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Maritime transport decarbonization: the role of Brazilian liquid biofuels

Francielle Mello de Carvalho

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Orientador(es): Alexandre Salem Szklo
Joana Portugal-Pereira
Martin Junginger

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Orientadores: Alexandre Salem Szklo
Joana Portugal-Pereira
Martin Junginger

Aprovada por: Prof. Dr. Alexandre Salem Szklo, D.Sc.
Prof. Dr. Joana Portugal Pereira, Ph.D.
Prof. Dr. Martin Junginger, Ph.D.
Prof. Dr. Pedro Rochedo, D.Sc.
Prof. Joaquim Eugênio Abel Seabra, D.Sc.
Dr. Vassilis Daioglou, Ph.D.

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"A persistência é o caminho do êxito."
- Charles Chaplin

"Se for difícil para você, faça por alguém."
- Pietro Mannarino

"Everything is hard before it is easy."
- J. W. von Goethe

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MARITIME TRANSPORT DECARBONIZATION: THE ROLE OF BRAZILIAN LIQUID BIOFUELS

Francielle Mello de Carvalho

Outubro/2022

Orientadores: Alexandre Salem Szklo
Joana Portugal Pereira
Martin Junginger
Programa: Planejamento Energético

A Organização Marítima Internacional estabeleceu metas para reduzir em 50% as emissões de gases de efeito estufa (GEE) do setor em 2050 em relação aos níveis de 2008, além de outras metas intermediárias. Dada a vida útil da frota existente e características do comércio entre regiões, a realização de análises regionais sobre combustíveis marítimos drop-in é relevante. Esta tese avalia se estes representam uma estratégia promissora de mitigação através de uma análise multicritério, compara o Brasil com outras potenciais regiões fornecedoras a partir de uma análise tecno-econômica e georreferenciada e avalia se o uso de combustíveis drop-in no transporte marítimo pode afetar a competitividade das exportações brasileiras. Os resultados revelam que biocombustíveis drop-in são a alternativa mais promissora no Brasil para descarbonizar o transporte marítimo no curto e médio prazo, dado seu perfil de comércio internacional. Ademais, o potencial de produção de biocombustíveis está mais concentrado geograficamente no Brasil comparado aos EUA, África do Sul e Europa, apresentando vantagens competitivas em termos de oferta e custo dos biocombustíveis comparado a estas regiões. Ademais, o uso de biocombustíveis drop-in nas exportações brasileiras de soja pode não elevar os custos de frete de forma a comprometer sua competitividade frente ao principal concorrente.

Abstract of Thesis presented to COPPE/UFRJ as a partial fulfillment of the requirements for the degree of Doctor of Science (D.Sc.)

MARITIME TRANSPORT DECARBONIZATION: THE ROLE OF BRAZILIAN LIQUID BIOFUELS

Francielle Mello de Carvalho

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Advisors: Alexandre Salem Szklo
Joana Portugal Pereira
Martin Junginger

Department: Energy Planning

The International Maritime Organization has established the aim to reduce greenhouse gas (GHG) emissions of the sector in 2050 by 50% compared to 2008 levels, in addition to other intermediary targets. Given the lifetime of the existing fleet and the characteristics of the trade between regions, it is relevant to perform region-specific analyses of low-carbon drop-in fuels to decarbonize the maritime transport sector. This thesis evaluates if these fuels are a promising maritime transport mitigation strategy for Brazil using a multicriteria analysis, compares Brazil with other potential supplier regions through a techno-economic and georeferenced analysis and evaluates if the use of alternative drop-in fuels in maritime transport could affect the competitiveness of Brazilian exports. Results reveal that drop-in biofuels are the most promising short- to mid-term alternative to decarbonize the maritime transportation in Brazil, given its international trade profile. Also, the biofuel production potential is more geographically concentrated in Brazil than in the USA, South Africa and Europe, resulting in, competitive advantages in terms of biofuel supply and costs compared to these regions. Further, drop-in biofuel use in Brazilian soybean exports may not lead to an increase in freight costs that compromise the country´s competitiveness face its main competitor.

Summary

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1. Introduction

International trade enabled the economic growth and the spread of knowledge and technologies around the world. It has evolved to an extent that, in different degrees, every nation relies on selling its products and buying the missing ones. Shipping is the most cost-effective and fuel-efficient way to promote the trading worldwide (IMO, 2016a). According to the United Nations Conference on Trade and Development (UNCTAD), around 80% of global trade by volume and over 70% by value are carried by sea and handled by ports (ICCT, 2018; UNCTAD, 2021). Merchant shipping has risen over the years along with world population and demand for traded goods. Approximately 10.7 billion tonnes of freight worth approximately $7 trillion are traded annually, consuming more than 330 million tonnes of oil products (FABER et al., 2020; IEA BIOENERGY, 2017; UNCTAD, 2021). The shipping activity has been strongly linked to gross domestic product (GDP) growth, however, a reduction in this trend has been observed in the past years (IEA, 2017; IMO, 2014; UNCTAD, 2021) due to trade policy tensions, sanctions, adverse economic environment, and social crisis in some countries; oil demand growth and supply-side disruptions (UNCTAD, 2019).

Given its high activity level, the maritime transport sector is responsible for a significant energy demand in the form of crude oil-derived liquid fuels. In national inventories, the consumption of crude oil products in the transportation sector includes aviation, road, rail and inland navigation, but excludes the fuel consumed in the international maritime transportation, known as marine bunker fuels (MAZRAATI, 2011). These fuels are produced in petroleum refineries and their characteristics are determined by the quality of oil or refinery scheme used. There are three major types of bunker fuels: residual fuel (heavy fuel oil, HFO), distillate fuel (marine gas oil, MGO) and a combination of both known as intermediate fuel (IFO). The residual and distillate fuels are blended into different combinations producing different of marine fuels (SMITH, 2006).

According to the Fourth IMO GHG Study, marine fuel consumption in 2018 totalized 339 million tonnes. The international shipping represents most of the fuel consumption, followed by domestic shipping[1] and fishing. Fuel consumption was dominated by HFO, which accounted for 66% of total fuel consumption, followed by

[1] Domestic shipping is defined as shipping between two ports in the same country.

MGO (31%), liquefied natural gas (LNG) (3%), and methanol (0.05%) (FABER et al., 2020).

Fuel consumption in shipping is responsible for a substantial amount of emissions, which include greenhouse gases (GHG) as carbon dioxide (CO_2) and air pollutants as sulphur and nitrogen oxides (SO_x and NO_x), carbon monoxide (CO) and particulate matter (PM). Estimates reveal that shipping[2] is responsible for around 1.08 billion tonnes (Gt) of CO_2e emissions, which accounts for approximately 3% of global GHG emissions (FABER et al., 2020). Shipping activity is expected to increase and, in the absence of proper mitigation measures, the emissions in 2050 could represent an increase of 130% compared to 2008 levels (FABER et al., 2020).

The International Maritime Organization (IMO) is responsible for regulating the international shipping and since 1997 attempts to propose measures to control the greenhouse gas (GHG) emissions from the maritime vessels. Under the United Nations Framework Convention on Climate Change (UNFCCC) 1997 Kyoto Protocol, IMO has committed to limit the GHG emissions from international shipping (RUTHERFORD; COMER, 2018). The IMO's Second GHG study, published in 2009 introduced different options to reduce GHG emissions from ships. The options discussed include a mandatory limit on the Energy Efficiency Design Index (EEDI) for new ships, a mandatory or voluntary reporting of the EEDI or the Energy Efficiency Operational Indicator (EEOI), the Maritime Emission Trading Scheme (METS), among others (IMO, 2009).

In 2011, the IMO adopted its first mandatory requirements with the EEDI. However, in 2015 international shipping and aviation were not explicitly included in the Paris Agreement mitigation goals, under which the UNFCCC Parties have pledged to take ambitious measures to reduce GHG emissions. Since then, the Maritime Environment Protection Committee (MEPC) formed by a group of South Pacific and European member states held meetings to push IMO to expressively reduce the GHGs emissions from international shipping. The meetings aimed to develop the strategy that was accepted as a resolution at MEPC 72 in April 2018. The strategy proposes a quantitative reduction in carbon intensity and GHG emissions for the international shipping sector that includes, among other goals, a reduction of 50% in GHG emissions in 2050 compared to 2008

[2] International, domestic and fishing. In recent years, international shipping CO2 emissions represents around 75% of total shipping CO2 emissions.

levels. It also includes a list of short-, mid- or long-term measures to be implemented to reach the emission targets (IMO, 2018; RUTHERFORD; COMER, 2018).

In 2021, during the MEPC 76 meeting, new regulations were adopted that combine technical and operational measures to improve the energy efficiency of ships, thus reducing their GHG emissions. Such measures require all ships to calculate their Energy Efficiency Existing Ship Index (EEXI) and their annual operational carbon intensity indicator (CII) that links the GHG emissions to the amount of cargo carried over travelled distances (IMO, 2021).

In short, strategies to curb GHG emissions will require a rapid adoption of efficient technologies and new fuels that will have significant consequences for the sector. A study performed by Smith et al. (2016) aimed to explore possible and different pathways to reduce CO_2 emissions from international shipping in the future. The study finds that the required average carbon intensity reduction in ships is higher than what can be achieved only through energy efficiency interventions. The results show that the use of low carbon fuels represents a possible alternative in combination with low operational speeds and conventional fuels (SMITH et al., 2016b). Bouman et al. (2017) performed an overview of the CO_2 emissions reduction potential and measures based on around 150 studies published in the literature. Their analysis revealed that standalone measures are not enough to reach considerable sector-wide reductions, but according to their review, the highest emissions reduction potential are associated with the use of alternative fuels, particularly biofuels. A similar conclusion was found by (NEPOMUCENO DE OLIVEIRA; SZKLO; CASTELO BRANCO, 2022a), indicating alternative fuels are crucial to reach the IMO's decarbonization goals. Then, it is expected that ships built in 2050 will be very different from today. A wide variety of low-carbon[3] fuels and corresponding energy converters technologies, such as sustainable biofuels, hydrogen, batteries, among others, are foreseen across the world's fleet (LLOYD'S REGISTER, 2018).

1.1. Alternative low-carbon fuels to decarbonize maritime transport

[3] Fuels whose utilization leads to a reduction in GHG emissions compared to conventional petroleum fuels in a life-cycle basis. These comprise not only fuels with zero carbon content (such as hydrogen and ammonia) but also biofuels and synthetic fuels made from captured carbon dioxide.

Reducing GHG emissions and establishing new propulsion technologies are the key challenges for the maritime transport in the upcoming years. The fleet of the future will have to rely not only on energy efficient ships but also on novel propulsion systems and low-carbon fuels (DNV GL, 2018a).

Although some literature (BP, 2022; STAPCZYNSKI; RATHI; MARAWANYIKA, 2021; TOTALENERGIES, 2020) includes as carbon-neutral fuels fossil carriers associated with carbon capture and storage (CCS) in their production or with emissions offset throughout their value chain, in this thesis the concept of low-carbon fuels will include only fuels from renewable energy sources whose GHG emission in a life-cycle basis is lower than the emissions from petroleum conventional fuels.

The potentially low-carbon fuels represent mid-to long-term alternatives to replace fossil fuels used in marine engines. Biofuels, methanol, hydrogen, ammonia, electrofuels, and electricity produced from renewable energy sources are typical energy carriers associated with low GHG emissions during their entire life cycle (AMPAH et al., 2021; DNV GL, 2019; LLOYD'S REGISTER; UMAS, 2020).

Prerequisites for introducing novel fuel alternatives include the availability of resources for their production in scales suitable for maritime transport, distribution network and bunkering infrastructure. Regions with high availability of resources, intense port activities and that are strategically located along major sea routes may emerge as potential world fuel suppliers. Additionally, the compatibility with current fleet and the need for retrofits and systems modifications is complex and requires significant costs (DNV GL, 2018a).

Several studies have compared different alternative fuels options. A comprehensive study carried out by DNV GL compared a set of potential alternative marine views by performing a review on their operational and economic viability according to the existing literature and assessed how distinct alternative fuels performed according to a set of parameters (DNV GL, 2019). Deniz and Zincir (2016) compared the economic and environmental performance of different alternative marine fuels (methanol, ethanol, liquefied natural gas, and hydrogen) according to eleven criteria and identified LNG as the most suitable alternative, followed by hydrogen. Andersson et al. (2020) conducted an overview of the criteria used in potential marine fuels assessments to identify the most important ones. They concluded that the minimum set of criteria should differ when assessing fuels that can be used in existing ships or that require new propulsion systems. Al-Enazi et al. (2021) explored the challenges and opportunities associated with cleaner fuels use in maritime transportation and compared them according to their technoeconomic feasibility and environmental dimensions, operational viability and required supply chain. As a result, they identified measures that could support the ship operators in the fuel transition. Xing et al. (2021) performed a technological review to identify most promising marine fuels according to the potential to reduce the emission of air pollutants and carbon dioxide and identified methanol as the most promising fuel, while hydrogen and ammonia could be suitable for domestic and short sea shipping. Romano and Yang (2021) performed a comprehensive review on the evolution of shipping decarbonization research by analyzing 294 papers published from 2000 to 2020. Their results indicated that more research is needed on low-cost biofuels, given their high climate change mitigation and short-term deployment potential.

While relevant, previous studies conducted technoeconomic and environmental assessments that typically do not evaluate context-specific parameters, such as particularities regarding foreign trade, cargo type, ship fleet age, engine types and transportation routes. Some foreign trade characteristics would pose additional challenges for the implementation of alternative fuels in some countries, such as geographic location, far away for their main partners and the type of products traded. Deep-sea shipping includes mostly large, ocean-going vessels covering long routes. Ships operating in long haul transportation require fuels globally available and with high energy density to maximize cargo space and ensure fuel autonomy. On the other side, some alternatives identified in the literature as promising options, are better suited for short-distance transportation. Additionally, most of the alternative fuels are likely to pose additional costs for maritime transport services. Even though it is expected that these alternatives will benefit from learning rates in the long-term, they may not be ready in the time span of the IMO goals, also given the extended lifetime of long-haul vessels, of up to 25 years (SAFETY4SEA, 2020). Therefore, the choice of mitigation measures for the shipping sector should be carefully evaluated given the economic impacts this might have on foreign trade and countries' economies. Moreover, the challenges might vary depending on the type of trade (e.g., containers versus bulk materials), fleet characteristics, and abatement options, including alternative fuels potential, which calls for regional or country specific studies. As of today, few studies have focused on country- or even product-specific studies.

1.2. Liquid biofuels as alternative marine fuels

Although several options are under discussion, there is no silver bullet for scalable potential low-carbon marine fuels. Specifically, drop-in fuels[4] can play a role in shipping sector energy transition pathway, as they are considered the most 'technology-ready' option of alternative fuels for shipping (GLOBAL MARITIME FORUM, 2022). Biofuels, produced from the upgrade of sugars, lipids or residual biomass feedstocks are considered a potential source to produce significant volumes of drop-in fuels (VAN DYK et al., 2019a). The less strict specifications and higher fuel supply flexibility[5], compared to road and aviation sector, for example, represent an opportunity to their use on maritime sector (IEA BIOENERGY, 2017). Also, the maritime sector's well-established infrastructure and long lifespan of ships (up to 25 years) makes drop-in biofuels the most feasible alternatives, at least in the mid-term (EC, 2019; PRUSSI et al., 2021).

Besides their benefits, major concerns regarding biofuels are associated with costs, supply guarantee and sustainability (LLOYD'S REGISTER; UMAS, 2020). Biofuel's use in ship engines is still in initial phase and a significant amount of testing and standardization is needed, especially for advanced biofuel technologies (GLOBAL MARITIME FORUM, 2022; GREEN MARINE, 2021; IEA BIOENERGY, 2017; NYK LINE, 2022; OFFSHORE ENERGY, 2022; SHIP TECHNOLOGY, 2021). Additionally, land use competition for resources with food production and with other energy sectors (e.g., aviation), increased water demand and land use changes may compromise their development (SSI, 2019).

Existing studies evaluated alternative biofuels to reduce the maritime transport sector emissions. ECOFYS presented a review of potential biofuels for shipping, assessing their technical, organizational and market limitations (ECOFYS, 2012a). IEA Bioenergy published an overview of maritime shipping sector and suggested implementation strategies to increase the share of biofuels in the maritime sector in light of its infrastructure and regulations (IEA BIOENERGY, 2017). Kesieme et al. (2019) examined key parameters that limit biofuel applications in the shipping sector and proposed solutions to enable their widespread use. Tanzer et al. (2019) developed an integrated screening model to compare the technological, economic, and environmental

[4] Drop-in fuels can directly replace conventional fossil fuels, with no or limited modifications in bunkering infrastructure or ships engines. They are fully compatible with the existing petroleum-based fuels infrastructure (VAN DYK, et al., 2019a).

[5] Marine diesel engines tolerate a wide range of fuel viscosities and are relatively insensitive to fuel quality, being capable operate with light and heavy fuel fractions. Thus, marine fuels require less specific physical and chemical properties and go through less refining steps.

performance of drop-in marine biofuel supply chains. Zhou et al. (2020) examined different liquid biofuel pathways according to a set of qualitative and quantitative criteria and provided a set of recommendations for policymakers. Van der Kroft et al. (2021) assessed the availability, costs and GHG reduction of marine drop-in biofuels under different scenarios from 2020 to 2050.

Only few studies presented region-specific analysis regarding marine biofuels. Panoutsous et al. (2021) applied value chain analysis and competitive priority theory to lignocellulosic biofuels in order to identify challenges that restrict their uptake and suggested effective policy interventions. Cortez et al. (2021) discussed the production of pyrolysis-based biofuels in Brazil according to feedstock type, conversion technology, sustainability, fuel properties, challenges, and opportunities. Bach et al. (2021) investigated how the development and implementation of biofuels in Norwegian coastal shipping are influenced by their technological similarities with conventional fossil marine fuels. Finally, Tan et al. (2022) assessed biofuel production capacity potential and price in the United States in the long-term and provided prospects for their adoption for marine propulsion.

These relevant studies have focused on identifying the potentials, benefits, and constraints for alternative marine fuels. However, knowledge gaps were found on the reviewed literature given that important logistic constrains to produce biofuels development were overlooked. The scalability of marine biofuels requires the assessment of the production chain logistic integration, which links the feedstock availability and seasonal variability with fuel consumption sites. Some factors that are crucial to determine marine biofuel production feasibility, such as seasonality, are usually neglected in most of biofuel technoeconomic assessments. Thus, even when significant, if biomass feedstocks are not available all over the year, additional costs associated with pre-treatment and storage or with idle capacity of production plants should be expected. Further, greatest biomass production sites are generally located in countryside areas, which tend to be far away from shipping fuel bunkering sites. In this sense, transportation modes could directly influence the biofuel production costs and their techno-economic feasibility. Finally, many studies have assessed the logistic chains logistics for biofuels in general or for other transportation modes in Brazil (CAMBERO et al., 2015; CERVI et al., 2020, 2021; GUTIÉRREZ-ANTONIO et al., 2021; LAN; PARK; YAO, 2020; NEVES et al., 2020; YUE; YOU; SNYDER, 2014; ZHANG et al., 2016), but not specifically linked to marine applications.

1.3. The use of biofuels in the marine international trade

As before mentioned, drop-in biofuels can directly replace or compose blends with fossil bunker fuels as they could be readily used, with minor adjustments (KEN WEI, 2021), in the existing ship engines and available bunkering infrastructure. The production of biofuels is foreseen to require significant investment and production costs, which means that their use in maritime transport would increase ocean freight rates and thereby affect trade. While shipping services demand is initially influenced by the world economy, other factors, such as fuel prices, could also contribute. Given that fuel costs are a critical part of vessel's operating costs[6], higher fuel expenses would increase freight rates, thereby affecting product's prices and trade. Such impacts can be particularly relevant for the trade of specific products and for long trade voyages (IEA, 2022a; MELAS; MICHAIL, 2021; MICHAIL; MELAS, 2020).

The consequences of increased fuel price on maritime transport costs and trade are very relevant, especially for emerging or low- and middle-income countries. Some studies have particularly focused on the link between fuel prices and maritime transport costs. Poulakidas and Joutz (2009) evaluated the impact of peak oil prices on tanker rates and concluded that a relationship exists between them. Korinek and Sourdin (2009) have analyzed, among other factors, the influence of fuel prices on maritime transport costs and found that the cost of bulk shipping rises together with oil prices. Angelopoulos et al. (2020) concluded that oil prices are the primary factor that affects commodity prices and thereby the freight markets, and Mikail and Melas (2020) provided additional proof of this relationship by examining the impact of dry bulk vessels charter rates on agricultural products prices. Finally, Melas and Mikail (2021) evaluated the relationship between freight rates and commodities prices in the dry bulk shipping segment.

Therefore, the previously highlighted literature gaps raise the need for studies that assess the potential of alternative fuels for maritime transport that are region- and context-specific. Considering all aspects of maritime transport, such as average fleet age, ports infrastructure and inflexibilities to deal with novel fuel alternatives, drop-in biofuels seem a promising alternative to decarbonize maritime sector, at least in the medium-term. Realizing that the GHG emitted now from maritime sector will last more than 100 years in the atmosphere, betting only in options that require the modification of propulsion

[6] Fuel costs represent about 45%-60% of vessel's operating costs (RODRIGUE, 2020, STRATIOTIS, 2018).

systems (such as hydrogen and ammonia) for the long-term would result in short term cumulative GHG emissions that would have to be compensated afterwards.

The need for region-specific analysis is derived from the particularities regarding foreign trade, cargo type, ship fleet age, engine types and transportation routes. Some foreign trade characteristics would pose additional challenges for the implementation of alternative fuels in some regions, which calls for regional or country specific studies. Region-specific studies are also relevant to identify the local availability of resources to produce the promising alternative fuels and assess its techno-economic feasibility. Additionally, the development of context-specific studies, applied to a defined ship type or product, for example, is important to evaluate the impacts of alternative fuels use on foreign trade routes.

Brazil can be considered a particularly relevant case study for this kind of analysis for a set of reasons. Firstly, it is worth stressing the country expertise in biofuels production, high share of renewable energy sources and low emission factor of electricity grid (EPE, 2021), which could be a competitive advantages to produce cleaner maritime fuels. Brazil is the second leading country in biofuel production worldwide and has the highest share of bioenergy supply in the world (IEA, 2021a; IEA BIOENERGY, 2021). Renewable energies represent 45% of primary energy demand, which makes the Brazilian energy sector one of the least carbon-intensive worldwide (IEA BIOENERGY, 2021).

Secondly, the inherent characteristics of Brazilian foreign trade make it a major commodity exporter whose unfavored geographical position increases the carbon intensity of its maritime transportation. The main goods exported are commodities with notorious discrepancy in terms of mass and value, such as are iron ore, soybeans, crude oil, and sugar. These products account for more than three-quarters of Brazil's exports in mass-basis and only a quarter of the country's exports in monetary values (COMEXSTAT, 2022; SCHAEFFER et al., 2018). Additionally, Brazil has an unfavorable geographical position, far away from its main trade partners (China, European countries and the U.S.A.), which means that the country deals with longer travel distances, higher fuel expenses and carbon intensities (SCHAEFFER et al., 2018).

Further, Brazil faces stiff competition in commodity exports, whose market share is influenced, among other factors, by the competitiveness of ocean freight rates that could be impacted by fuel shifts in maritime transport (SALIN, 2020a; SALIN; AGAPI SOMWARU, 2020).

1.4. Objective

In this context and considering abovementioned knowledge gaps in the literature, this thesis aims to evaluate the Brazilian biofuels contribution to GHG mitigation goals of the international maritime sector. The objectives of this thesis are threefold and related to Brazil in different ways. First, this thesis evaluates the hypothesis that low-carbon drop-in fuels for maritime transportation are an alternative mitigation strategy for Brazil. Second, this thesis compares Brazil with other potential maritime drop-in biofuel supplier regions. And third, this thesis analyses if the use of drop-in biofuels in maritime transport could affect the competitiveness of Brazilian exports.

In this context, this thesis presents the following research questions:

- Research Question 1: *"Are low-carbon drop-in biofuels an effective alternative maritime fuel for Brazil?"*.
- Research Question 2: *"How does Brazil compare with other major potential drop-in biofuel supplying regions?"*.
- Research Question 3: "C*ould the use of drop-in biofuels in maritime transport affect the competitiveness of Brazilian exports?*".

To answer the first question, this thesis performs a region-specific comparative analysis of potentially low-carbon fuels in Brazil for maritime transportation based on a set of indicators. To this end a multicriteria analysis is performed, which enables the identification of the most promising options according to different dimensions. This analysis is critical for assessing the potential of different alternatives according to the inherent characteristics of the country and would support local policy makers to define strategies to comply with the IMO's GHG emissions reduction goals.

Second, this thesis performs a georeferenced analysis to identify potential localities for marine biofuels production, logistic supply and costs in strategic regions of the world: Brazil, Europe, South Africa and the U.S. Such regions were chosen for the following reasons: (i) relevant agricultural production; (ii) presence of major world ports outside Asia; (iii) greatest trade centers; (iv) location among strategic sea routes. Thus, the identification of marine biofuels potential in these regions is valuable to prospect major players and design tailored solutions for shipping decarbonization.

Finally, this thesis also aims to test the hypothesis that fuel switches in the international shipping sector can affect the commodity trade. To this end, a case study is performed to conjointly evaluate the potential of biofuels to decarbonize specific maritime transport routes. The utilization of lignocellulosic marine biofuels in soybean trade routes from Brazil and the U.S. to China are evaluated in terms of supply volumes, GHG emissions reduction and increase on ocean freight rates.

Soybean trade to China is chosen given that soybean ranks in the second position in Brazilian exports and its international competitiveness is directly influenced by transportation costs (COMEXSTAT, 2022; GALE; VALDES; ASH, 2019; SALIN, 2020a; SALIN; AGAPI SOMWARU, 2020). Lignocellulosic biofuels[7] are chosen given their additional advantages over conventional biofuels. First, they would potentially minimize the "food versus fuel" debate and land use change risks, that are considered the major concerns regarding biofuels produced from dedicated crops (DAIOGLOU et al., 2020; SHRESTHA; STAAB; DUFFIELD, 2019; TANZER et al., 2019; VAN DER HILST et al., 2018; ZAIMES et al., 2015). Additionally, the high fuel volumes required for maritime sector makes the lignocellulosic feedstock attractive to produce marine biofuels, given that residues from agriculture and forestry are abundantly available and have relatively low costs (BARUYA, 2015; RAUD et al., 2019).

1.5. Thesis outline

Each research question is addressed in a separate scientific article[8], that covers from the research question 1, which has a broader context on low-carbon fuel alternatives for maritime sector, to question 3, which applies a case study to evaluate biofuels use in specific trade routes. Figure 1shows the system boundary of each research question and the relationship between them. The papers attempt to cover the gap in the literature on region-specific analysis to identify the potential of biofuels to decarbonize maritime transport.

[7] Biofuels produced from lignocellulosic feedstocks such as straws and wood chips.

[8] Research Question 1 is addressed in the paper "Prospects for carbon-neutral maritime fuels production in Brazil" (CARVALHO et al., 2021b) published in the Journal of Cleaner Production. Research Question 2 is addressed in the paper "Biofuels for Maritime Transportation: A Spatial, Techno-Economic, and Logistic Analysis in Brazil, Europe, South Africa, and the USA" (CARVALHO, et al., 2021b) published in Energies. And Research Question 3 is addressed in the paper "Lignocellulosic biofuels use in the international shipping: the case of soybean trade from Brazil and the U.S. to China" which was submitted for publication, and it is currently under review.

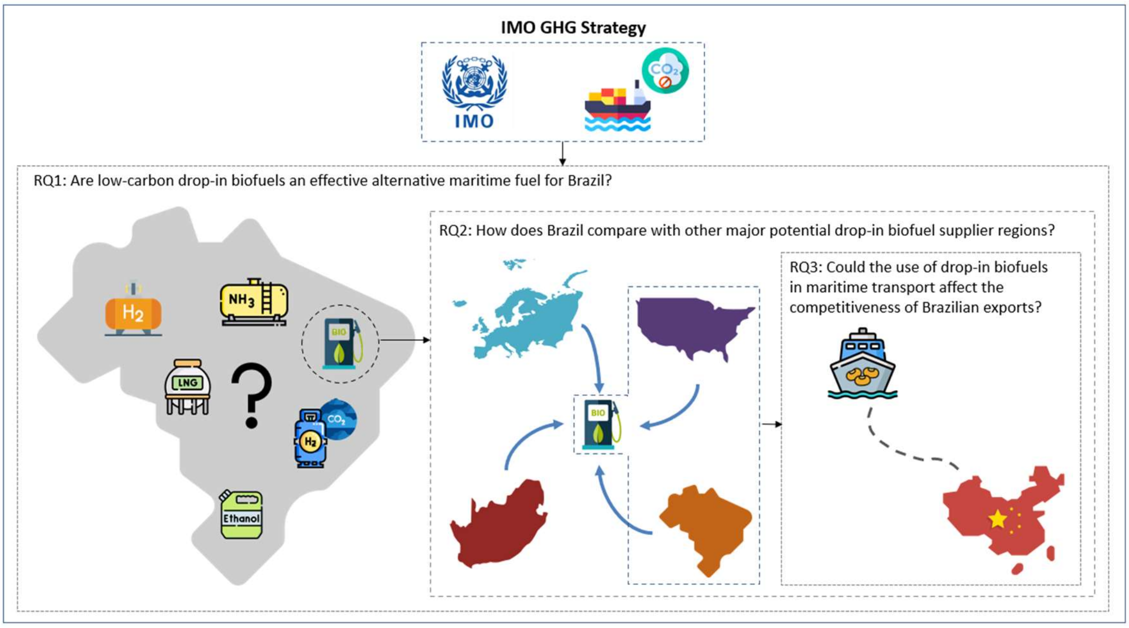

Figure 1: System boundary of the research questions

Chapters 2-4 are self-contained pieces of work and can be individually read. Nevertheless, together, they constitute an investigation of the role of liquid biofuels produced in Brazil in maritime decarbonization that goes from a comparative analysis of promising carbon-neutral alternative marine fuels, the technoeconomic and georeferenced assessment of liquid biofuels production in different world regions and the evaluation of liquid biofuels use in specific trade routes. Finally, in Chapter 5, the final remarks, conclusions and suggestion for future works are presented.

2. Prospects for carbon-neutral maritime fuels production in Brazil

Francielle Carvalho , Eduardo Müller-Casseres, Matheus Poggio, Tainan Nogueira, Clarissa Fonte, Huang Ken Wei, Joana Portugal-Pereira, Pedro R. Rochedo, Alexandre Szklo, Roberto Schaeffer

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2.1. Abstract

The International Maritime Organization (IMO) has compromised to reduce its greenhouse gas (GHG) emissions in the mid- and long-terms. Besides energy efficiency measures, the development of potentially carbon neutral fuels in the upcoming years is key to achieve the sector's goals. Brazil is a major commodity exporter whose unfavored geographical position increases the carbon intensity of its maritime transportation. In this context, this study presents a multicriteria methodology to compare possible alternative fuels for the Brazilian maritime trade. To this end, 14 fuel options are evaluated according to technical, economic, and environmental criteria to which different weights are assigned. The ranking of results indicates that drop-in fuels such as Fischer-Tropsch diesel, alcohol-based diesel, straight and hydrotreated vegetable oils and e-diesel stand out as promising mid-term alternatives. Biomass-based liquefied natural gas (Bio-LNG) performance in the evaluation is hampered mostly by the risk of methane slip. Green hydrogen and green ammonia, on the other hand, seem to be less competitive alternatives in the mid-term horizon for Brazil but may become alternatives for cabotage transport in the long-term.

2.2. Introduction

The international shipping industry has set ambitious targets for reducing its greenhouse gas (GHG) emissions. The strategy defined by the International Maritime Organization (IMO) proposes a quantitative reduction in carbon intensity and GHG emissions in the sector which includes, among other targets, a 50% reduction in GHG emissions by 2050 compared to 2008 levels (RUTHERFORD; COMER, 2018). Among the main potential measures to be adopted in the mid- and long-terms, neutral emission fuels are listed. Several alternatives can be considered, such as distilled biofuels, bio-

Liquefied Natural Gas (bio-LNG), bio-alcohols, hydrogen, ammonia and the so-called electrofuels (e-fuels).

Maritime transport is the most efficient way to promote medium and long-distance trade around the world. Despite the cargo containerization process observed in the recent past, long-haul shipping still focuses heavily on the transportation of mineral and agricultural commodities (UNCTAD, 2019). Additionally, while the trade of higher value-added products (typically containerized) is concentrated on the intra-Asia, Asia-North America, and Asia-Europe routes, on a mass basis the major part of the sea trade is associated with the supply of raw materials by countries of the Global South. These are typically low value-added products sold in bulk and transported in large vessels (UNCTAD, 2019).

Brazilian foreign trade, for example, is strongly based on primary products. The main goods exported are iron ore, soybeans, crude oil, and sugar, which are commodities with notorious discrepancy in terms of mass and value. On a mass basis, these four products account for more than three-quarters of Brazil's exports while, in terms of value, they represent only a quarter of the country's exports (SCHAEFFER et al., 2018). Furthermore, Brazil has an unfavorable geographical position of its maritime trade. Far from East Asia, Europe, and the United States, and with no access to the Pacific Ocean, the country must deal with longer travel distances and higher fuel expenses and carbon intensities[9].

Deep-sea shipping includes mostly large, ocean-going vessels covering long routes and often without a regular schedule (except for containerships). Vessels operating in long distance transportation require fuels that are globally available and have good energy density in order to maximize the space availability for cargo and ensure fuel autonomy. Therefore, the choice of mitigation measures in the Brazilian shipping sector should be carefully evaluated given the economic impacts this might have on the country's foreign trade.

From a technical and economic perspective, various potentially carbon-neutral fuels could serve as mid- to long-term alternatives to replace fossil fuels used in marine engines. Possibilities are diverse, ranging from the direct use of vegetable oils to the use

[9] In the period 2001-2018 China was, by far, the main destination of Brazil's exports, accounting for 46% of the iron ore, 64% of the soybeans and 27% of the crude oil shipments of these products. The shipping distance between the Brazilian coast and China's main importing centers is around 11,900 nautical miles (Santos-Shanghai taken as a reference), a very high value compared to the average haul length of 4,200 nautical miles (Schaeffer et al., 2018)

of synthetic fuels produced from hydrogen and recycled carbon dioxide. In addition, technological routes optimized to produce high-quality biofuels, such as biomass-derived jet (bio-jet), could also co-produce fuels suitable for maritime transportation.

Brazil can be considered a potential producer of marine biofuels in view of the high availability of biomass resources and its expertise in biofuels production (CARVALHO, 2017; CARVALHO; PORTUGAL-PEREIRA; SZKLO, 2019; PORTUGAL-PEREIRA et al., 2015). Also, the significant participation of renewable energy sources and the low emission factor of the Brazilian power grid would benefit the production of green hydrogen, green ammonia, and e-fuels. Therefore, Brazil may have competitive advantages to produce fuels suitable for long-sea shipping that could be used in its major trade routes and/or make it an important international exporter of such fuels.

Previous studies have assessed the possibilities of using alternative marine fuels. While some of them focused on the benefits and challenges of specific options (ELLIS; TANNEBERGER, 2015), others tried to understand the potential pathways and scenarios for the future of international shipping as a whole (BALCOMBE et al., 2019; SMITH et al., 2016b). A number of these studies points out hydrogen as a promising alternative for reducing shipping's emissions. DNV GL, an accredited certification company, conducted three studies regarding alternative low-carbon energy sources for the maritime transportation sector (DNV GL, 2018a, 2018b, 2019). The most recent one assessed the commercial and operational viability of six alternative fuels compared to LNG according to several criteria based on existing literature (DNV GL, 2019). Further, (LLOYDS, 2017) and (LLOYD'S REGISTER; UMAS, 2020) investigated the potential of zero-emission vessels in 2030. Both studies examined the application of distinct technological options for different types of ships and performed a techno-economic analysis of zero-carbon fuels for shipping in view of their economic viability, technological feasibility and emissions.

While relevant, previous studies did not perform context-specific analyses that consider particularities regarding foreign trade, such as cargo, ship types and transportation routes. Also, some fuel alternatives, such as ammonia and e-fuels, identified in the literature as promising options, would be better suited for short-distance transportation. Even though it is expected that these alternatives will benefit from learning rates in the long-term, they may not be ready in the time span of the IMO goals, given also the extended lifetime of long-haul vessels (MAN DIESEL & TURBO, 2013).

To fill this gap, the objective of this study is to perform a comparative analysis of 14 potentially carbon-neutral fuels produced in Brazil for maritime transportation based on a set of indicators. The analysis identifies the main advantages and disadvantages of each alternative according to technical, economic, and environmental parameters. To the authors knowledge, this is the first assessment of the operational, commercial, and sustainable aspects of fuel alternatives for the maritime transport sector with a country-specific approach. This kind of analysis is critical for assessing the potential of different alternatives according to the inherent characteristics of the country. Also, it can support local decision makers to define the best strategies to comply with the sector's GHG emissions reduction goals in the upcoming years.

This paper is structured as follows. Section 2 details the technological pathways to produce non-fossil maritime fuels. Section 3 presents the methodology developed to perform a comparative analysis of the 14 alternative fuels, while Section 4 ranks the most promising ones. Finally, section 5 discusses the results obtained and section 6 presents the final remarks and suggestions for future studies.

2.3.Non-fossil alternative fuels for ships

Currently, there are various options of potentially carbon-neutral maritime fuels produced from renewable energy sources, which could serve as alternative, in the mid- to long-terms, to petroleum fuels currently used for the propulsion[10] of ships (LLOYD'S REGISTER; UMAS, 2020) . Carbon-neutral fuels produce no net-CO_2 emissions, which means that they offset |CO_2 combustion emissions generated during their production processes. Synthetic fuels use captured CO_2 from the atmosphere or industrial process, while biofuels CO_2 capture occurs during biomass growth through photosynthesis. The carbon neutrality of biofuels is controversial and has been extensively discussed in the literature (AGOSTINI; GIUNTOLI; BOULAMANTI, 2014; BENTSEN, 2017; BERNDES et al., 2016; CALVIN et al., 2021; COWIE; BERNDES; SMITH, 2013; COWIE et al., 2021; CREUTZIG et al., 2015; SMITH et al., 2016a). Also, fuels carbon neutrality depends on all life cycle input sources (such as hydrogen, chemicals, and power) and this concept does not consider the emissions of other relevant non-CO_2 GHGs.

[10] Naturally, the major part of the energy demand of a ship comes from its propulsion. However, energy is also required to the production of heat and electricity onboard. Today, this demand is also met by oil products.

For this reason, the fuels evaluated in this work are called 'potentially carbon neutral' fuels.

To better describe the technological possibilities, this study divided the fuels into three groups (Table 1 and Figure 2). Group 1 encompasses distillate fuels suitable for diesel (compression ignition) engines. Group 2 comprises alcohols and liquefied gases suitable for spark ignition or dual-fuel engines. Finally, group 3 includes hydrogen, ammonia, and hydrogen-based synthetic fuels (e-fuels).

Liquid distilled biofuels are classified as drop-in fuels (or almost drop-in) produced from vegetable oils, lignocellulosic biomass (e.g., agricultural and forest residues) or bio-alcohols (Figure 1(a)). Biofuels produced from vegetable oils are the straight vegetable oils (SVO) and hydrotreated vegetable oils (HVO), while biofuels produced from lignocellulosic biomass and bio-alcohols are the hydrotreated pyrolysis oil (HDPO), Fischer-Tropsch diesel (FT-diesel) and Alcohol-based diesel (ATD), respectively.

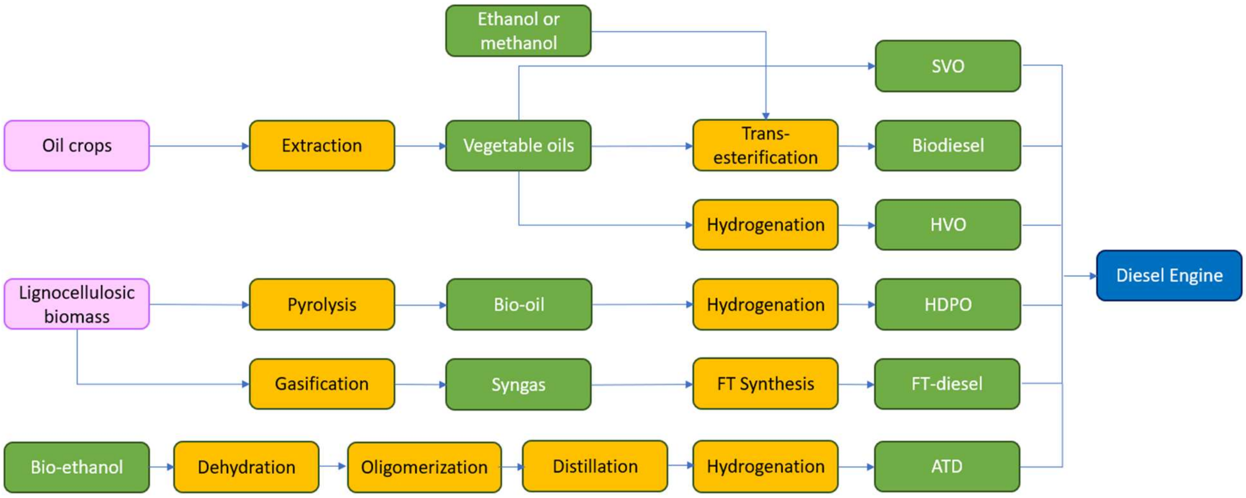
Alcohol and liquefied gases form the second group of fuels and represent fuels that are not suitable for direct replacement of conventional marine fuels (not drop-in), but whose application might be interesting, especially given the growing use of dual fuel engines in the maritime fleet. Group 2 is formed by liquefied biomethane (Bio-LNG) and biomass-based methanol and ethanol (biomethanol and bio-ethanol, respectively) (Figure 1(b)).

