook the low technological maturity of both processes. Although the Brazilian CCS potential is impressive, there are significant technological, economic, and regulatory barriers that may limit carbon capture expansion. For example, the development of a CO2 transportation network is a major challenge (Rochedo et al., 2016).

Finally, the IATA/ICAO IMO (Kerosene exports) scenario is a sensitivity case with changes in the demand for renewable kerosene. In view of the high potential for bioenergy production in Brazil, some global mitigation scenarios see the country as an important biofuel exporter in the coming decades (Daioglou et al., 2020). Therefore, the IATA/ICAO IMO (Kerosene exports) scenario represents a view of the Brazilian energy system in which, in addition to the domestic jet fuel demand, the country would supply renewable kerosene to the international market. For the sake of simplicity, the export volume is taken to be equal to total domestic consumption (which should be a reasonable order of magnitude).

RESULTS

Fuel consumption

The two panels in Figure 7 show the yearly consumption of aviation and marine fuels in 2050 for the main scenarios. In 2050, the demand for jet fuel is around 230 PJ (compared with 95 PJ in 2020), whereas marine fuel consumption is approximately 460 PJ (compared with 200 PJ in 2020). This represents increases of 140% and 130%, respectively, over a 30-year period.

In the IATA/ICAO scenario, with the aviation supply restricted to a small amount of fossil fuel, most of the energy (84%) comes from biokerosene from the BtL route. Contrastingly, in the absence of climate policy the shipping energy mix continues to be dominated by fossil bunker. A tiny fraction (4%) of shipping fuels comes from BtL-kerosene plants as by-products.

The opposite situation is observed in the IMO scenario. While the aviation sector remains almost 100% fossil (with some biokerosene coproduced in HEFA/HVO plants), the shipping energy mix shifts from fossil to bio-based fuels to meet the required emission reduction. SVO and HVO (which are based on the same feedstock) stand out as the main options. Together, these fuels account for 81% of the marine energy supply in 2050.

Table 3. Design of scenarios

| Scenario     | IATA2050 | IMO2050 | National climate policy |
|--------------|----------|---------|-------------------------|
| IATA/ICAO    | Yes      | No      | None                    |
| IMO          | No       | Yes     | None                    |
| IATA/ICAO IMO| Yes      | Yes     | None                    |
| B2C          | Yes      | Yes     | Yes                     |

Table 4. Sensitivity scenarios

| Scenario                      | Difference compared with base scenarios         |
|-------------------------------|-------------------------------------------------|
| IATA/ICAO IMO (Small BtL)     | Smaller BtL plants                              |
| IATA/ICAO IMO (Kerosene exports) | Higher kerosene demand                         |
| B2C (Small BtL)               | Smaller BtL plants                              |
The results of the IATA/ICAO IMO scenario combine the fuel mixes of the two individual scenarios. By imposing the targets from IATA and IMO in the model, findings show that the aviation sector relies mostly on BtL-kerosene (although the AtJ route starts to appear), while the shipping sector still relies on SVO and HVO (with some participation of AtJ- and BtL-biobunker coproduced in kerosene plants).

In the B2C scenario, the existence of a climate policy for the whole Brazilian economy significantly impacts the aviation and marine fuel supplies. In the jet fuel market, regular BtL plants are entirely replaced by plants equipped with carbon capture and storage (CCS), which provide negative emissions. In the shipping energy mix, SVO continues to be an important fuel (30% of the total supply) but HVO is replaced by biobunker coming mostly from BtL-road diesel plants (42% of the total supply). Biobunker from BtL- and AtJ-kerosene plants account for a residual share, as well as biobunker from coprocessing. Interestingly, an ambitious target to Brazil automatically implies the low-carbon fuel shares required by IATA and IMO.

As shown in Figure 8, with more pessimistic assumptions for the BtL technology (IATA/ICAO IMO scenario [Small BtL] scenario), results change significantly compared with the IATA/ICAO IMO scenario. Most of the BtL-kerosene is replaced by AtJ-kerosene, which accounts for 50% of the total supply in 2050. Moreover, a small share (6%) of the demand is met by biokerosene from coprocessing in oil refineries. In this scenario, 13% of the marine fuel supply is based on coproducts of AtJ-kerosene.