Finally, the third group is formed by alternative energy carriers based on hydrogen, which includes not only pure hydrogen (H_2), but also ammonia (NH_3), and synthetic fuels (composed by electrolysis-based hydrogen and captured CO_2) called electrodiesel, electromethane and electromethanol (Figure 1(c)). As this study evaluates potentially carbon neutral fuels, group 3 considers only renewable-based hydrogen and non-fossil captured CO_2.

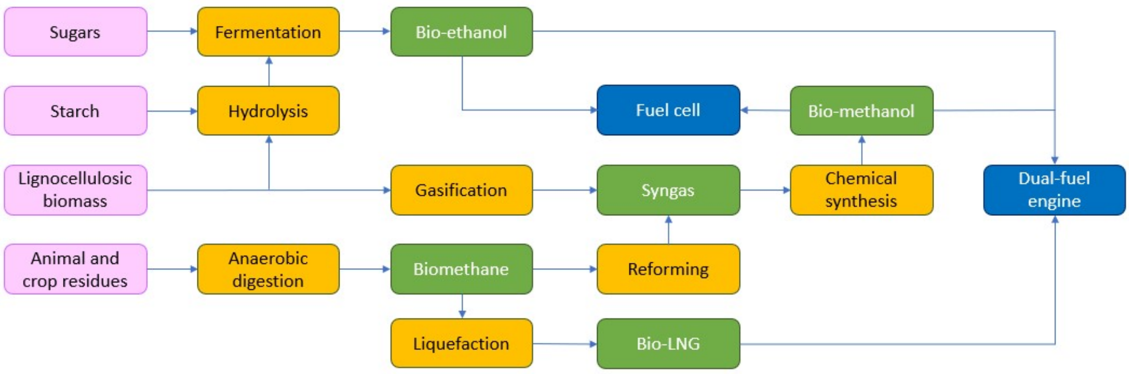
Table 1: Groups of fuels considered in the analysis

Fuel pathways		
Group 1 Liquid distilled biofuels	SVO	Straight vegetable oil
	Biodiesel	Biodiesel produced using FAME/FAEE
	HVO	Hydrotreated vegetable oil
	HDPO	Hydrotreated pyrolysis oil
	FT-diesel	Biomass-derived diesel
	ATD	Alcohol-based diesel (Alcohol-to-Diesel)

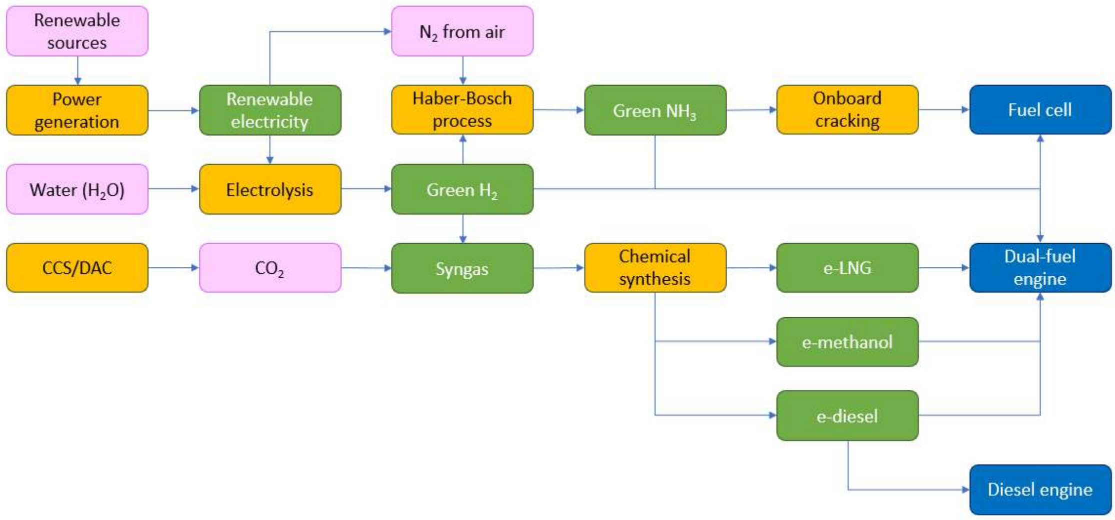
Group 2 Alcohol and liquefied gases	Bio-LNG Bio-CH_3OH Bio-C_2H_5OH	Liquefied bio-methane Biomass-derived methanol (bio-methanol) Biomass-derived ethanol (bio-ethanol)
Group 3 Hydrogen, ammonia, and e-fuels	Green H_2 Green NH_3 e-diesel e-LNG e-CH_3OH	Renewable-based hydrogen Renewable hydrogen-based ammonia Renewable hydrogen-based diesel (electrodiesel) Renewable hydrogen-based methane (electromethane) Renewable hydrogen-based methanol (electromethanol)



(a)



(b)



(c)

Figure 2: Potentially carbon-neutral fuels. 1a: Group 1 - distilled biofuels[11], 1b: Group 2 - alcohol and liquefied gases; 1c: Group 3 – hydrogen, ammonia and electrofuels

The categorization is based on the similarities between the fuel-motorization systems of the different alternatives. Group 1 is composed of almost drop-in fuels, derived from biomass feedstocks and routes that produce or co-produce distillates. Although biodiesel reveals stability problems (IEA BIOENERGY, 2017) and SVO has viscosity issues (ECOFYS, 2012a; KHAN, 2018a; NGUYEN; TRAN; DANG, 2015; VAN UY; THE NAM, 2018), they are more compatible with the existing motorization of the Brazilian shipping fleet, even to be blended with diesel used in the 4-stroke auxiliary motors. Group 2 is composed of fuels from biomass feedstocks that require more severe adjustments in logistics, bunkering, storage, and motorization to be used. Finally, group 3 includes fuels associated with the renewable hydrogen chain. Notwithstanding, such categorization is limited by the interrelationships between these groups, given the complexity of fuel pathways. For instance, e-diesel is analyzed from the perspective of hydrogen, although, in terms of chemical composition, it is identical to FT-diesel. The description of relevant physical-chemical properties for maritime fuels and their values for each fuel evaluated in this study are presented in the Appendix A.

2.4. Methods

[11] For biodiesel to be a carbon-neutral alternative, renewable methanol, or ethanol (not FAME, but FAEE, in this case) must be used in the transesterification process.

The aim of this work is to compare the fuels described in Section 2.3 based on a set of criteria adapted to Brazilian specificities. Figure 3 illustrates the different stages of the adopted methodology.

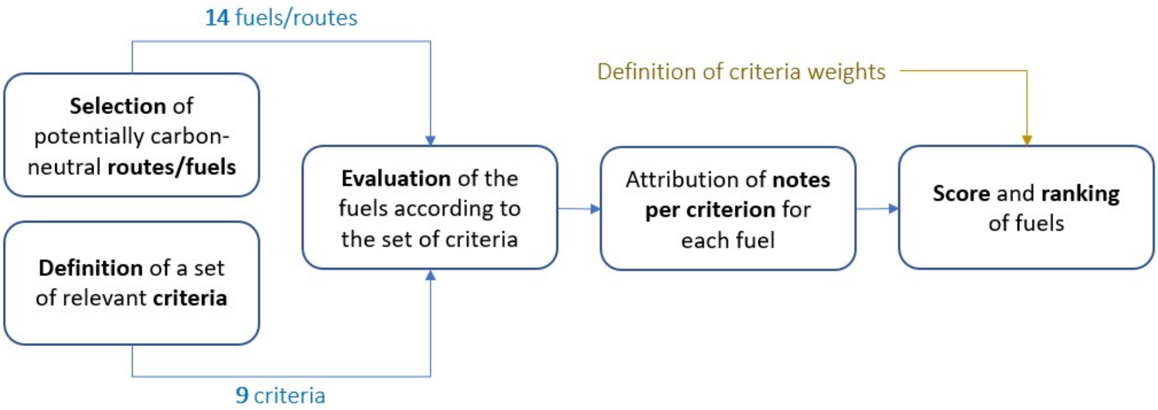


Figure 3: Overview of the methodology for comparison of alternative fuels.

First, a set of nine criteria, involving technical, economic, and environmental aspects, was defined (Table 2). A qualitative analysis was developed for each fuel from the viewpoint of this theoretical framework. Then, these criteria were turned into quantitative indicators through the attribution of notes from 1 (Very Bad) to 5 (Very Good). Criteria weights (from 1 to 3) were attributed for each criterion. One criterion received weight 3, five criteria received weight 2 and three criteria received weight 1 (Table 2). Then, the final score was calculated for each fuel, establishing a ranking of the alternatives. Given the score range (from 1 to 5) and weights (1, 2 or 3) of the indicators, the maximum fuel score (when it is evaluated with note 5 in all criteria) would be 80.

Table 2: Criteria/indicators considered in the comparative analysis

Index	Criteria	Description	Weight
1	**Availability**[a]	Availability of feedstock and infrastructure facilities	2
2	**Applicability**	Compatibility of the fuel with the operating fleet and current infrastructure for transportation, storage, and bunkering	2
3	**Technological maturity**	Readiness level of the production and utilization technologies	2
4	**Energy density**	Volumetric energy density, reflecting the need for space related to fuel storage onboard	2
5	**Economic**[b]	Levelized costs, comprising fuel production, bunkering infrastructure, and ship modifications (engines and tanks)	1
6	**Safety**	Safety in operation, fuel handling and toxicity.	2
7	**Standards**	Existence of fuel standards and/or certifications that prove renewable origin	1

8	**Global sustainability**	GHG emissions related to the fuel use and production and distribution chain and land use changes threats	3
9	**Local sustainability**	Air pollutant emissions (AP) impacts on biodiversity and water resources	1
Notes: [a] Availability criterion also evaluates the feedstock competition with other sectors. [b] Fuel levelized costs in the economic criterion includes coproduct benefits/revenues. c In this study, we included SOx, Particulate Matter (PM) and NOx. In high concentrations, nitrogen oxides (NOx) are highly toxic and cause health problems. They participate in various atmospheric reactions, producing tropospheric ozone and PM. NOx is a precursor of acid rain, diminishes air visibility and contributes to nutrient pollution in coastal waters (CHONG; BRIDGWATER, 2014a; EPA, 2016a). Emission of high SO2 concentrations lead to the formation of other sulfur oxides (SOx) which will react with various atmospheric components, increasing the levels of PM in the atmosphere. These are harmful to human health (respiratory diseases) and precursors of acid rain (EPA, 2016b, 2016c; WHO, 2006). Particulate matter (PM) emissions occur by the agglomeration of small particles of partially burned fuel, by the ash content of the fuel and lubricating oil and the presence of sulfates, water and hydrocarbons in the partially burned fuel (EPA, 2016b).			

For the sake of a better understanding, the ratings were normalized to fit a decimal scale. The normalization was performed so that the highest achievable score is 100. Thus, the total score of the fuels was multiplied by 100 and then divided by 80. The score x of a particular fuel is given by equation (1), in which w_i and p_i stand for the weight and the score of the fuel in the criteria of index i.

$$x = \sum_{i=1}^{9} w_i p_i / 0.80 \quad (1)$$

In order to rank the most promising alternatives, weights were attributed to the different criteria. Weight 3 was attributed to global sustainability, as this study focus on IMO's goals. On the other hand, weight 2 was attributed to technical criteria (availability, applicability, energy density and technological maturity) and safety criteria, as they indicate the need to adapt logistic systems, bunkering, motorization, and tanking in ships, being prerequisites for potential use of these fuels. The other criteria (economy, local sustainability, and standardization) received weight 1. Their lower weight does not mean that these aspects are not important for the development of alternative fuels. It rather suggests that these criteria have lower relative relevance compared to the other criteria, considering the scope of the study. Furthermore, it is worth noting that, despite the relevance of the economic criterion from a practical point of view, technological costs can be significantly reduced over time due to green investments to scaled up production (IEA, 2021b). In addition, the mandate to reduce GHG emissions may induce, in the short- to mid-terms, a niche market for alternative fuels, as long as they have scale and applicability. Regarding local sustainability, a lower weight was chosen given that the IMO's have already set regulations on fuel's sulfur content (HONG LIANG, 2017; IMO, 2016b). In this sense, it is implicit that any alternative fuel used for maritime transportation must address local sustainability issues. Also, for the ratings of criteria 4 (energy density) and 5 (economic), for which there are very straightforward quantifications, a normalization of the indicators is required to keep the analysis consistent.

In the case of the energy density indicator, the normalization is based on the volumetric energy content of the fuels, as shown in Figure 4.

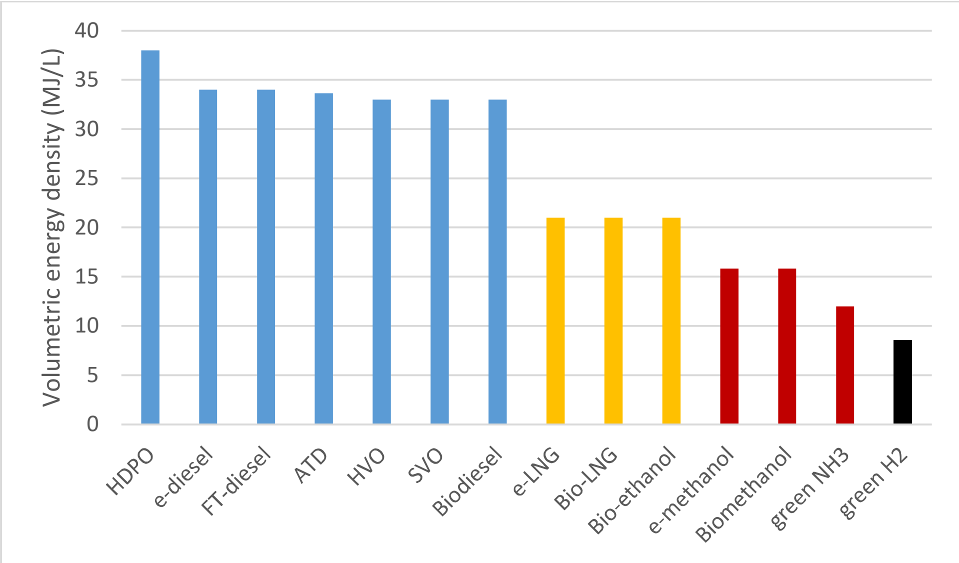


Figure 4: Volumetric energy density scale. Based on (DNV GL, 2016, 2019; ECOFYS, 2012a; GLOBAL COMBUSTION SYSTEMS, 2020; HORTA NOGUEIRA et al., 2008; JIMÉNEZ ESPADAFOR et al., 2009; KASS et al., 2018; STENGEL; VIUM, 2015)

For the economic indicator, the normalization is based on average costs of energy, using the bunker (HFO) price as a reference (Figure 5).

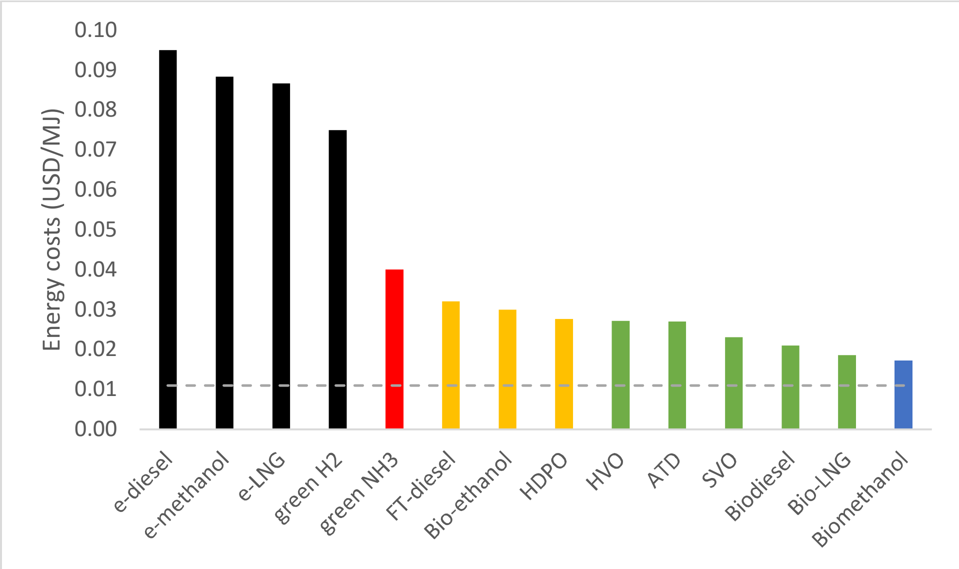


Figure 5: Cost normalization to compare the different fuel alternatives (dashed line represents HFO energy costs). Ratings based on the ratio fuel cost/bunker cost (5: until 200%, 4: 200-250%, 3: 250-300%, 2: 300-400%, 1: above 400%).
Elaborated with data from (ANP, 2019a; ASH; SCARBROUGH, 2019a; BRYNOLF et al., 2018; CARVALHO; PORTUGAL-PEREIRA; SZKLO, 2019; DAAG, 2013; GELEYNSE et al., 2018; GLOBAL PETROL PRICES, 2018; IEA, 2019a; INDEXMUNDI, 2018a; KASS et al., 2018; MANIATIS; WALDHEIM; KALLIGEROS, 2017; NESTE, 2019; SHIP&BUNKER, 2019; STAPLES et al., 2014; TAGOMORI; ROCHEDO; SZKLO, 2019).

2.5. Results

Table 3 presents the scores (in color and number scales) of the 14 fuels according to the Brazilian context. After evaluating the alternatives, the final score was determined according to the weights defined for the different criteria (Table 4).

The ranking was led by FT-diesel, followed by HVO and ATD. In general, liquid biofuels (group 1) occupied higher positions in the ranking, mostly due to their drop-in characteristics, that indicate low or, in some cases, negligible need for modifications in logistics, bunkering and ships engines for fuel use. In fourth and fifth places appear SVO and e-diesel, the best placed fuel from Group 3, given its drop-in characteristic and despite its high cost. Biodiesel and biomethanol are tied in the sixth position. Biomethanol is the best performed fuel from Group 2 and has some advantages associated with bunkering but is penalized by its low energy density. In an intermediate range figure HDPO, bio-LNG, bio-ethanol and electromethanol. Full evaluation of fuels and their scores are presented in the Appendix A. Below, some discussions on each fuel results are presented.

Table 3: Evaluation of fuels according to the defined criteria

	SVO	Biodiesel	HVO	HDPO	FT-diesel	ATD	Bio-LNG	Biomethanol	Bioethanol	Green H2	Green NH3	e-diesel	e-LNG	e-metanol	Weight
Availability	2	2	2	3	4	3	2	4	3	3	3	1	1	1	2
Applicability	4	3	5	5	5	5	3	4	2	1	2	5	3	4	2
Technology Readiness	5	5	5	2	3	4	5	4	3	3	2	3	2	2	2
Energy Density	5	5	5	5	5	4	3	2	3	1	2	5	3	2	2
Economic	4	4	4	3	3	4	4	5	3	1	2	1	1	1	1
Safety	5	5	5	3	5	4	3	3	4	2	2	5	3	3	2
Standards	3	3	4	4	4	4	4	5	5	1	1	4	4	5	1
Local Sustainability	4	4	4	4	5	4	5	4	4	3	3	3	3	3	1
Global Sustainability	3	3	3	4	5	4	3	4	2	5	5	5	4	5	3
TOTAL	62	60	65	59	71	64	54	60	48	40	43	61	44	48	

Table 4: Final score of fuels evaluation

Ranking	Score	Fuel
1	89	FT-diesel
2	81	HVO
3	80	ATD
4	78	SVO
5	76	e-diesel
6	75	Biodiesel
7	75	Biomethanol
8	74	HDPO
9	68	Bio-LNG
10	60	Bioethanol
11	60	e-methanol
12	55	e-LNG
13	54	Green NH_3
14	50	Green H_2

SVO

Besides being a drop-in alternative, SVO has the advantages of high technological maturity and good energy density to replace heavy fuel oil (HFO). Depending on operational conditions, SVO should be pre-heated prior to the injection in diesel engines (KHAN, 2018b; NGUYEN; TRAN; DANG, 2015). However, its current utilization in the food industry and for biodiesel production may affect its availability. Also, sustainability issues may hamper its utilization as a maritime fuel, especially if produced from oil crops such as soybeans and palm (SSI, 2019).

Biodiesel

Biodiesel's energy density and technological maturity comprise its largest advantages as a marine fuel. Also, its consolidated market and distribution chain enhance its economic feasibility, at least in the near-term. To produce a totally renewable biodiesel, renewable alcohols should be used in the transesterification process, which may increase fuel costs. Notwithstanding, the fuel's low stability and the possibility of water contamination hinder its utilization as a drop-in alternative (ECOFYS, 2012b; IEA BIOENERGY, 2017). Furthermore, biodiesel's current utilization in road transport and some of its sustainability issues reduce its attractiveness to the shipping sector (SSI, 2019). Sustainability concerns are related to oil crops production, as the fuel is produced from SVO, and to the use of fossil methanol in the current conversion process.

HVO

HVO represents a drop-in alternative to replace fossil maritime fuels. Its high energy density, its current production at commercial scales and the growth forecast for the upcoming years make it an interesting replacement of fossil fuels (GREENEA, 2017). However, sustainability issues regarding oil crop-based biofuels may compromise its availability. Further, the high quality of HVO may make it a more suitable alternative for use in the aviation sector (SSI, 2019).

HDPO

HDPO is also a drop-in alternative produced from lignocellulosic biomass, which is a largely available resource throughout the world and especially in Brazil. The high energy density of HDPO makes it a suitable option to replace fossil fuels in ocean-going vessels. Although the technology is not mature yet, new conversion facilities are under construction (ENVERGENTTECH, 2016; GOODFUELS, 2019; IEA BIOENERGY, 2017). Finally, concerns regarding its low flash point and high costs may become a barrier for its use as a maritime fuel.

FT-diesel

FT-diesel is another drop-in alternative that uses residual biomass as feedstock, which may be an advantage for Brazil. The fuel's high energy density and mitigation potential makes it an interesting choice to replace fossil fuels in long-distance shipping. Also, the high value co-products (road diesel, naphtha, jet fuel etc.) may enhance FT plants feasibility. However, up until now, the technology has been demonstrated at a pilot-scale but is not commercially available yet (GREENCAR, 2018; TIJMENSEN, 2002; TOTAL, 2016). Moreover, as a high-quality and costly alternative (around 0,03 USD/MJ), FT-diesel may be better suited for the aviation sector, whose fuel is highly priced.

ATD

ATD is also a drop-in alternative that uses bio-based alcohols to produce distillate fuels. The fuel has the advantages of high applicability, technological maturity, and energy density. As for FT-diesel, the high value co-products may encourage the development of alcohol-based biorefineries and, therefore, enhance fuel competitiveness. However, as biomass-based alcohols has been widely used in the road transportation sector, it may not be available to produce maritime biofuels, at least in the medium term. Notwithstanding, the use of residual biomass to produce second generation alcohols and the prospects of road transport electrification may significantly increase its availability in the mid- to long-terms.

Bio-LNG

Bio-LNG represents a biofuel alternative that is not suitable for diesel engines, that comprise the major part of the world shipping fleet. Some LNG-fueled vessels, equipped with dual-fuel engines, are already in operation (BALCOMBE et al., 2019; DNV GL, 2015). Bio-LNG's development is mostly limited by the availability of bunkering facilities around the World. Also, the technological processes to produce the fuel are fully developed. However, this fuel has lower volumetric energy density in comparison to distillate fuels (about 20 MJ/L), which means that it requires 80% more storage space in ships (DNV GL, 2019). Also, bunkering costs represent an economic challenge for its use as maritime fuel (IMO, 2016c). Nonetheless, the existence of standards for gaseous maritime fuels and the potential reduction in GHG and air pollutant emissions make bio-LNG a potentially attractive alternative.

Biomethanol (Bio-CH3OH)

Biomethanol is a liquid fuel under ambient temperature and pressure. It can be produced from several feedstocks and relies on a solid existing infrastructure, especially if produced from biomethane. It has also a good economic performance, with reasonable production costs in comparison to other low-carbon options, for the biodigestion route (BRYNOLF; FRIDELL; ANDERSSON, 2014). Despite not being a drop-in fuel, methanol has good applicability on the global fleet, since its use requires minor modifications on dual-fuel engines and bunkering infrastructure, with the possibility of flex-fuel operation. Moreover, biomethanol provides significant air pollution and GHG emissions cutbacks (BRYNOLF; FRIDELL; ANDERSSON, 2014; DNV GL, 2016). The main inconvenient related to the use of biomethanol as a maritime fuel is its low energy density, as it requires approximately twice as much space as distillate fuels. Also, in the case of the biodigestion route, bio-CH3OH depends on geographically dispersed feedstock.

Bioethanol (Bio-C2H5OH)

Ethanol is the most used biofuel in transport sector, with the US being the largest producer followed by Brazil. Given its high availability, bioethanol prices are low compared to other carbon-neutral fuels (ELLIS; TANNEBERGER, 2015). However, ethanol has not been used as a fuel in large maritime engines. In order to make it a drop-in alternative for diesel engines, it is necessary to increase its cetane number and lubricating power, which could substantially raise its production cost (MCCORMICK; PARISH, 2001). For the long term, ethanol fuel cells may become an option, though (BADWAL et al., 2015; DOGDIBEGOVIC; FUKUYAMA; TUCKER, 2020; GIDDEY et al., 2012; KAMARUDIN et al., 2013). Moreover, bioethanol has about half the energy density of diesel, which implies in additional fuel storage space. In terms of safety, it can be corrosive to some materials, but it easily dissolves in water and is biodegradable. At the same time, bioethanol can contribute to local and global impacts, considering its aldehydes and CO_2 emissions and, depending on engine characteristics, nitrogen oxides (NO_x) as well (ELLIS; TANNEBERGER, 2015).

Green Hydrogen

Hydrogen (H_2) use in fuel cells is the main alternative in ship propulsion, but the adaptation of internal combustion engines (ICEs) cannot be neglected. Its use as a fuel does not generate direct GHG emissions or air pollution. Nevertheless, green H_2 has relevant disadvantages to be used as a maritime fuel. In addition to being highly flammable, producing an invisible flame and having a very low volumetric energy density, the fuel also has high production, transport and bunkering costs (total costs ≈ 0.03 USD/MJ) (BALCOMBE et al., 2019; DNV GL, 2017, 2019). Technological readiness is also an issue, especially when produced from intermittent renewable energy sources. Moreover, the existing infrastructure is completely based on non-renewable energy and the production via electrolysis puts extra pressure on water resources, indicating its current lack of feedstock and infrastructure for its production and use (IEA, 2019a). On the other hand, remaining global solar and wind energy potentials are vast, which would be a plus for green hydrogen production and use in the future (IEA, 2019b).

Green Ammonia

Green ammonia is potentially a carbon-neutral fuel (reduction of at least 95% in life cycle GHG emissions) that also leads to significant reductions in air pollutants (except for NO_x). It could be used as a maritime fuel in internal combustion engines or in fuel cells (either directly or as an energy carrier for H_2) and both pathways face technological and technical challenges. The use of pure NH_3 in ICEs, for instance, is hindered by its combustion properties (such as narrow flammability range and low flame speed). Alternatively, it could be used as a support fuel, such as green H_2, biomethanol or biogas (DE VRIES, 2019). In the case of fuel cells, an onboard plant would be required to crack the NH_3 molecules and produce H_2. To this end, high-temperature fuel cells, which are not fully developed, would be required. Thus, NH_3 is not a fully mature technology yet (especially in terms of its use as a fuel) and has low applicability to the existing fleet. Energy density is also a problem given that NH_3 requires a volume three times higher than conventional bunker fuel (ASH; SCARBROUGH, 2019b; DNV GL, 2019). Due to the high cost of electrolysis, green ammonia's economic performance is also weak (≈ 0.04 USD/MJ), with levelized energy costs around two times those of distilled biofuels. Finally, although NH_3 is safe from a flammability perspective, it is corrosive and highly toxic, harnessing its operational safety (ASH; SCARBROUGH, 2019a; DE VRIES, 2019). This is particularly important for releases into the sea (spills), as shown by (RAJ; REID, 1978). A possible pathway for NH_3 as a fuel in long-distance travel ships could be, firstly, based on the least-cost fossil derived-NH_3. This would allow converting harbors and fleet. Then, a green NH_3 industry could be deployed in large scale. However, as of today, Brazil is already highly dependent on ammonia/urea imports as fertilizer, and the country´s existing ammonia plants have been recently closed (DOS SANTOS; SZKLO, 2016).

Electrodiesel (e-diesel)

Electrodiesel is the same fuel as FT-diesel in terms of chemical composition. Thus, it has very good energy density, applicability, and safety ratings. Also, from a global sustainability perspective, the e-diesel is a promising fuel, presenting very low or nearly zero life cycle GHG emissions. Its main drawback is the economic aspect, with production costs around 0.1 USD/MJ (BRYNOLF et al., 2018). The production of H_2 from intermittent energy sources implies high costs and several technical challenges. Besides, there is another relevant issue regarding feedstock availability, given the fact that CO_2 must come from CCS[12] or DAC[13], which are currently not available in large scales (KÖBERLE, 2019).

Electromethane (e-LNG)

Electromethane is chemically identical to biomethane. Therefore, many of the bio-LNG ratings also apply to e-LNG. Furthermore, similarly to e-diesel, e-LNG has a weak performance in terms of costs (≈ 0,1 USD/MJ) and feedstock availability (again, CO2 from CCS or DAC) (BRYNOLF et al., 2018).

Electromethanol (e-CH3OH)

Electromethanol shares many of the biomethanol ratings because they are equivalent fuels in terms of molecular composition. Similarly to the other e-fuels, e-methanol faces challenges regarding feedstock availability (once again, CO_2 from CCS

[12] Carbon Capture and Storage (CCS) is the process of capture, transport, and storage of waste CO_2 from different sources (industries, refining, and biomass conversion plants, for example).

[13] Direct Air Capture (DAC) represents the capture of CO2 directly from the atmosphere to produce a concentrated stream of CO_2.

or DAC) and technology readiness level. However, its production costs tend to be slightly lower than those of e-diesel and e-LNG, which could be an advantage (BRYNOLF et al., 2018).

2.6. Discussion

FT synthetic diesel occupies the first position in the ranking followed by HVO and ATD. The potential for reducing GHG emissions of FT-diesel favors its evaluation and the drop-in characteristics of FT-diesel, HVO and ATD that indicate low or negligible/zero need for engines, bunkering and logistics modifications contribute to their high scores. SVO, e-diesel and biodiesel figure in fourth, fifth and sixth positions. Even though SVO has the advantages of high availability, technology maturity and almost drop-in characteristics, sustainability concerns threat its utilization as marine fuel. The same applies to biodiesel, whose utilization in marine diesel engines is limited by up to 7% mass basis (DAN BUNKERING, 2017; SHIP & BUNKER, 2017a). E-diesel has the best score among the e-fuels given its drop-in characteristic, despite its high cost and availability challenges.

In an intermediate range figures biomethanol, HDPO, bio-LNG and bioethanol. Biomethanol has advantages in terms of bunkering but is penalized by its low energy density. In case of HDPO, the fuel has the advantage of being a drop-in alternative that uses residual biomass as feedstock, while the technological maturity represents its major drawback. For bio-LNG, the lack of infrastructure, safety concerns and methane fugitive emissions, hamper its utilization as marine fuel. Regarding bioethanol, even though the fuel is largely produced in Brazil, issues regarding its applicability and energy density undermine its use as marine fuel in the short term.

Electromethanol, electromethane, green ammonia and green hydrogen occupy the worst positions in the ranking. Electromethanol has similar evaluation to biomethanol, with the additional challenges regarding, feedstock availability, technology readiness and high costs. Electromethane's high costs and low technology readiness and availability penalize its evaluation in addition to biomethanol's. Finally, even though green ammonia and green hydrogen have high potential to reduce GHG emissions, their low energy density, high cots, safety, and applicability issues hamper their utilization in the short term. In the case of ammonia, it is worth mentioning that, even though some studies enhance its use as an alternative fuel, they highlight its applicability only for short-distance transportation (ASH; SCARBROUGH, 2019a).

Besides the evaluation of the fuels in each criterion, the choice of criteria weights may impact the results. Hence, a sensitivity analysis was conducted to evaluate differences in the ranking according to different criteria weights. First, it was considered weight 1 for all criteria (case S1). Then, weight 2 was attributed to economic criterion (case S2) and the same weight as in the baseline case (Table 2) for the others. **Erro! Autoreferência de indicador não válida.** summarizes the attributed weights in sensitivity analysis cases in comparison with the baseline.

Table 5: Sensitivity analysis cases

Sensitivity analysis - Criteria weights	**Baseline**	**S1**	**S2**
Availability	2	1	2
Applicability	2	1	2
Technology Readiness	2	1	2
Energy Density	2	1	2
Economic	1	1	2
Safety	2	1	2
Standards	1	1	1
Local Sustainability	1	1	1
Global Sustainability	3	1	3

Erro! Autoreferência de indicador não válida. compares the final ranking for each sensitivity case with the baseline (as shown in Table 4). These results show that modifications in criteria weights have minor impact the ranking, as most of the fuels remains in nearly position. FT-diesel, HVO, ATD and SVO registered the same performance in all cases, occupying the fourth first positions.

E-diesel was the only fuel whose performance varies considerably in each of the sensitivity cases. In the baseline scenario, e-diesel occupies the fifth position while in cases S1 and S2, it occupies the ninth and eighth positions, respectively. Such difference is justified by e-diesel's high potential to reduce GHG emissions, which favors its evaluation in the baseline scenario and its high costs, which undermines its performance in case S2.

Biomethanol, biodiesel, HDPO, Bio-LNG remain in intermediary positions, while ethanol occupies the same position in all cases. E-methanol, e-LNG, green NH3 and green H2 registered the lowest scores in all cases, mostly due to their high costs, low technological maturity, availability, and energy density.

Table 6: Fuel ranking in the sensitivity analysis cases

Results					
Baseline		**S1**		**S2**	
FT-diesel	89	FT-diesel	87	FT-diesel	87
HVO	81	HVO	82	HVO	81
ATD	80	ATD	80	ATD	80
SVO	78	SVO	78	SVO	78
e-diesel	76	Biomethanol	78	Biomethanol	76
Biodiesel	75	Biodiesel	76	Biodiesel	75
Biomethanol	75	HDPO	73	HDPO	73
HDPO	74	Bio-LNG	71	e-diesel	73
Bio-LNG	68	e-diesel	71	Bio-LNG	68
Bioethanol	60	Bioethanol	64	Bioethanol	60
e-methanol	60	e-methanol	58	e-methanol	58
e-LNG	55	e-LNG	53	Green NH_3	53
Green NH_3	54	Green NH_3	49	e-LNG	53
Green H_2	50	Green H_2	44	Green H_2	48

Overall, results obtained are helpful to identify the most promising fuel alternatives to decarbonize Brazilian maritime transport sector. These results are relevant in a global context, given that Brazil is a major commodity exporter whose localization is geographically unfavored and far away from its main commercial partners (MÜLLER-CASSERES et al., 2021; SCHAEFFER et al., 2018; SCHIM et al., 2018). Thus, the utilization of low carbon fuels in Brazilian maritime transportation would have a direct impact in global emissions. Further, Brazil could act as a major player and supplier of alternative marine fuels, given the advantages identified in this study. In this sense, instruments such fuel mandates would promote investments in research and development of promising technologies (such as FT-diesel, HVO and ATD) in the country.

However, the use of alternative fuels might be constrained by the lack of supply and/or restrictions in trade partner regions. For this reason, international standards should be applied to alternative fuels in maritime sector, similarly to what has been done in the aviation sector, in which fuels goes through an extensive procedure of tests and norms (ASTM INTERNATIONAL, 2017; CAAFI, 2021; IATA, 2019). Also, in the case of biofuels, certification procedures are needed to ensure their sustainability and exclude pathways that may contribute to deforestation, increased energy consumption, water demand, among others.

2.7. Final Remarks

The evaluation and comparison of 14 fuel alternatives carried out in this study aimed to identify the main advantages, disadvantages, and application possibilities of these alternatives in the Brazilian long-distance maritime transport sector. Distilled biofuels are the most promising alternative, at least in the short-term, given their high energy density and their compatibility with the existing infrastructure. This is particularly relevant in the case of Brazil, whose international trade profile is characterized by long-distance transportation of low added value products. However, the availability of sustainable biomass and competition with other sectors may hinder its application in the production of biofuels for the maritime transport sector.

In this sense, the use of biomass residues that are currently not used reduces the concerns associated with sustainability and allows the production of bioenergy on a large scale. Also, some technological pathways co-produce high value products, such as biojet fuel and naphtha, that may stimulate the construction of novel biorefineries in which bio-based bunker fuels are considered as residual products and, therefore, have lower production costs.

However, logistical issues associated with the dispersed location of residues resources and large-scale production plants can increase the costs and emissions of biofuels. Bio-LNG represents a mid- and long-term alternative once constraints related to lack of supply infrastructure and its low energy density are solved.

Biomethanol is also shown to be a favorable alternative due to its technological maturity and a consolidated transport and distribution infrastructure. It has good applicability in the current fleet of ships, but has low energy density, which makes it demand twice as much space on the vessels when compared to distillate fuels. The use of bioethanol as a marine fuel is particularly interesting for Brazil, one of its main world producers. However, its low energy density, the need for additives, the risk of corrosion and its current use in road transport reduce its competitiveness for navigation.

Green hydrogen seems to be a distant alternative for the Brazilian case, mainly due to its low performance in terms of costs, energy density and applicability. Green ammonia, which has slightly better ratings in these criteria, may be an option for a hydrogen carrier or an alternative for Brazilian cabotage transport. On the other hand, e-fuels are an interesting option from both a technical and a sustainability perspective, but still face significant challenges in terms of cost and technological maturity in the medium term.

Finally, despite the efforts to conduct a preliminary assessment for Brazilian potential to produce carbon-neutral fuels for maritime transportation, some limitations should be addressed in future studies to investigate in further details the implications of fuel replacements to comply with IMO goals 2050. For instance:

i. Site-specific life cycle assessments, georeferenced and economic analysis would determine the mitigation potential, logistic and economic challenges regarding novel fuels production and utilization in Brazil and may alter fuels evaluation in global sustainability, availability, and economic criteria.
ii. The inclusion and/or choice of new criteria may provide alternative ranking results.
iii. Also, the inclusion of fuel technology pathways, as well as a better representation of shipping engines and types, in integrated assessment models (IAMs) can provide a better understanding of the impacts on energy and land-use of replacing conventional maritime fuels by carbon-neutral alternatives, and test the criteria associated with the food-energy-water nexus. (MÜLLER-CASSERES et al., 2021).
iv. Some alternative fuels that have low temperature storage (BOULOUGOURIS; CHRYSINAS, 2015; MOKHATAB et al., 2013) (such as hydrogen and bio-LNG) and some biofuels (due to its oxidation and corrosivity properties) (LIN, 2013a; MATHEW; THANGARAJA, 2018) require special materials for storage tanks, piping systems, pumps, engines and others. Fuel compatibility aspects include all ships systems that het in contact with fuel (e.g., engines, pumps, storage tanks, pumps, etc.), auxiliary bunkering ships and fuel storage terminals and define their technical feasibility (KESIEME et al., 2019). Thus, a detailed evaluation of fuel compatibility can provide a better understanding of its applicability.
v. Fuel blends with diesel have already been tested in marine engines (biodiesel (LIN, 2013b; OGUNKUNLE; AHMED, 2020), ethanol (GALINDO; BARBOSA CORTEZ; TEIXEIRA FRANCO, 2020), methanol (PAULAUSKIENE; BUCAS; LAUKINAITE, 2019), ammonia (DINCER; SIDDIQUI, 2020) (KOBAYASHI et al., 2019), SVO (BLIN et al., 2013; LABECKI et al., 2012; TRAN; DANG; NGUYEN, 2019) and HDPO (CHONG; BRIDGWATER, 2014b). Therefore, studies that focus on testing different levels of promising maritime fuel blends and/or determining the

maximum feasible blends are necessary to evaluate their applicability and mitigation potential.

vi. An assessment of some options that can co-produce jet- and diesel-range fuels, for example, is key. In such cases, coupled strategies for 'hard to decarbonize' sectors (shipping and aviation) may reduce costs and speed up the development of alternative fuel pathways.

3. Biofuels for maritime transportation: a spatial, techno-economic, and logistic analysis in Brazil, Europe, South Africa and the USA

Francielle Carvalho, Joana Portugal-Pereira, Martin Junginger and Alexandre Szklo
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3.1.Abstract

Low or zero carbon fuels are crucial for maritime transportation decarbonization goals. This paper assesses potential localities for maritime biofuels (biobunkers) production in Brazil, Europe, South Africa, and United States considering geographical, logistic, and economic aspects. This assessment combines georeferenced and techno-economic analyses to identify suitable fuel production hotspots based on not only plant performance and costs, but also on logistic integration and biomass seasonality. Five technology pathways were considered: Straight vegetable Oils (SVO), Hydrotreated Vegetable Oils (HVO), Fischer-Tropsch Biomass-to-liquids (FT-BTL), Alcohol oligomerization to middle distillates (ATD) and Hydrotreated Pyrolysis Oil (HDPO). Findings reveal that biomass concentration in Brazil makes it the region with highest biobunker potential that are mostly close to coastal areas and surpasses regional demand. Although other regions registered more limited potentials, hotspots proximity to ports would enable fossil fuel replacements in these areas. For all cases, biobunker costs (US$ 21-104/GJ) are higher than conventional marine fuels prices (US$11-17/GJ). For only 15% of the hotspots carbon prices that would allow its competitiveness are lower than US$ 100/tCO2. Alternatives to incentivize biobunker production would be, first, to stablish mandatory fuel blends and second, to join forces with other sectors that would be benefited from the co-production of advanced biofuels.