When accounting for a higher renewable jet demand (460 PJ) due to the international market (IATA/ICAO IMO scenario [Kerosene exports] scenario), the expansion of the biokerosene supply continues to be based on the BtL technology. In this scenario, 83% of the jet fuel demand is met by BtL-biokerosene. There is also a moderate impact on the marine fuel market, with a larger share of biobunker (9%) coproduced in BtL-kerosene plants.

As shown in Figure 9, in the B2C (Small BtL) scenario, results do not change significantly compared with the base scenario. In view of the need for negative emissions due to the carbon budget of 24 GtCO2, the BtL technology continues to be widely deployed. The reduction in the share of BtL-kerosene is only 7% (compensated by an increase of AtJ-kerosene).
CO₂ emissions

Figure 10 shows the annual CO₂ emissions from Brazil in current policies and B2C scenarios from 2020 to 2050. In the absence of national climate policies, emissions continue to grow over the period, reaching 1.00 GtCO₂/year in 2050. Contrastingly, in mitigation scenarios, emissions fall from 0.74 to 0.53 GtCO₂/year in 2030. Between 2030 and 2050, with the rise of emission reduction technologies and the large-scale deployment of Bioenergy with Carbon Capture and Storage (BECCS), there is a steep reduction in the country’s emissions, reaching ~0.55 GtCO₂/year in 2050. The CO₂ emission pathway of B2C scenarios is in line with other mitigation scenarios from the literature. For instance, global IAMs typically show annual emissions in Brazil between ~2.30 and 0.80 GtCO₂/year by 2050 (Ko¨berle et al., 2022). Specifically, studies focusing on the decarbonization of the country have been showing emissions around 0.40 GtCO₂/year in 2030 and -0.50 GtCO₂/year in 2050 (Schaeffer et al., 2020), which is very close to the B2C pathway.

Land-use change

Figure 11 shows the cumulative change in land use in Brazil for the period 2020-2050. Results show that, without national mitigation measures, there is a strong expansion of pastures for livestock (24–27 Mha), which engenders native forest (10 Mha) and savanna (15 Mha) losses. The effect of large-scale use of oil-seeds on land use is also evident: in scenarios that include the IMO target, with heavy reliance on oilseed-derived fuels, the growth of the area devoted to agricultural crops is far higher than that observed in the IATA scenario. This also means that the compliance with the IMO target must be associated with the control of land-use change impacts.

When the national climate policy is considered (B2C scenario), the dynamics of land-use change is completely different. Although there is forest loss (0.1 Mha), when considering the planted area over the period (16 Mha), there is a net increase in forest cover between 2020 and 2050, as well as in carbon retention. In the case of savanna areas, there is a significant loss (19 Mha), but this change does not occur in Permanent Preservation Areas. Furthermore, most of the land-use change observed in climate policy scenarios is related to the recovery of degraded pastures (64 Mha). Finally, there is an important role for integrated...
systems (such as crop-livestock-forest integration, in line with studies from the Brazilian Public Agricultural Research Corporation [Embrapa 2018, 2021]).

DISCUSSION

Clearly, considering the projected increase in demand and the limits of energy efficiency gains over the next decades, the replacement of most fossil fuels by renewable fuels in the aviation and shipping sectors will be essential to meet their sectoral emissions targets in 2050. However, the portfolio of renewable fuels to be used can vary significantly.

For aviation, in the absence of a national climate policy, the production of BtL-kerosene without CCS is the preferred route across scenarios. Even with higher demand, BtL-kerosene represents more than 80% of the jet fuel supply in 2050. When accounting for uncertainties related to the development of the BtL technology, the AtJ route increases its share and has an important role to play. When decarbonization goes hand in hand with a low-carbon pathway in Brazil, the BtL technology becomes dominant again, but this time associated with CCS.

The decarbonization of shipping follows a different path. Oilseed-based fuel routes, which account for most of the energy supply in 2050 in all scenarios without a national climate policy, are more cost-competitive than BtL routes. Owing to its low cost, SVO is the first option when it comes to renewable fuels for shipping. However, quality issues limit the demand for SVO, creating a need for higher-quality fuels. This demand is met by HVO, which represents most of the energy supply in these scenarios. In the context of a low-carbon future in Brazil (B2C scenario), the renewable marine fuel supply changes significantly. Although SVO continues to be important, a large share of the energy demand is met by biobunker coming as a by-product of BtL-diesel plants with

![Figure 10. Annual CO2 emissions in Brazil across scenarios](image-url)

The “Current policies” line represent the IATA/ICAO, IMO, and IATA/ICAO IMO scenarios, as well as their sensitivity cases.

![Figure 11. Cumulative changes in land use between 2020 and 2050](image-url)
CCS. As such, in these scenarios, there is a remarkable synergy between the decarbonization of shipping, not with aviation, but with the road transport sector. As pointed out in the STAR Methods sections, the demand for shipping follows a conservative projection, with significant increase in 30 years. With a lower demand, the synergy with the road transport sector could be even larger. In such a scenario, biobunker from BtL would possibly meet a very high share of the sector's energy demand.

The transportation sector portrayed by the B2C scenario can be summarized as follows: in the passenger road transport, electrification is significant but ethanol keeps its role as a relevant renewable energy carrier. Furthermore, part of the automotive gasoline is replaced by its bio-based equivalent, produced in FT-liquids plants. However, the most important product of these facilities is FT-diesel, outputted in large quantities to fuel Brazil’s road-dependent freight system. Using BECCS, the production of green diesel becomes the most important source of negative emissions in the country. Finally, FT-liquids also become the dominant solution in aviation (with dedicated biokerosene plants) and shipping (through biobunker as a by-product). Vegetable oils play a complementary role in the marine fuel supply.

As it became clear, our results indicate some synergies in the decarbonization of the aviation and shipping sectors in Brazil, with the replacement of fossil fuels taking place through different energy chains for each sector (Figure 12). The first one is the coproduction of kerosene in HVO-diesel plants: across scenarios, between 4% and 12% of the jet fuel demand is met by this by-product. In the other way around, the production of BtL-kerosene always happens together with the production of BtL-bunker. As such, across scenarios, between 3% and 9% of the shipping energy supply corresponds to BtL-bunker associated with biokerosene.

The absence of a full-scale synergy is strongly associated with the different scales of the two sectors in Brazil. While the aviation fuel demand is close to 95 PJ in 2020, the bunker market is twice as much, accounting for around 200 PJ. Considering the biorefinery yields presented in the Introduction and the fact that kerosene has higher added value compared with bunker (being therefore the main product of production plants), it can be inferred that higher levels of synergy might be observed if the marine fuel market is smaller than the aviation market (and therefore more suitable to be supplied by a by-product of biokerosene plants). Interestingly, as shown in Figure 13, the relation between the aviation and fuel markets in Brazil is approximately 0.48, whereas this is around 1.5 worldwide. This indicates a much larger potential for synergies globally.

Limitations of the study
This study sought to assess the potential synergies in the decarbonization of aviation and shipping, two major hard-to-abate sectors. To that end, the specific case of Brazil was examined, considering GHG abatement targets proportionally compatible with the international mitigation goals in both sectors. Given the existence of fuel routes that coproduce renewable kerosene and maritime bunker fuels, the specific aim was to answer the question stated in the title of the article benefitting from an integrated perspective provided by the BLUES model.
Four scenarios were developed to compare the impacts of decarbonizing aviation, shipping, and the Brazilian economy individually or in a joint way. Results varied widely, with sectoral decarbonization targets having little impact beyond their own scope. Moreover, when considered together, the aviation and shipping targets showed limited synergies mostly associated with the BtL and HEFA/HVO routes (and to a lesser extent with the oligomerization route). Finally, in the deep decarbonization scenario (Brazil compatible with a world well below 2°C), the need for CCS engendered a significant synergy between shipping and road transport (and, on a much smaller scale, between aviation and shipping). In short, for all cases, the total annual potential exceeds by far the current demand of both sectors (Carvalho et al., 2021b).