3.2. Introduction

The ocean-going ships consume a large amount of petroleum derived fuels, and the maritime sector is responsible for over 3% of anthropogenic GHG emissions (FABER et al., 2020). In 2018, the International Maritime Organization (IMO) pledged to reduce by at least 50% of annual GHG emissions from international shipping by 2050 compared to 2008 levels. Together with optimized operations and energy efficiency, alternative low or zero carbon fuels are crucial for maritime transportation (ECOFYS, 2012a; IEA, 2018a; PRUSSI et al., 2021).

Biofuels represent an important option to simultaneously reduce fossil fuel dependence and GHG and air pollutants emissions. The less strict specifications and higher flexibility in terms of fuel supply (than road and aviation sector, for example), represent an opportunity to produce maritime biofuels (hereafter biobunker) (IEA BIOENERGY, 2017). Also, in view of the sector's well established operational structure and long lifespan of ships, drop-in fuels are the most feasible alternatives, at least in the mid-term (EC, 2019; IEA BIOENERGY, 2017; PRUSSI et al., 2021).

Different biobunkers can be considered to the maritime transport sector. For diesel engines, biodiesel, straight vegetable oils (SVO), hydrotreated vegetable oils (HVO), dimethyl-ether (DME) and FT-diesel (or BTL) are considered the front runner options (ETIP, 2017). For Otto or dual fuel engines, the options are liquefied biomethane (Bio-LNG), liquefied biogas (LBG) and biomethanol (ANDERSSON et al., 2020; ETIP, 2017; MÜLLER-CASSERES et al., 2021).

Besides their benefits, major concerns regarding biofuels are associated with costs, supply guarantee and sustainability (LLOYD’S REGISTER; UMAS, 2020). The performance of most biofuels in ship engines is not well understood yet and thus, a significant amount of testing and standardization is needed to develop drop-in biofuels appropriately (IEA BIOENERGY, 2017). Additionally, competition for resources with food production and with other sectors (e.g., aviation), in-creased water demand and land use changes may compromise their development (SSI, 2019).

Some regions may emerge as potential biobunkers producers given their availability of resources, intense port activities and/or location along major sea routes. Brazil and the United States (US) are among the world's major agricultural producers and, therefore, have significant biomass residues potential. Together with the European Union (EU) these countries are the major biofuels producers and consumers in the world (OECD-FAO, 2020). The EU and US host the major world ports outside Asia and are one of the biggest trade centers in the world. South Africa has limited bioenergy production given its low primary productivity, constrained by rainfall, and intensified by inter-annual variability (HUGO, 2016; SCHULZE et al., 2008). Notwithstanding, South Africa’s strategic lo-cation along sea routes that connect Asia to Occident may encourage local biobunker production (NOTTEBOOM; PALLIS; RODRIGUE, 2019). Thus, the identification of biobunker potential in such regions is useful to prospect major players and design tailored solutions for shipping decarbonization.

Studies already performed in the literature discuss about alternative biofuels to reduce the maritime transport sector emissions. (AL-ENAZI et al., 2021; ECOFYS, 2012b) performed a technical over-view of different alternatives. (BOUMAN et al., 2017; BRYNOLF; FRIDELL; ANDERSSON, 2014; GILBERT, 2014; GILBERT et al., 2014, 2018) focused on emissions mitigation potential and (DNV GL, 2019; KESIEME et al., 2019; PRUSSI et al., 2021; ZHOU et al., 2020) explored the potential and barriers of maritime biofuels. (TANZER et al., 2019) developed an integrated screening model to compare the technological, economic, and environmental performance of drop-in marine biofuel supply chains. (LLOYD'S REGISTER; UMAS, 2020) performed a tech-no-economic analysis of zero-carbon fuels while (ANDERSSON et al., 2020) developed a decision support analysis to choose sustainable marine fuels. Finally, (MÜLLER-CASSERES et al., 2021) provided an Integrated Assessment Model perspective of the production and distribution of alternative marine fuels in Brazilian ports.

While relevant, previous studies have focused on identifying the potentials, benefits, and constraints for alternative marine fuels, overlooking important logistic con-strains for their development. To develop novel fuels, it is necessary to assess the logistic integration of their production chains, which links feedstock availability and seasonal variability with fuel consumption sites. To fill this gap, this study performs a georeferenced analysis to identify potential localities for biobunker fuels production, logistic supply and costs in Brazil, Europe, South Africa, and United States. Five technology pathways were considered: Straight vegetable Oils (SVO), Hydrotreated Vege-table Oils (HVO), Fischer-Tropsch Biomass-to-liquids (FT-BTL), Alcohol oligomerization to middle distillates (ATD) and Hydrotreated Pyrolysis Oil (HDPO). This study is the first attempt to compare marine biofuel production in different regions of the world regarding their potential, techno-economic and logistic performance. Results obtained are relevant to identify the regional capabilities that could make some regions potential biobunker fuel suppliers.

This paper is structured as follows: section 2 presents the methodology of the study that details biomass potential, the georeferenced analysis and feedstock and fuel production costs estimates. Then, section 3 details the results of each analysis and Sec-tion 4 discusses the main findings. Finally, Section 5 summarizes this paper conclusions, limitations, and suggestions for future work.

3.3. Methodology

The methodology applied was divided into two steps (Figure 6). The first one aims to identify bioenergy hotspots for the implementation of biobunker refineries by the quantification of bioenergy technical potential and a georeferenced analysis. The georeferenced analysis enables the spatial identification of biomass hotspots and is useful to evaluate their proximity to ports, fuel handling infrastructure, and transportation networks in these areas. The second step aims to determine the total biobunker fuel costs, composed by feedstock costs, levelized cost of fuel (LCOF), and fuel transport cost. Together, these assessments aim to identify the regional capabilities, economic implications, and barriers to produce biobunker fuels in each region.

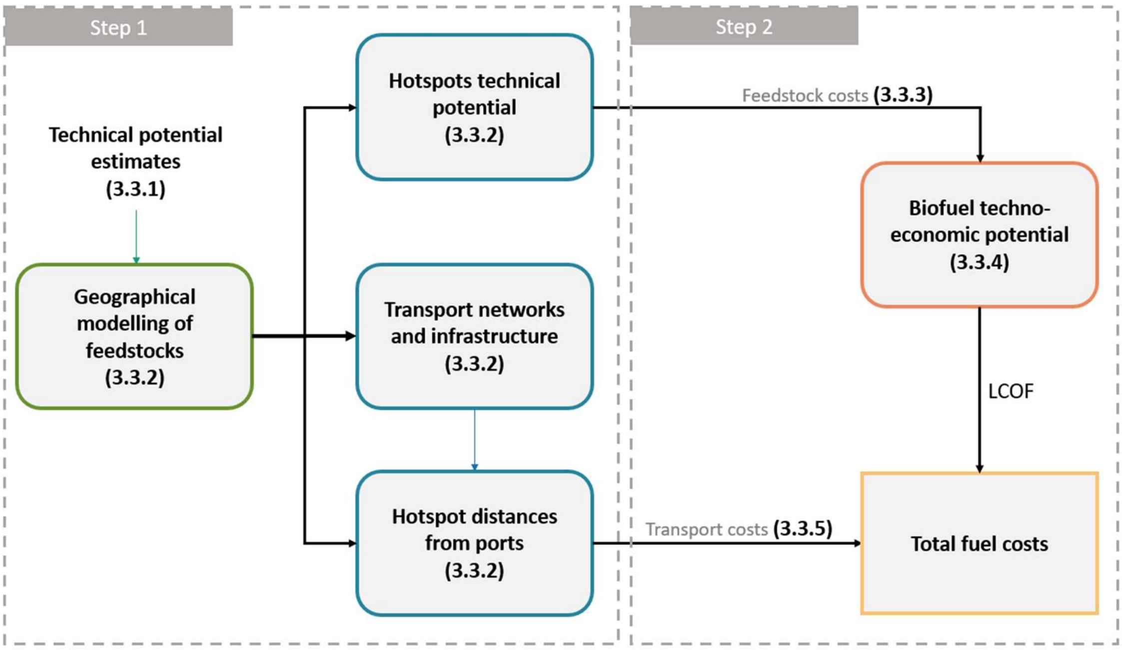


Figure 6: Methodological framework of this study. Numbers in the figure refer to the text sections below for a more elaborate description.

3.3.1. Feedstock availability

3.3.1.1. Brazil

The first step of this study evaluates the technical potential of residual biomass and straight vegetable oils (SVO). The technical potential represents the fraction of theoretical potential available given technological possibilities, logistical restrictions, and competition for non-energy uses. The methodology adopted was based on the indirect quantification of the residues and SVO through a bottom-up analysis (equations 2 and 3) and followed the methodology described in (CARVALHO et al., 2019; PORTUGAL-PEREIRA et al., 2015). Data for agricultural area, crop productivity and production were obtained for each Brazilian municipality (IBGE, 2018a, 2018b). Table 7 summarizes the crops and parameters considered to estimate residues and SVO production potential.

$$RP_j = \sum A_i . P_i . RPR_{j,i} . ESR_j . AR_j \quad (2)$$

In which:

RPj: Residues technical potential (TJ/yr)

Ai: Agricultural area (ha)

Pi: Crop productivity (kg/ha)

RPRj,i : Residue-to-product ratio of residue j produced by crop i (Dimensionless. Mass basis.)

ESRj: Environmentally sustainable removal rate of residue j (%)

ARj: Availability rate of residue j (%)

$$OP_j = \sum P_i . OSR_{j,i} . EE_j . LHV_j . AO_j \quad (3)$$

In which:

OPj: Vegetable oil potential (TJ/yr)

Pi: Oil crop i production (t/yr)

OSRj,i: Oil j content in oil crop i (-)

EEj: Oil j extraction efficiency (%)

LHVj: Low heating value of oil j (MJ/kg)

AOj: Oil j availability factor (%)

Table 7: Parameters considered for potential estimates in Brazil

Crop	Agricultural and forest residues[a]	RPR[b]	ESR[c]	AR[d]	LHV (MJ/kg)[e]	Reference
Sugarcane	Straw	0.22	34%	65%	18.6	(PORTUGAL-PEREIRA et al., 2015)
Soybean	Straw	2.01	30%	100%	20.1	
Corn	Stover	1.53	25%	100%	18.7	
Wheat	Straw	1.55	15%	100%	19.5	
Eucalyptus	Forestry residues	0.10	50%	100%	25.2	(CANTO, 2009; IPEA, 2012)
	Wood cuts	0.45	100%	100%	20.3	

Pinus	Forestry residues	0.10	50%	100%	25.2		
	Wood cuts	0.45	100%	100%	21.8		
Forest extraction	Forestry residues	0.60	50%	100%	25.2		
	Wood cuts	0.18	100%	100%	19.4		
Crop	**Straight Vegetable Oils**	**OSR[a]**		**EE[b] (%)**	**LHV (MJ/kg)**	**AO[c] (%)**	
Cotton	Cotton oil	22%		95%	39.5	15%	(BIODIESELBR, 2011; EMBRAPA, 2018; JIMÉNEZ ESPADAFOR et al., 2009; OECD, 2019)
Peanut	Peanut oil	43%		95%	39.8	15%	
Sunflower	Sunflower oil	43%		95%	39.6	15%	
Mamon	Mamon oil	46%		95%	39.5	15%	
Soybean	Soybean oil	18%		95%	39.6	15%	
Corn	Corn oil	4%		95%	39.5	15%	

Notes for agricultural residues: a: Wood cuts represent primary forest residues, i.e., obtained until the basic product production (charcoal, wood chips and sawdust), including cutting and peeling activities. Forestry residues are timber and other forest products that remain with no defined use due to technological or market limitations (IPEA, 2012); b: For agricultural residues an average factor was considered based on (PORTUGAL-PEREIRA et al., 2015). For forest residues, data from (DIAS et al., 2012; IPEA, 2012) were considered; c: Based in (DIAS et al., 2012; IPEA, 2012; PORTUGAL-PEREIRA et al., 2015); d: Regarding sugarcane, a coefficient that express residues availability for energy purposes was adopted. In this study, it was assumed that 65% of sugarcane straw is available for energy production, taking into consideration the rate of agricultural fields that use mechanical harvesting without open-air burning (DIAS et al., 2012; MACEDO; SEABRA; SILVA, 2008; PORTUGAL-PEREIRA et al., 2015; SANTOS, 2013); e: Dry basis.

Notes for straight vegetable oils: a: Obtained from average values from Brazilian institutions (BIODIESELBR, 2011; EMBRAPA, 2018); b: The same efficiency in oil extraction was considered for all crops; c: Oil availability factors were based on OECD/FAO projections for vegetable oils utilization in food industry (49%) and biofuels production (36%) in the period from 2021 to 2018. Thus, vegetable oil availability to produce maritime biofuels discounts its utilization in its current markets. Same availability factor was considered for all oils, although not all are used to biofuels production.

3.3.1.2. Europe[14]

Biomass residues potentials estimate was based in the S2Biom project (DEES et al., 2017). Biomass residues potentials were calculated for each region according to NUTS-3 classification. The nomenclature of territorial units for statistics (NUTS) is a geographical system that divides European Union into hierarchical levels: NUTS-1, NUTS-2 and NUTS-3. In S2Biom project, 3 classes of potential for biomass were considered (Consult Suppple-mentary Material). For the agricultural residues, the 'User potential' was selected, while for forest residues, only the primary residues from forestry activities were considered and 'User defined potential 5' chosen. Table 8 presents the parameters considered for biomass residues potential estimate in Europe.

[14] Europe region in this study includes EU28, Western Balkans, Moldova, Turkey and Ukraine.

Table 8: Parameters considered for agricultural and forest residues potential estimates in Europe.

Biomass residues potential from S2Biom		Moisture Content[b] (%)	LHV[c] (MJ/kg)
Agricultural residues	Cereal Straw	15	17.0
	Maize Stover	15	16.0
	Sunflower straw	20	16.7
Forest residues	Logging residues from final fellings from conifers (LR_FF_C)	53.6	19.2
	Logging residues from final fellings from non-conifers trees (LR_FF_NC)	53.6	19.2
	Logging residues from thinning from conifers trees (LR_TH_C)	53.6	18.7
	Logging residues from thinning from non-conifers trees (LR_TH_NC)	53.6	18.7
	Stem wood from final felling from conifers and trees (ST_FF_C)[a]	53.9	19.3
	Stem wood from final felling from non-conifers trees (ST_FF_NC)[a]	53.6	19.3
	Stem wood from thinning from conifers trees (ST_TH_C)[a]	53.6	19.2
	Stem wood from thinning from non-conifers trees (ST_TH_NC)[a]	53.6	19.2

Notes: a: Final fellings and thinnings from coniferous/non-coniferous plantations and semi-natural forests are the small trees from management operations or left over after a final harvest for which there may be no demand (or no suitability) for use as pulp wood. For this reason, stemwood was considered in this study for Europe; b: As received (S2BIOM, 2017a); c: Dry basis (S2BIOM, 2017a).

3.3.1.3. South Africa

Estimates for biomass residues potential in South Africa was based on the South Africa Bioenergy Atlas that brings together information about the factors of biomass production, potentials and yields for a variety of biomass resources for each country province (HUGO, 2016). The Bioenergy Atlas provides information of a variety of biomass residues production. However, a substantial part of agricultural production results from subsistence farming with typically very low yields (<2 tonnes/ha) and residues from some agricultural and forestry activities are already used for low-efficiency energy generation. Then, feedstocks produced by low yield crops or already used in other applications were not considered. Table 9 summarizes the assumptions made for biomass potential estimates in South Africa.

Table 9: Parameters considered for agricultural residues potential estimates in South Africa.

Crop[a]	Residue	RPR[b]	ESR (%)[c]	AR (%)[d]	Moisture content[e] (%)	LHV[f] (MJ/kg)

Sugarcane	Bagasse	0.9	100%	-	50%	10.0
	Field residues (Straw)	0.9	50%	100%	42%	7.1
Maize	Stover	2.6	50%	35%	42%	11.5
Wheat	Straw	1.3	50%	35%	42%	11.5

Notes: a: Crop and residue production data were included in BioAtlas files (SAEON, 2020); b: Residue-to-product ratio determined by the ratio between lignocellulosic residue yield and primary crop yield obtained in the Atlas metadata files (HUGO, 2015; HUGO; SAEON, 2015); c: 50% of residues should remain on field for soil conditioning (HUGO, 2015); d: Sugarcane bagasse availability data provided already discounted its use for internal energy demand. Sugarcane field residues are currently not available given the burning practice in sugarcane harvesting. However, this study considered that this practice will be extinguished in the near term in view of its environmental and health impacts. For wheat and maize residues, it was assumed that 35% are used for animal feed and bedding (HUGO, 2015, 2016); e: Moisture content of sugarcane bagasse was informed in the metadata available at SAEON Bioenergy Atlas website (SAEON, 2020). For other crops, moisture content values were obtained in (HUGO, 2017); f: Dry mass basis refer to air-dried biomass. In South Africa, average temperatures are high, and humidity is low. Thence, and air-dried lignocellulosic residues register a moisture content between 10% and 20%. Energy density is based on the generic values for agricultural residues (HUGO, 2016). For sugarcane bagasse, LHV was determined using the moisture and ash content and brix percentages (SUGARTECH SA, 2020).

3.3.1.4. United States (US)

Biomass residues estimates for the United States were obtained in the U.S. BioAtlas (U.S. DEPARTMENT OF ENERGY; NREL, 2016), which is based in the methodology of (MILBRANDT, 2005). Potentials were determined for agricultural and forest residues for each US county. Crop residues availability were estimated using crop production, residue to product ratio, moisture content, amount of residue left on the field for soil protection and used for grazing, bedding, and other agricultural activities (Table 10).

Table 10: Parameters considered for corn and wheat residues potential estimates in the US.

Crop[a]	Residue	RPR[a] (%)	ESR[b] (%)	AF[c] (%)	OU[d] (%)	Moisture content[e] (%)	LHV[f] (MJ/kg)
Corn	Stover	1.0	70%	20%-25%	10%-15%	15.5	17.3
Wheat	Straw	1.3				13.5	17.8

Notes: a: Crop production obtained in the U.S. National Census of Agriculture (USDA, 2017); b: (MILBRANDT, 2005; PERLACK; STOKES, 2011); c: 30% residue cover is reasonable for soil protection (MILBRANDT, 2005); d: Other uses (OU) are mainly associated to animal feeding. According to (MILBRANDT, 2005) animals rarely consume more than 20%-25% of the stover in grazing; e: About 10% to 15% of the crop residue is used for other purposes, such as bedding, silage, etc. (MILBRANDT, 2005); f: (ECN, 2020).

Forest residue data by county was derived from the USDA Forest Service's Timber Product Output database (U.S. FOREST INVENTORY ANALYSIS, 2015). In this category logging residues and other removals were included. Logging residues represent the unused portions of trees cuts or killed by logging and left in the woods. Other removals include trees cuts or otherwise obtained by cultural operations or land clearings and forest uses not directly linked with round wood product harvests (MILBRANDT, 2005).

3.3.2. Georeferenced analysis

The quantified biomass technical potential was allocated to the maps of each region. Thus, it was possible to identify, for each regional division (municipalities, counties, or provinces), the yearly biomass technical potential in energy basis. From these vector datasets containing the biomass potential, kernel density maps (or heat maps) were constructed considering a 100 km distance spread. This value represents an optimistic estimate for the transport of biomass, representing twice the distance recommended by Hoffmann et al. as an economically viable distance to transport biomass for energy purposes (CARVALHO et al., 2019; VAN DYK et al., 2019b). These maps show the bioenergy distribution beyond the geographical divisions and enables the identification of hotspots (locations with the greatest potential) for each feedstock.

Hotspots' identification followed a first- and second-best approach according to areas with the highest biomass potential or areas with considerable potential near coastline or ports. Crops with very low potential were discarded. The potential in each hotspot was defined by the sum of potential of the regional divisions contained within a 100 km radius (Figure 7). The distances between each regional division inside the 100 km area and the hotspot were also determined.

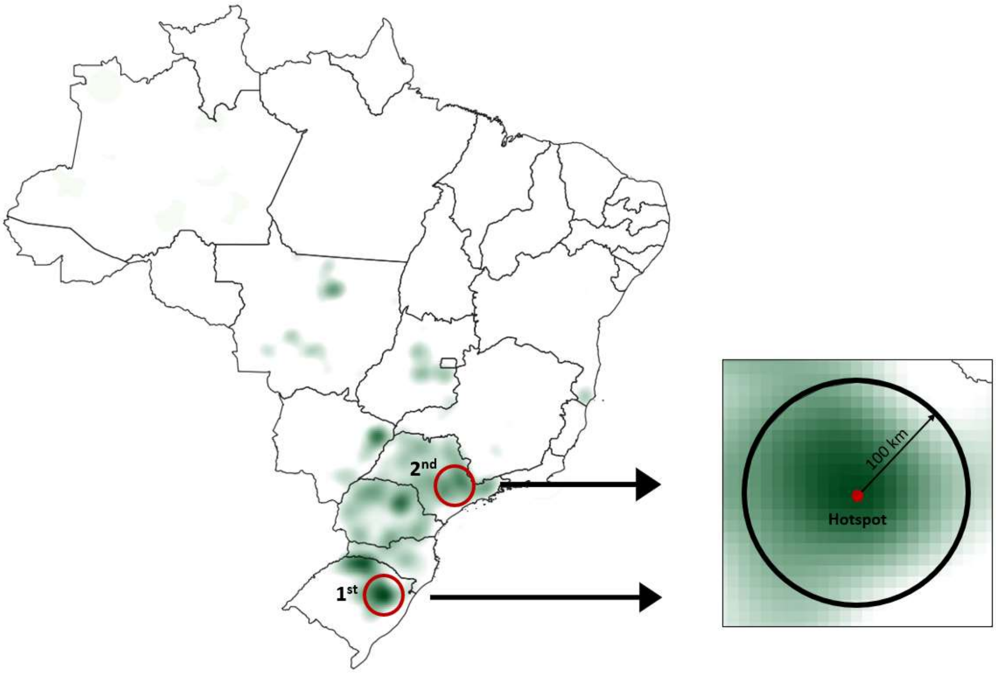


Figure 7: Hotspot's potential identification (Brazilian map used as an example).

Finally, infrastructure for feedstock and fuel logistics, such as oil and vegetable oil refineries, and ports were also identified (Figure 8). Distances among the hotspots and the nearest ports were determined. Maps with biomass potential and hotspots for all regions are detailed in the Appendix B.

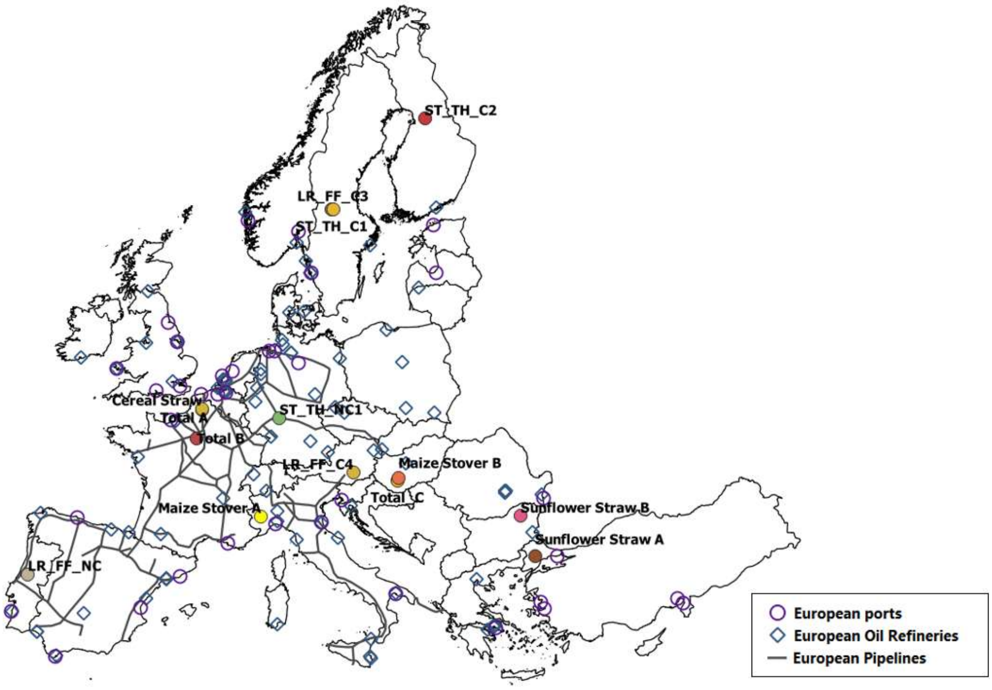


Figure 8: Hotspots and infrastructure localities for fuel production. (European map used as an example)

3.3.3. Feedstock cost estimation

Feedstock costs is composed by biomass collection costs and transportation costs (equation 4). For the SVO, feedstock cost is composed by current SVO prices plus its transportation costs from the nearest SVO refinery to hotspots. Road transport was considered for feedstock transportation and a tortuosity factor of 1.27 applied (SULTANA; KUMAR, 2014). Collection and transport costs considered to estimate feedstock costs for all regions can be consulted in the Appendix B.

$$C_f = C_{cb} + C_{tb}.d.t_f \ or \ C_f = P_{SVO} + C_{to}.d.t_f \qquad (4)$$

Where:

C_f: Feedstock costs (US$/GJ)

C_{cb}: Biomass collection costs (US$/GJ)

C_{tb}: Biomass transport costs (US$/GJ.km)

P_{SVO}: Vegetable oil prices (US$/GJ)

C_{to}: Vegetable oil transport costs (US$/GJ.km)

d: Distances between each regional division inside the 100 km area and the hotspot (km)

t_f: tortuosity factor (-)

3.3.4. Technoeconomic pathways to produce maritime biofuels

Five technology pathways to produce maritime biofuels were selected: SVO and HVO (only applicable for Brazil), FT-BTL, HDPO and ATD. SVO are suitable fuel options for diesel engines and are feedstocks for HVO production. These fuels were only considered for Brazil given the country significant production and potential application in maritime sector (MÜLLER-CASSERES et al., 2021). Even though majority of HVO facilities in the world are located in Europe and US, most of them process residual oils. Also, European REDII banned vegetable oil use for biofuel production (LLOYDS, 2017; MERROW; PHILLIPS; MYERS, 1981). South Africa oil crop pro-duction reported in South Africa Bioenergy Atlas is directed to subsistence. In this sense, SVO or HVO production were not considered for these regions.

For FT-BTL route, two logistic configurations were considered to evaluate the cost benefits of biomass pre-treatment prior to final conversion to fuel. Process and technologies for each pathway have been extensively discussed in the literature (BLIN et al., 2013; CERVI et al., 2020; DE JONG et al., 2015a; DIEDERICHS, 2015; DIEDERICHS et al., 2016; DIMITRIOU; GOLDINGAY; BRIDGWATER, 2018; ECOFYS, 2012a; ETIP BIOENERGY, 2019a; GELEYNSE et al., 2018; GUELL et al., 2012; IEA, 2018a; JIMÉNEZ ESPADAFOR et al., 2009; JONES et al., 2013; KENNEY, K., CAFFERTY, K.G., JACOBSON, J.J., BONNER, I.J., GRESHAM, G.L., SMITH, W.A., THOMPSON, D.N., THOMPSON, V.S., TUMULURU, J.S. AND YANCEY, 2013; KHAN, 2018b; KLEIN et al., 2018; MEYER et al., 2020; PEARLSON, 2011; PRIHARTO et al., 2019; SAMAVATI et al., 2017; TAGOMORI; ROCHEDO; SZKLO, 2019; WANG; TAO, 2015). It is worth mentioning that HVO, ATD and FT are in theory full drop-in fuels, while SVO and HDPO (depending on the quality of finished fuel) would compose fuel blends (CERVI et al., 2020; KESIEME et al., 2019). Fuel production yields for each technology can be consulted in the Appendix B. Figure 9 summarizes the pathways considered in this study.

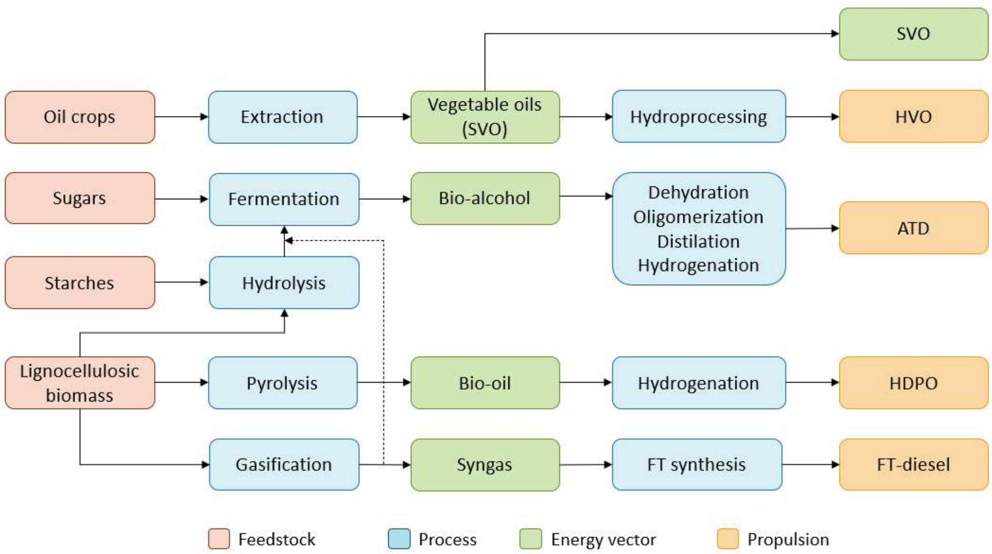


Figure 9: Fuel production pathways considered for biobunker production.

Biobunker production from FT-BTL route was evaluated according to two configurations. In the centralized configuration, biomass is converted into biobunker, without being previously pre-treated, while in the decentralized configuration, biomass is torrefied and transported to nearest port areas, where its conversion to biobunker takes place (Figure 10). Two gasifier types were considered. Fluidized bed gasifiers (FBG) and entrained flow gasifiers (EFG) are pointed as the most promising candidates for biofuels production. In this study, FBG were attributed to the hotspots formed by a mix of residues ("Total hotspots"), given their flexibility in terms of feedstock and suitability for larger scales. EFG were chosen for the decentralized configuration (torrefied biomass feed) and for single crop hotspots in view of their cost-effectiveness for small-scales and tighter feed specifications (SAFARIAN; UNNÞÓRSSON; RICHTER, 2019).

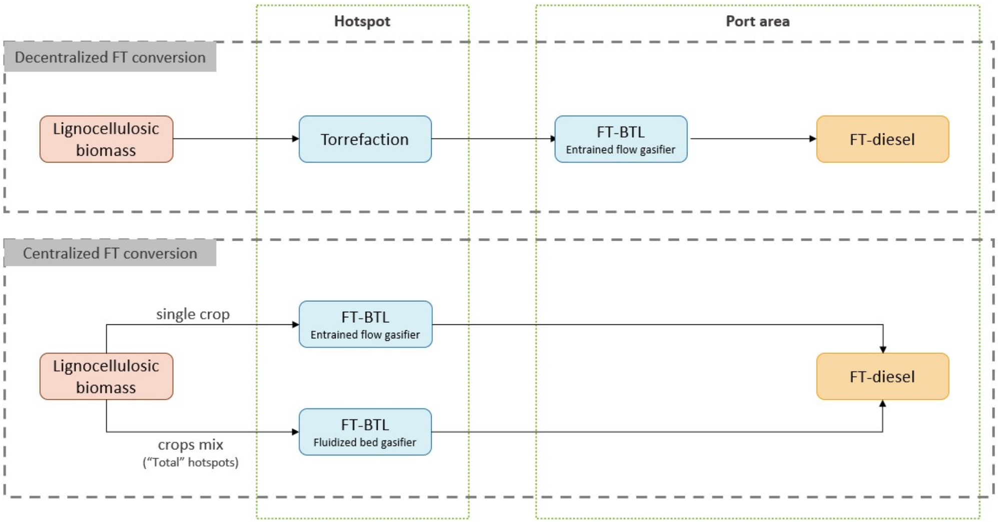


Figure 10: FT-BTL configurations.

The techno-economic analysis focused on determining the levelized cost of fuel (LCOF), based on costs and revenues related to each production route. For each route, the costs considered were capital costs (CAPEX), fixed and variable operational and maintenance costs (FOM and VOM, while revenues represent the sales of co-products (Rcop). LCOF are compared to conventional marine fuels prices.

Equipment costs informed in the literature refer to different production scales than the hotspots potentials. Thus, the number of feasible plants in each hotspot was determined when their potentials were greater than twice the reference scales. Otherwise, an adjustment was made according to equation 5.

$$C_{hotspot} = C_{ref} \cdot \left(\frac{S_{hotspot}}{S_{ref}}\right)^{FE} \qquad (5)$$

Where:

$C_{hotspot}$: Equipment costs in the hotspot scale (US$)

C_{ref}: Equipment costs in the reference plant scale (US$)

$S_{hotspot}$: Scale in the hotspot plant

S_{ref}: Scale in the reference plant

FE: Escalation factor

Reference costs were also adjusted to 2018 dollars using the Chemical Engineering Plant Cost Index (CEPCI) (equation 6) [81].

$$C_{2018} = C_t . \frac{CEPCI_{2018}}{CEPCI_t} \qquad (6)$$

Where:

C_{2018}: Costs adjusted to 2018 values (US$)

C_t: Costs in the reference year (US$)

$CEPCI_{2018}$: CEPCI value for 2018

$CEPCI_t$: CEPCI value the reference year

For each region different costs with inputs were considered and regional labour cost factors were determined. Regarding co-products, international spot prices were considered. Prices and factors considered to estimate inputs costs and co-products revenues can be consulted in the Appendix B.

Also, biomass seasonality reduces its availability throughout the year and, consequently, the plant utilization factor (FUT). Thus, different FUTs were considered according to crops seasonality and considering a short-time residues storage (biomass residues storage in closed warehouses up to 3 months leads to negligible losses (3%) and increases plant utilization factor (HOFFMANN; SALEM; SCHAEFFER, 2013; IFPEN, 2020; MORRISON et al., 2016; SCARLAT NICOLAE et al., 2019). Figure 11 shows the seasonality, storage times and FUT considered for each crop. Forest residues are not seasonal, therefore, a FUT of 0.85 was considered. Hotspots for total residues have feedstock available all over the year, given the biomass seasonal complementarity, and a FUT of 0.9 was considered.

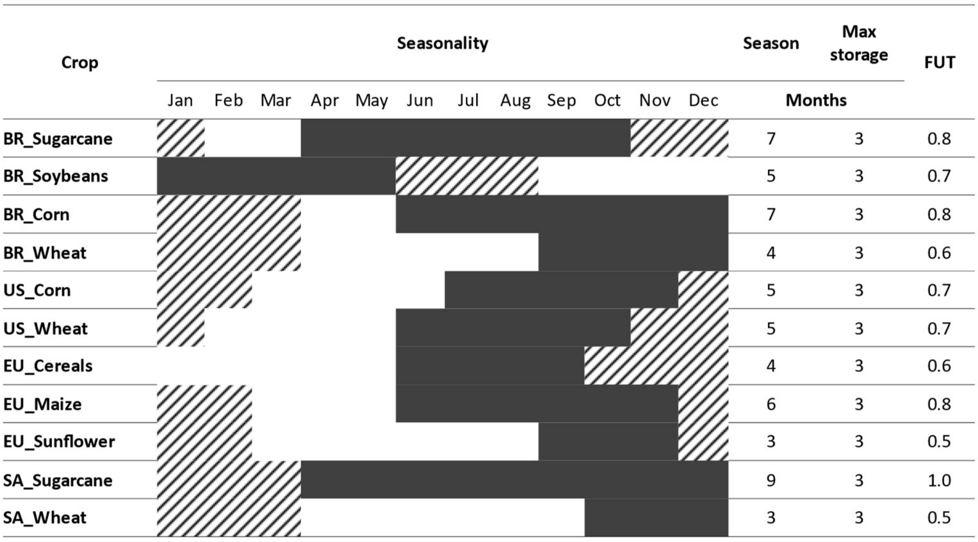


Figure 11: Crop's seasonality, storage times and FUT in each region. Note: filled bars represent the crop's seasonality while the striped bars represent the storage period.

Finally, LCOF is then given by equation 7. For all technologies, a horizon of 30 years [10] was considered and a discount rate of 7% (PAVLENKO; SEARLE; CHRISTENSEN, 2019).

$$LCOF = \frac{\sum_{i=0}^{n}(CAPEX_i + VOM_i + FOM_i - R_{cop_i})}{\sum_{i=1}^{n}\frac{P_{biobunker}}{(1+r)^i}} \quad (7)$$

Where:

n: Plant lifetime (30 years)

$P_{biobunker}$: Biobunker production (GJ)

r: Discount rate (%)

3.3.5. Total biobunker costs

The final step of the methodology aimed to estimate the total biobunker costs, composed by the feedstock (section 3.3.3), LCOF (section 3.3.4) and transportation costs. Transportation costs represent the fuel or biochar transport from the hotspots to the nearest port. On short distances, truck transport is the cheapest and most flexible option, benefitting from low capital costs (HOEFNAGELS et al., 2014; VISSER; HOEFNAGELS; JUNGINGER, 2020). Thus, for distances smaller than 80 km, road transport is the preferable mode. Otherwise, the choice of transport mode was based on the existing road, rail, inland waterway, or pipeline infrastructure evaluated in the georeferenced analysis (section 3.3.2). Tortuosity factors were considered for each mode (KIM; DALE, 2015; STROGEN; HORVATH; MCKONE, 2012; SULTANA; KUMAR, 2014). Transport cost considered for each mode can be consulted in the Appendix B.

3.4.Results

3.4.1. Feedstock availability

The estimated technical potential of biomass residues totalized 45 PJ/yr in South Africa, 3,050 PJ/yr in the US, 3,903 PJ/yr in Brazil and 4,083 PJ/yr in Europe. Results were compared with literature (Figure 12).

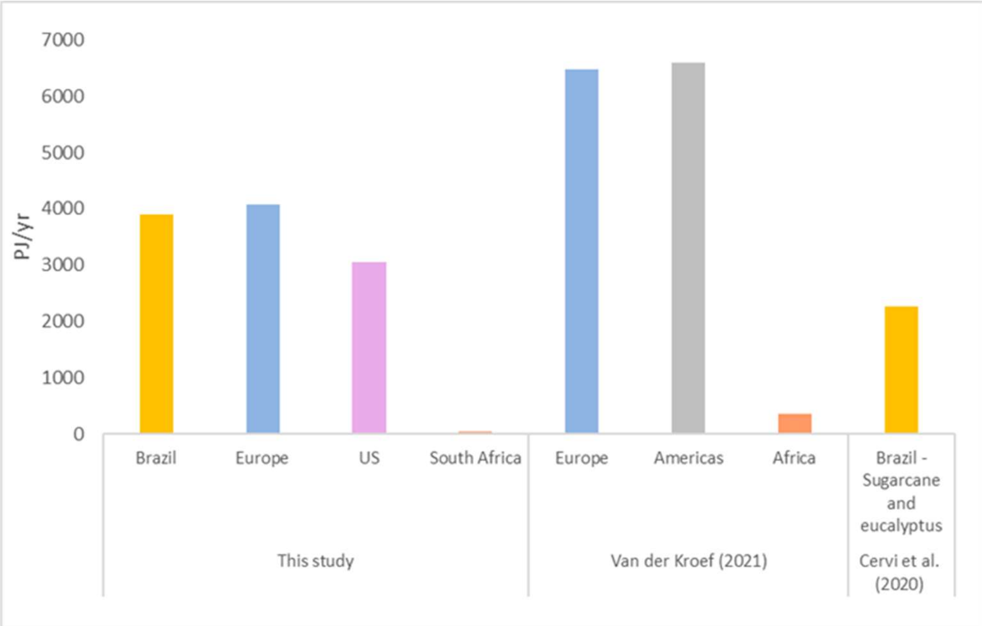


Figure 12: Biomass residues potential compared to other studies.

In addition, SVO total technical potential in Brazil totalized approximately 1,000 PJ/yr. Maps with biomass potential in each regional division were constructed (see Appendix B) and kernel maps enabled the evaluation of bioenergy dispersion and the identification of hotspots in each region (Figure 13, Figure 14 and Figure 15).

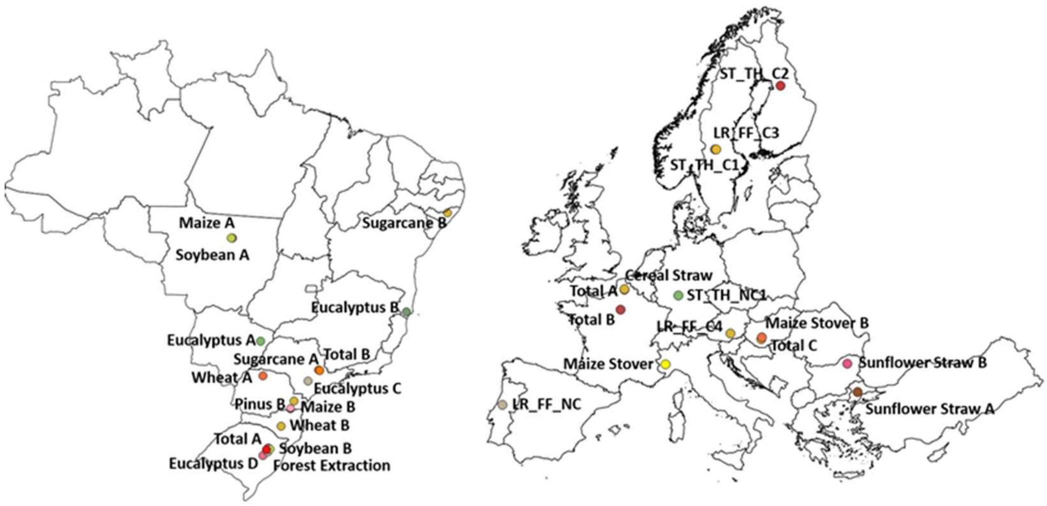


Figure 13: Biomass residues hotspots in Brazil (left) and Europe (right). Note: Some hotspots in Europe registered very low potentials and were excluded (LR_FF_C1, LR_FF_C2, LR_TH_C, LR_TH_NC, ST_FF_C, ST_FF_NC).