Several aspects not widely discussed in this work can be explored in future studies. For example, potential synergies between the decarbonization of aviation and shipping could be analyzed on a world scale. Furthermore, other potential biomass feedstocks from wastes such as Used Cooking Oils and wet-waste-derived Volatile Fatty Acids, currently not represented in the BLUES model, could be assessed (Foteinis et al., 2020; Huq et al., 2021). Under a methodological perspective, studies questioning the perfect foresight approach used in this article might also add value to the literature. Recursive dynamic optimization, for instance, can provide "myopic" runs to see if more readily available technological options would be favored in terms of market share. Besides, it is important to highlight that this work treated aviation and shipping demand as exogenous, possibly overlooking demand-side mitigation measures (e.g., sustainable lifestyle changes), which can be critical for passenger aviation. In the case of shipping, there can be impacts related not only to avoided fossil fuel trade but also to structural changes in global supply chains due to the energy transition. Future works could focus on a detailed representation of maritime cargoes (e.g., iron ore, copper, and capital goods) and their linkages with the energy sector.

STAR METHODS

Detailed methods are provided in the online version of this paper and include the following:

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AUTHOR CONTRIBUTIONS

Conceptualization, E.M.-C., A.S., and R.S.; methodology, E.M.-C., A.S., P.R.R.R., J.P.-P., and R.S.; formal analysis and investigation, E.M.-C., C.F., F.C., L.B.B., P.L.B.M., and R.D.; resources, L.B.B. and P.R.R.R.; writing – original draft, E.M.-C., C.F., F.C., P.L.B.M., and R.D.; writing – review & editing, A.S., J.P.-P., and R.S.; visualization, E.M.-C.; supervision, A.S., J.P.-P., P.R.R.R., and R.S.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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STAR METHODS

KEY RESOURCES TABLE

| REAGENT OR RESOURCE | SOURCE | IDENTIFIER |
|---------------------|--------|------------|
| Software and algorithms | Rochedo et al. (2018) IAMC (2020) de Oliveira et al. (2021) (Müller-Casseres et al., 2021a) |

Other

| Fischer-Tropsch BtL plant costs Historical aviation demand Historical marine fuel demand Historical foreign trade International trade scenarios | (Carvalho et al., 2021b) ANAC (2021) EPE (2019b) (MDIC, 2020) IMO (2015) and DNV GL (2018) |

RESOURCE AVAILABILITY

Lead contact
Further information and requests should be directed to the lead contact, Roberto Schaeffer (roberto@ppe.ufrj.br).

Material availability
Not applicable.

Data and code availability
- Data that support the analysis within this paper is available from the lead contact upon reasonable request.
- This paper does not report original code.
- Any additional information is available from the lead contact upon reasonable request.

METHOD DETAILS

Energy demand
To project the demand for aviation, income-demand elasticities are calculated for Brazil using linear regression on a natural logarithmic model. The gross domestic product (GDP) was assumed as a proxy of income. Demand for aviation is disaggregated in passenger and freight, measured in revenue passenger kilometres (RPK) and revenue tonne-kilometres (RTK), respectively. Historical demand is established based on data from the Brazilian National Civil Aviation Agency (ANAC 2021). GDP data is obtained from the Institute for Applied Economic Research (IPEA 2021) and the Brazilian Micro and Small Business Support Service (DataSebrae 2021). It is worth noting that aviation demand is completely exogenous, following a Business-As-Usual (BAU) scenario with rapid post-Covid recovery. As such, demand-side mitigation measures are not assessed in this study, and the projection used can be seen as a conservative one.