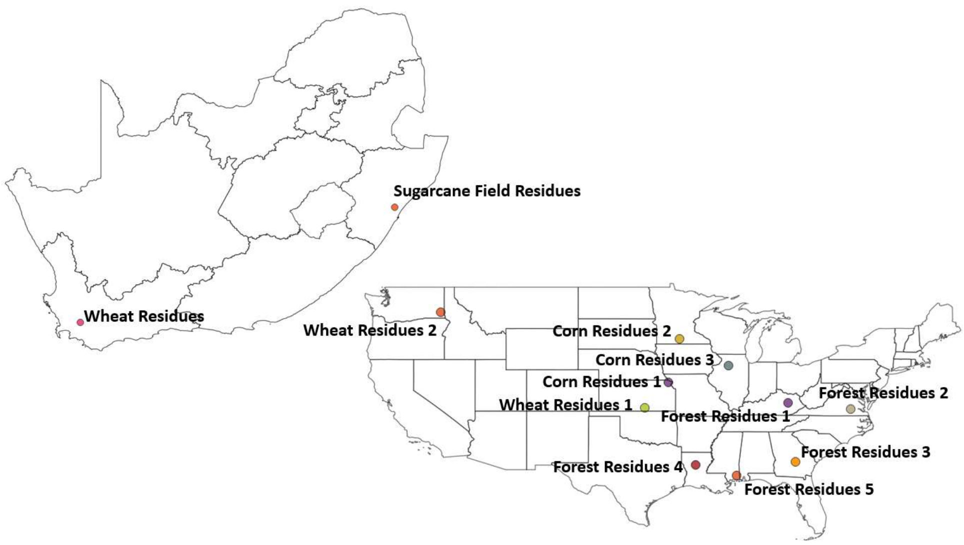


Figure 14: Biomass residues hotspots in South Africa (right) and US (left).

Figure 15: SVO hotspots in Brazil.

Figure 16 compares the potentials and average feedstock costs for biomass residues hotspots and Figure 17 presents SVO hotspots potentials and costs. In Brazil, sugarcane, soybeans, and eucalyptus registered the highest potential. "BR_Total A" hotspot includes residues from all crops and presents the highest potential among all regions (almost 200 PJ/yr), followed by "BR_Total B" (nearly 150 PJ/yr) that considers residues from soybeans and maize[15]. In Europe, cereal straw and maize stover residues registered the highest potentials (89.9 PJ/yr and 53.2 PJ/yr, respectively). In the US, corn residues registered the highest potentials (around 50 PJ/yr), while South African hotspots potentials are among the lowest ones (inferior to 20 PJ/yr). SVO potentials are well below than crop residues, even when considering the total SVO hotspot (13 PJ/yr). Soybean oil hotspot registered the highest potential (8.6 PJ/yr) and mamon and sunflower oil potentials are almost inexpressive. Regarding feedstock costs, Brazil and US are the regions with lower estimates (from US$ 0.8/GJ to US$ 1.7/GJ), while values for Europe are far higher (from US$ 2.0/GJ to US$ 5.0/GJ). Feedstock costs for SVO represents its market prices ranging from US$ 20/GJ to US$ 45/GJ, much higher than residues costs.

[15] Soybean and maize are complementary crops planted in crop rotation systems in Brazilian Midwest.

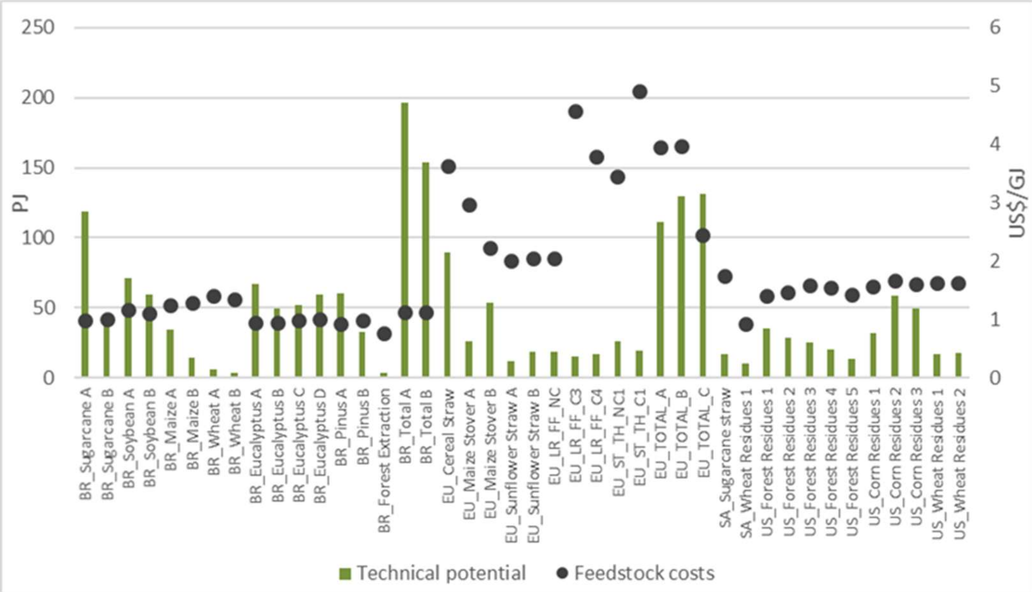


Figure 16: Biomass residues potential and average costs in hotspots.

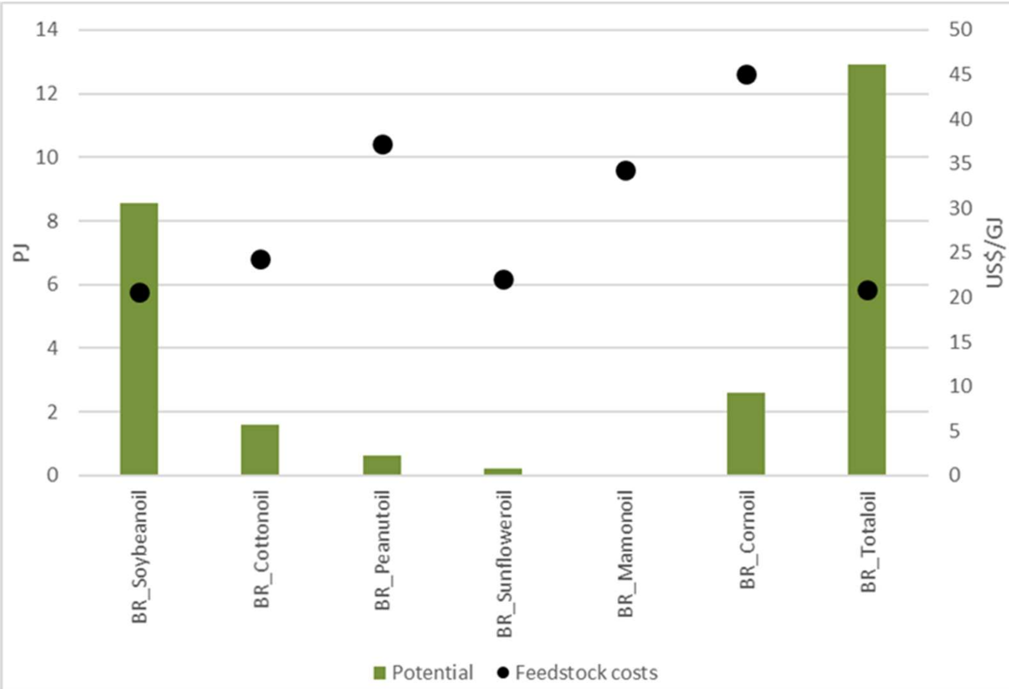


Figure 17: SVO potential and average cost in hotspots.

Maps were developed including the hotspots for all regions with associated infrastructure (Figure 18 and Figure 19) (for a better visualization of the maps, consult the Appendix B). In Brazil, most hotspots are located near oil refineries and ports. However, for Soybean A, Maize A and almost all SVO, hotspots are in country-side areas and therefore, far away from ports. The same is observed in Europe and the US, except for hotspots "EU_ST_TH_C2" and "US_W2". Finally, in South Africa, the hotspots are localized very close to ports and oil refineries. The distances between the hotspots and the nearest port were determined and can be consulted in the Appendix B.

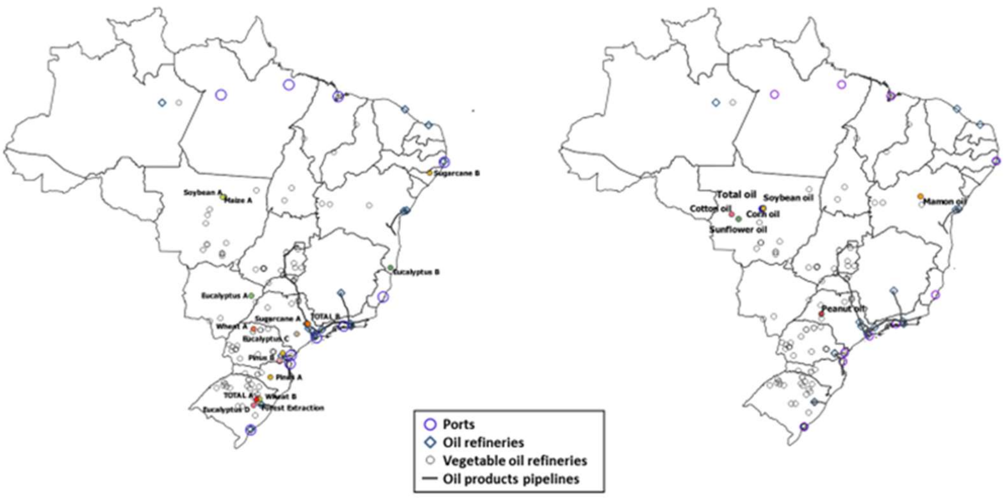


Figure 18: Hotspots and infrastructure in Brazil (biomass residues hotspots - left; SVO hotspots - right).

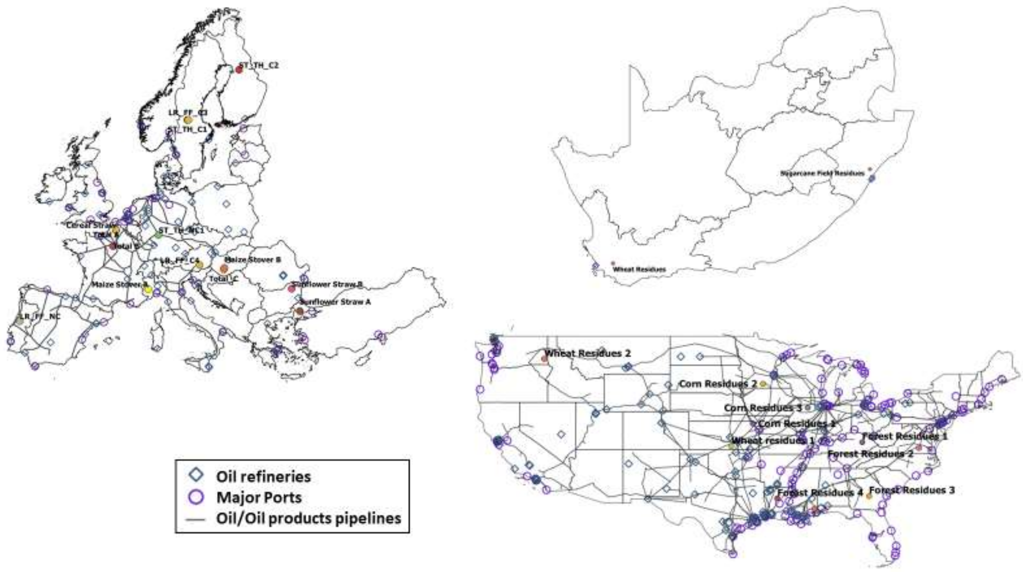


Figure 19: **Hotspots and infrastructure in Europe (left), South Africa (top right) and US (bottom right).**

3.4.2. Levelized costs of fuel

The number of plants in each hotspot[16] was determined according to the reference capacities (see section 3.3.4). This number for each hotspot can be consulted in the Appendix B. Figure 20 and Figure 21 show the fuel production in the hotspots.

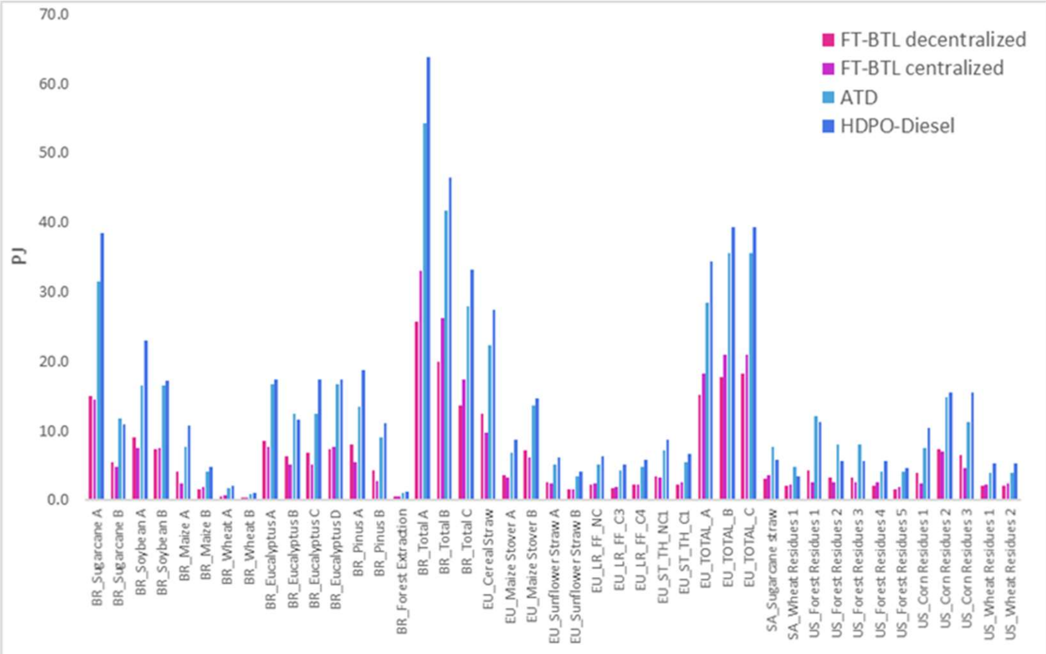


Figure 20: Biofuel production levels in each hotspot for FT-BTL, ATD and HDPO pathways.

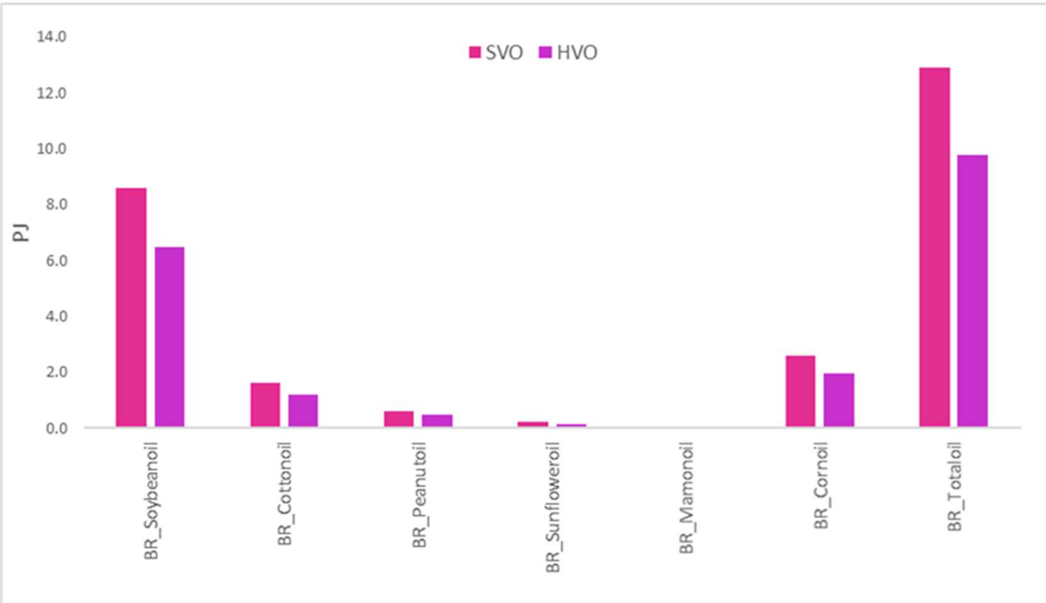


Figure 21: Biofuel production levels in each hotspot for SVO and HVO pathways. Note: BR_Mamonoil potential is 0.03.

[16] Some hotspots in Europe registered very low potentials and were excluded (LR_FF_C1, LR_FF_C2, LR_TH_C, LR_TH_NC, ST_FF_C, ST_FF_NC).

Adding up the fuel production in the "single-crop" hotspots, the regional biobunker supply was identified (Figure 22). Brazil is the major producer, followed by Europe, and United States (up to 240, 93.5 and 84.4 PJ fuel/yr, respectively). SVO and HVO production levels are much lower (up to 13.0 and 10 PJ/yr, respectively). Fuel production levels were compared to regional marine fuels demand (Figure 22). See Appendix B to consult fuel production potentials and regional demands.

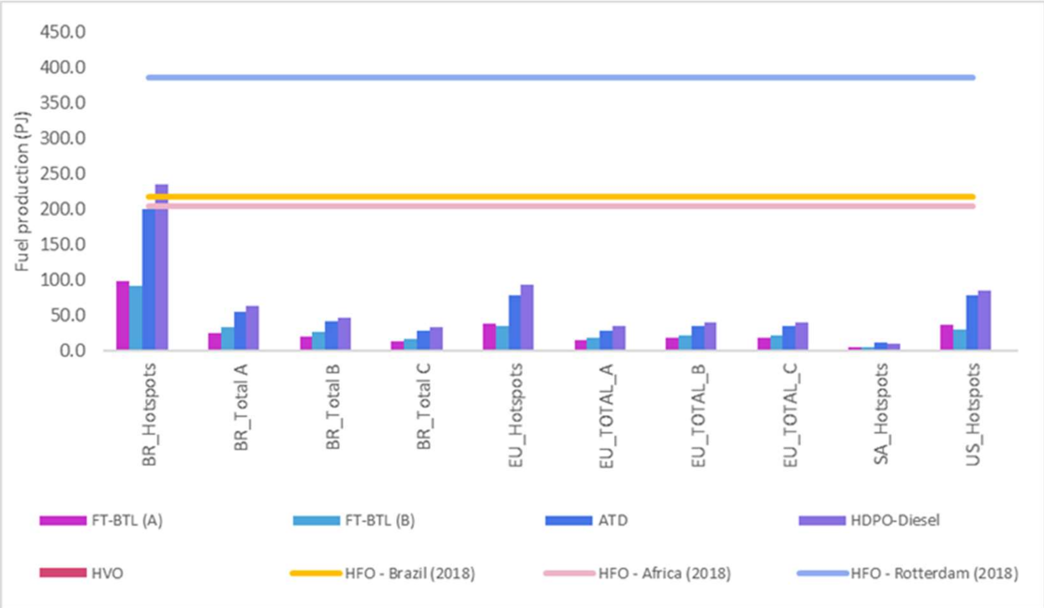


Figure 22: Regional biobunker supply and bunker fuel demand.

The LCOF vary widely depending on the region and fuel production technology (Figure 23 and Figure 24). For all hotspots, the LCOF was higher than HFO and MGO prices in 2018. In Brazil, a wide cost range is observed for all technologies, specially ATD (up to US$ 104/GJ). Highest ATD LCOFs were observed to hotspots with lower potentials (forest extraction – 3.4 PJ/yr and wheat B – 3.1 PJ/yr). FT-BTL-centralized, HVO and HDPO stands as the lowest cost options. In Europe, a wide cost range is also observed, and all pathways are in a range of US$ 30-58/GJ, except for FT-BTL-decentralized (above US$ 60/GJ). In South Africa, FT-BTL-centralized is the lowest cost technology (US$ 23-25/GJ). Finally, in the US, little variation in LCOF is observed for each pathway. FT-BTL-centralized and HDPO are the least cost alternatives (US$ 25-31/GJ), while FT-BTL-decentralized is the highest (around US$ 60/GJ). Notable difference is observed comparing FT-decentralized and FT-centralized LCOFs. It is explained by the lower base capacity considered for FT-decentralized plants. Thus, down scale is required for gasification and FT processes, which increase fuel costs.

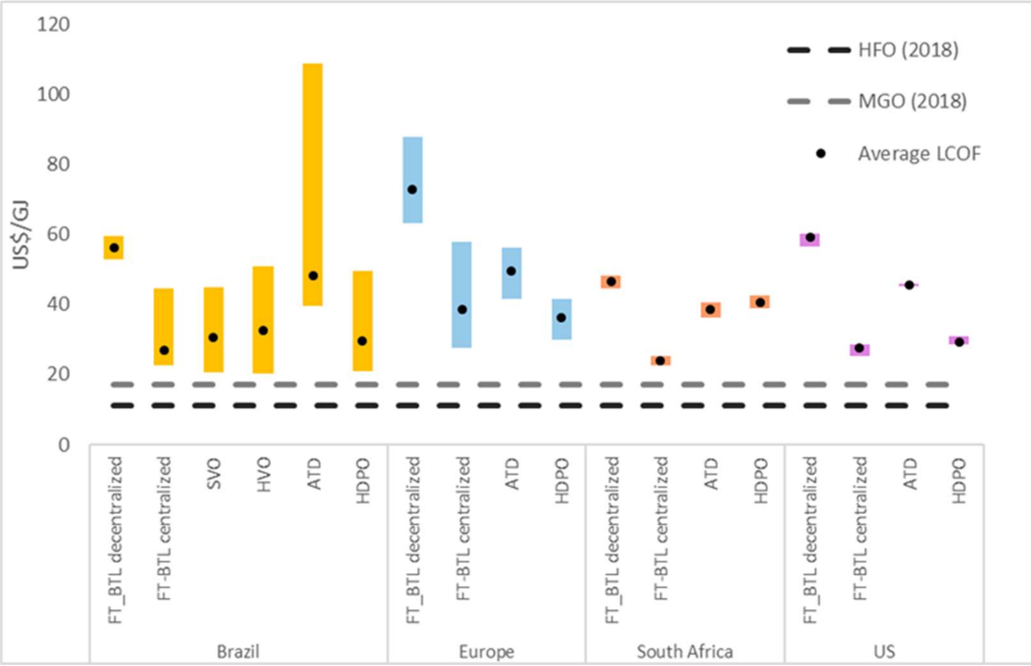


Figure 23: LCOF ranges.

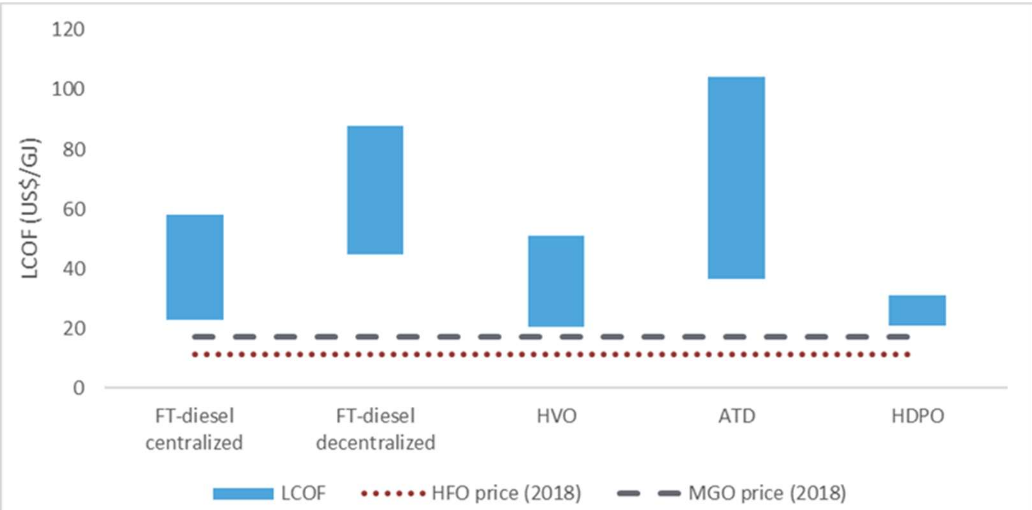


Figure 24: LCOF ranges (minimum and maximum values) for different technologies compared to average bunker fuel prices.

LCOF breakdown for each technology and region is shown in Figure 25. LCOF for residue-based technologies are mostly influenced by CAPEX (from 30 to 40%), and benefit from co-products revenues. For FT-BTL-decentralized, VOM costs are mostly associated with power purchase for torrefaction. In the FT-BTL-centralized with EF gasification, biomass has a significant contribution to LCOF. However, with FB gasification, FOM is more expressive. In ATD, FOM costs are related to expenses with consumables (e.g., catalysts), and maintenance. For HDPO, FOM costs is associated with catalysts and maintenance expenses, while VOM is dominated by natural gas purchase for hydrogen production. For HVO pathway, results totally differ. HVO costs are highly influenced by vegetable oils prices (US$ 18.9/GJ to US$ 44.6/GJ), that are internationally traded commodities whose prices are higher than MGO's (US$ 21.2/GJ). Biomass contribution to LCOF is more significant in FT-centralized (EF) among all technologies and in Europe and US.

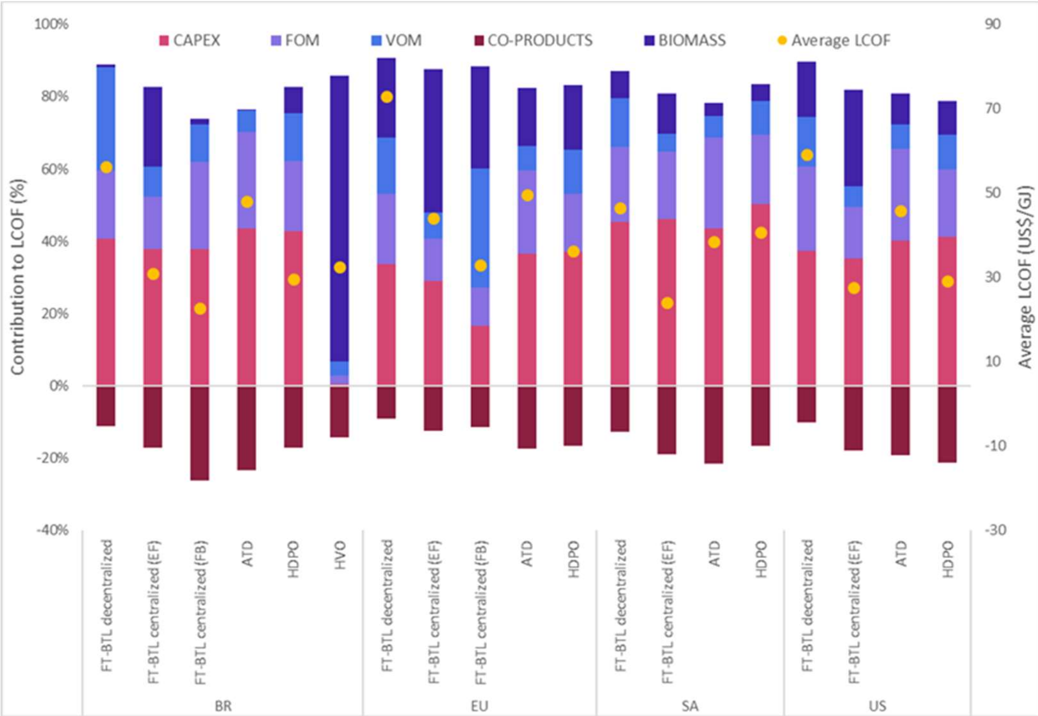


Figure 25: LCOF breakdown for each technology and average LCOF values. Note: SVO is not represented given that its LCOF is its prices.

Besides fuel different fuel potentials are observed for each technology, it is important to consider the technology readiness of each one. Some biofuel production routes considered in this study have already achieved commercialization stage (SVO and HVO), while others are in the validation stage. Figure 26 compares the fuel production levels with the technology maturity of each pathway.

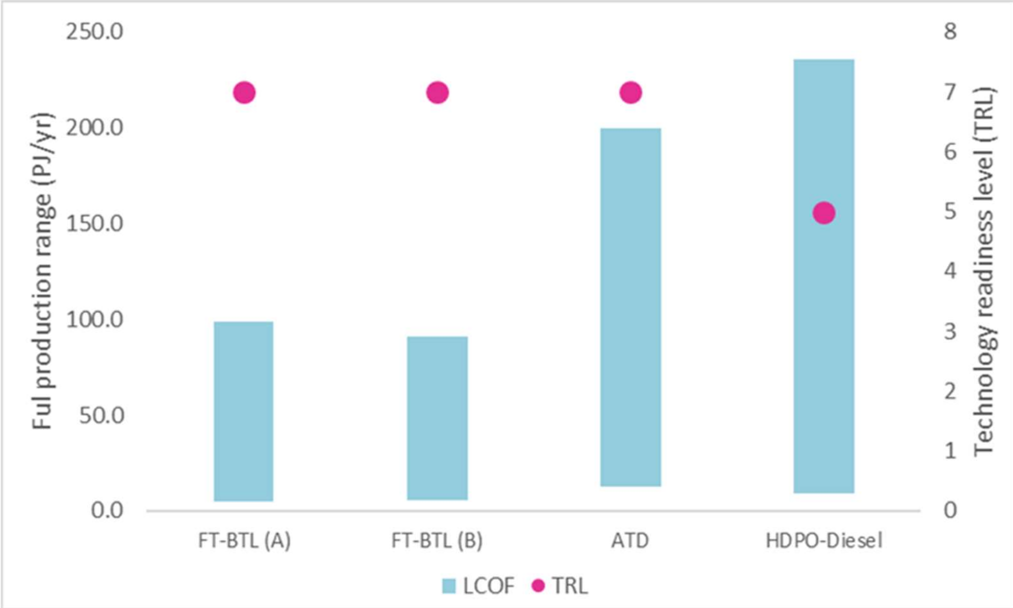


Figure 26: Fuel production and technology readiness for each biobunker fuel pathway. Note: As SVO and HVO fuel production levels were far below than other technologies, they are not represented. However, both are mature technologies.

3.4.3. Total biobunker costs

Total biobunker cost is composed by the LCOF and fuel or biochar transportation costs. Transportation cost depends on transport mode suitable for each hotspot (see Appendix B). Figure 27 shows the total biobunker costs ranges for each technology and region, divided into LCOF and transport costs. Results show that the final transport from biofuel production plant to port represents a small fraction of total costs. However, in the US, transport costs may represent a considerable increase to LCOF (up to US$ 5/GJ) mainly due to long transportation distances from some hotspots to the nearest port (>350 km).

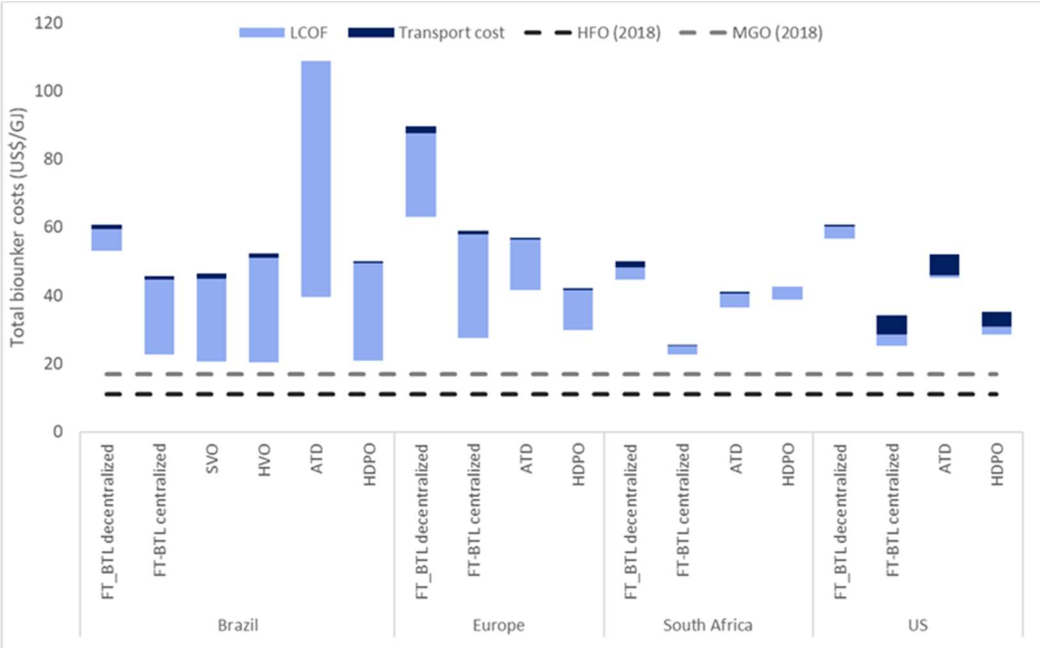


Figure 27: Total biobunker cost range.

3.5.Discussion

The total technical potential of biomass residues varies from 45 to 4.085 PJ/yr. Europe registered the highest potential, followed by Brazil, U.S., and South Africa and results were compared with the literature (Figure 12). However, in the defined hotspots, Brazil stands out as the region with the highest potentials (see Figure 16). Highest feedstock costs were observed in Europe (up to US$ 4.9/GJ), mostly given the high biomass collection costs, while Brazil and U.S registered the lowest values (up to US$ 1.4/GJ and US$ 1.7/GJ, respectively). Feedstock costs for SVO were far higher (from US$ 20.6-45.0/GJ), as they are commodities whose prices are higher than marine fuels (US$ 11.0-18.0/GJ).

Considering the regional biobunker supply, Brazil is the major producer, followed by Europe, and United States (up to 240, 93.5 and 84.4 PJ fuel/yr, respectively). In Brazil, HDPO production in hotspots surpasses current HFO demand, while FT-BTL and ATD represents 45% and 92%, respectively (Figure 22). In Europe, biofuel production is substantially lower (less than 6%) than European HFO demand (1.526 PJ) but represents up to 24% of Rotterdam Port demand (385 PJ/yr) (Figure 22). Similar trend is observed for South Africa and United States (Figure 22). Fuel production in these regions represents less than 4% and 9% of regional marine fuel demands, respectively.

Fuel production levels were compared with literature. (KROFT, 2020) estimated a marine biofuel supply (discounting biomass use for other transport sectors - road and aviation) in Europe of about 300 PJ/yr from 2025 to 2030 mainly from Pyrolysis-based fuels and HVO, using agricultural residues and imported used and vegetable oils as feedstocks. (CERVI et al., 2021) estimate a biojet fuel production of 450 PJ/yr from sugarcane and eucalyptus residues in Brazil, while (CARVALHO et al., 2019) estimates totalize 120 PJ/yr. Results obtained are lower than literature findings, but the estimated potentials in this study are constrained to the 100 km collection area from the hotspots and considered seasonality impacts in plant operation.

In all regions, highest biofuel production volumes were observed for HDPO. Notwithstanding, HDPO has not achieved commercial stage and is less mature than other biofuel technologies (Figure 26) (CERRUTI et al., 2020; IEA BIOENERGY, 2020; LI; WRIGHT, 2020; OLBRICH et al., 2016; SORUNMU; BILLEN; SPATARI, 2020; YUN, 2020). Thus, investing in technologies that are closer to the commercialization stage in the near- to mid-term, may accelerate the uptake of maritime biofuels, despite their lower yields.

Techno-economic analysis showed a significant gap between biobunkers LCOFs and marine fuel prices (Figure 24). Among all technologies, HDPO registered the lowest LCOFs. Even though biomass torrefaction improves the feedstock logistics and gasification performance, the additional capital expenses made FT-diesel in decentralized configuration the costliest technology in most regions, except for ATD in Brazilian hotspot with lowest potential. However, technological learning may increase efficiency and drive down production costs, but this would require a large number of FT plants and may take decades (DE JONG et al., 2015b).

Capital costs represent the major component of fuel total costs, except for HVO. FOM and VOM share varies among technologies and regions, given the differences in feedstock and inputs prices and labor costs. Transport costs were only expressive in regions with lowest LCOFs and higher transportation distances (Figure 27). Thus, in such cases, biofuels would be more competitive for other applications (such as road or air transportation), given that fuel consumption hubs would be closes to hotspots.

Therefore, biofuel competitiveness in the near-term could be achieved by carbon taxes application (Table 11). However, carbon prices required for the biobunkers to reach price parity with MGO were estimated and varies from US\$ 68/tCO_2 (FT-centralized in South Africa) to US\$ 516/tCO_2 (FT-decentralized in Europe). For only 15% of the hotspots, CO_2 prices would be lower than US\$ 100/tCO_2. Also, the lower prices of conventional marine fuels compared to other sectors (such as road and aviation) increases the cost gap between bio and fossil fuel alternatives. Assessing biobunker competitiveness by the application of carbon taxes and having jet fuel prices of 2018 (US$ 20/GJ) (INDEXMUNDI, 2018b) as base for comparison led to CO_2 prices from US$ 40/tCO_2 to US$ 488/tCO_2. In this sense, fuel mandates seem more realistic in the near term as they would lead to pioneer plants development and lower fuel costs.

Table 11: Carbon prices required for biobunkers competitiveness.

	Carbon intensity gCO_2/MJ fuel	US$/t$CO_2$			
		BR	EU	SA	USA
FT-decentralized	27[b]	195	516	288	390
FT-centralized	27[b]	120	237	68	103
ATD	38[c]	320	336	221	290
HDPO	23[d]	116	175	210	125
SVO	58[e]	217	-	-	-
HVO	58[f]	175	-	-	-
MGO	137[g]				
Max US$/t$CO_2$	516		FT-decentralized (EU)		
Min US$/t$CO_2$	68		FT-centralized (SA)		

Notes:
[a] Average literature values for different world regions
[b] (BENGTSSON, FRIDELL, et al., 2012, CARVALHO, et al., 2019, KASS, Mike, ABDULLAH, et al., 2018)
c (KLEIN, CHAGAS, et al., 2018, LAPOLA, SCHALDACH, et al., 2010, PLEVIN, JONES, et al., 2010, STAPLES, MALINA, et al., 2014)
d (IRIBARREN, PETERS, et al., 2012, PETERS, IRIBARREN, et al., 2015, VIENESCU, WANG, et al., 2018)
e (CARVALHO, et al., 2019, ECOFYS, 2012a)
f (CARVALHO, et al., 2019, KASS, Mike, ABDULLAH, et al., 2018, STENGEL, VIUM, 2015)
g (BALCOMBE, BRIERLEY, et al., 2019, BENGTSSON, FRIDELL, et al., 2012, LLOYD'S REGISTER, UMAS, 2020, ZHOU, PAVLENKO, et al., 2020)

To sum up, biobunker fuel production may play a role in maritime decarbonization in all regions. Nevertheless, this study selected only specific crops to identify and evaluate biobunker hotspots and actual technical potentials might be significantly higher in all regions. On the other hand, no sustainability constraints were considered in this study, which in turn may again lower potentials. Even though potentials were not significant compared to fuel demand in some regions, hotspots proximity to ports would enable fossil fuel replacements in these areas. Also, SVO or Pyrolysis oil co-processing in oil refineries would benefit from the existing infrastructure and may represent a cost-effective solution to kick off the production of cleaner maritime fuels (IEA BIOENERGY, 2019a; PINHO et al., 2015; VAN DYK et al., 2019b). Furthermore, this study presents a sectoral-based analysis and potentials were determined without considering biomass demand for other sectors, such as aviation and power. Yet, as some technologies can co-produce jet- and diesel-range biofuels, coupled strategies for biofuels development may favor both sectors. Also, the stablished decarbonization goals and variabilities regarding oil prices may offer an opportunity to improve biobunkers competitiveness.

3.6.Conclusions

The present study sought to identify potential areas for biobunker fuels production from agricultural and forestry residues in Brazil, Europe, South Africa, and United States considering geographical, logistic, and economic aspects. The combination of the georeferenced analysis, with logistic integration, seasonality and, techno-economic analysis represents an innovative methodology to assess regional capabilities that could make some regions potentially biobunker fuel suppliers.

The feedstock availability analysis revealed that total biomass residues potential was greater in Europe (4083 PJ/yr), followed by Brazil, US, and South Africa (3903, 3050, 45 PJ/yr, respectively). SVO potentials were only considered for Brazil and estimates are far below compared to residues. The georeferenced analysis enabled the identification of suitable localities for biobunker refineries development. Considering the available potential in such areas (hotspots), Brazil is the region with the greatest potential among all regions (196.5 PJ/yr). Also, together with the US, Brazil is the region with lowest feedstock costs (ranging from US$ 1.4/GJ to US$ 0.8/GJ).

The techno-economic analysis results revealed fuel production levels in each region. Specific feedstock and inputs prices, labor costs, biomass seasonality and fuel transport modes were considered to capture the impact of regional differences on biobunker total costs. However, same discount rates, plant construction time and yields were assumed, which make the economic results comparable.

In general, HDPO stands out as the technology with higher yields and lowest costs in all regions. It is also the least developed technology, which may compromise its high potential. Thus, investing in readiest biofuel technologies, while pursuing efforts to accelerate the development of more advanced pathways, will be crucial.

Total fuel costs varied from US$ 20.4 – 104.2/GJ. For all hotspots, values were higher than fossil marine fuels prices. Costs are mostly driven by capital expenses, except for HVO, and transportation costs shares were not substantial for most regions. In the near-term, fuel blending mandates might be the best alternative to guarantee the utilization of biobunker fuels, given that required carbon prices are high and may be not realistic. Nevertheless, uncertainties regarding oil prices and the expected commitment of maritime industry towards decarbonization may offer an opportunity for biofuels development.

In the end, biobunker fuel production may play a role in maritime decarbonization in all regions and support IMO mitigation strategies. Even though the estimated supply is lower than current demand in most regions, the proximity between potential fuel production areas and ports would incentivize their production. Also, maritime decarbonization will require a mix of solutions, and other fuel options and technologies that are being extensively discussed, such as hydrogen and ammonia, will also play a role (AL-ENAZI et al., 2021; LLOYDS, 2017; LLOYD'S REGISTER; UMAS, 2020; PRUSSI et al., 2021). Thus, diverse strategies to incentivize biobunker production should be considered.

The application of fuel blending mandates would allow the competitiveness of readiest pathways in the near term, while technology learning would enable advanced technologies development. Also, speeding up maritime decarbonization could be achieved by joining forces with other sectors that would be also benefited from advanced biofuels development.

Finally, this study presents some limitations that should be addressed in future works, such as:

i. Feedstock availability assessment have not considered biomass use in other hard to decarbonize sectors, such as aviation and industry;
ii. Economic analysis was based in Nth plants. This tends to underestimate capital costs, construction and commissioning times and overestimate fuel production yields compared to pioneer plants (DE JONG et al., 2015b; MERROW; PHILLIPS; MYERS, 1981; MORRISON et al., 2016);
iii. Fuel transport mode choice was based on proximity to infrastructure and not to main transport stations, what could increase fuel transportation costs;
iv. Perform an integrated assessment to capture in greater details the impacts in energy and land-use of replacing conventional maritime fuels for biofuels.

4. Lignocellulosic biofuels use in the international shipping: the case of soybean trade from Brazil and the U.S. to China

Francielle Carvalho, Eduardo Müller-Casseres, Joana Portugal-Pereira, Martin Junginger, Alexandre Szklo

4.1. Abstract

Future low-carbon fuels use in the maritime transport to curb greenhouse gas emissions can increase freight rates and affect trade, especially for commodities transported over long distances. This study performed a case study to evaluate lignocellulosic marine biofuels use in soybean trade routes from Brazil and U.S. to China, in terms of supply volumes, greenhouse gas emissions and potential increase on freight costs. Two scenarios and three technologies were considered for biofuels availability from 2020 to 2050. Findings reveal that Brazil benefited from higher biofuel supply and four Brazilian biofuel pathways meet total bunker fuel demand in 2050, while U.S. pathways supplied up to 24%. However, emissions reduction come at significant cost increase with abatement costs reaching more than US$ 300/tCO2e for some Brazilian and U.S. pathways. To reduce this cost gap, market instruments, such as carbon price of at least US$ 100/tCO2e would be required. Nevertheless, fuel cost increase has not resulted in significant cost variation between Brazilian and U.S. vessel routes. Hence, Brazilian trade routes could keep lower freight costs than U.S. even with higher biofuel shares. This indicates that regions capable of supplying low-carbon fuels can become more competitive in their exports in a decarbonized maritime trade.

4.2. Introduction

The maritime transport is the backbone of the international trade and the global economy given that over 80% of the international trade volume in goods is carried by sea (UNCTAD, 2021). To perform this service, the ocean-going ships consume large amounts of petroleum derived fuels making the maritime sector responsible for almost 3% of global anthropogenic greenhouse gas (GHG) emissions (FABER et al., 2020). In 2018, the International Maritime Organization (IMO) committed to reduce by 50% the annual GHG emissions from international shipping by 2050 compared to 2008 levels. To achieve this goal, besides optimized operations and energy efficiency, the development of alternative low or zero carbon fuels will be crucial (ECOFYS, 2012a; IEA, 2018a; NEPOMUCENO DE OLIVEIRA; SZKLO; CASTELO BRANCO, 2022b; PRUSSI et al., 2021)

Drop-in biofuels could be used in existing ship engines and bunkering infrastructure and, thus, can directly replace or compose blends with fossil bunker fuels. Biofuels produced from residual lignocellulosic feedstocks (e.g.: straw or wood chips) would potentially avoid the “food versus fuel” debate and land use change risks that arises from dedicated biofuel crops (DAIOGLOU et al., 2020; SHRESTHA; STAAB; DUFFIELD, 2019; TANZER et al., 2019; VAN DER HILST et al., 2018; ZAIMES et al., 2015). Additionally, lignocellulosic residues from agriculture and forestry are abundantly available (Baruya, 2015) and their relatively low cost makes them attractive for high-volume marine biofuel production (BARUYA, 2015; RAUD et al., 2019). However, lignocellulosic biofuels have only reached limited production scales and their performance in ship engines is not well understood yet. Therefore, a significant amount of testing and standardization is needed (BROWN et al., 2020; CARVALHO et al., 2021a; IEA, 2022b; IRENA, 2019).

Investment and production costs for lignocellulosic biofuels are presently high, so the fuel shifts in maritime transport can increase ocean freight rates and affect trade. Such impacts can be particularly relevant for the trade of low-value-added products (e.g. agricultural products) and for long trade voyages (IEA, 2022a; MELAS; MICHAIL, 2021; MICHAIL; MELAS, 2020). The case of soybeans is particularly representative given that its international competitiveness is largely influenced by transportation costs. Moreover, an eventual rise of soybeans supply costs may directly threat food security of the population (GALE; VALDES; ASH, 2019; SALIN, 2020a; SALIN; AGAPI SOMWARU, 2020). With a current trade volume of about 110 million tonnes imports to China, it also constitutes a major global trade flow.

China concentrates more than half of soybean international market and Brazil and U.S, the leading world producers, are its main exporters (INTERNATIONAL TRADE CENTER, 2020). Both countries face stiff competition in Chinese market, whose market share is also influenced by the competitiveness of ocean freight rates (SALIN; AGAPI SOMWARU, 2020). Maritime routes from U.S Gulf to China are shorter, compared to Brazilian routes, however, the latter often benefits from the absence of canal fees and by economies of scale by using large vessels. Historically, it has been observed that relatively small changes in voyage costs modify the market share of soybean exporters in the Chinese market (SALIN, 2020a).

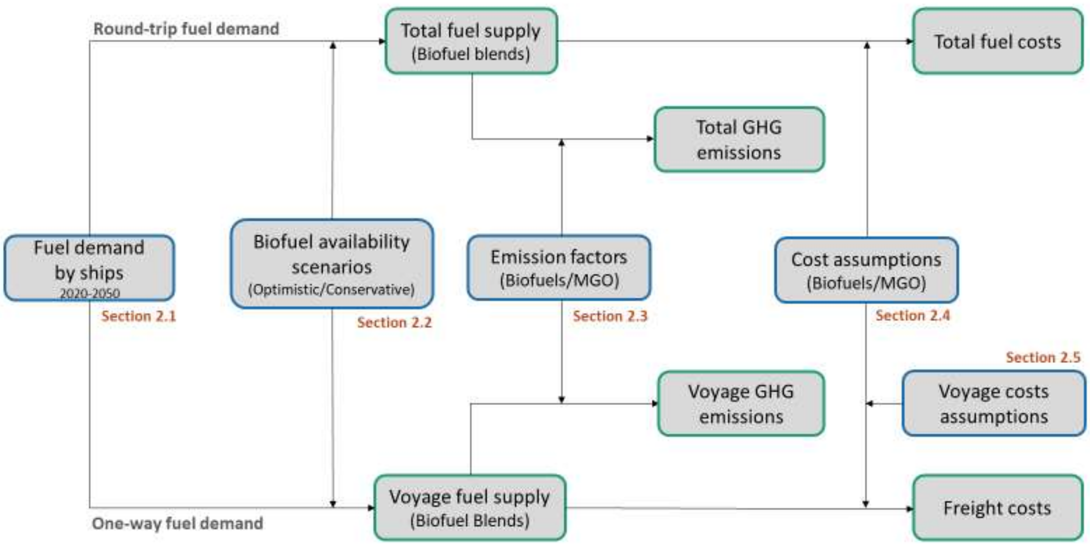
Previous studies have explored the potential of maritime biofuels production. Tanzer et al. (2019), Tan et al. (2021), Carvalho et al. (2021) evaluated the technological, economic, and environmental performance of drop-in lignocellulosic marine biofuels. Zhou et al. (2020) and Carvalho et al. (2021b) compared marine biofuel pathways to assess their potential to decarbonize maritime trade. Also, several studies evaluated the soybean trade to in China: Salin et al. (2020) and Salin (2020a) evaluated the effects of ocean freight and infrastructure developments on soybean exports to China. Gale et al. (2019) discussed China's position as major soybean importer and the factors that affect the import flows from its major exporters.

While relevant, such studies have evaluated separately (i) the potential of biofuels to decarbonize maritime transport according to their techno-economic and environmental performance or (ii) the factors that affect the competitiveness of major soybean trade players. Taking both aspects into consideration, this study aims to test the hypothesis that fuel switches in the international shipping sector can affect the commodity trade. To do so, it performed a case study to evaluate the utilization of lignocellulosic marine biofuels in soybean trade routes to China in terms of supply volumes, GHG emissions reduction and increase on ocean freight rates. To authors' knowledge, this is the first attempt to assess biofuel use in a specific major product trade. To this end, main trade routes of soybean trade from U.S and Brazil to China were considered and three biofuel technologies. Results obtained are relevant to identify how some regions would benefit from the supply of low-emission fuels and whether biofuel use would affect maritime trade competitiveness.

This paper is structured as follows: section 2 presents the methodology of the study that details the fuel demand and biofuel supply projection, the GHG emissions, the fuel and freight costs calculations. Then, chapter 3 details the results obtained for each analysis and Section 4 discusses main findings. Finally, section 5 summarizes this paper's conclusions, limitations and suggestions for future work.

4.3. Methods

The methodology applied in this study was divided into five steps (Figure 28**Erro! Fonte de referência não encontrada.**). The first one aims to estimate fuel demand of selected soybean export routes from Brazil and the U.S. to China from 2020 to 2050. The second step assesses the total biofuel supply in these regions and develops biofuel availability scenarios to determine the biofuel shares in the evaluated period. The third calculates the total GHG emissions for the selected soybean trade routes, while the fourth estimates their total fuel costs. Finally, the fifth step analyses the increase on freight rates for the selected maritime routes by biofuel utilization and evaluates the impacts on soybean exporter's competitiveness. It is worth noting that, for simplicity reasons, it was assumed that the selected maritime trade routes would not change during the evaluated period, nor the way freight costs are composed. Also, it was hypothetically considered that cellulosic fuels would be certified during this period.



Note: MGO: Marine Gas Oil

Figure 28: Methodological procedure adopted in this study

4.3.1. Fuel demand

To estimate the final energy demand associated with the soybean trade flows from Brazil and the U.S. to China between 2020 and 2050, a few assumptions were adopted. China's total soybean imports were projected based on a detailed study of the country's future food demand (ZHAO et al., 2021). As shown in Figure 29, annual imports are expected to increase 30% by 2030 and then stabilize around 130 Mt/yr. Furthermore, although soybean meal and oil have significant shares of the global soybean market, Chinese imports are highly concentrated (>98%) on whole soybeans (ITC, 2022). As such, the country's imports are assumed to fall entirely into this category.

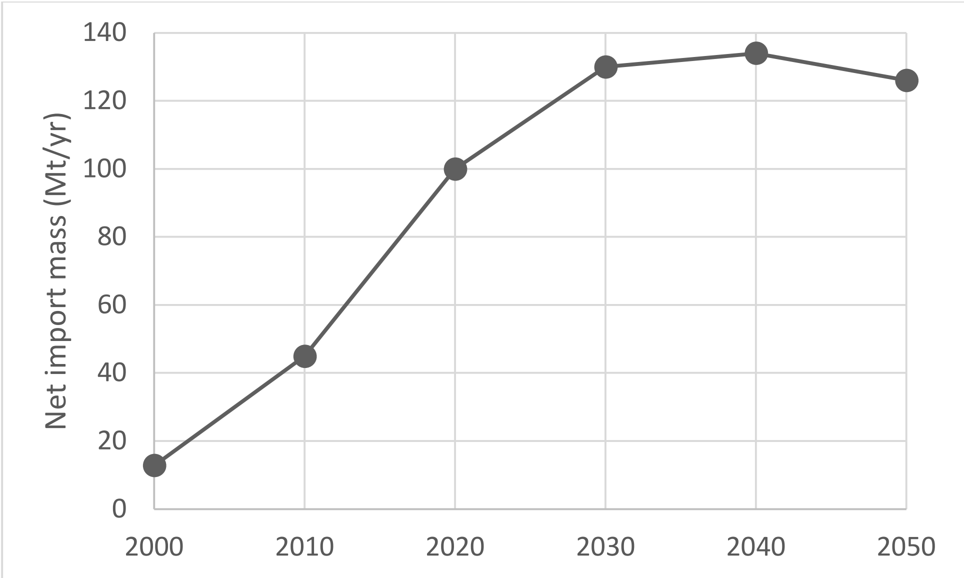


Figure 29: Historic and projected Chinese soybean imports (mass). Data obtained from (ZHAO et al., 2021)**.**

As discussed, global soybean exports are currently dominated by Brazil and the U.S.. On average, these two countries accounted for 88% of Chinese soybean imports over the past few years. However, each country's share varied significantly between 2015 and 2020 (ITC, 2022) (Table 12), especially due to the commercial conflicts between China and the U.S. (CNN POLITICS, 2022). To account for the effect of this variability into account, the long-term projection of soybean trade was based on the average market shares over the period 2015-2020 (Brazil 58%; U.S. 30%). The projected flows can be consulted in the Appendix C.

Table 12: Brazil and U.S. share in the Chinese soybean market between 2015 and 2020.

	2015	**2016**	**2017**	**2018**	**2019**	**2020**	**Average**
Brazil	46%	46%	53%	75%	65%	64%	58%
U.S.	40%	40%	34%	19%	19%	26%	30%

Having projected the trade flows, the calculation of the final energy demand depends on the transport work and energy conversion assumptions. Transport work vectors were created using typical travelling distances, which were calculated based one the online tool (SHIPTRAFFIC, 2022) considering major agricultural ports (DERICOFF; PRATER; BAHIZI, 2014; GALE; VALDES; ASH, 2019; SALIN, 2020b). Both in the case of Brazil and the U.S., the shortest maritime routes from major ports were considered (Figure 30). The Santos-Qingdao distance is approximately 11,300 nautical miles, while the New Orleans-Qingdao distance is approximately 10,000 nm (through the Panama Canal).

Figure 30: Maritime soybean trade routes considered in the energy modelling.

Energy conversion was modelled by assigning typical vessels and corresponding energy efficiencies to each trade route. In both cases, a 50,000-dwt bulk carrier was selected as the standard ship. The assumed average fuel consumption (fuel joules per tonne-mile) was obtained by combining IMO's average Energy Efficiency Operational Indicator (EEOI, grams of CO_2 per tonne-mile) for this vessel category (bulk carrier between 35,000 and 59,999 dwt) in 2018 (FABER et al., 2020) with the CO_2 emission factors for HFO and MDO (grams of CO_2 per fuel joules) (FABER et al., 2020). Additionally, conservative efficiency gains were included in the calculation (see Appendix C), engendering a 15% lower specific consumption in 2050 (BOUMAN et al., 2017).

4.3.2. Biofuel supply

The analysis of biofuel supply was based on (CARVALHO et al., 2021a) (see Chapter 3) that identified potential maritime biofuel production sites in Brazil and in the U.S. The closest biofuel supply sites (hotspots) to Santos and New Orleans ports were selected (Figure 31). Production sites were classified as "Sugarcane", "Eucalyptus" and "Residues Mix" in Brazil and "FRs-Louisiana" and "FR-Mississippi", in the U.S, where FR means "Forest Residues". Residues Mix sites represent the utilization of residues from crops available[17] in that region. Three lignocellulosic biofuel production routes from

[17] Sugarcane, soybeans, maize, wheat, eucalyptus, pinus and forest extraction, as evaluated in Carvalho et al. (2021a)

(CARVALHO et al., 2021a) were selected: Alcohol-to-diesel (ATD); FT-diesel (FT-diesel) and Hydrotreated Pyrolysis Oil Diesel (HDPO-diesel). Table 13 presents the biomass and biofuel supply from each pair feedstock-technology.

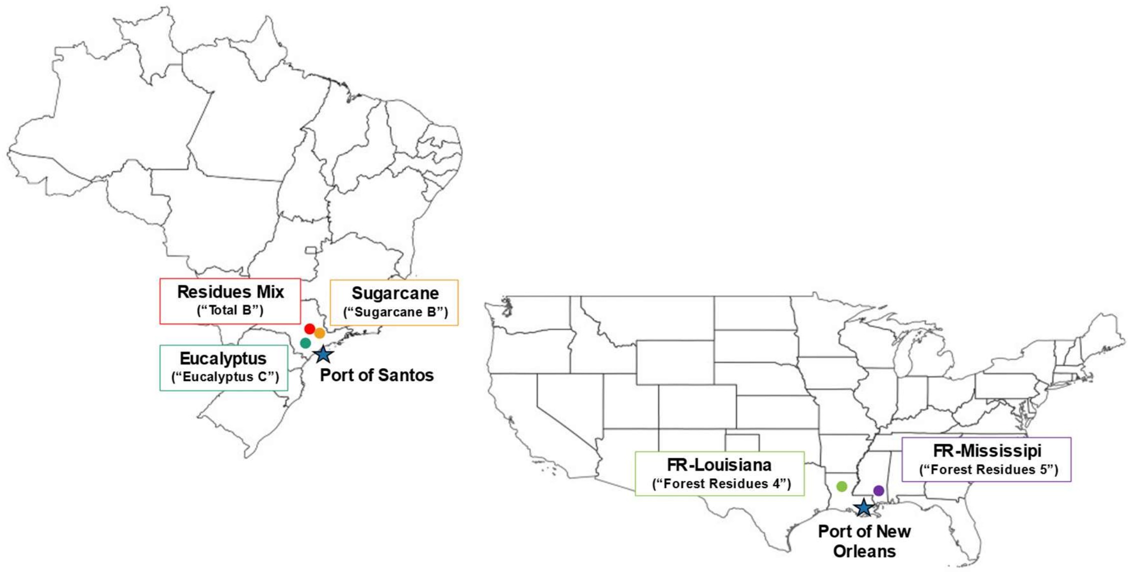


Figure 31: Biofuel supply hotspots (names in parenthesis correspond to nomenclatures used by (CARVALHO et al., 2021a) **(see Chapter 3).**

Table 13: Biomass and biofuel supply potential in the hotspots considered in this study for each pair feedstock-technology.

Supply potential in hotspots (PJ/yr)	Raw biomass residues	FT-BTL	ATD	HDPO-Diesel
Brazil - Sugarcane	118	14.4	31.5	38.4
Brazil - Eucalyptus	52	5.1	12.5	17.3
Brazil – Residues Mix	154	26.2	41.7	46.4
U.S. - FR-Louisiana	20	2.3	4.0	5.2
U.S. – FR-Mississipi	13	1.7	4.0	4.3

The crop productivity from 2020 to 2050 was projected to increase over time (Figure 32). For Brazil, sugarcane-based fuels supply follows the projected sugarcane productivity while for eucalyptus-based fuels the supply follows the forest production increase. For fuel produced in the residues mix hotspot, the average of sugarcane and eucalyptus projections was considered. For U.S., forest-residue-based fuels follows the forest production projections. The projections considered can be consulted in the Appendix C.

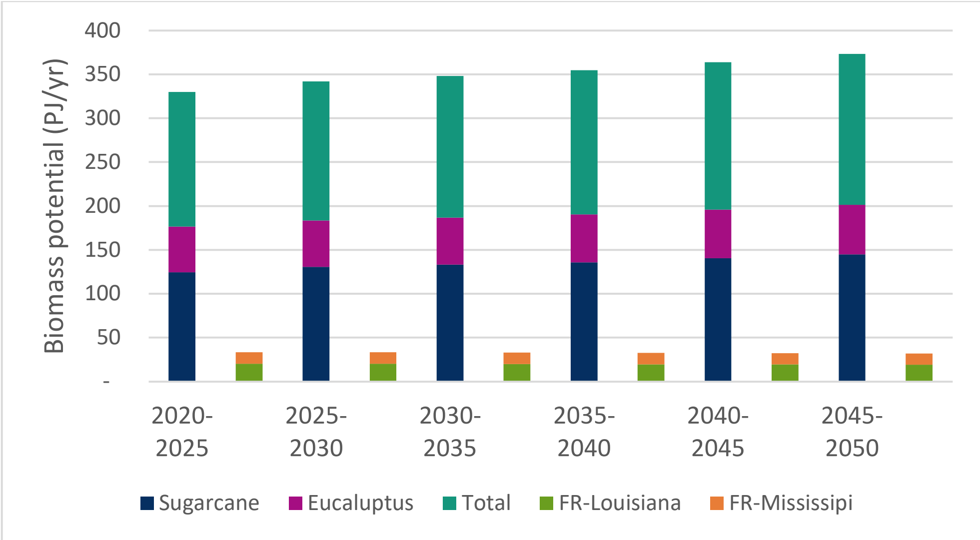


Figure 32: Biomass supply projections in the selected hotspots from 2020 to 2050.

The technologies and the infrastructure to synthetize maritime biofuels are not yet available at a commercial scale. For this reason, two scenarios of maritime biofuels supply expansion were modelled from 2020 to 2050 considering 5-year periods: Conservative and Optimistic. Assumptions were based on the IEA Technology Perspectives (IEA, 2020) and historical ethanol development in Brazil (Observatório da Cana, 2021) Table 14.

IEA (2020) estimates that lignocellulosic maritime biofuel technologies would take 6-8 years from first large prototypes to a full-scale demonstration followed by a 7-10 years period to a first commercial introduction. Thus, the conservative scenario considers the first commercial introduction of maritime biofuels within 20 years (around the upper boundary of IEA estimates), while in the optimistic scenario it takes 10 years (around the lower boundary of IEA estimates). After reaching commercial scales, maritime biofuels introduction would follow a similar trend as observed in the Brazil´s ethanol industry, whose production peaked in its first 15 years. In the initial 5 years, 20% of peak capacity was achieved and 60% within 10 years.

A baseline scenario where no biofuel is used is also considered for comparison purposes. In this case, fuel supply follows the demand projections as presented in Section 4.3.1. Table 14 presents the assumptions considered for biofuels uptake in each scenario.

Table 14: Assumptions for biofuel uptake in the optimistic and conservative scenarios. Based on (IEA, 2020; OBSERVATÓRIO DA CANA, 2021)

Period	% of total potential entering into operation

	Conservative	Optimistic
2020-2025	0%	0%
2025-2030	0%	0%
2030-2035	0%	5%
2035-2040	5%	20%
2040-2045	20%	60%
2045-2050	60%	100%
Note: Baseline scenario considers no biofuel use, thus, the percentage of biofuel uptake is zero from 2020 to 2050.		

Then, fuel supply was determined for each 5-year period from 2020 to 2050 based on biofuel availability. Given that lignocellulosic biofuels would not be readily available and may not be enough to achieve the demand levels, blends with MGO were considered. Fuel supply from 2020 to 2050 was determined on one-way trip basis (voyage fuel supply). It is worth mentioning that this study did not account for the impacts of freight cost increases on soybean demand. This would require a specific study on the cost pass-through mechanisms and the elasticity of the Chinese demand.

4.3.3. GHG emissions

To evaluate the mitigation potential of lignocellulosic biofuels use in soybean trade from Brazil and U.S. to China, GHG emissions were determined for each scenario. To this end, the emission factors (EFs) of marine gas oil (MGO) and maritime biofuels were considered (Table 15). MGO was the conventional marine fuel considered in this study. The EFs assumed for each pair feedstock-biofuel were based on an attributional life-cycle analysis (LCA) that applied energy allocation methods. Average national data were considered for Brazil and the U.S. Biofuels life-cycle EFs refer basically to the emissions occurring in the upstream activities, given that their combustion emissions are treated as carbon neutral.

Table 15: Emission factors for fossil and biofuels for maritime transportation.

Emission factors (gCO_{2e}/MJ of fuel)		
	Brazil	**U.S.**
FT-BTL	4.4	6.1
ATD	9.3	10.4
HDPO	12.9	15.0
MGO	90.0	
Note: Emissions factor sources		

Brazil: FT-BTL diesel (SCHAEFFER et al., 2020); ATD and HDPO (MORENO RUIZ et al., 2021) U.S.: FT-BTL diesel and ATD - GREET model database (U.S. DOE, 2022); HDPO (KASS et al., 2021) MGO: (ZHOU et al., 2020)

4.3.4. Total fuel costs

Biofuel cost estimates for Brazil and the U.S. include Table 16 feedstock costs, levelized costs of fuel production (LCOF) and transportation costs (Carvalho et al., 2021a) (Table 16). For MGO, average 2019 price (US$ 16.4/GJ) was considered (MABUX, 2022). This study assumed steady biofuel costs and MGO prices from 2020-2050. This is a simplification given the unpredictability of oil prices and the low technology readiness of maritime biofuels. A detailed projection of maritime biofuels cost is out of the focus of this study that seeks, to compare the trade routes in Brazil and the US.

Table 16: Biofuel costs for each pair feedstock-technology.
Source: (CARVALHO et al., 2021a) **see (Chapter 3).**

Biofuel costs (US$/GJ)	**FT-BTL**	**ATD**	**HDPO-Diesel**
Brazil - Sugarcane	27.4	40.4	28.1
Brazil - Eucalyptus	28.0	40.8	27.0
Brazil - Residues Mix	23.1	41.0	27.3
U.S. - FR-Louisiana*	28.7	44.6	30.0
U.S. - FR-Mississipi*	28.7	43.5	31.1
MGO price 2019 (US$/GJ)	16.4		
Note: FR-Louisiana and FR-Mississipi refers to Forest Residue 4 and 5, respectively, in (CARVALHO et al., 2021a) (See Chapter 3).			

After determining the fuel costs for soybean export routes from Brazil and the U.S. to China, the maritime biofuel competitiveness against MGO was assessed in three ways. Firstly, by determining the required CO_2e prices for biofuels costs to reach parity with MGO prices (see equation 7). Secondly, by evaluating the minimum MGO price to reach the maritime biofuels producers price levels, considering the blends used within each period (see equation 8), and finally by determining the maritime biofuel zero profit price (ZPP), as suggested by (CARVALHO et al., 2019). ZPP represents the marine biofuel selling price in a perfect competitive market condition, assuming revenues of carbon credits and excluding selling margins and taxes (see equation 9).

$$P_{CO_2} = \frac{P_{biofuel} - P_{MGO}}{E_{MGO} - E_{biofuel}} \text{ equation 7}$$

$$P_{MGO,R}\ x\ D_{fuel} = P_{MGO}\ x\ D_{MGO} + P_{biofuel}\ x\ D_{biofuel} \quad \text{equation 8}$$

$$ZPP = P_{CO_2} * (E_{biofuel} - E_{MGO}) + P_{biofuel} \quad \text{Equation 9}$$

Where:

P_{CO_2} : CO_2e price (US$/t$CO_{2e}$)

$P_{MGO,R}$: Required MGO price (US$/GJ)

P_{MGO}: Baseline MGO price (US$/GJ)

$P_{biofuel}$: Biofuel "price" (US$/GJ)

D_{fuel} : Total demand for fuel (GJ)

D_{MGO}: MGO demand (GJ)

$D_{biofuel}$: Biofuel demand (GJ)

ZPP: Zero profit price (US$/GJ)

$Note: D_{fuel} = D_{MGO} + D_{biofuel}$

Given that MGO price has strong correlation with crude oil prices and its considerable variability, this study performed a sensitivity analysis by considering two additional MGO price levels (other than 2019 average) according to different Brent oil prices (Table 17).

Table 17: MGO price according to Brent Oil price levels.

Brent (US$/bbl)	MGO (US$/mt)	MGO (US$/GJ)
20	366	9
70	627[a]	16[a]
100	882	22

Note:
[a]Default price level considered in this work (Average MGO 2019 price)

4.3.5. Freight cost calculation

Freight costs for the soybean transport from Brazil and the U.S (via Panama Canal)[18] to China were determined based on (SALIN; AGAPI SOMWARU, 2020). Freight costs influence the competitiveness of soybean exports. These are given by the ocean freight spread, which represents the cost variation between different vessel routes.

[18] The shortest voyage routes were chosen between U.S. and Brazil to China (Section 4.3.1).

Freight costs are composed by fuel costs, crew expenses, ballast bonus payment and canal and port fees. Additionally, assumptions on the cargo capacity, the number of voyage days and the laytime (at both departure and destiny locations) were considered. The expenses not related to fuel were assumed constant over the period.

Fuel costs from 2020 to 2050 were determined according to biofuel blends established for each scenario on voyage basis (Section 4.3.2). Hire rates and ballast bonus were obtained from (SALIN; AGAPI SOMWARU, 2020) and adjusted to 2020 values using GDP deflators (FRED, 2022). Ballast bonus is an additional payment when the ship must sail on ballast to reach the loading port. Port and canal fees and wait times were updated to 2020 values, according to Port Authority information (CANAL DE PANAMÁ, 2022; PORT OF NEW ORLEANS, 2022; SANTOS PORT AUTHORITY, 2022). Table 18 presents all assumptions used to determine freight costs.

Table 18: Assumptions to determine fright costs from Brazil and U.S soybean trade routes to China.

	Brazil (Port of Santos) - China (Port of Qingdao)	U.S. (Port of New Orleans) - China (Port of Qingdao)
Cargo quantity (mt)	60,000	60,000
Vessel type	Panamax	Panamax
Route via	Cape of Good Hope	Panama Canal
Nautical miles	11,285	10,018
Voyage days (at 12 knots)	40	35
Panama Canal waiting time (days)	0	6
Laytime both ends (days)	20	15
Total voyage days	60	56
Daily hire rates (US$/day)	16,698	18,216
Ballast bonus (US$)	657,800	809,600
Fuel costs	Depending on biofuel blend ratios (section 2.2) and costs (section 2.4) from 2020-2050	
Port fees (US$/mt)	0.79	0.85
Panama Canal fees - one way only (US$)	-	151,700
Note: mt: metric tonnes		

4.4.Results

4.4.1. Fuel demand for each route

Figure 33 present the fuel demand from 2020 to 2050 for soybean exports from Brazil (Port of Santos) and United States (Port of New Orleans via Panama Canal) to

China (Port of Qingdao) in voyage bases, respectively. The fuel demand for the Brazil-China route is almost twice of the U.S.-China's due longer voyage distances. The fuel demand is expected to grow from 2020 to 2030, being more expressive for the U.S route (59%) than for Brazil (6%) and mainly driven by the expected increase in soybean imports by China. This is followed by a slight reduction from 2030-2050 given the expected operational efficiency improvements. From 2020-2050 fuel demand is expected to reduce 8% for the Brazilian route, while for the U.S. it is expected to increase 37%.

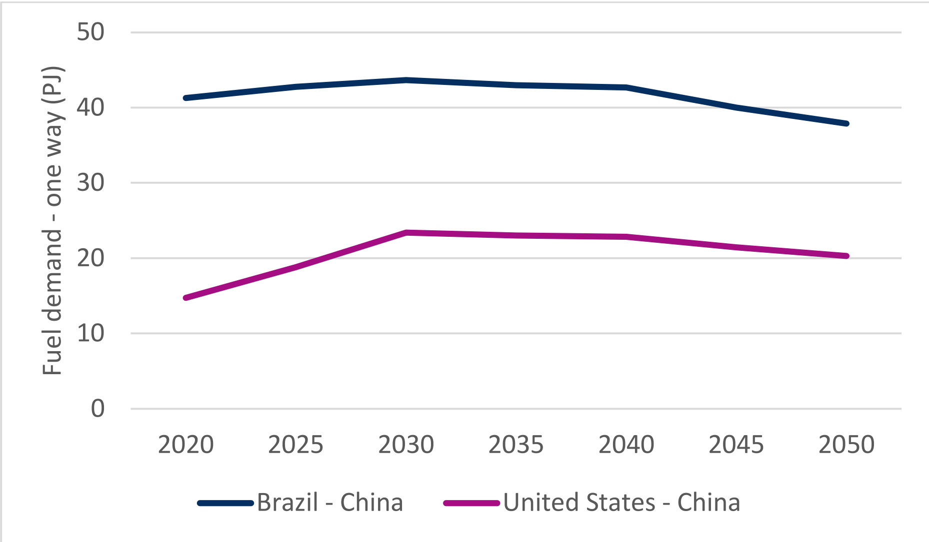


Figure 33: Fuel demand on an one way (voyage) basis from Brazil and U.S to China.

4.4.2. Biofuel supply

The maritime biofuel supply varies according to the pair feedstock-technology and the scenario considered for biofuels uptake.

Figure 34 and Figure 35 present the biofuel supply and the fuel demand from 2035[19]-2050 on a voyage basis for the optimistic and conservative scenarios. The HDPO option achieved highest biofuel supply levels, followed by ATD and FT-BTL. The Brazilian "Sugarcane HDPO-Diesel/ATD" and "Residues Mix HDPO-Diesel/ATD" pathways are able to satisfy total fuel demand in 2050 in the optimistic scenario. In the conservative scenario, only "Residues Mix HDPO-Diesel" satisfy total demand in 2050. Regarding U.S. pathways, the highest supply is observed for the "FR-Louisiana HDPO-Diesel" pathway, achieving 24% of demand in 2050 in the optimistic scenario. In the conservative scenario, maximum supply is observed for the same pathway and

[19] No biofuel production is observed from 2020-2030, thus results for this period were not included in the figures for visualization purposes. Results for the entire period can be consulted in the supplementary material.

corresponds to 15% of demand in 2050. Table 19 presents the share of the voyage fuel in the optimistic and conservative scenarios.

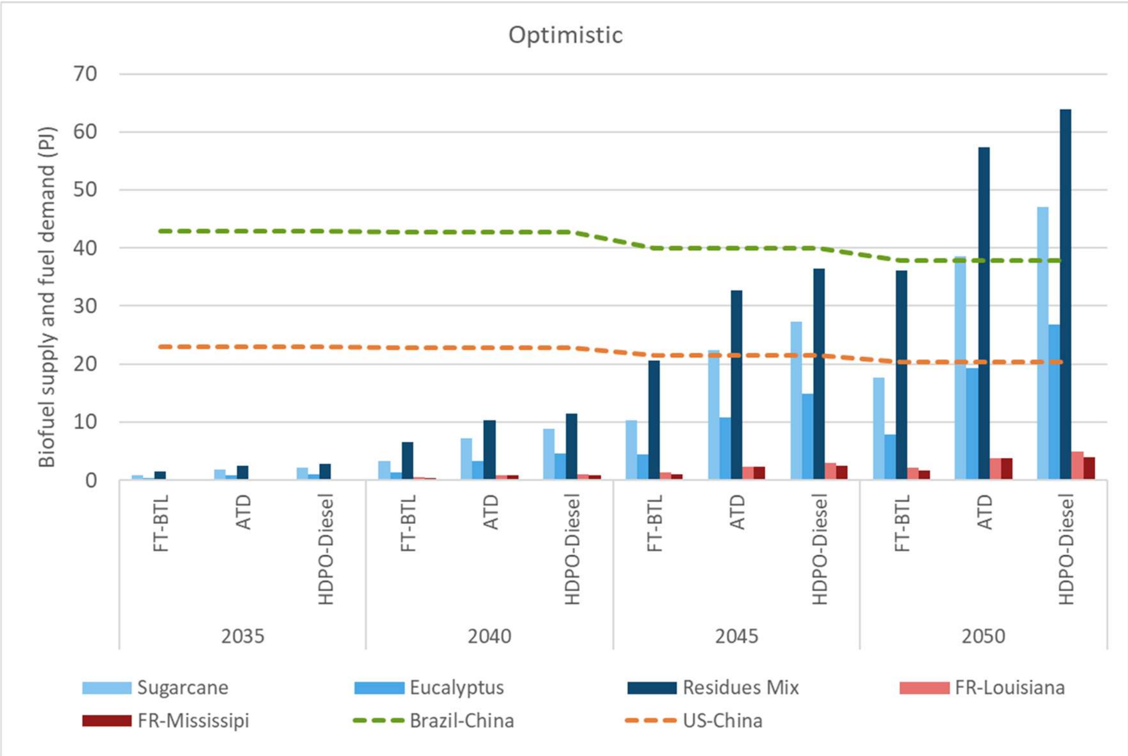


Figure 34: Biofuel supply and fuel demand on voyage basis for the optimistic scenario. Note: Brazil pathways in blue and U.S. in red.

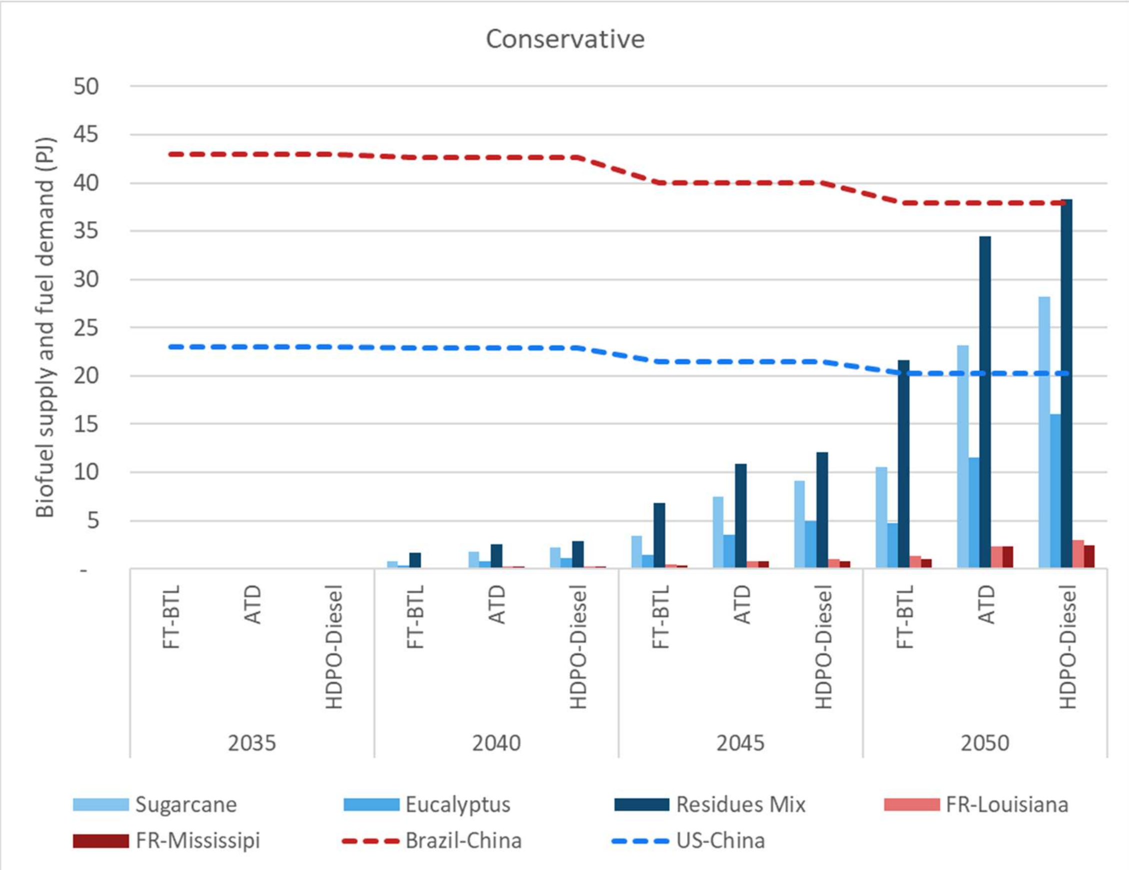


Figure 35: Biofuel supply and fuel demand on voyage basis for the conservative scenario. Note: Brazil pathways in blue and U.S. in red

Table 19: Share of biofuels in 2050 for each hotspot (pair feedstock technology).

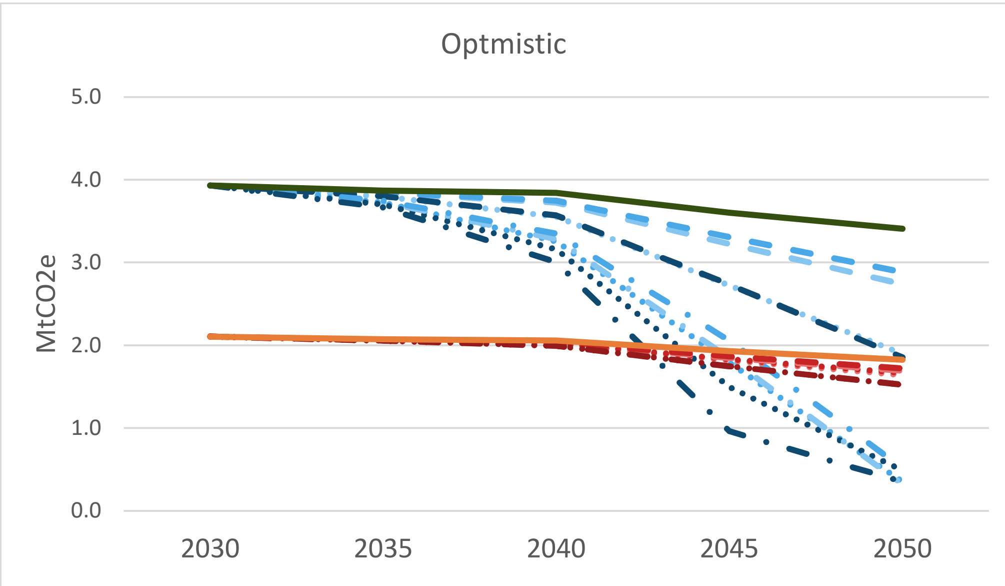
Share of fuel voyage demand attained by biofuels in 2050 (%)							
Region	**Feedstock/ Technology**	**Optimistic**			**Conservative**		
		FT-BTL	**ATD**	**HDPO-Diesel**	**FT-BTL**	**ATD**	**HDPO-Diesel**
Brazil	Sugarcane	47	100	100	28	61	74
	Eucalyptus	21	51	71	12	30	42
	Residues Mix	95	100	100	57	91	100
US	FR-Louisiana	11	19	24	7	11	15
	FR-Missisipi	8	19	20	5	11	12

4.4.3. GHG emissions

Figure 36 shows the GHG emissions for the biofuel pathways for the soybean trade routes from Brazil and U.S. to China in the optimistic and conservative scenarios. Emissions in the baseline scenario totalize 3.4 and 1.8 $MtCO_{2e}$ for the Brazilian and U.S. routes, respectively. Brazilian biofuel pathways lead to higher GHG emissions reduction, abating up to 91% of the emissions in 2050 ("Residues Mix FT-BTL") in the optimistic scenario. Given the higher biofuels blends (Table 8), five Brazilian pathways ("Residues

Mix HDPO-Diesel/ATD/FT-BTL", "Sugarcane HDPO-Diesel/ATD") registered lower emissions than U.S. pathways in the optimistic scenario, even with the higher transport distances. U.S. biofuel pathways reach a maximum of 17% reduction ("FR-Louisiana/FR-Mississipi-HDPO Diesel") in GHG emissions in 2050 in the optimistic case.