The demand for shipping follows a previous study (Müller-Casseres et al., 2021a), having as a core assumption that Brazil’s main export products will not change over the period of analysis. This simplified approach assumes that the ratio mass exported/mass imported remains constant between 2010 and 2050, with the share between export products also fixed. It is a high demand scenario based on a BAU transport work projection (IMO 2015). As in the case of aviation, this methodology is not capable of capturing changes in the dynamics of demand (e.g., avoided fossil fuel trade or increases in bioenergy exports). For its substantial growth in 30 years, it can be seen as a conservative projection. Marine fuel demand is determined using a simplified energy model and calibrated with historical data for 2010 and 2018 (EPE 2019a).
Demand for aviation

To project the mobility demand for aviation in Brazil, income-demand elasticities are calculated using linear regression on a natural logarithmic model. The gross domestic product (GDP) was assumed as a proxy of income. Demand for aviation is disaggregated in passenger and freight, measured in revenue passenger kilometres (RPK) and revenue tonne-kilometres (RTK), respectively. Historical demand was established based on data from the Brazilian National Civil Aviation Agency (ANAC 2021). GDP data is obtained from the Institute for Applied Economic Research (IPEA 2021) and the Brazilian Micro and Small Business Support Service (DataSebrae 2021). The analysis was disaggregated between passenger and freight demand, for the domestic and international market, and regionalized for Brazil territory. Strong linear relations were found between the demand and GDP, with high statistical relevance. R-squared values found range from 0.89 to 0.98 for passenger, domestic demand; 0.83 to 0.92 for passenger, international demand; 0.77 for freight, both international and domestic market, showing overall good response assertiveness. Freight modeling only showed satisfactory results at national level; thus, it was not disaggregated into regions as passenger did. All p values found for the elasticities were much less than 0.05%, revealing statistical relevance for the estimators in the model.

Covid-19 impacts were quantified as modifiers of demand growth, considering GDP shrinkage, calculating activity reduction due to pandemic in 2020 and 2021 relative to 2019 data. During the elaboration of this model, only the first half of 2021 data was available, thus it was extrapolated for whole year. A rapidly, 2-year recovery scenario is assumed, meaning that modifiers actively reduce the demand further than the GDP reduction only for the years of 2020 and 2021.

Equation 1 presents the elasticity-based projection. Using the elasticities calculated from historical data, base data and future GDP projections, future demand is calculated. Base year is 2010 with time step of 5 years.

\[
D(t) = D(t-1) \times \left( e \times \frac{GDP(t) - GDP(t-1)}{GDP(t-1)} \times MOD + 1 \right) \quad \text{(Equation 1)}
\]

In which:

- \(D(t)\) = future demand, in RPK or RTK
- \(D(t-1)\) = past demand, in RPK or RTK
- \(e\) = demand-income elasticities, for passenger or freight aviation demand, for domestic or international markets, for each Brazilian region (only for passenger demand)
- \(GDP(t)\) = future GDP
- \(GDP(t-1)\) = past GDP
- \(MOD\) = Covid-19 demand growth modifiers, for passenger or freight aviation demand, for domestic or international markets, for each Brazilian region (only for passenger demand), in percentage

Demand for shipping

This part of the STAR methods section is based on Müller-Casseres et al. (2021a). International shipping was originally not represented in BLUES, given that it is a national model. As such, an important part of the methodology here is the incorporation of the shipping fuel demand into BLUES. This was performed based on the assumption that only a fraction of the fuel required by Brazil’s international trade is provided by national ports. The remaining part is supplied by ports of the commercial partners or along the shipping routes.

Brazil’s exports are way higher than its imports on a mass basis. 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 (MDIC 2020). Furthermore, iron ore is divided into two categories, reflecting the two different kinds of vessels used to transport it (Schaeffer et al., 2018). Coastal navigation is also modeled. 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.
Below table shows the estimation of the transport work related to Brazilian exports, imports, and coastal navigation (MDIC, 2020, Sea Distance, 2020). The proportion of the fuel supplied by Brazilian ports is similar for all products (around 31%). Estimates derive from the comparison of the results of the modeling with historical data for the base year (5.3 million tonnes of bunker in 2018) (EPE 2019b).

| Product                     | 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. The low demand scenario is based on the activity growth reported in DNV’s maritime forecast (DNV GL 2018), while the high demand scenario is based on the Business as Usual (BAU) scenario of IMO’s third GHG study (IMO 2015). It is assumed that the exported products do not change over the period of analysis. 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.