In the conservative scenario, maximum 82% and 10% GHG emissions reduction in 2050 are observed for "Residues Mix HDPO-Diesel" in Brazil and the "FR-Louisiana/FR-Mississipi-HDPO-Diesel" in the U.S., respectively. Even with the higher biofuel blends, Brazilian pathways present higher emissions than the U.S. for all biofuels, except for three hotspots ("Residues Mix HDPO-Diesel/FT-BTL" and "Sugarcane HDPO-Diesel") reaching a minimum of 0.6 $MtCO_{2}e$ in 2050 (Residues Mix HDPO Diesel), 62% lower than lowest U.S. biofuel pathways emissions in 2050 (1.6 $MtCO_{2e}$).



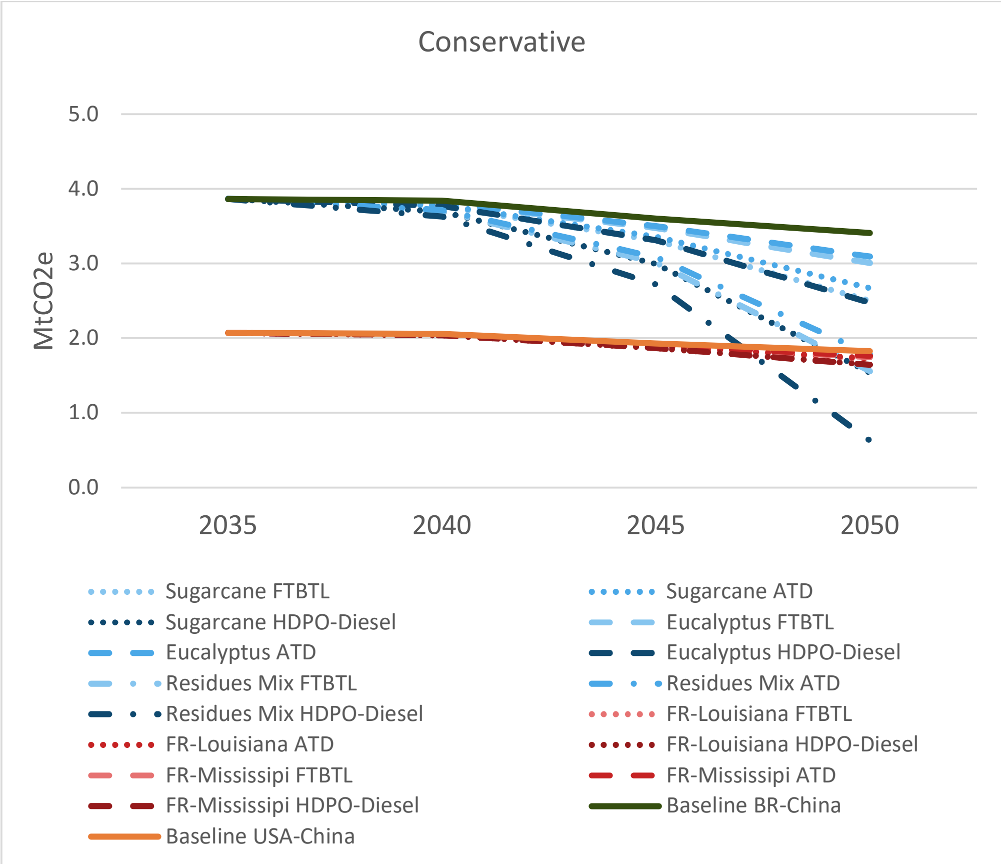


Figure 36: GHG emissions for the soybean trade routes from Brazil and U.S. to China in the optimistic and conservative scenarios. Note: Brazil pathways in blue and U.S. in red.

4.4.4. Total fuel costs

Figure 37 present the yearly cost increase relative to baseline for the optimistic and conservative scenarios, respectively. Baseline cost in 2050 totalize US$ 621 and US$ 333 million dollars for the Brazilian and U.S. routes, respectively. In the optimistic scenario, cost increase reaches the order of US$ 931 million in 2050 while in the conservative scenario it goes up to US$ 706 million. In both scenarios, Brazilian routes present greater cost increase than in the U.S., due to higher maritime biofuel shares. Among biofuel routes, ATD presents the highest cost increase relative to baseline scenario, more than doubling the cost in 2050 in the optimistic scenario ("Residue Mix/Sugarcane ATD").

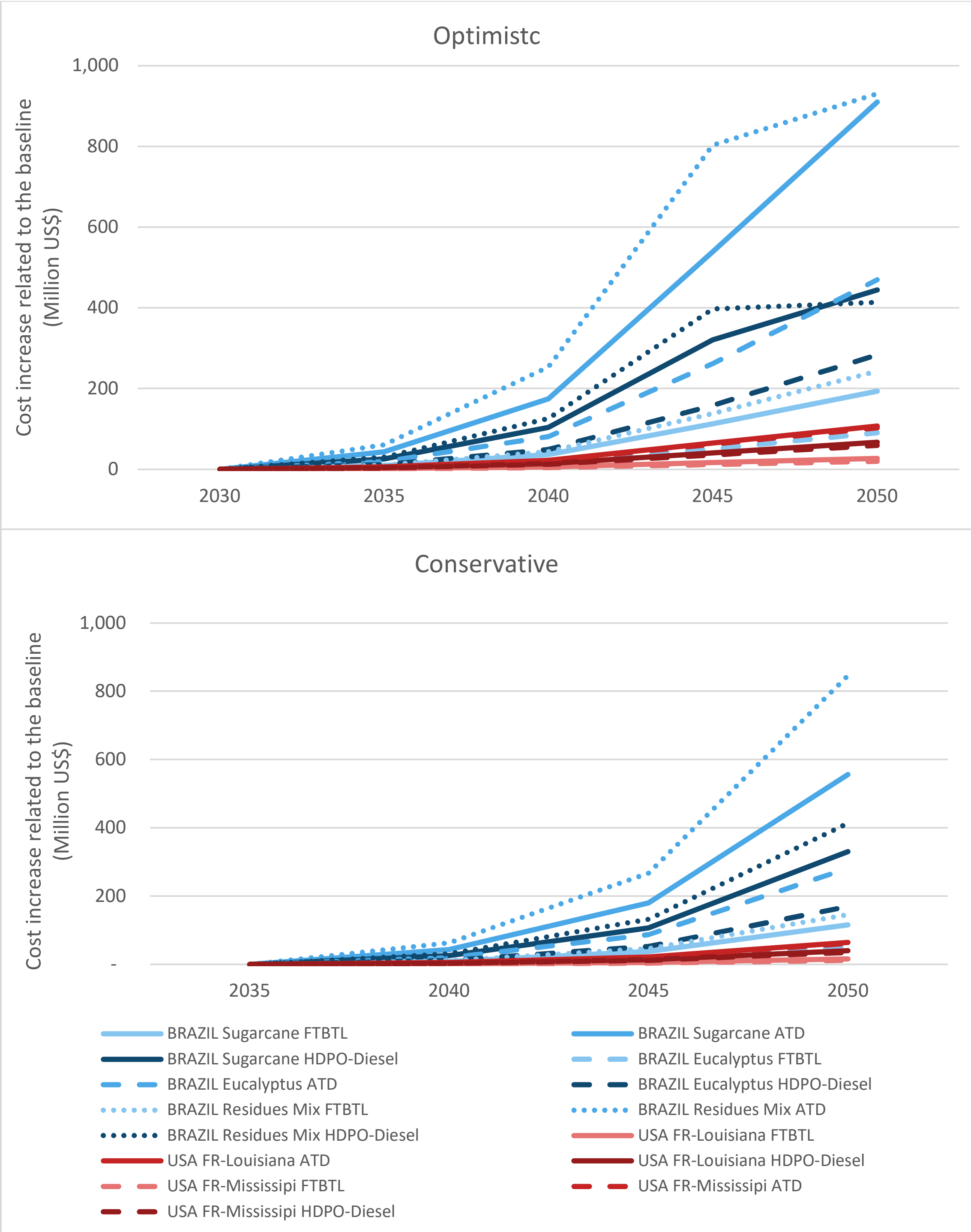


Figure 37: Relative cost increase for the selected pathways for soybean transportation to China. Note: Brazil pathways in blue and U.S. in red.

The mitigation abatement costs for each biofuel pathway are shown in Figure 38. Abatement costs for Brazilian and U.S. maritime biofuel pathways are in similar levels for both regions and exceeds US\$ 300/tCO_{2e}. The lowest abatement cost is observed for the Brazilian Residues Mix FTBTL pathways (US\$79/tCO_{2e}), while the highest is observed for ATD routes. Comparing both regions regarding other biofuel technologies

(FT-BTL and HDPO), Brazilian pathways present lower abatement costs than U.S., while reduces more GHG emissions. The “Residue mix FTBTL” pathway clearly shows both high total avoided emissions and lower abatement cost, while ATD performs badly in terms of costs per tonne of CO_{2e} and typically has lower avoided emissions for the U.S compared to the other fuel technologies. In Brazil, however, it is not the case given that ATD has high avoided emissions.

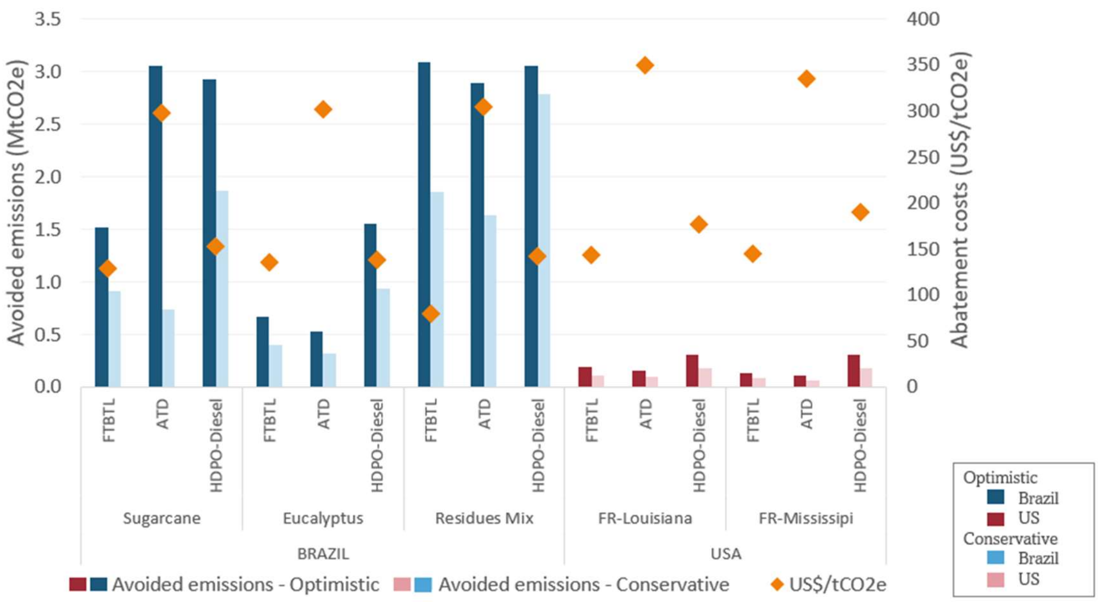


Figure 38: Abatement cost and avoided emissions for each biofuel pathway in the optimistic and conservative scenarios.

Required MGO prices for biofuels to reach price parity were determined for all hotspots in the optimistic and conservative scenarios. Results show that increased MGO prices enable sooner competitiveness of biofuels (Figure 39). In the optimistic scenario, for oil prices between US$ 70-100/bbl, most of biofuel pathways are competitive by 2050. Only four biofuel pathways require higher MGO prices to reach competitiveness (“Residues Mix HDPO-Diesel/ATD” and “Sugarcane HDPO-Diesel/ATD”). In the conservative scenario, only two biofuel pathways are not competitive with oil prices below US$100/bbl (“Residues Mix/Sugarcane ATD”).

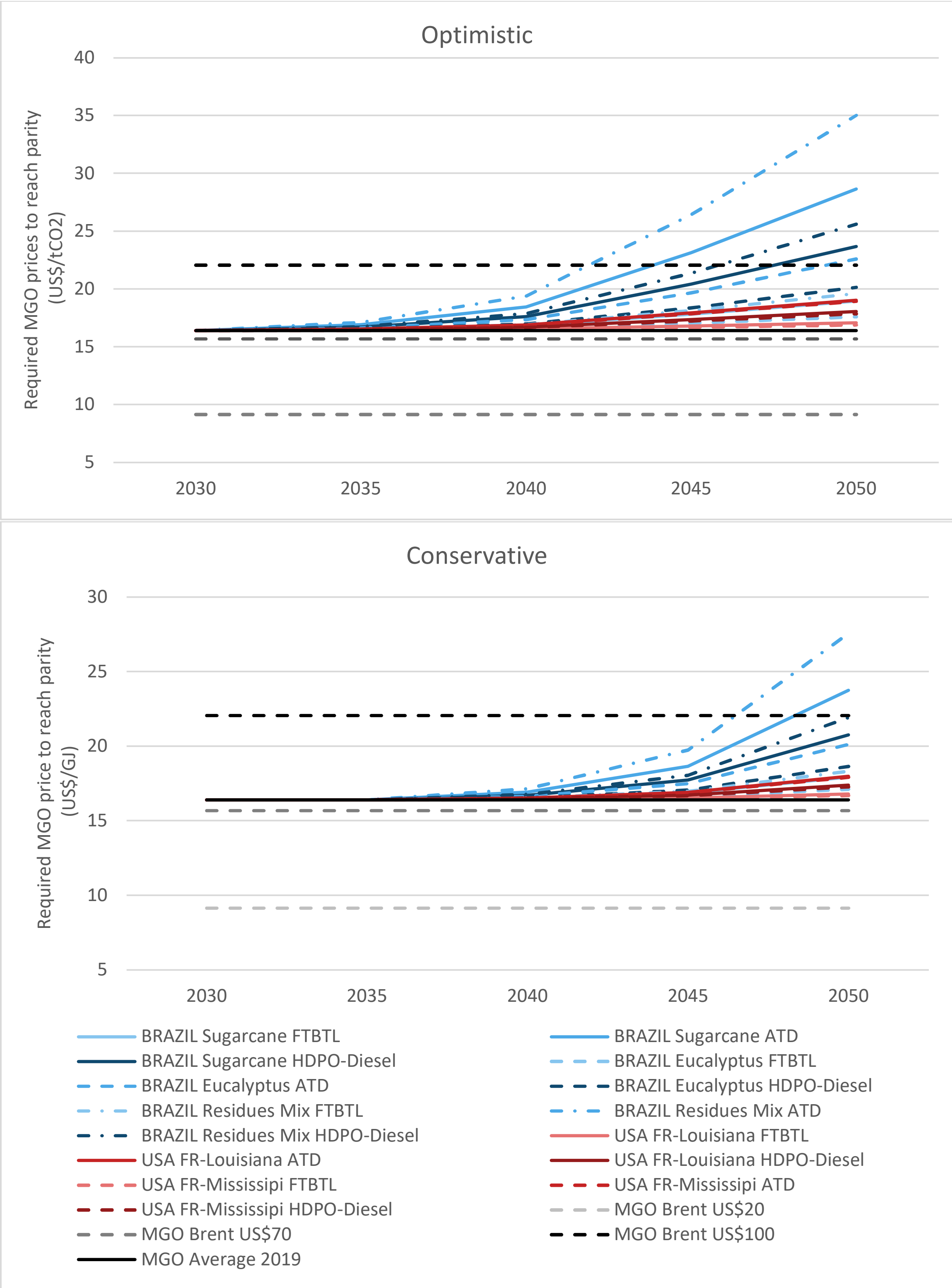


Figure 39: Required MGO prices for each biofuel pathway from 2020 to 2050 compared with different MGO price levels for the optimistic and conservative scenarios.

Biofuels ZPP was determined according to different CO_{2e} price levels and considering average 2019 MGO price (US$16/GJ) (Figure 40). The competitiveness of biofuels can be observed when their ZPP are lower than MGO price. Results reveal that below US$100/t$CO_{2e}$, no biofuel pathway is competitive; at US$100/t$CO_{2e}$, only one registered competitive ZPP ("Residues Mix FT-BTL"). At US$150/t$CO_{2e}$, four additional pathways register competitive ZPP: two Brazilian ("Sugarcane FT-BTL", "Eucalyptus FT-BTL") and two from the U.S. ("FR-Louisiana FT-BTL" and "FR-Mississippi FT-BTL"). Increasing to US$200/t$CO_2$ three additional biofuel pathways reaches competitive ZPP ("Sugarcane HDPO-Diesel", "Eucalyptus HDPO-Diesel" and "Residues Mix HDPO-Diesel"), all Brazilian. The seven biofuel pathways left ("Sugarcane ATD", "Eucalyptus ATD", "Residues Mix ATD", "FR-Louisiana/-Mississippi HDPO-Diesel", "FR-Mississippi ATD/ HDPO-Diesel") would require carbon prices higher than US$200/t$CO_{2e}$. All ZPP values can be consulted in the Appendix C.

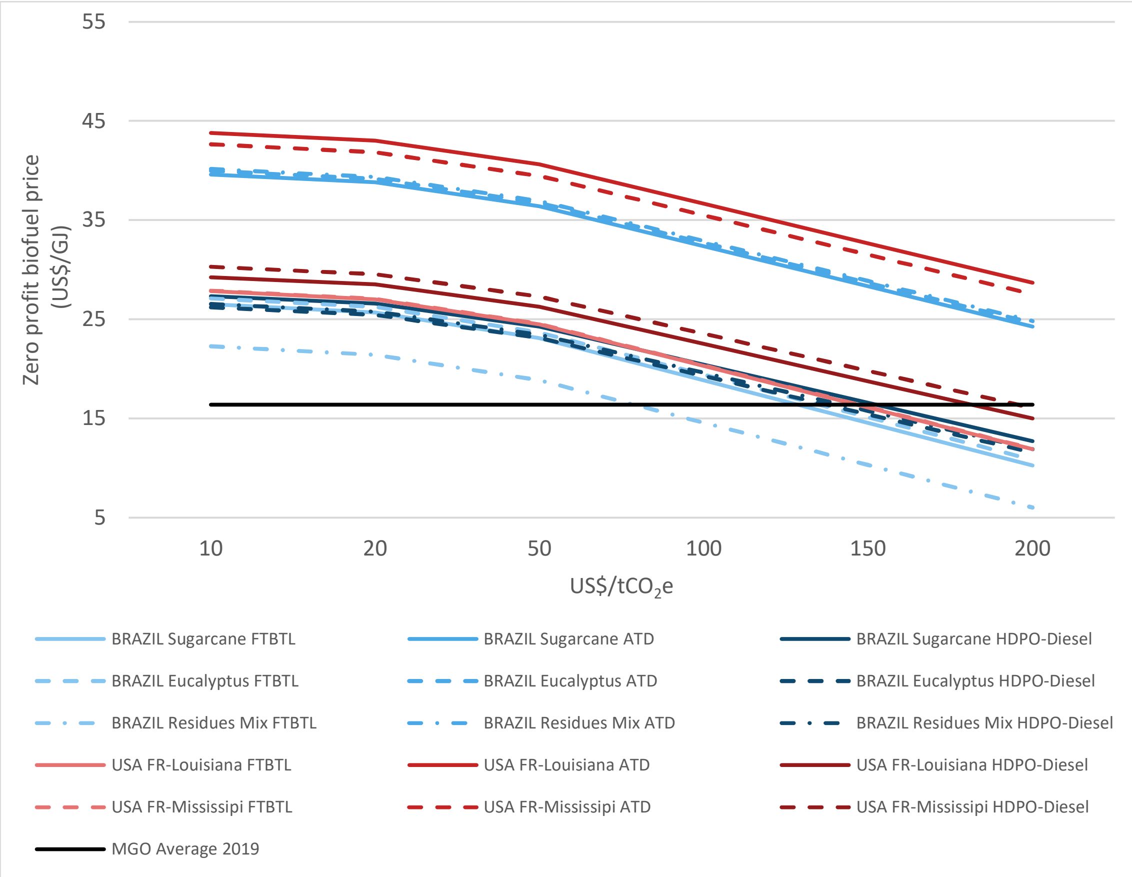


Figure 40: ZPP of biofuel pathways for different CO2e price levels.

4.4.5. Impacts on freight

4.4.5.1. Freight costs

Freight costs were determined for each pathway according to biofuel share on voyage basis (section 4.3.2 and 4.3.5). Figure 41 present the freight costs, given in US$ per tonne of transported soybean in 2050 for the optimistic and conservative scenarios for the FT-BTL, ATD and HDPO pathways. Brazilian pathways present lower freight costs than the U.S. for all cases. In the optimistic scenario the difference between Brazilian and U.S. freight costs ranges from 9% ("Residue Mix ATD") to 26% ("FT-BTL Eucalyptus"). In the conservative scenario the spread between Brazilian and U.S fright costs goes from 21% ("Residues Mix ATD") to 26% (all FT-BTL pathways and "Eucalyptus HDPO").

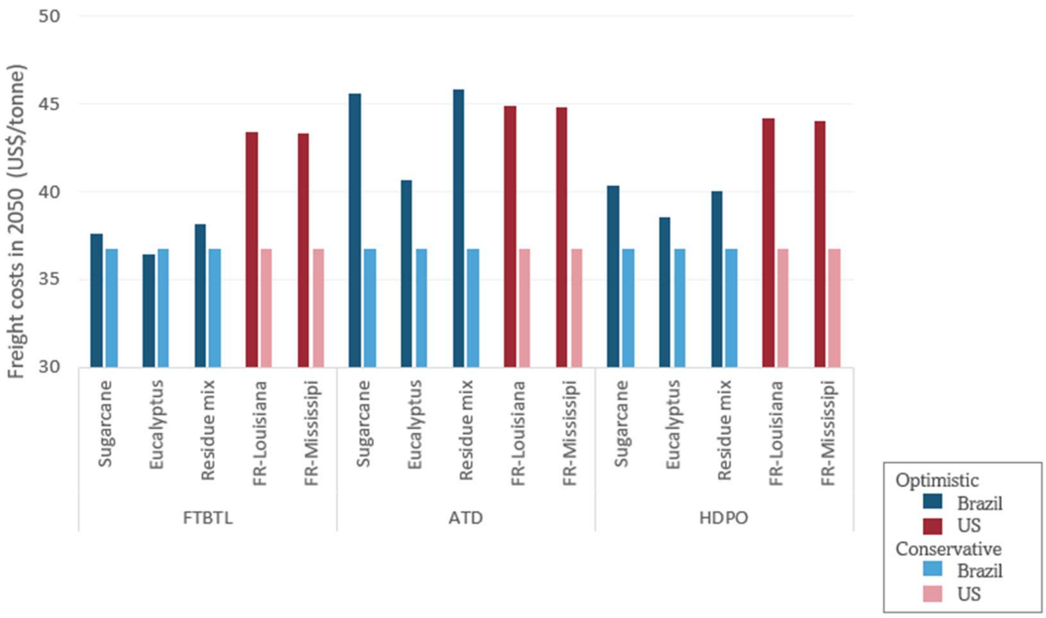


Figure 41: Freight costs in 2050 in the optimistic scenario.

However, given the higher biofuel blends, the increase in freight relative to baseline is more significant for Brazilian than for U.S. pathways, especially for ATD, reaching more than 25% increase in 2050 for both optimistic and conservative scenarios

(Figure 42). For the U.S. cost increase relative to baseline reaches up to 5% and 3% for ATD in the optimistic and conservative scenarios, respectively.

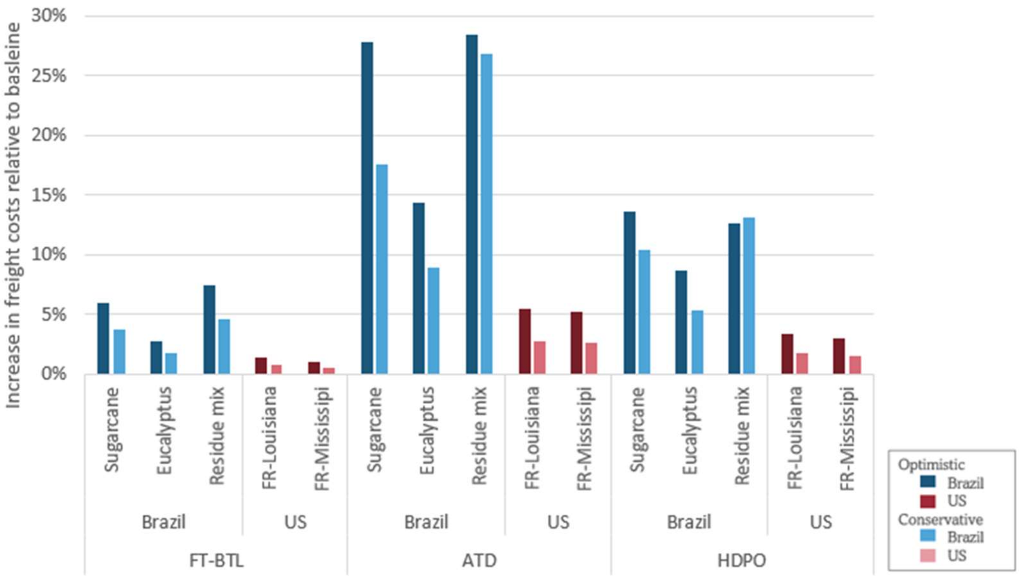


Figure 42: Freight cost increase relative to baseline in 2050 for the optimistic and conservative scenarios.

As freight costs are composed by costs other than fuel, the fuel share in total freight costs were determined for the Brazilian and U.S routes in both scenarios. In the best case, the fuel share in total freight costs is as low as 15% (FT-BTL for the FR-Louisiana/Mississippi) and can be as high as 38% for "Sugarcane ATD" in the optimistic scenario. Fuel share in freight costs is lower for the U.S. pathways given the port and canal fees expenses. Fuel share in freight costs in 2050 for all pathways can be consulted in the Appendix C.

4.4.5.2. Avoided emissions per cargo transported

Using the biofuel shares on voyage basis (section 4.3.2), the emission factors (section 4.3.3) and the amount of soybean transported by ships (section 4.3.5), it was possible to estimate the avoided emissions per tonne-kilometer of soybean transported from Brazil and U.S. to China from 2020 to 2050 (Figure 43). In the optimistic scenario, maximum avoided emissions per mt of soybean are observed for Brazilian "Residues Mix FT-BTL" pathway (-1.7gCO_{2e}/tonne-km). This is almost six times the best U.S. case, observed for "FR-Louisiana and FR-Mississippi HDPO-Diesel" (-0.3 gCO_{2e}/tonne-km). In the conservative scenario, the highest avoided emissions among all evaluates routes per mt of soybean are observed for "Residues Mix HDPO-Diesel" (-1.4gCO_{2e}/tonne-km) in Brazil, more than eight times higher than best U.S. pathway (FR-Louisiana and FR-Mississippi HDPO-Diesel, -0.17 gCO_{2e}/tonne-km).

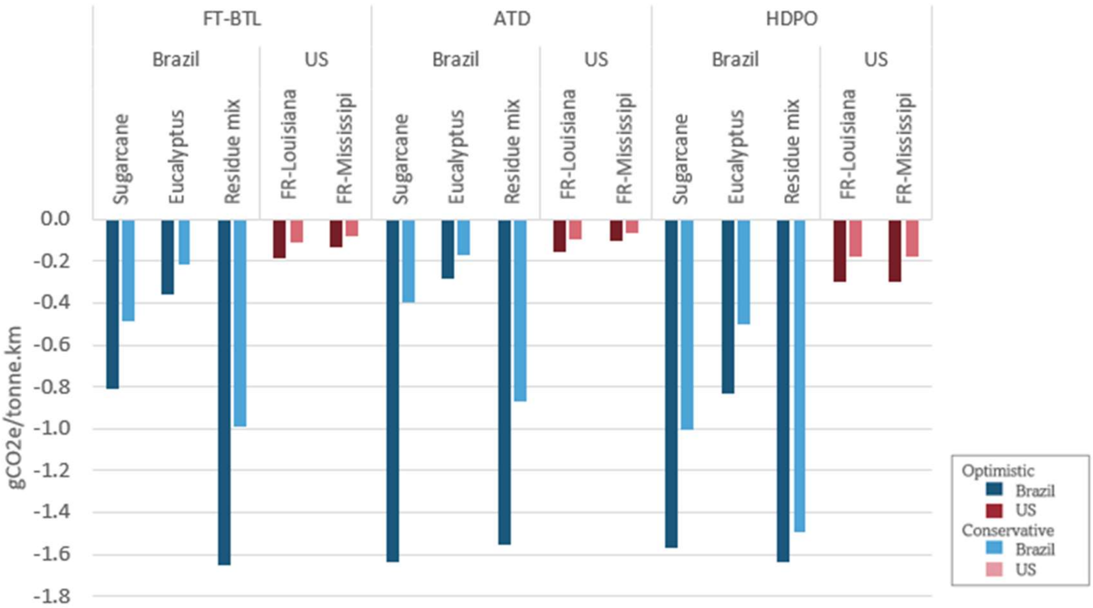


Figure 43: Avoided emissions per tonne-kilometer of soybean transported in 2050 in the optimistic and conservative scenarios.

4.5.Discussions

This study evaluated the maritime biofuel use in selected soybean trade routes from Brazil and U.S to China from 2020 to 2050. Maritime biofuel shares were determined according to projected fuel availability near soybean loading ports. Available maritime biofuel amounts were assumed to entirely supply the selected trade routes, without considering competition of other sectors, such as heavy road and aviation transport sectors. Furthermore, bunkering ships do not necessarily occur in loading ports, but follows logistic and cost advantages, such as the geographic location along busy trade routes, steady fuel supply and lower fuel prices. Also, bunkering is not specific for determined ship types, products or trade routes. In this sense, considering the use of maritime biofuel blends for a specified product trade is an approximation of reality.

Nevertheless, this work intended to perform a case study for trade routes that would be more sensitive to freight cost increase by using low-carbon and, therefore, more expensive fuels. Further, given the need to decarbonize the maritime sector, the availability of new fuels and propulsion technologies is expected to affect the bunkering dynamics worldwide. In this sense, regions capable of supplying alternative fuels may become future bunkering hubs and benefit from being more competitive in their exports.

Regarding biofuel supply estimates, only the available biofuel hotspots near the Port of Santos (for Brazil) and the Port of New Orleans (for the U.S.) were considered based on (CARVALHO et al., 2021a)). Even though such assumptions benefited Brazilian pathways, considering biofuel availability near consuming centers facilitates logistics, minimize costs and emissions in production chain. Additionally, this study assumed two distinct hotspots for the same feedstock in the U.S. (forest residues). Given their proximity, merging them into a single hotspot would lead to higher supply in U.S. trade route. However, given that biofuel costs are different in each one as presented in (CARVALHO et al., 2021a), they were kept as separate biofuel hotspots.

Total biofuel supply differs significantly in optimistic and conservative scenarios. Optimistic scenario assumptions consider a faster technology development of biofuel technologies, reaching commercial scales in half the time compared to the conservative scenario. Biofuel supply in the optimistic scenario meets the demand levels in four biofuel pathways (all Brazilian), while in the conservative scenario it reaches up to 84% of the demand.

Table 20 summarizes the main results obtained regarding the following topics: maximum avoided emissions in 2050, highest cost increase in 2050, abatement costs range for the evaluated biofuel pathways and maximum increase in freight rates in 2050. Bellow, a detailed discussion in each of these topics are presented.

Table 20: Summary of main findings

	Avoided emissions in 2050 ($MtCO_{2e}$)		**Maximum costs increase relative to baseline**		**Abatement costs (US$/$tCO_{2e}$)**		**Maximum increase in freight rates**	
	O	**C**	**O**	**C**	**Low**	**High**	**O**	**C**
Brazil	3.1	2.8	150%	136%	79	304	28%	27%
U.S.	0.3	0.2	32%	19%	144	349	5%	3%

Note:
O: Optimistic
C: Conservative

Total emissions for soybean transportation from Brazil and the U.S. to China were determined based on region- and technology-specific emission factors for the biofuel pathways based on available life cycle emissions data estimated following a common methodology. Brazilian biofuel pathways lead to higher GHG emissions reduction given the higher biofuel shares from 2020 to 2050. In the optimistic scenario, Brazilian maritime biofuels pathways reduced up to 91% of GHG emissions in 2050 relative to baseline, while U.S. pathways reached a maximum of 17%. Similar results were observed in the conservative scenario, where reductions of up to 82% and 10% in GHG emissions were observed for Brazil and the U.S. in 2050, respectively.

To estimate fuel costs of soybean trade routes, steady MGO prices and biofuel costs levels were assumed from 2020 to 2050. Although such assumption is a simplification of the complexity of oil markets, the volatility of oil prices, subjected to market forces, geopolitical and other diverse factors, and the low technology readiness of lignocellulosic biofuel technologies, hamper long-term price/cost projections. The analysis performed tried to capture these uncertainties by using a range of values (two for the biofuels penetration rate and three for the Brent prices). Also, biofuel cost used in the analysis is based on Nth of a kind (NOAK) plants LCOF estimates, which besides excluding taxes and margins that compose final fuel prices, tends to underestimate capital costs and overestimate fuel yields (DE JONG et al., 2015b; MERROW; PHILLIPS; MYERS, 1981; MORRISON et al., 2016).

Results revealed that cost increase is more significant for Brazil. In both optimistic and conservative scenario, fuel cost increase reaches more than twice of the baseline in 2050 for some Brazilian pathways. In the U.S, the fuel cost increase reaches up to 32% and 19% in the optimistic and conservative scenario, respectively. Abatement costs varied from US\$ 79/tCO_{2e} (“Residues Mix FTBTL”) to US\$ 371/tCO_{2e} (“FR-Louisiana ATD”). However, lower abatement costs were observed for all Brazilian pathways compared to the U.S., while reducing on average 8 times more GHG emissions. Values obtained are comparable to estimates for marine biofuels reported by Lindstad et al. (2015) (~ US\$ 200/tCO_{2e}) and Tan et al. (2021) (up to US\$ 400/tCO_{2e})[20]. The results are also in line abatement cost reported for other alternatives to decarbonize the marine sector, such as electrofuels (up to US\$800/tCO_{2e})(MALINS, 2017).

ZPP results reveal that for CO_{2e} prices below US\$100/tCO_{2e}, no biofuel pathway is competitive. At US\$ 100/tCO_{2e}, only one Brazilian biofuel pathway registered competitive ZPP (Residues Mix FT-BTL). When it increases to US\$ 150/tCO_{2e}, only 30% of the evaluated biofuel pathways are competitive. Nearly half of the evaluated pathways (47%) would require carbon prices higher than US\$ 200/tCO2e to be competitive. ZPP results are consistent with 2050 carbon prices from the IPCC Sixth Assessment Report for 2°C (US\$ 65-130/tCO_{2e}) and 1.5°C (US\$ 467-1075/tCO_{2e}) mitigation pathways (IPCC, 2022). Additionally, (HANSSON et al., 2019) revealed that

[20] Depending on the reference marine fossil fuel price considered.

carbon prices above 300 $/tCO_{2e}$ would be necessary to promote the competitiveness of alternative marine fuels.

Regarding freight costs, the Brazilian pathways could keep lower levels than U.S. even with higher biofuel use. However, in relative terms, the freight cost increase compared to baseline is more significant for Brazil, reaching a 28% increase in the optimistic scenario, while for U.S. the maximum is 5%. Furthermore, fuel represents a higher share of freight rates for Brazilian pathways (up to 38%) compared to the U.S. (up to 19%), which indicate that Brazil's competitiveness in soybean trade to China could be more sensitive to the utilization of more expensive fuels. Notwithstanding, avoided emissions per tonne-kilometer are more significant for Brazil, reducing up to 6 and 8 times more emissions compared to the U.S. in the optimistic and conservative scenario, respectively.

To sum up, drop-in maritime biofuels may play a role in long maritime trade routes of agricultural commodities given the need of low-carbon fuels with higher energy density to guarantee ship autonomy and optimize cargo space. Regions capable of supplying such fuels may emerge as future maritime bunkering hubs. However, biofuel supply potentials evaluated in this study were limited to areas near selected soybean export ports. Although maritime biofuel use increases overall fuel costs, it may not provide significant spread in total cost for the soybean importer, as the freight costs are well below soybean prices (average US$ 270/tonne in 2020) (MACROTRENDS, 2022). Nevertheless, lignocellulosic biofuel technologies are not commercially available yet and their actual prices can be far higher than the costs estimates considered. Additionally, the volatility of oil prices and the application of carbon taxes in maritime transport may influence biofuels competitiveness.

4.6. Final remarks

This work performed a case study to evaluate the utilization of lignocellulosic marine biofuels in soybean supply routes to China from Brazil and the U.S. The study assessed the maritime biofuel supply potential near selected soybean export ports and estimated annual fuel costs, GHG emissions and potential increase in ocean freight rates from 2020 to 2050. This is the first attempt to assess the maritime biofuel use in a specific product trade that identified competitive advantages for biofuels use in the maritime transport, which could be replicated for other fuel types, trade commodities and maritime trade routes.

The estimated maritime biofuel supply considered two scenarios for biofuels uptake, given that their technologies would not be readily available in the short-term. Under the optimistic scenario, four Brazilian biofuel pathways supply could meet the total Brazil-China fuel demand, while for the U.S maximum biofuel supply levels represent 24% of the demand. In the conservative scenario, one Brazilian pathway supply meets the demand levels, while for the U.S. maximum supply corresponds to 15% of the demand.

Brazilian biofuel pathways lead to higher GHG emissions reduction. In the optimistic scenario Brazilian pathways reduce up to 91% emissions in 2050, saving up to 3.1 $MtCO_{2e}$ in 2050, while U.S. pathways achieve maximum 17% reduction, that corresponds to 0.3 $MtCO_{2e}$ savings. In the conservative scenario, up to 82% and 10% reduction in GHG emissions were observed for Brazilian and the U.S. pathways in 2050, that correspond to abatements of 2.8 and 0.2 $MtCO_{2e}$, respectively.

The cost increase relatively to the baseline scenario more than double in 2050 for some Brazilian pathways in optimistic and conservative scenarios, while for the U.S. pathways up to 32% cost increase is observed in the optimistic scenario. Among biofuel technologies, ATD registered highest cost increase in 2050, almost doubling the baseline in the optimistic scenario. Abatement costs are high for both Brazilian and U.S. biofuel pathways, reaching levels above US\$300/tCO_{2e}. Lower abatement cost are overall observed for Brazilian biofuel pathways, reaching a minimum of US\$78.8/tCO_{2e}, 50% shorter than lowest U.S. abatement costs estimate.

Lignocellulosic biofuels use in maritime transport could lead to significant cost increase, which may affect trade relationships, countries' economies and food affordability in China. However, the unpredictability and volatility of oil-based bunker fuels prices, places maritime transport subject to fuel price variations which may increase biofuels competitiveness. Additionally, only the application of meaningful carbon taxes in maritime transport and in line with expected global carbon prices, could reduce the price gap of lignocellulosic biofuels, as findings revealed that at least US\$ 100/tCO_{2e} levels would be required. Nevertheless, as the maritime industry is committed to reduce emissions in line with IMO GHG strategy, initiatives and ongoing projects are expected to encourage the development of such drop-in fuels alternatives.

The analysis on freight rate revealed that, even with higher biofuel blends, freight costs remained lower for Brazilian trade routes compared to the US ones. However, the freight costs increase relative to baseline is more significant for Brazil (up to 21% increase in 2050). Nevertheless, fuel share in freight rates is more significant for Brazilian pathways compared to the U.S., which indicates that Brazil's competitiveness in soybean trade to China could be more sensitive to the utilization of more expensive fuels. It is worth mentioning that this study focused on a specific part the soybean supply chain and has not assessed the freight costs impacts on soybean demand in China.

In the end, drop-in lignocellulosic biofuels may play a role in soybean trade routes to China. Biofuel supply potentials evaluated in this study were limited to areas near selected Brazilian and American soybean export ports, which favored Brazilian pathways in terms of higher biofuel share and emissions reduction potential, but at significant fuel cost increase. Such increase has not provided significant freight spread, as Brazilian trade routes could keep lower freight rates even with higher biofuel shares. This indicates that Brazil has competitive advantages to use of biofuel in its soybean trade routes compared to its main competitor.

Finally, despite the efforts to conduct an accurate analysis of lignocellulosic biofuels use in maritime trade, this work presents limitations that should be addressed in future studies, such as:

- Biofuel availability and cost assumptions were based on NOAK plants estimate, that tends to underestimate total levelized cost of fuel and overestimate biofuel yields;
- Ships bunkering was assumed to occur on loading ports and biofuel use considered for a specific product trade route;
- MGO prices and biofuel costs were assumed to be unchanged from 2020 to 2050. Future studies could run a probabilistic approach (e.g. Monte Carlo simulation for a distribution function of Brent prices) to assess the uncertainties regarding oil prices;
- No consideration of competition for biomass residues feedstock between marine and other sectors (aviation, heavy road, etc);

- Increasing productivity of crops and yields does not take into account extreme weather events that may affect crops productivity.
- Evaluate freight costs impacts on soybean trade contract modes and on the elasticity of demand for soybean in China.

5. Conclusions

Low-carbon fuels will be needed to meet international shipping's decarbonization targets. Drop-in biofuels are the readiest alternative, although their potential depends on the characteristics of each potentially supplying region. Prerequisites for introducing novel fuel alternatives include the availability of resources in suitable scales for maritime transport, and the existence of distribution network and bunkering infrastructure. Regions with high availability of resources, required infrastructure and intense port activities may emerge as potential world fuel suppliers. Given the Brazilian biomass availability and background in biofuels production, the country could leverage the production of marine drop-in biofuels, which would contribute to decarbonize the maritime transportation. However, the development of such fuels will require significant investment and production costs, which means that their use in maritime transport can increase fuel expenses. Given that fuel costs are a critical part of vessel's operating costs, the use of alternative and costlier fuels is expected to increase freight rates, thereby affecting the product's costs and trade economic competitiveness.

This thesis therefore aimed to evaluate the Brazilian biofuels contribution to the GHG mitigation goals of the international maritime transport sector t. This included the comparative analysis of promising low-carbon alternative marine fuels in Brazil, the technoeconomic and georeferenced assessment of drop-in biofuels production in different world regions compared to Brazil, and the evaluation of drop-in biofuels use in specific trade routes.

The analysis presented in this work is related to Brazil in different ways, and its choice as a region of focus is driven by: (i) the country expertise in biofuels production, significant share of renewable energy sources and low emission factor of electricity grid, which could be competitive advantages to produce drop-in biofuels; (ii) the inherent characteristics of Brazilian foreign trade that is a major commodity exporter whose long-distance to its main trade destinies increases the carbon emission of its maritime transportation; (iii) the stiff competition faced in commodity exports, whose market share is influenced, among other factors, by the competitiveness of ocean freight rates that could be impacted by fuel shifts in maritime transport.

Herein, this thesis aimed to answer three research questions to evaluate the potential role of Brazilian liquid biofuels to decarbonize maritime transport. The focus of this thesis was on liquid biofuels, given their drop-in characteristics that make them ready decarbonization alternatives. To answer the first research question (*"Are low-carbon drop-in biofuels a promising alternative maritime fuel for Brazil?"*) a multicriteria analysis was developed to compare possible low-carbon alternative fuels for the Brazilian maritime trade. The second research question (*"How does Brazil compare with other major potential drop-in biofuel supplier regions?"*) was addressed by performing an assessment of potential localities for maritime liquid biofuels production in Brazil, Europe, South Africa, and United States considering geographical, logistic, and economic aspects. Finally, to address the third research question (*"Could the use of drop-in biofuels in maritime transport affect the competitiveness of Brazilian exports?"*), a case study was conducted to evaluate the use of lignocellulosic marine biofuels in soybean trade routes from Brazil and U.S. to China, in terms of supply volumes, GHG emissions reduction and potential increase on freight costs. This conjoint analysis of the role of Brazilian liquid biofuels in maritime decarbonization enabled to test what are the most promising low-carbon marine fuels for Brazil; if Brazil would emerge as potential marine biofuel suppliers; or if the use of biofuels in Brazil and its main competitor soybean exports routes could affect the commodity trade.

5.1. Summary and key findings

The first analysis, shown in Chapter 2, applied a multicriteria methodology to compare possible alternative low-carbon fuels for the Brazilian maritime trade. To this end, 14 fuel options were evaluated according to technical, economic, and environmental criteria that were assigned to different weights. Findings revealed that drop-in biofuels (such as Fischer-Tropsch diesel, alcohol-based diesel, straight and hydrotreated vegetable oils (SVO and HVO) and e-diesel) occupied the top-ranking positions (Fischer-Tropsch diesel in the first position, followed by HVO, ATD, SVO and e-diesel) and stood out as the most promising mid-term alternatives. Biomethanol was also ranked high (seventh position) due to its technological maturity and established infrastructure – and the fact that it is liquid at normal conditions. It has good applicability in the current fleet, but demand twice as much space on the vessels when compared to distillate fuels. Other alternatives, such as biomass-based liquefied natural gas (Bio-LNG), green hydrogen and green ammonia, that ranked in ninth, thirteenth and fourteenth positions, respectively, seem to be less competitive alternatives at least in the mid-term for Brazil due to their low energy density, high cots, safety, and applicability issues. Nevertheless, these fuels may become alternatives for short-distance transport in the long-term.

The analysis performed was useful to identify the potential of different alternatives according to the inherent Brazilian characteristics and could support national strategies to comply with the sector's GHG emissions reduction goals. However, important aspects for the development of promising fuel alternatives were not evaluated in details in this study, such as a country-specific evaluation of resources and fuel production potential, competition with other markets and the logistic integration of the production chain.

The second analysis, presented in Chapter 3, identified and assessed potential sites, or hotspots, for marine drop-in biofuels production in Brazil, Europe, South Africa, and United States considering geographical, logistic, and economic aspects. To this end, a combination of georeferenced and techno-economic analyses was conducted to identify fuel production hotspots based not only on plant performance and costs but also on logistic integration and biomass seasonality. Five drop-in biofuel technology pathways were considered: Straight vegetable Oils (SVO), Hydrotreated Vegetable Oils (HVO), Fischer–Tropsch Biomass-to-liquids (FT-BTL), Alcohol oligomerization to middle distillates (ATD), and Hydrotreated Pyrolysis Oil (HDPO). Only direct substitutes for HFO or MGO were considered in this analysis, and it justify why some well-ranked alternative fuels, such as methanol, were left out of this analysis. The choice of these four bunker supply regions was determined by a set of factors such as agricultural production, presence of major world ports and trade centers, and strategic location. Findings indicate that Brazil has the highest marine biofuel production potential due to its biomass concentration, located close to coastal areas and that surpasses regional fuel demand. The Brazilian hotspot with highest biofuel production registered almost 200 PJ/year, while for Europe, South Africa and the U.S. maximum levels observed were up to 90, 50 and 20 PJ/year, respectively. Although other regions registered more limited potentials, hotspots proximity to ports would enable fossil fuel replacements in these areas. For all cases, marine biofuel costs (USD 20-104/GJ) are higher than conventional marine fuels prices (USD 11-18/GJ).

The third analysis, presented in Chapter 4, developed a case study to evaluate the use of lignocellulosic marine biofuels in soybean trade routes from Brazil and U.S. to China. To this end lignocellulosic biofuels produced from agricultural and forest residues were evaluated in terms of supply volumes, greenhouse gas emissions reduction and potential increase on freight costs. Two scenarios of biofuel availability from 2020 to 2050 and three technologies (Fischer–Tropsch Biomass-to-liquids (FT-BTL), Alcohol oligomerization to middle distillates (ATD), and Hydrotreated Pyrolysis Oil (HDPO)) were considered. As in the previous analysis (Chapter 3) only direct substitutes for HFO or MGO were considered in this analysis. The optimistic and conservative scenarios are distinguished by the speed at which total biofuel supply would be available until 2050. Findings revealed that Brazil benefits from higher biofuel supply and some Brazilian biofuel pathways could meet total bunker fuel demand in 2050. However, biofuel use in soybean trade routes is expected to come at significant cost increase with abatement costs reaching levels higher than US$ 300/tCO_2e. Freight cost increase compared to baseline was more significant for Brazil (up to 28% increase in the optimistic scenario) than for the U.S. (maximum 5% increase). Nevertheless, fuel cost increase has not changed the trade competitiveness and Brazilian trade routes could keep lower freight costs than U.S. even with higher biofuel shares. Furthermore, fuel represents a higher share of freight costs for Brazilian pathways (up to 38%) compared to the U.S. (up to 19%), mostly due to the canal fees in the U.S. trade route. This indicates that Brazil has competitive advantages to use drop-in biofuels in its soybean trade routes compared to its main competitor. Notwithstanding, biofuel supply potentials evaluated in this study were limited to areas near selected Brazilian and North American soybean export ports, which favored Brazilian pathways in terms of higher biofuel share and GHG emissions reduction potential.

5.2. Overarching conclusions

In sum, the multicriteria analysis (Chapter 2) showed that drop-in biofuels are the most promising short- to mid-term alternative to decarbonize maritime transportation in Brazil, whose international trade profile is characterized by long-distance transportation of low added-value products. Characteristics that made biofuels promising an alternative are their high energy density and drop-in characteristics. However, the limited availability of sustainably produced biomass in scales suitable for maritime sector and the competition with other energy and transport sectors may hinder its application. In this sense, the adoption of biomass residues that are currently not used are beneficial, given that they reduce concerns related to sustainability and could be produced on large scales. Yet, logistical issues associated with the dispersed location of residues resources and large-scale production plants, can increase the costs and emissions of biofuels.

Furthermore, future climate change impacts under high levels of global warming may reduce the crop yields and therefore reduce the residues supply potential.

In this context, the technoeconomic analysis (Chapter 3) that considered specific feedstock and inputs prices, labor costs, biomass seasonality, and fuel transport modes, revealed that even though total biomass residues potential was greater in Europe, Brazil is the region where the potential is most geographically concentrated among all regions investigated. Although the estimated supply is lower than current demand in most regions, the proximity between potential fuel production areas and ports could incentivize their production. Brazil benefits from having suitable locations for marine biofuel refineries' development. In addition, Brazil is one of the regions with lowest feedstock costs. Regarding drop-in biofuel production technologies, HDPO stands out as the one with higher yields and lowest costs. Nonetheless, it is also the least developed technology, which may compromise its high potential in the mid-term. However, for all regions and technologies, total biofuel costs were higher than conventional marine fuel prices.

Shifting for specific applications of drop-in biofuels use in maritime sector, findings from the applied case study (Chapter 4) emphasized the Brazilian advantages. Under an optimistic scenario, the estimated maritime biofuel supply revealed that some Brazilian pathways could meet the total Brazil-China fuel demand for soybean trade, while in the U.S case maximum biofuel supply represent less than a third of the demand. For this reason, Brazilian biofuel pathways led to higher GHG emissions reduction in maritime transport routes, reaching up to 91% GHG emissions mitigation in 2050, compared to a maximum 17% in the U.S. case. Still, lignocellulosic biofuels use in maritime transport is expected to cause a significant cost increase. Nonetheless, even with higher biofuel blends, freight costs remained lower for Brazilian trade routes compared to the US ones. However, the freight costs increase relative to baseline is more significant for Brazil (up to 21% increase in 2050), which indicates that Brazil's competitiveness in soybean trade to China could be more sensitive to the adoption of more expensive fuels.

Considering all aspects of maritime transport, such as average fleet age, ports infrastructure and inflexibilities to deal with novel fuel alternatives, drop-in biofuels seem a promising alternative to decarbonize maritime sector, at least in the medium-term. Also, realizing that the some GHG emitted now from maritime sector could last more than 100 years in the atmosphere, immediate and far-reaching actions would be needed to stabilize global warming. Thus, betting only in not yet ready options (such as ammonia and hydrogen) for the long term would result in cumulative GHG emissions that needs to be compensated afterwards.

However, this study indicated that liquid biofuels costs are far above conventional fossil marine fuel prices. Still, the unpredictability and volatility of oil-based bunker fuels prices, places maritime transport subject to fuel price variations which may increase biofuels competitiveness. In addition, some measures could reduce the price gap of liquid biofuels, such as the establishment of fuel mandates, the development of biofuel production technologies, and the application of meaningful carbon taxes in maritime transport and in line with expected global carbon prices.

In the end, this thesis highlighted the opportunity of Brazil to produce drop-in biofuels for maritime sector decarbonization. First, drop-in biofuels seem the most promising alternative to decarbonize maritime transportation in Brazil at least in the medium-term, given its international trade characteristics. Second, Brazil could have competitive advantages in terms of biofuel supply and costs, compared to other regions of the world. Third, the utilization of drop-in biofuels in soybeans export routes might not lead to a significant increase in freight costs, therefore not affecting the country competitiveness in international markets.

5.3. Limitations and recommendations for further studies

Despite the efforts to bring relevance to the field, this thesis presents limitations that might be addressed in future work. First, the inclusion and or/choice of new parameters in the multicriteria analysis presented in Chapter 2 would provide alternative ranking results for the evaluated fuels. Second, the feedstock availability assessment presented in Chapter 3 and also used in Chapter 4 has not considered competition for biomass with other sectors such as road and aviation transport and industry nor climate change impacts. Also, regarding the evaluation of bioenergy potential in Chapter 3, the consideration of site-specific parameters (such as residue to product ratio and residue removal rate) within each region would affect the results. Additionally, the techno-economic analysis (in Chapter 3 whose results were also used in Chapter 4) relied on N^{th} plants, which tends to underestimate costs and overestimate fuel production yields compared to pioneer plants. Still in the economic analysis, the choice of fuel transport mode was based on the hotspots' proximity to infrastructure (roads, railways, etc.) and not to main transport terminals, which could increase its transportation costs. Finally, in the analysis presented in Chapter 4, it was assumed that ships bunkering occurs on soybean loading ports and that biofuel use was specific for soybean transport routes, which does not necessarily represent the real-world procedures. Also, MGO prices and biofuel costs were kept constant from 2020 to 2050. This was a simplification given the unpredictability of oil prices and the low technology readiness of maritime biofuels.

To increase the robustness of our results and to expand research lines, the following further research is suggested/proposed:

- Evaluate different levels of maritime fuel blends performance in marine engines and/or establish the maximum feasible blends to assess their applicability and mitigation potential;
- Use integrated assessment models (IAMs) to assess competition of other energy and transport sectors on biomass feedstocks;
- Perform a life cycle assessment to capture in greater detail the mitigation potential of liquid biofuels produced in Brazil, which includes a consequential analysis to capture the indirect impacts of bunker fuel and other products displacement;
- Evaluate impacts of marine biofuels production in terms of local environmental indicators and ecosystem services, such as water resources, air pollution, soil quality, biodiversity, and land competition;
- Expand the case study of soybean trade to other commodities and evaluate the potential creation of green trade corridors;
- Assess biofuel production potential in Asian countries, such as Southeast Asia and China, that represent major maritime transport hubs.
- Develop an integrated assessment study to evaluate potential competition and synergies for biomass resources between other transport sectors and related induced land use changes;
- Conduct deeper studies in the cost formation of the freight rates that discuss how they could change under deep decarbonization scenarios; this might also include the analysis of the cost pass through between producers, fleet operators and consumers. If increasing costs are transferred to consumers, depending on the price elasticity, demand can be affected.
- Develop national policies to promote advanced biofuel production technologies.
- Better assess the adjustments that should be made for introducing drop-in fuels in terms of material compatibilities.

5.4. Final remarks

This thesis emphasizes the opportunities Brazil has to produce and use drop-in marine biofuels. Investing in drop-in solutions for maritime transport would contribute with the achievement of IMO GHG emissions reduction targets and place Brazil as a frontrunner in this decarbonization agenda. Further, this thesis findings reveals that Brazil could have competitive advantages to produce drop-in biofuels, which added to the country experience in biofuels production, could support the establishment of national policies to promote advanced biofuel technologies and attract investments.

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Appendix A

A.1 Fuel properties

Table A 1: Physicochemical properties relevant for maritime fuel specifications

Properties	Description
Density (ρ)	Indicates the weight present in a given volume of fuel. Its specification is useful in determining fuel aromaticity (Calculated Carbon Aromaticity Index, CCAI) and ignition (Calculated Ignition Index, CII) index. The higher the density, the higher are the CCAI and CII, and more difficult is for the fuel to ignite (PETROBRÁS, 2019).
Cinematic viscosity (μ)	Viscosity is crucial for maritime fuels specification, as it determines the storage and handling conditions and the need of a heating system prior to injection. As well as density, it is useful for determining CCAI and CII. Viscous oils must be heated to reach ideal viscosity levels for operation (PETROBRÁS, 2019).
Cetane number (CN)	Cetane number represents fuel ability to ignite when compressed. The higher it is, the easier fuel starts to ignite (cold start)(BLIN et al., 2013; ECOFYS, 2012a; PETROBRÁS, 2019). This parameter is applied only to marine diesel or diesel. For HFO, the ignition quality is indirectly controlled by the CCAI (Calculated Carbon Aromaticity Index) and the CII (Calculated Ignition Index). Higher the CCAI and CII values indicate easier ignition. Low CII values indicate that the fuel hampers the engine start and reduces the operating load (JIMÉNEZ ESPADAFOR et al., 2009).
Calculated Ignition Index (CII) and Calculated Aromaticity Index (CCAI)	For marine fuel oil, the ignition quality is indirectly controlled by the CCAI (Calculated Carbon Aromaticity Index) and the CII (Calculated Ignition Index). As for CN, the higher the CCAI and CII values, easier it is for the fuel to ignite. Low CII indicates that the fuel delays the engine starts and reduces the operating load, increasing combustion temperature and pressure, producing NOx and noise. Low-speed marine diesel engine manufacturers recommend CII values above 30 (JIMÉNEZ ESPADAFOR et al., 2009).
Low heat value (LHV)	The low heat value indicates the energy density of the fuel. It can be expressed on a volumetric (MJ/L) or mass (MJ/kg) basis.
Flash point (FP)	Flash point indicates the lowest temperature at which a liquid can form a flammable mixture in the air near the liquid's surface. Fuels with high flash point are less flammable and/or dangerous. The lower the flash point, the greater the need of safety operational measures of a given fuel.
Cloud point (CP)	Cloud point represents the temperature below which the formation of crystals in the fuel occurs. This parameter indicates the tendency of the fuel to clog filters or small holes at low operating temperatures.
Pour point (PP)	Pour point indicates the temperature below which a liquid loses its flow characteristics. It represents the minimum temperature at which an oil can flow under the action of gravity.

Table A 2: Physico-chemical properties of alternative fuels.

	ρ (kg/L)	μ (40°C) (cSt)	CN (CII)	LHV (MJ/kg)/ (MJ/nm3)	FP (°C)	References
HFO	0.96-0.99	180-380a	(32.7)	40.0-41.0	60	(AATOLA et al., 2008; BABU; SUBRAMANIAN, 2013; EAGAN et al., 2019; ECOFYS, 2012a; IEA BIOENERGY, 2017; JIMÉNEZ ESPADAFOR et al., 2009; KASS et al., 2018; LUNING PRAK et al., 2015a; STENGEL; VIUM, 2015)
MDO/ MGO	0.89-0.90	2.0-11.0	35.0-40.0	45.6	60	
Soybean oil	0.91b	65.00b/9.00c	37.9	39.6	254	
Corn oil	0.92b	48.00b/10.50c	37.6	37.8	277	
Sunflower oil	0.88b	10.00b/7.50c	45.00-52.00	40.6	274	
Biodiesel	0.88	4.00-6.00	47.00-65.00	37.2	>130.00	
HVO	0.78	2.00-4.00	>70.00	44.1	>61.00	
HDPO	0.84-0.90	2.8	High[e]	45.20d	35.00-39.00	
FT-diesel	0.77	2	>70.00	43	74	
ATD	0.76f	2.1f	~50	43-44g	49	
Bio-LNG	0.47	Low	n/a	55.2/(35.80)	-188	(EICHLER et al., 2015; ELLIS; TANNEBERGER, 2015; GIIGNL, 2010)
Bio-methanol	0.79	Low	n/a	19.9	11.1	
Bio-ethanol	0.79	Low	n/a	26.7	16.6	
Hydrogen	0.07e	Low	n/a	120/(10.75)	Flammable	(PUBCHEM, 2020)
Ammonia	0.7	Low	n/a	18.6/(14.10)	132	

Notes:
LHV: Low heating value
n/a: Non applicable
a: at 38°C
b: at 15°C
c: Minimum value
d: High calorific value (HHV) (MJ/kg)
e: References found presented high variability, so it was classified as high or low.
e: Liquid hydrogen
f: Reference values for ATJ
g: Middle distillate average

A.2 Evaluation of alternative fuels

In this study, 14 fuel possibilities were evaluated (see Table A 3) according to 9 criteria (Table A 4).

Table A 3: Groups of fuels considered in the analysis.

Fuel pathways		
Group 1 Liquid distilled biofuels	SVO	Straight vegetable oil
	Biodiesel	Biodiesel produced using FAME/FAEE
	HVO	Hydrotreated vegetable oil

	HDPO	Hydrotreated pyrolysis oil
	FT-diesel	Biomass-derived diesel
	ATD	Alcohol-based diesel (Alcohol-to-Diesel)
Group 2 Alcohol and liquefied gases	Bio-LNG	Liquefied bio-methane
	Bio-CH_3OH	Biomass-derived methanol (bio-methanol)
	Bio-C_2H_5OH	Biomass-derived ethanol (bio-ethanol)
Group 3 Hydrogen, ammonia, and e-fuels	Green H_2	Renewable-based hydrogen
	Green NH_3	Renewable hydrogen-based ammonia
	e-diesel	Renewable hydrogen-based diesel (electrodiesel)
	e-LNG	Renewable hydrogen-based methane (electromethane)
	e-CH_3OH	Renewable hydrogen-based methanol (electromethanol)

Table A 4: Criteria considered in the comparative analysis.

Index	Criteria	Description	Weight
1	**Availability**[a]	Availability of feedstock and infrastructure facilities	2
2	**Applicability**	Compatibility of the fuel with the operating fleet and current infrastructure for transportation, storage, and bunkering	2
3	**Technological maturity**	Readiness level of the production and utilization technologies	2
4	**Energy density**	Volumetric energy density, reflecting the need for space related to fuel storage onboard	2
5	**Economic**[b]	Levelized costs, comprising fuel production, bunkering infrastructure, and ship modifications (engines and tanks)	1
6	**Safety**	Safety in operation, fuel handling and toxicity.	2
7	**Standards**	Existence of fuel standards and/or certifications that prove renewable origin	1
8	**Global sustainability**	GHG emissions related to the fuel use and production and distribution chain and land use changes threats	3
9	**Local sustainability**	Air pollutant emissions (AP), impacts on biodiversity and water resources	1

Notes:
[a] Availability criterion also evaluates the feedstock competition with other sectors.
[b] Fuel levelized costs in the economic criterion includes coproduct benefits/revenues.

For the ratings of criteria 4 (energy density) and 5 (economic), for which there are very straightforward quantifications, a normalization of the indicators was performed. For the other criteria, whose evaluation requires a qualitative analysis, fuel alternatives were penalized according to each disadvantage identified in the criterion. Figure A 1**Erro! Fonte de referência não encontrada.** details the methodology adopted to evaluate fuels in each criterion.

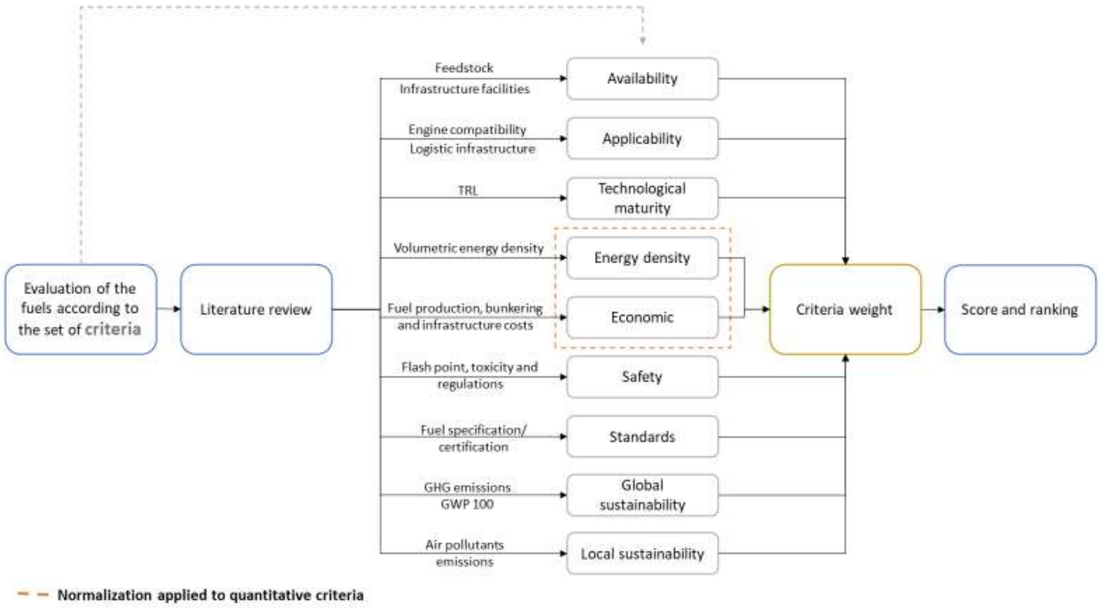

Figure A 1: Evaluation Methodology

In the case of the energy density and economic indicators, the normalization was based on the volumetric energy content of the fuels and on average costs of energy, respectively (Figure A 2 and Figure A 3).

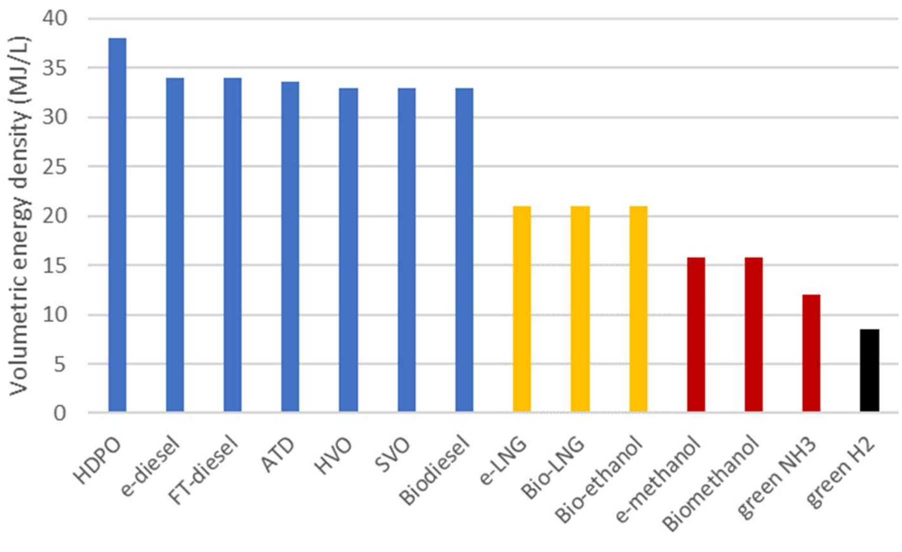

Figure A 2: Volumetric energy density scale.

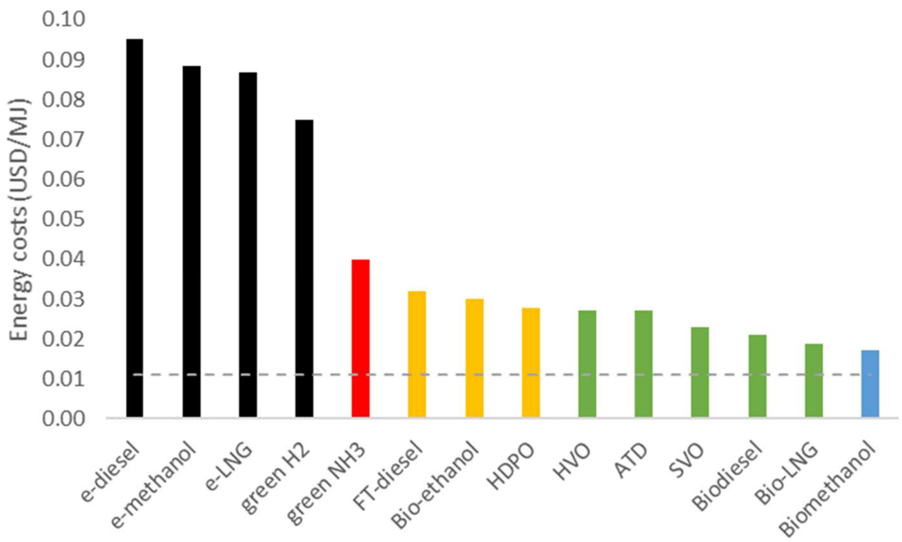

Figure A 3: Cost normalization to compare the different fuel alternatives (dashed line represents HFO energy costs). Ratings based on the ratio fuel cost/bunker cost (5: until 200%, 4: 200-250%, 3: 250-300%, 2: 300-400%, 1: above 400%).

Table A 5 summarizes safety aspects regarding some of the assessed fuels and represents a guide to evaluate them in the safety indicator. Table A 6 presents a summary of the existing regulations for using alcohols as fuels for bunkering procedures and identifies areas where additional regulation is required.

Table A 5: Safety and environmental risks of selected fuels. Based on (VAN UY; THE NAM, 2018)**.**

	MGO	LNG	CH_3OH	H_2 (liq.)	NH_3 (liq.)
Flammability	Liquid and flammable vapor	Extremely flammable gas	Highly flammable liquid and vapor	Extremely flammable gas	Flammable gas
Pressurized gas	-	Chilled gas: cryogenic burn risks	-	Chilled gas: cryogenic burn risks	Pressurized gas: risk of explosion if heated.
High toxicity	Harmful if inhaled.	-	Toxic if inhaled, ingested or in contact with skin.		Toxic, if inhaled
Inhalation risks	May be fatal if inhaled or ingested.	-	-		-
Skin corrosion	Skin irritation/burns	-	-		Several damage to skin and eyes
Marine environment	Toxic for marine life (Long lasting effect)	-	-		Very toxic for marine life (Long lasting effect)

Table A 6: Regulations for use alcohols as fuels (ELLIS; TANNEBERGER, 2015)**.**

Item	Methanol	Ethanol
Use as marine fuel		
IMO	IGF	IGF
Class Rules	DNV, LR	DNV
Rules for cargo transportation		
IMO – Rules for bulk chemicals transport	MARPOL Annex II and Code IBC	MARPOL Annex II
IMO – Rules for dangerous cargo transport	Code IMDG	Code IMDG
Rules for cargo transport in internal waterways		
European rules for dangerous cargo transport	ADN	ADN
Bunkering		
Ships bunkering	MARPOL Annex II e Code IBC	MARPOL Annex II
Trucks bunkering	ADR	ADR
Port operations	ISM	ISM
Fuel standards		
Fuel quality standards	IMPCA – Reference specifications for methanol and/or ASTM D-1152/97	EM 15376 or ASTM D 4806 specifications for ethanol as blend fuel

1.1 Availability

1.1.1 Group 1 - Liquid distilled biofuels

- SVO

SVO are produced on a large scale around the world (FAO, 2019). In Brazil, soy is the main oilseed processed for producing vegetable oil, followed by sunflower and cotton (ABIOVE, 2019). Currently, main markets for SVO are the food industry and biodiesel production. Forecasts presented by the Sustainable Shipping Initiative (SSI) indicate that, although the supply of sustainable biomass is greater than the estimated demand from the maritime transport sector, its use to produce fuels for other sectors should also be considered (SSI, 2019). In addition, pressure on SVO production may lead to the expansion of agricultural boundaries and deforestation (PORTUGAL-PEREIRA; KOBERLE; SCHAEFFER, 2016). Only land-use models or integrated assessment models (IAMs) are able to foresee the combined impacts of food, energy and materials demand on land use. Thus, it is attributed to the SVO poor performance in the availability (score 2).

- Biodiesel

Biodiesel represents an alternative to replace MDO and MGO in ships with low and medium-speed diesel engines (IEA BIOENERGY, 2017). The availability of sustainable biomass and biodiesel current use in road transport may compromise its availability for use in the maritime sector or promote its production in a non-sustainable way (SSI, 2019). As biodiesel is produced from SVO, it presents the same challenges associated with availability. Thus, biodiesel is evaluated with a poor performance in availability (score 2).

- HVO

HVO is a drop-in fuel produced from the hydro-processing of oils or fats. HVO has been produced on commercial scales around the world (IEA Bioenergy 2017a). Table A 7**Erro! Fonte de referência não encontrada.** shows the installed and planned HVO production plants.

Table A 7: Installed and planned HVO production plants in the world

Company	Location	Capacity
AltAir Fuels	USA	125,000 MT
Diamond Green Diesel	USA	500,000 MT (expansion to 800,000 MT)
REG	USA	250,000 MT
Emerald Biofuels	USA	280,000 MT (status not known)
Petrobrás	Brazil	230,000 MT (status not known)
CEPSR	Spain	180,000 MT (co-processing)
REPSOL	Spain	60,000 MT (co-processing)
TOTAL	France	500,000 MT
ENI	Italy (Venice)	600,000 MT
	Italy (Gela)	750,000 MT
PREEM	Sweden	180,000 MT (co-processing)
UPM	Finland	100,000 MT
NESTE	Netherlands	1,000,000 MT
	Finland	260,000 MT
	Finland	260,000 MT
	Singapore	1,000,000 MT
PETRIXO	UAE	400,000 MT (status not known)

SINOPEC	China	200,000 MT (status not known)

Source: (DIAMOND GREEN DIESEL, 2020; ENI, 2020a, 2020b; GREENEA, 2017; JOHNSON, 2019; TOTAL, 2020)

Global HVO production is expected to grow by more than 40% by the end of 2020 (GREENEA, 2017). However, the total volumes produced are much lower than the demand from the maritime transport sector, and the availability of sustainable feedstock (SVO) may limit new production units (DNV GL, 2018c; IEA BIOENERGY, 2017). Nevertheless, as HVO does not have a consolidated use in the transport sector yet, it may favour its availability for marine use. As HVO is produced from SVO, it presents the same challenges regarding availability. Thus, HVO was evaluated with a poor performance in availability (score 2).

- HDPO

HDPO is a drop-in biofuel produced from rapid pyrolysis of biomass followed by upgrade. Using lignocellulosic biomass as feedstock is a great advantage of the process, given its availability around the world, especially in Brazil (PORTUGAL-PEREIRA et al., 2015), (TAGOMORI; ROCHEDO; SZKLO, 2019), (CARVALHO et al., 2019; CARVALHO; PORTUGAL-PEREIRA; SZKLO, 2019). Even though initiatives to produce pyrolysis-based biofuels are being implemented (GOODFUELS, 2019), the technology is still in development stage and is not produced or commercialized worldwide. For this reason, HDPO is evaluated with an average performance in availability (score 3).

- FT-diesel

FT-diesel is a drop-in biofuel for maritime transportation. Using lignocellulosic biomass as feedstock is a great advantage of the process, in view of its high availability around the world, especially in Brazil (CARVALHO et al., 2019; PORTUGAL-PEREIRA et al., 2015; TAGOMORI; ROCHEDO; SZKLO, 2019). To date, the FT-BTL process has been demonstrated in pilot plants and some ongoing projects aim to increase production scale (GREENCAR, 2018; RRB, 2019; TOTAL, 2016; VELOCYS, 2019). Thus, FT-diesel was evaluated with a good performance in availability (score 4).

- ATD

Bioethanol produced from starch- or sugar-based biomass is the feedstock for ATD production. Ethanol is currently the most produced and consumed biofuel, being

Brazil the second world major producer (RFA, 2019). The existence of a consolidated market for ethanol as fuel, may reduce its availability for maritime fuel production. However, the development of second-generation ethanol would be an advantage for this pathway, considering the high availability of lignocellulosic feedstock around the world, especially in Brazil.

Regarding fuel conversion, the upgrading steps (Dehydration, oligomerization, and hydrogenation) to produce medium distillate hydrocarbons from alcohols are well known industrial technologies applied at commercial scales (TAO et al., 2017). The main challenge relies on process integration (DÍAZ-PÉREZ; SERRANO-RUIZ, 2020).

Thus, ATD is evaluated with medium performance in terms of availability (score 3).

1.1.2 Group 2 – Alcohol and liquefied gases

- Bio-LNG

Biogas can be produced from different feedstocks, including animal manure, agricultural and agro-industrial residues, solid waste, and sewage sludge. For utilization on ships, biogas should be upgraded to increase methane content and liquefied. Even though biogas production has been increasing in Brazil, the upgrade and, principally, liquefaction processes are not widespread in the country (CIBIOGÁS, 2019). Also, the dispersed location of feedstock poses logistic challenges for fuel production.
Thus, bio-LNG was evaluated with a poor performance in availability (score 2).

- Biomethanol

In order to assess biomethanol availability, the specificities of each production route should be taken into account. In the case of biomethanol produced by steam reform of bio-LNG, the analysis of the availability indicator is similar to that performed for bio-LNG (score 2). For biomass gasification pathway, the assessment is similar to FT-diesel (score 4).

Considering the production pathway that requires available resources and that methanol production infrastructure is well developed, biomethanol was evaluated with a good performance in availability (score 4).

- Ethanol

Ethanol is currently the most produced and consumed biofuel, being the United States its largest producer, followed by Brazil (RFA, 2019). Globally, there is a large experience in using ethanol as a fuel or additive, especially in Brazil (DE ARAÚJO MARTINS et al., 2014).

Bioethanol can be produced from sugar and starch biomass. The development of technologies to produce ethanol 2G represents a great advantage (see ATD). However, the existence of a consolidated market for ethanol compromises its availability for the maritime transport, at least in the short-to-medium terms.
Thus, ethanol is evaluated with a median performance in terms of availability (score 3).

1.1.3 Group 3 - Hydrogen, ammonia and e-fuels

- Green H2

The existing hydrogen production infrastructure is almost entirely based on fossil sources and electrolysis represents less than 5% of installed capacity. On the other side, huge wind and solar power potential (IEA, 2019a) could stimulate green H_2 production. However, water requirements for electrolysis may limit its production (HANASAKI et al., 2013).

Thus, green H_2 is evaluated with an average performance in availability (score 3).

- Green NH3

Green ammonia availability is limited by green hydrogen availability. Also, its production depends on atmospheric N_2 supply which does not offers limitations regarding resources or infrastructure. Thus, it is considered that the availability of green ammonia is similar to green H_2 (score 3).

- e-diesel

The e-diesel evaluation is similar to green hydrogen, as it is a feedstock for fuel production. CO_2, another input resource, should be produced from technologies not available in large scales yet (CCS and DAC). Furthermore, there are no infrastructure in place for converting syngas into e-diesel (FT synthesis) in scales comparable to marine fuel demands.

Thus, e-diesel is evaluated with a very poor performance in availability (score 1).

- e-methane

The evaluation presented for methane also applies to electromethane. The production of electro-LNG would depend on renewable hydrogen supply (with high water consumption) and carbon capture. However, the infrastructure for chemical synthesis not available in large scales yet. Furthermore, its use depends on the availability of liquefaction plants, currently not unavailable in the required amount.

Thus, electromethane is evaluated with a very poor performance in availability (score 1).

- e-methanol

Similar to previous e-fuels, electromethanol depends on the production of renewable H_2 and on the availability of recycled CO_2. Therefore, electromethanol is evaluated with a very poor performance in availability (score 1).

1.2 Applicability

1.2.1 Group 1 - Liquid distilled biofuels

- SVO

SVO can fully replace HFO in diesel engines and does not require any modifications in supply infrastructure (IEA BIOENERGY, 2017). SVOs are technically compatible with all types of engines (ECOFYS, 2012a). However, their high viscosity and boiling points may affect their flow properties and compromise the combustion in engines (its use can cause problems in the pumping and fuel injection systems, formation of deposits in the engine, among others) (Table A 8). Such problems can be reduced by blending SVOs with HFOs or less viscous oils and/or by heating them prior to injection in the engines (KHAN, 2018b; NGUYEN; TRAN; DANG, 2015; VAN UY; THE NAM, 2018). However, in areas with higher average annual temperatures, their viscosity is reduced (ECOFYS, 2012a).

Table A 8: Viscosity of different SVO

Fuel	µ (cSt)
Soybean oil	29^b-33^a
Palm oil	40^a-45^b
Sunflower oil	34^a-36^b
Corn oil	31-35^a
Rapeseed oil	35-37^a
Cotton oil	34^b
Peanut oil	40^b
Sesame oil	36^b
MDO	2-11
MGO	2-6
HFO	180-380
^{a} 37,8°C ^{b} 40,0°C	

The CN of the main vegetable oils is in the range of 37 to 42, values near those of MGO (>40) and MDO (>35) (BLIN et al., 2013; ECOFYS, 2012a; PETROBRÁS, 2019). For HFO, the ignition quality is indirectly controlled by two parameters: the CCAI and the CII. Manufacturers of low-speed marine diesel engines recommend CII values above 30 for fuels. All, SVO fits the recommended specifications presenting values higher than those of HFOs (Table A 9).

Table A 9: SVO and HFO properties

Fuel	ρ kg/m³ (15°C)	μ (cSt, mm²/s) (at 38°C)	CII
HFO	960-990	180-380[a]	32.7
Soybean oil	910	32.6	47.4
Palm oil	920	39.6	45.4
Sunflower oil	920	37.1	45.2
Corn oil	920	34.9	47.6
Rapeseed oil	910	37.0	47.8
Cotton oil	910	33.5	44.9
Peanut oil	900	39.6	50.5
Sesame oil	910	35.5	47.6

The parameters presented above indicate that SVOs have high applicability in the maritime transport sector. The only limitation is associated with the high viscosity of some SVOs at low temperatures and the need for pre-combustion heating.
Thus, SVO is evaluated with a good performance in applicability (score 4).

- Biodiesel

Biodiesel has good combustion characteristics, higher flash point and CN when compared to conventional marine fuels. Its viscosity is lower than HFO's but in the same range of MDO and MGO (Table A 10). In addition, biodiesel can act as a lubricant, preventing wear on fuel pumps and injectors, and reducing the formation of smoke and soot (ECOFYS, 2012a; IEA BIOENERGY, 2017; UKP&I, 2018). However, the high cloud point may clog filters and hamper its flow at temperatures below 32ºC (IEA BIOENERGY, 2017).