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 (Lindstad and Eskeland 2015; Bouman et al., 2017). The total hull resistance \( R_T \) and the associated brake power \( P_B \) are presented in Equations 2 and 3, respectively.

\[
R_T = \frac{1}{2} \rho C_T S v^2 \quad \text{(Equation 2)}
\]

\[
P_B = \frac{(1 + m) R_T v}{\eta_T} \quad \text{(Equation 3)}
\]

In Equations 2 and 3, \( \rho \) 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 \( \eta_T \) is the total propulsion efficiency. These parameters are estimated based on ship sizes and categories. Table above 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 modes (at-berth, at-anchorage, maneuvering and at-sea) (Vale 2014; Kristensen 2012; MAN 2015; Mitsui OSK Lines, 2020; Vale 2018; Transpetro 2019; Bulk Carrier Guide 2010; Vessel Finder, 2020) (see below table).
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. See below table 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 (Kim et al., 2020). Differences in investment costs are also considered (MAN 2013; Clarksons Research 2017; Kim et al., 2020).

### 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                                       |

As shown in the below table, depending on the motorization, significant increases in the total CAPEX are observed, especially for the case of fuel cells. However, some drop-in alternative fuels need only minor changes of the ship and bunkering to be directly used.

### Investment costs for the vessels considered in the modeling

| Ship                  | Powertrain | CAPEX (2010 kUSD) |
|-----------------------|------------|-------------------|
| Bulk - Valemax        | 2S-D       | 81,000            |
| Bulk - Valemax        | DF         | 87,000            |
| Bulk - Capesize       | 2S-D       | 38,000            |
| Bulk - Capesize       | DF         | 42,000            |
| 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 the below table, specific fuel consumption (SFC) varies according to the fuel used (Gilbert et al., 2018; IMO 2015; Kim et al., 2020).
Efficiency gains are also modeled, 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 (ICCT 2013; Bouman et al., 2017) and with the Energy Efficiency Design Index (ICCT 2011), when compared to 2010, new vessels are taken to be 20% more efficient in 2030 and 30% in 2050.

### Fuel potential and production routes

The techno-economic potential of SVO, HVO and FT-liquids is based on the values found by (Carvalho et al., 2021b).

For shipping, the fuel conversion options represented in the model are greatly based on a previous study that summarized pros and cons of different marine fuels (Carvalho et al., 2021a). While shipping fuel options are relatively diverse, the aviation sector is restricted to conventional kerosene and fully drop-in alternatives (therefore, options such as natural gas and hydrogen are not allowed to be used by aircrafts). This methodological choice is due to the low technological feasibility of using fuels other than kerosene in commercial aviation (at least during the next few decades) (IEA 2020b). Although there are some initiatives that aim at using hydrogen and LNG as aviation fuels (Roberts et al., 2015; Kadyk et al., 2019; Bruce et al., 2020), energy density concerns make their large-scale deployment unlikely (Gray et al., 2021). For example, in light of the International Energy Agency’s deep mitigation scenario, by 2050 the global aviation fuel market would likely be dominated by (both bio- and hydrogen-based) synthetic fuels (IEA 2021b).

Similarly to Müller-Casseres et al. (2021a), the modeling of shipping fuels includes several fossil-, bio- and hydrogen-based options. Among the fossil alternatives, there are conventional marine fuels (diesel and heavy fuel oil), but also methanol and LNG. For biofuels, the production routes are approximately the same as the ones used to make kerosene (as explained, this is the main motivation of this work). However, in the case of shipping, the direct use of SVO and the production of biomethanol are also modeled. In terms of hydrogen-based alternatives, the use of ammonia as a marine fuel is also represented.

In addition to dedicated aviation and marine fuels production routes, the coprocessing of SVOs and POs in petroleum refineries (see section 2) is also included in the BLUES model. Coprocessing yields are obtained using the Carbon And Energy Strategy Analysis for Refineries (CAESAR) model, an auxiliary model that performs detailed simulation of oil refineries (Guedes et al., 2019). The calculation performed by CAESAR assumes reduced crude oil input in refineries (that is, in the atmospheric distillation column) due to the presence of bioliquids in specific units (FCC and/or HDT), outputting thereby new yields used as inputs to the BLUES model.

---

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