Table A 10: Biodiesel and marine fuels properties

Fuel	ρ (kg/L)	μ (40°C) (cSt)	CN	FP (°C)
Biodiesel	0.88	4-6	47-65	110-195
MDO/MGO	0.89-0.90	2-11	35-40	60
HFO	0.99	180-380	n/a	60

Main issues regarding biodiesel applicability are associated with water contamination, low oxidative stability, reduced performance at low temperatures and solubilization of solid deposits in fuel systems. Adding antioxidants, chemical additives and biocides to biodiesel prevents damage to engines and fuel systems (IEA BIOENERGY, 2017). Biodiesel blends of up to 20% with conventional diesel does not cause operational problems in the engines (ECOFYS, 2012a; ETIP, 2017). However, IUMI (International Union of Marine Insurance) reported problems with biodiesel blends utilization (SAPP, 2018). Therefore, it is recommended that engine manufacturers are consulted on the amount of biodiesel to be used (IEA, 2013).

In this way, biodiesel is evaluated with a median performance in applicability (score 3).

- HVO

HVO is compatible with current supply infrastructure and can be used directly in diesel engines. It is oxygen-free, which guarantees its stability for long periods. Also, HVO density is slightly lower than conventional marine fuels, due to its paraffinic content (Table A 11**Erro! Fonte de referência não encontrada.**) (NESTE CORPORATION, 2016). HVO viscosity complies with fuel standards and CN is higher than MDO and MGO, indicating that the fuel has high performance, cleaner and efficient combustion (AATOLA et al., 2008; KASS et al., 2018; STENGEL; VIUM, 2015) (Table A 9).

Table A 11: HVO properties compared to conventional bunker fuels.

	ρ (kg/L)	**μ (40°C) (cSt)**	**CN**
HVO	0.78	2-4	>70
MDO/MGO	0.89-0.90	2-11	35-40
HFO	0.99	180-380	n/a

Source: (ECOFYS, 2012a; KASS et al., 2018; NESTE CORPORATION, 2016; STENGEL; VIUM, 2015)

For this reason, HVO was evaluated with a very good performance in applicability (score 5).

- HDPO

HDPO is a drop-in fuel that can be directly used in diesel engines, without requiring adaptations in engines or infrastructure. HDPO density and viscosity are in the same range as MDO/MGO and HFO and has higher CN than fossil fuels (Table A

12**Erro! Fonte de referência não encontrada.**), indicating its high performance (CATALUÑA et al., 2013; ECOFYS, 2012a; KASS et al., 2018).

Table A 12: Properties of HDPO and conventional bunker fuels

	ρ (kg/L)	μ (40°C) (cSt)	CN	LHV (MJ/kg)
HDPO	0.84-0.90	2.80	"High"[a]	45.20
MGO/MDO	0.89-0.90	2.00-11.00	35-40	45.60
HFO	0.99	180-380	n/a	42.30
Note: [a]Reference values present wide range that only a reference such as "high" could be made.				

Source: (ECOFYS, 2012a; KASS et al., 2018)

For such reasons, HDPO is evaluated with a very good performance in applicability (score 5).

- FT-diesel

FT-diesel is a drop-in fuel and can be directly used on diesel engines. Its density is slightly lower than conventional fuels and viscosity in the same range as MDO/MGO. FT-diesel high CN, indicates its good performance in diesel engines (Table A 13)(KASS et al., 2018).

Table A 13: Properties of FT-diesel and conventional bunker fuels

	ρ (kg/L)	μ (40°C) (cSt)	CN
FT-diesel	0.77	2	>70
MDO/MGO	0.89-0.90	2-11	35-40
HFO	0.99	180-380	n/a

Source: (KASS et al., 2018)

Therefore, FT-diesel was evaluated with a very good performance in applicability (score 5).

- ATD

It is expected that the produced ATD has similar properties than ATJ. The produced diesel has near-zero sulfur/polyaromatic content and higher content of branched alkanes and may differ from FT-diesel only in cetane number (LUNING PRAK et al., 2015a). Experiments at pilot scale using novel catalysts produced middle distillates with cetane number of 50 (EAGAN et al., 2019). ATD has slightly lower density than conventional fuels, viscosity in the same range as MDO/MGO and higher CN. Therefore, it is expected that the fuel has high performance (Table A 14**Erro! Fonte de referência não encontrada.**).

Table A 14: Properties of ATD compared to conventional bunker fuels.

	ρ (kg/L)	**μ (40°C) (cSt)**	**CN**
ATD	0.76[a]	2.10[a]	50[b]
MDO/MGO	0.89-090	2-11	35-40
HFO	0.99	180-380	n/a

[a]: ATJ properties from (LUNING PRAK et al., 2015b)
[b]: CN from (EAGAN et al., 2019)

Thus, ATD is evaluated with a very good performance in applicability (score 5).

1.2.2 Group 2 – Alcohol and liquefied gases

- Bio-LNG

The LNG-powered fleet has increased in recent years. However, Brazil does not have ships powered by LNG yet (THE MARITIME EXECUTIVE, 2019). For bio-LNG bunkering, it would be necessary to develop new infrastructure to supply ships. LNG supply infrastructure is concentrated in Europe and USA. And some Asian ports are developing LNG supply facilities (UMAS, 2018). Up until now, no liquefaction plants were built in Brazil that has only 3 regasification terminals in operation.

Therefore, bio-LNG was evaluated with median performance in applicability (score 3).

- Biomethanol

Despite not being a drop-in fuel, biomethanol is suitable for operation in dual-fuel engines, requiring incremental adaptations (ANDERSSON; SALAZAR, 2015; DOLAN, 2019; MAN, 2015). Also, biomethanol would benefit from the existing infrastructure of fossil methanol, especially in Chinese and European ports, the major Brazilian trade partners (ANDERSSON; SALAZAR, 2015; METHANEX, 2019a, 2019b).

Thus, biomethanol is evaluated with good performance in applicability (score 4).

- Ethanol

Regarding ethanol use on ships, the properties that make ethanol suitable for Otto engines, make it unattractive for Diesel engines. To date, no projects of bioethanol use in ships have been identified. To become a drop-in fuel in diesel engines, additives should be used to increase its cetane number and lubrification. Also, metal-based materials may suffer corrosion by ethanol use (HORTA NOGUEIRA et al., 2008). Ethanol use in diesel engines has been encouraged for road transport, especially in buses (MOREIRA, J.R.; VELÁZQUEZ, S.M.S.G.; APOLINÁRIO, S.M., MELO, E. H. , ELMADJIAN, 2009). The development of multifuel diesel engines would incentive its use as marine fuel, but this technology is far from readiness (ELLIS; TANNEBERGER, 2015). Also, ethanol can be fuelled in direct or indirect (with a reformer) fuel cells, a technology already tested in road transportation, but not widespread yet (NISSAN, 2019) and starting to be seen as an alternative to smaller ships (KAMARUDIN et al., 2013).

Thus, bioethanol was scored with poor performance in applicability (score 2).

1.2.3 Group 3 - Hydrogen, ammonia and e-fuels

- Green H2

The main technological alternative for hydrogen utilization in ships is the fuel cell. It is a different technology than the current fleet, which would require a complete remodeling of propulsion systems. Also, hydrogen requires a complex distribution chain, as it needs to be gasified or liquefied to be stored in cryogenic tanks and transported. The bunkering activities are also a concern because given the limited experience of maritime industry (HYDE; ELLIS, 2020).

Thus, green H_2 is evaluated with a very poor performance in applicability (score 1).

- Green NH3

Ammonia can be used in fuel cells and ICE. To be used fuel cells, NH_3 requires the development of new powertrain systems, especially for its use in solid oxide cells (SOFCs). For ICE, it also poses technical challenges and requires a backup fuel.

Thus, green ammonia is evaluated with poor performance in applicability (score 2).

- e-diesel

The evaluation of the electrodiesel in this indicator is equivalent to that of FT-diesel (section 4.1.4.2).

Thus, e-diesel is evaluated with a very good performance in applicability (score 5).

- e-methane

Despite their different production processes, bio-LNG (section 4.2.1.2) and electro-LNG are, from the physical and chemical point of view, the same fuel. Thus, e-methane is similarly evaluated in this indicator.

For this reason, e-methane is evaluated with an average performance in applicability (score 3).

- e-methanol

Electromethanol is identical to biomethanol regarding its properties as a fuel and is similarly evaluated in this indicator.

Thus, electromethanol has a good performance in applicability (score 4).

1.3 Technological maturity

1.3.1 Group 1 - Liquid distilled biofuels

- SVO

SVO production is greatly developed worldwide. In view of its use in the food industry and for biofuels production, SVOs may not be available to supply maritime transportation demand (SSI 2019). Notwithstanding, given that their production is well-established worldwide, SVOs received the highest score in the technological maturity indicator (score 5).

- Biodiesel

Biodiesel production technology is well-developed and is largely produced worldwide (MÜLLER-LANGER; MAJER; O'KEEFFE, 2014).

Thus, biodiesel is evaluated with a very good performance in technological maturity (score 5).

- HVO

HVO is already produced on commercial scales. The technology has reached technological maturity and the fuel produced is destined to different applications in the transportation sector (DNV GL, 2019; GREENEA, 2017; KASS et al., 2018).

Thus, HVO was evaluated with a very good performance in the technological maturity indicator (score 5).

- HDPO

Some biomass-based pyrolysis plants are already in operation around the world. ETIP Bioenergy mapped and classified these units according to their stage of development (ETIP BIOENERGY, 2019b). None of the units produce HDPO-diesel. Also, HDPO is still in the development stage (bench scale) (KASS et al., 2018).

Thus, HDPO was evaluated with poor performance in technological maturity (score 2).

- FT-diesel

Although the individual components of FT-BTL process are well known and have been demonstrated in industrial scales, the process integration and demonstration are yet to achieve commercial stage (TRL 6)[21] (ARUP; E4TECH; RICARDO-AEA, 2014). To date, FT-BTL process has been demonstrated in pilot plants and large-scale plants are not yet in operation. While some industrial scale demonstration projects have been cancelled (ETIP, 2019), several initiatives are still underway (GREENCAR, 2018; RRB, 2019; TOTAL, 2016; VELOCYS, 2019).

In this context, FT-diesel is evaluated with an average performance in technological maturity (score 3).

- ATD

Ethanol production from biomass is a well-developed process applied on large scales worldwide. The upgrading steps to produce medium distillate hydrocarbons from alcohols are industrial technologies applied at commercial scales. The main challenge lies in the process integration (DÍAZ-PÉREZ; SERRANO-RUIZ, 2020). Currently, several companies are developing this technology to produce jet fuels, such as Gevo Inc., Byogy, Vertimass, LanzaTech and Swedish Biofuels (GELEYNSE et al., 2018; TAO et al., 2017).

Thus, ATD is evaluated with good performance on technological availability (score 4).

1.3.2 Group 2 – Alcohol and liquefied gases

- Bio-LNG

All technological processes to produce biomethane until liquefaction have are already reached maturity (CIBIOGÁS, 2019). Technologies to upgrade biogas to

[21] The Technology Readiness Level (TRL) is a methodology to measure technological development. TRL 6 indicates that the technology has already been demonstrated in relevant environment, that is, very similar to real conditions.

biomethane separation process are economically nowadays and liquefaction has been applied since the 1950s.

Thus, Bio-LNG was evaluated with very good performance in technological maturity (score 5).

- Biomethanol

Regarding biomethanol production via biomethane reform, the technology is mature (see section 4.2.1.3). Methanol synthesis from syngas is also a mature process. However, when considering lignocellulosic biomass as feedstock the technology is less developed, since biomass gasification has not reached large scales yet (see FT-diesel, section 4.1.4.3). Biomethanol use as fuel is ships has reached maturity (CHESKO, 2019).

Thus, biomethanol was evaluated with good performance in this indicator (score 4).

- Bio-ethanol

Bioethanol production from sugar and starch is a mature technology. For second generation ethanol, technologies are being developed to increase its competitiveness (BNDES, 2008). However, regarding its use as marine fuel in diesel engines, bio-ethanol still has low technological maturity (ELLIS; TANNEBERGER, 2015).

Thus, bio-ethanol is evaluated with a median performance in technological maturity (score 3).

1.3.3 Group 3 - Hydrogen, ammonia and e-fuels

- Green H2

Given the specificities regarding renewable sources (especially its intermittency), the most suitable hydrogen production technology is the polymeric membrane electrolysis (PEM). PEM electrolysers are in initial development stage and presents, lower efficiencies, high investment costs and short life span.

Regarding fuel cell use on ships, three technologies are promising: PEMFC, HT-PEMFC and SOFC (PEMFC: Proton Exchange Membrane Fuel Cell, HT-PEMFC: High-Temperature Proton Exchange Membrane Fuel Cell, SOFC: Solid Oxide Fuel Cell) (DNV GL, 2017). While PEMFCs are a mature technology, SOFCs and HT-PEMFCS have low to intermediate maturity. Then, hydrogen has a reasonable technological maturity in terms of use as a fuel, but low in terms of production from intermittent renewables.

Thus, H_2 is attributed an average performance from the point of view of technological maturity (score 3).

- Green NH3

Regarding green ammonia production, the analysis is similar to green hydrogen, since the electrolysis from intermittent renewable sources limits its production. Ammonia production from hydrogen (via Haber-Bosch synthesis) is mature and largely applied in industry. Regarding ammonia utilization as a fuel, little knowledge about NH_3 burning in ships engines is available and fuel cells do not seem to be an option in the medium term.

Thus, green ammonia is evaluated with poor performance technological maturity (score 2).

- e-diesel

In terms of e-diesel use as a marine fuel, the technological maturity is the highest possible, considering the widespread use of diesel in ships. However, regarding fuel production, e-diesel entirely depends on technologies that have not reached maturity yet, such as green H_2 production, CO_2 production from capture technologies and large-scale Fischer-Tropsch synthesis.

Thus, e-diesel is evaluated with a medium performance in terms of technological maturity (score 3).

- e-methane

Technological maturity for electro-LNG is similar to bio-LNG only considering fuel use. Regarding fuel production, the technological is far from maturity, depending on renewable H_2 production.

Thus, e-LNG is evaluated with a poor performance in terms of technological maturity (score 2).

- e-methanol

To evaluate electro-methanol in this indicator it is necessary to consider the maturity of its use as marine fuel and electrochemical production route. As discussed in 4.2.2.2, dual-fuel engines can be adapted to operate with methanol. However, fuel production via PEM electrolysis and chemical synthesis are not mature technologies.

Therefore, e-CH3OH evaluated with poor performance in this indicator (score 2).

1.4 Energy Density

1.4.1 Group 1 - Liquid distilled biofuels

- SVO

SVOs' energy density is slightly lower than that of conventional marine fuels. Such difference does not imply a considerable increase in weight and storage space on ships.

For this reason, SVOs were evaluated with a very good performance in energy density (score 5).

- Biodiesel

Biodiesel has lower energy density than conventional marine fuels (HFO, MDO and MGO) due to its higher oxygen content. However, this difference is not significant and does not imply in considerable increase in weight and storage space on ships.

For this reason, biodiesel is evaluated with a very good performance in the energy density (score 5).

- HVO

HVO has similar energy density than conventional marine fuels (Figure 2)(DNV GL, 2019; KASS et al., 2018; STENGEL; VIUM, 2015). Therefore, additional space requirements for storage and increase in weight due to HVO utilization as fuel on ships would not be observed.

Thus, this alternative was evaluated with a very good performance in the energy density indicator (score 5).

- HDPO

Regarding energy density, HDPO is very close to MGO/MDO and HFO. Thus, HDPO does not require additional storage space or increase the weight carried by ships.

Thus, HDPO was evaluated with very good performance in energy density (score 5).

- FT-diesel

Regarding energy density, FT-diesel are close to MGO/MDO and HFO. Thus, utilization of FT-diesel would not require additional storage space or significantly increase ships weight (Figure 2).

Thus, the FT-diesel was scored with a very good performance in energy density (score 5).

- ATD

No data regarding alcohol-based diesel energy density was found in the literature. However, it is expected that its energy density is in the range of HVO-diesel and FT-diesel and, therefore, similar to conventional bunker fuels.

Then, according to the scale proposed (Figure 2), ATD has a good performance in energy density (score 4).

1.4.2 Group 2 – Alcohol and liquefied gases

- Bio-LNG

Bio-LNG LHV is 52 MJ/kg. However, on a volumetric basis, its LHV is 20.3 MJ/L, which indicates that the fuel requires approximately 50% more storage space on the ship compared to HFO (Figure 2) (GLOBAL COMBUSTION SYSTEMS, 2020).

Thus, regular performance was attributed to bio-LNG in this energy density (score 3).

- Biomethanol

Biomethanol has low LHV (around 20 MJ/kg) and volumetric energy density (16 MJ/L - 57% lower than that of diesel). It is expected that methanol requires twice of the space for fuel storage in relation to conventional marine fuels (Figure 2) (DNV GL, 2019).

Thus, biomethanol is evaluated with poor performance in energy density (score 2).

- Bioethanol

Ethanol has approximately half the energy density of conventional bunker fuels (22.35 MJ/L), thus requires more space for on-board storage. It has an intermediary energy density among the fuels evaluated in this study (Figure 2).

Thus, ethanol was evaluated with a median performance in energy density (score 3).

1.4.3 Group 3 - Hydrogen, ammonia and e-fuels

- Green H2

Despite its high mass-basis energy density (120 MJ/kg), hydrogen has a very low volumetric energy density (0.01 MJ/L). When compressed or liquefied, the energy content per volume increases and is well below diesel values (Figure 2). Also, the loss of space on board due to the cryogenic storage system or pressurization should be considered.

Thus, H_2 is evaluated with very poor performance in energy density (score 1).

- Green NH3

Low volumetric energy density of ammonia (12MJ/L) would imply losses in ships autonomy and an increase in space requirements for fuel tanks (Figure 2). However, its energy density is considerably higher than H_2.

Therefore, green ammonia is evaluated with poor performance in this indicator (score 2).

- e-diesel

E-diesel evaluation in terms of energy density is similar to FT-diesel (score 5).

- e-methane

The evaluation of electro-LNG in this indicator is identical to that of bio-LNG (score 3).

- e-methanol

The evaluation of e-methanol in this indicator is identical to that of biomethanol (score 2).

1.5 Economic

1.5.1 Group 1 - Liquid distilled biofuels

- SVO

SVOs are commodities with high value-added and, therefore, have higher prices than HFOs (BIX, 2018; INDEXMUNDI, 2018a).

However, according to the normalization proposed (Figure 3), SVOs were well evaluated in this indicator (score 4).

- Biodiesel

The high demand for biodiesel and competition with other markets makes it a less viable alternative to supply the maritime transport sector. Biodiesel prices negotiated in recent Brazilian auctions were 60% higher than HFO prices (ANP, 2019b; SHIP&BUNKER, 2019). Considering the international price of biodiesel (FAME), the difference is almost three times the price of HFO (NESTE, 2019). Further, considering the production of entirely renewable biodiesel may increase its prices due to the use of renewable alcohols in transesterification. Nevertheless, the utilization of residual feedstock such as UCO[22], non-energy oil crops and tallow may reduce its costs (MOHD NOOR; NOOR; MAMAT, 2018). According to the normalization scale proposed (Figure

[22] Used cooking oil.

3), biodiesel would receive score 5 ("Very good") in this indicator. However, due to the possibility of using renewable alcohols, this alternative will be penalized.

Thus, biodiesel was evaluated with a good performance in the economic indicator (score 4).

- HVO

The high feedstock costs reduce HVO's competitiveness in relation to bunker fuels (CARVALHO; PORTUGAL-PEREIRA; SZKLO, 2019; DNV GL, 2019; ECOFYS, 2012a; IEA BIOENERGY, 2017; KASS et al., 2018). Average HFO and MGO prices in 2017 were US$ 0.70/L and US$ 0.41/L, respectively (SHIP & BUNKER, 2017b). HVO prices estimates range from $0.72/L to $ 1.15/L (KASS et al., 2018). Estimates for the levelized costs of HVO-diesel produced in Brazil range from US$1.22/L to US$ 1.41/L (CARVALHO; PORTUGAL-PEREIRA; SZKLO, 2019).

In view of the proposed scale (Figure 3), HVO has a good performance in economic indicator (score 4).

- HDPO

Given the premature stage of development, HDPO cost estimates are high, ranging from US$0.76/l to US$1.50/l (KASS et al., 2018), (MANIATIS; WALDHEIM; KALLIGEROS, 2017; OVERWATER, 2019). Compared to conventional marine fuel prices (US$ 0.41/l – HFO; US$0.70/l - MGO), HDPO would increase fuel costs by up to three times (SHIP & BUNKER, 2017b) .

Thus, according to the cost scale proposed (Figure 3) HDPO is evaluated with median performance in the economic indicator (score 3).

- FT-diesel

Estimates reveal that FT-diesel has high costs (KASS et al., 2018). FT-diesel produced in Brazil from pine and eucalyptus residues cost estimates ranges from US$ 1.26/l to US$ 1.31/l, respectively (TAGOMORI; ROCHEDO; SZKLO, 2019). Considering different plant scales, levelized costs for FT-diesel produced in Brazil ranges from US$ 0.88/l to US$ 0.50/l (CARVALHO; PORTUGAL-PEREIRA; SZKLO, 2019). Also, the high investment required may affect the attractiveness of FT-BTL projects and compromise fuel competitiveness (CARVALHO; PORTUGAL-PEREIRA; SZKLO, 2019; ECOFYS, 2012a; KASS et al., 2018). Such estimates are for Nth of a kind plant (NOAK). These estimates tend to underestimate production costs and overestimate plant performance.

For this reason and, according to the scale proposed (Figure 3), FT-diesel was evaluated with an average performance in the economic indicator (score 3).

- ATD

Cost estimates from Staples et al. reveal that middle distillates produced from sugarcane-based alcohols are approximately US$ 0.61/l (STAPLES et al., 2014). Geleynse et al. estimate for alcohol-based diesel range from US$1.17/l to US$3.87/l, considering the added costs for an alcohol production facility to produce distillate fuels and the total costs to produce them from sugar, respectively (GELEYNSE et al., 2018). Tao et al. results indicate that MSP (minimum selling price) for co-produced diesel in ATJ plants is US$ 0.07/l (TAO et al., 2017). Thus, considering diesel as a co-product of ATJ production may increase its competitiveness.

According to the cost scale proposed (Figure 3), ATD is evaluated with a good performance in the economic indicator (score 4).

1.5.2 Group 2 – Alcohol and liquefied gases

- Bio-LNG

Estimated bio-LNG price is approximately US$ 900-1000/metric-ton. Also, bunkering costs should be considered and range from US$ 90/metric-ton to US$ 250/metric-ton (DAAG, 2013).

Thus, according to scale proposed (Figure 3), bio-LNG was evaluated with a good performance in the economic indicator (score 4).

- Biomethanol

Biomethanol costs are higher than fossil methanol (around US$ 0.008/MJ). However, compared to other potentially carbon-neutral fuels, biomethanol may be an interesting alternative (Figure 3). Average cost for gasification route is US$ 0.025/MJ. For the biomethane route, average cost estimated is US$ 0.017/MJ (IRENA, 2013).

Therefore, biomethanol is evaluated with a very good performance in economic indicator (score 5).

- Ethanol

The sugar and starch-based bioethanol are less costly than other biofuels (around 0,6 USD_{2020}/l in the United States and 0.77 USD_{2020}/l in Brazil) (PRICES, 2020). However, to be used as marine fuel, bioethanol needs to upgraded with fuel additives and becomes less economically attractive (MCCORMICK; PARISH, 2001). According to the scale proposed (Figure 3), ethanol costs would be approximately, 3 times higher than HFO.

Thus, it can be considered that the fuel has an average economic performance (score 3).

1.5.3 Group 3 - Hydrogen, ammonia and e-fuels

- Green H2

In addition to the fact that electrolysis, in general, constitutes a less economical technology to produce H_2 than those based on fossil resources, the most suitable technology to produce H2 from renewables is based on polymeric membranes, which is even more expensive. Furthermore, the price of hydrogen as a marine fuel could be strongly affected by additional costs for transport, storage and bunkering. According to the economic scale presented (Figure 3), the cost of marine green H_2 would be 7 times the price of the bunker (DNV GL, 2018b; IEA, 2019a).

Thus, the fuel is evaluated with a very poor performance in the economic indicator (score 1).

- Green NH3

Green ammonia cost is strongly affected by renewable hydrogen cost. The synthesis of NH_3 itself is not an expensive process. Considering H_2 production from natural gas, ammonia costs are approximately 150 USD/t. However, from renewable hydrogen, the cost goes up to 800 USD/t (ASH; SCARBROUGH, 2019a).

Thus, according to the cost scale proposed (Figure 3) green ammonia is evaluated with poor performance in economic indicator (score 2).

- e-diesel

E-diesel production cost in 2015 was between 0.04 and 0.20 USD/MJ and is expected to reduce to 0.03-0.10 USD/MJ until 2030 (Table A 1515**Erro! Fonte de referência não encontrada.**) (BRYNOLF et al., 2018).

Table A 15: e-fuels costs in 2015 and 2030

Production costs (USD/t*)	**2015**	**2030**
Electrodiesel	1700-10.000	1400-4400
Electromethane	1900-9900	1500-4400
Electromethanol	800-4200	700-1500
*1,1 USD/€.		

Source: (BRYNOLF et al., 2018)

Even so, e-diesel costs estimates are far higher than other potentially carbon-neutral fuels (Figure A 3), given that its production combines expensive technologies (water electrolysis via renewable power and Fischer-Tropsch synthesis).

Thus, e-diesel is evaluated with a very poor performance in economic indicator (score 1).

- e-methane

As with e-diesel, the economic performance of the electromethane route is poor. In 2015, fuel production costs ranged in the range of 0.04 to 0.20 USD/MJ (Table A 1515). It is expected that the fuel price drops by 2030 to 0.03-0.09 USD/MJ. Also, bunkering costs (around 0.01 USD/MJ) should be considered.

Given the cost scale proposed (Figure A 3), e-methane is evaluated with a very poor performance in economic indicator (score 1).

- e-methanol

Similarly to other e-fuels, electromethanol has poor economic performance, even with the perspective of reduction to 2030 (Table A 1515).

Therefore, given the cost scale proposed (Figure A 3), e-methanol is evaluated with a very poor performance in economic indicator (score 1).

1.6 Safety

1.6.1 Group 1 - Liquid distilled biofuels

- SVO

SVOs have a flash point much higher than those of conventional marine fuels (Table A 16), are non-toxic and, therefore, do not require additional safety procedures for operation (DNV GL, 2019; ECOFYS, 2012a; JIMÉNEZ ESPADAFOR et al., 2009).

Table A 16: Flash point of conventional bunker fuels and SVO

Fuel	FP (°C)
HFO	60
MGO	60
MDO	60
Soybean oil	254
Palm oil	267
Sunflower oil	274
Corn oil	277
Rapeseed oil	246

Cotton oil	234
Peanut oil	271
Sesame oil	260

Thus, SVOs were evaluated with a very good safety performance (score 5).

- Biodiesel

Regarding the safety, biodiesel has a high flash point (Table A 2), offering no flammability risks. Also it is not toxic (MOHD NOOR; NOOR; MAMAT, 2018). Therefore, biodiesel was evaluated with very good performance in safety (score 5).

- HVO

HVO is non-toxic and its flash point (>61°C) is approximately the same as that of conventional marine fuels (> 60°C) (Table A 2).
In this way, HVO has a very good performance in the safety indicator (score 5).

- HDPO

Few data regarding safety and toxicity of HDPO-diesel were found. Some studies revealed that its low flash point may limit its use as a fuel (inflammation risk) (Table A 17). Also, HDPO is not toxic.

Table A 17: Flash point of HDPO and conventional bunker fuels

Fuel	FP (°C)	Reference
HDPO	35-39	(WILDSCHUT et al., 2009)
	35-53	(DĘBEK, 2019)
MGO/MDO	>60	(ECOFYS, 2012a)
HFO	>60	

Thus, the HDPO was evaluated with median performance in the safety indicator (score 3).

- FT-diesel

Regarding safety and toxicity, studies show that the flash point of FT-diesel is higher than marine fuels (Table A 18) (LUND et al., 2015; SUBRAMANIAN, 2017). So, FT-diesel do not offer operational security risks. Also, it is a non-toxic fuel.

Table A 18: FT-diesel e conventional maritime fuels flash point.

Fuel	FP (°C)
FT-diesel	74
MGO/MDO	>60

HFO	>60

Source: (ECOFYS, 2012a; KASS et al., 2018; LUND et al., 2015)

Thus, FT-diesel was evaluated with a very good performance in safety indicator (score 5).

- ATD

Few data regarding safety and toxicity of ATD was found. Considering ATJ flash point as reference, it is expected that the fuel does not offer operational risks (LUNING PRAK et al., 2015b). However, its flash point is lower than for HVO-diesel (>61°C), FT-diesel (87-91°C) and conventional marine fuels (Table A 19**Erro! Fonte de referência não encontrada.**). Regarding toxicity, ATD is a non-toxic fuel.

Table A 19: Flash point for ATD (ATJ) and conventional marine fuels

Fuel	**FP (°C)**
ATD (ATJ)	49
MGO/MDO	>60
HFO	>60

Therefore, ATD is evaluated with a very good performance in safety (score 4).

1.6.2 Group 2 – Alcohol and liquefied gases

- Bio-LNG

Bio-LNG presents additional risks compared to traditional marine fuels (Table 5). Given its cryogenic conditions, risks associated with extremely low temperatures and heat transfer must be controlled to ensure the integrity and safety of fuel tanks and ships. Its flammability characteristics (LNG burns when it vaporizes in the gas phase) requires that fuel transfers are carried out by trained staff and the low temperatures require that special materials are used. Also, handling and storage temperatures (–162°C) are dangerous for human health (PGW, 2015). Minimum ignition energy for methane is almost 100 times inferior than that of MDO, indicating that small sparks are sufficient for ignition (DNV GL, 2019; PGW, 2015).

Thus, bio-LNG was evaluated with regular performance in safety (score 3).

- Biomethanol

Table 5 presents safety aspects of methanol and other marine fuels. Methanol, although less toxic than conventional marine fuels, is very explosive, with relatively wide flammability range and a flash point. Such characteristics may pose risks to ship's crew, especially during transportation and supply activities. However, as biomethanol is liquid at room temperatures, it dismisses cryogenic storage needs.

Thus, biomethanol is evaluated with an average performance in safety (score 3).

- Bioethanol

Bioethanol is not toxic to humans, water-soluble and biodegradable. Therefore, its impacts in the event of spills are much smaller compared to fossil fuels (ELLIS; TANNEBERGER, 2015). Ethanol flash point is bellow all maritime fuels (Table 2), offering some flammability risks (NERF, 2017).

Thus, ethanol is evaluated with a good performance in safety (score 4).

1.6.3 Group 3 - Hydrogen, ammonia and e-fuels

- Green H2

Safety aspects of H_2 were summarized in Table 5.Although not toxic, hydrogen is a highly explosive substance with a wide range of flammability. Therefore, safe operation requires frequent monitoring and ventilation systems installation (U.S. DEPARTMENT OF ENERGY, 2020). For H_2 storage in liquefied form, there are additional risks regarding cryogenic temperatures.

Thus, hydrogen is evaluated with given a poor performance in safety (score 2).

- Green NH3

Despite not being highly explosive (narrow flammability range, ≈15-25%), ammonia is a very toxic fuel, constituting a significant threat to human health and environment, even though the industry has well-specified and dominated safety procedures. The dissolution of ammonia in water forms ammonium hydroxide that increases water pH, is destructive to flora and fauna and is not safe for human consumption (RAJ; REID, 1978).

Thus, ammonia is evaluated with a poor performance in the safety indicator (score 2).

- e-diesel

Eletrodiesel's evaluation in this indicator is similar to that of FT-diesel (score 5).

- e-methane

The evaluation of bio-LNG applies to electro-LNG (score 3).

- e-methanol

The evaluation of biomethane and electromethane are identical in this indicator (score 4).

1.7 Standards

1.7.1 Group 1 - Liquid distilled biofuels

- SVO

Up until now, no regulations have been defined for using SVO as maritime fuel, but manufacturers of diesel engines have already tested and proven its possibility to replace HFO (IEA 2013; ECOFYS 2012a). Further, concerns associated with biofuels sustainability, especially first-generation ones, indicate the necessity to certificate their production chain, what is not stablished yet (SSI 2019).

For this reason, an average performance in the standards indicator was attributed to SVO (score 3).

- Biodiesel

The most recent edition of the specifications for marine fuels (ISO 8217: 2017) incorporated a new class of specifications that allowed blends of up to 7% biodiesel (FAME) on a volumetric basis (DNV GL, 2018d; MOLLOY, 2017). For blends with higher biodiesel content, additional specifications are required (IEA BIOENERGY, 2017). Similarly to SVO, concerns regarding sustainability indicate the necessity to certify the production chain.

Thus, biodiesel is evaluated with an average score in the standardization indicator (score 3).

- HVO

Up until now, no specifications are applied exclusively to marine drop-in biofuels. ISO 1217: 2017 allows the use of up to 100% HVO on ships, if the fuel meet the required specifications (DNV GL, 2019). However, as in the case of SVO and biodiesel, concerns regarding biofuel sustainability indicate the need to certify fuel production chain (SSI 2019).

Thus, HVO is evaluated with a good performance in standards (score 4).

- HDPO

As previously mentioned, there are no specifications applied exclusively to marine drop-in biofuels. ISO 1217: 2017 allows the use of alternative fuels on ships if they meet the required specifications (DNV GL, 2019). The possibility of using lignocellulosic biomass reduces sustainability concerns. However, the production chain should be certified, proving its potential to reduce GHG emissions and the absence of impacts on land use, water resources, food production and biodiversity (SSI, 2019).

In this way, the HDPO is evaluated with good performance in standards (score 4).

- FT-diesel

As before mentioned, there are no specifications applied exclusively to marine drop-in biofuels. ISO 1217: 2017 allows the use of alternative fuels on ships if they meet required specifications (DNV GL, 2019). The possibility of using lignocellulosic biomass as feedstock reduces concerns associated with sustainability. However, it is important that production is certified, proving its potential to reduce GHG emissions and the absence of impacts on land use, water resources, food production and biodiversity (SSI, 2019).

In this way, FT-diesel was evaluated with good performance in standards (score 4).

- ATD

As mentioned before, there are no specifications applied exclusively to marine drop-in biofuels. ISO 1217: 2017 allows the use of alternative fuels on ships if they meet required specifications (DNV GL, 2019). Ethanol (process feedstock) production in Brazil has specific regulations and guidelines. However, it is important that its production is certified, proving its potential to reduce GHG emissions and the absence of impacts on land use, water resources, food production and biodiversity (SSI, 2019).

In this way, ATD is evaluated with a very good performance in the standards indicator (score 5).

1.7.2 Group 2 – Alcohol and liquefied gases

- Bio-LNG

Standards for LNG use as marine fuel, production and bunkering are already in place. The new ISO 20519 guides operators to select fuel suppliers that comply with the safety and quality standards (ISO 2017a, b). For bio-LNG, currently produced mainly from industrial or municipal waste, it is relatively easy to prove its non-fossil origin.

Therefore, good performance is attributed to bio-LNG in standards (score 4).

- Biomethanol

Handling, transportation and use of methanol as marine fuel is relatively new, but regulations are already available. Table 6 provides a summary of the main existing regulations for using methanol as fuel.

In this context, methanol was evaluated with a very good performance in standards, especially when compared to other fuels (score 5).

- Ethanol

Despite standards for ethanol handling, transport and in automotive vehicles has well-specified regulations and guidelines, for use in ships, ethanol regulations should be developed. However, it could benefit from other sectors experience (Table 6).

Considering the current standardization of bioethanol, it was evaluated with a very good performance in standards (score 5).

1.7.3 Group 3 - Hydrogen, ammonia and e-fuels

- Green H2

Currently, there are no specifications applied exclusively to hydrogen as a marine fuel. In addition, the certification of its production chain is necessary, to prove its renewable origins.

Thus, the fuel is evaluated with a very poor performance in the standards criteria (score 1).

- Green NH3

To date, there are no specifications applied exclusively to ammonia as a marine fuel. In addition, it is necessary to certify the production chain, to prove its renewable origin.

Therefore, ammonia is evaluated with a poor performance in the standards indicator (score 1).

- e-diesel

Eletrodiesel's evaluation in this indicator is similar to FT-diesel (score 4).

- e-methane

The evaluation of biomethane and electromethane are identical in this indicator (score 4).

- e-methanol

The evaluation of biomethanol and electromethanol are identical in this indicator (score 4).

1.8 Local sustainability

1.8.1 Group 1 - Liquid distilled biofuels

- SVO

Regarding air pollutant emissions, SVOs do not present additional impacts when compared with conventional fuels. Due to the high CII values (section 4.1.1.2), better combustion properties are observed, decreasing NO_x formation. SVOs are practically sulfur free and, therefore, do not produce SO_x emissions. Also, there is no formation of PM by the utilization of SVOs in diesel engines. Also, the use of SVOs reduces black carbon emissions (COMER, 2019; ICCT, 2018).

Thus, SVO performance in local sustainability indicator was classified as good (score 4).

- Biodiesel

Several studies show that the use of biodiesel as an alternative to fossil fuels reduces emissions of SO_x, PM and black carbon, but increases NO_x (GABIÑA et al., 2016; JIANG et al., 2013; KUMAR et al., 2015; MAN; CHEUNG; NING, 2015; MURILLO et al., 2007; PUŠKÁR et al., 2018; ROSKILLY et al., 2008; SALAMANCA et al., 2012). This increase is associated with the high oxygen content of biodiesel.

Thus, biodiesel is evaluated with a good performance in local sustainability (score 4).

- HVO

Divergent opinions regarding HVO potential to reduce NO_x emissions were found. Some authors argue that using HVO in diesel engines has no significant impact on NO_x emissions (STENGEL; VIUM, 2015). Others indicate that HVO can reduce NO_x emissions by up to 25% (AATOLA et al., 2008; HAPPONEN et al., 2012; NESTE CORPORATION, 2016). HVO is a sulfur-free fuel and, thus, drastically reduces SO_x, PM and black carbon emissions by replacing fossil alternatives (KASS et al., 2018; NESTE CORPORATION, 2016).

For this reason, HVO is evaluated with a good performance in local sustainability (score 4).

- HDPO

Regarding local air pollution, it is expected that HDPO will perform similarly to HVO. The absence of sulfur in the fuel significantly reduces emissions of SO_x, PM and black carbon. Regarding NO_x emissions, experiments carried on diesel engines revealed that HDPO may increase NO_x emissions, given the fuel easy ignition properties (IEA BIOENERGY, 2019b).

In this way, the HDPO is evaluated with good performance in the local sustainability indicator (score 4).

- FT-diesel

FT-diesel is practically sulfur-free, what expressively reduces SO_x and PM emissions (KASS et al., 2018). Regarding NO_x emissions, experiments with FT-diesel produced from forest residues in diesel engines, indicate reduction compared to conventional diesel (GILL et al., 2011).

Thus, FT-diesel was evaluated with a very good performance in the global sustainability indicator (score 5).

- ATD

ATD may reduce emissions of local air pollutants. It is practically sulfur-free, reducing SO_x and PM emissions (LUNING PRAK et al., 2015b). No literature information regarding NO_x emissions from ATD consumption in diesel engines was found, but it is expected that it would be largely unchanged compared to conventional fossil fuels (MILLER et al., 2013).

Thus, ATD was evaluated with a good performance in the local sustainability indicator (score 4).

1.8.2 Group 2 – Alcohol and liquefied gases

- Bio-LNG

Emissions of local air pollutants are close to zero for bio-LNG (PORT OF ROTTERDAM, 2019), (GILBERT et al., 2018). For NOx, emissions depend on engine technology (STENERSEN; THONSTAD, 2017).

Thus, bio-LNG was evaluated with a very good performance in local sustainability (score 5).

- Biomethanol

In general, methanol is a very clean fuel. Its use in marine engines may reduce SO_x emissions by more than 99%, particulate matter emissions by 95% and black carbon emissions between 55% and 95% compared to conventional fuels (COMER, 2019). Also, methanol may considerably reduce NO_x emissions in mixtures with water (DOLAN, 2019).

Therefore, biomethanol was evaluated with good performance in local sustainability (score 4).

- Bioethanol

During bioethanol production, local emissions are mainly associated with boilers exhaust (COMER, 2019; PORTUGAL-PEREIRA et al., 2015). Sugarcane manual harvest that leads to air pollutants and GHG emissions are being discontinued by Brazilian government (FREDO; CASER, 2017; HORTA NOGUEIRA et al., 2008). Bioethanol has a significant reduction in emissions of sulfur oxides (SO_x), hydrocarbons and other polluting compounds. It has higher emission of aldehydes (carcinogenic potential and are local concern) and, depending on engine characteristics, nitrogen oxides (NO_x). However, catalysts reduce these pollutants to tolerable levels.

Thus, bioethanol is evaluated with a good performance in the local sustainability indicator (score 4).

1.8.3 Group 3 - Hydrogen, ammonia and e-fuels

- Green H2

Green H_2 is a clean fuel and does cause direct emissions of NO_x, SO_x, PM or black carbon. Furthermore, as it is produced from renewable electricity, there is no emissions of local pollutants in fuel production (GILBERT et al., 2018). Nonetheless, the consumption of large amounts of water in electrolysis is a concern, unless the process uses recycled water.

Thus, the fuel is evaluated with median performance in local sustainability (score 3).

- Green NH3

Green ammonia is a clean fuel, as it does not emit NO_x, SO_x, PM or black carbon. As its production is based on renewable electricity, no emissions of local pollutants occurs in fuel production process (GILBERT et al., 2018). However, the consumption of large amounts of water in electrolysis is a concern, unless recycled water is used.

Thus, the fuel is evaluated with a median performance in local sustainability (score 3).

- e-diesel

The analysis of e-diesel in local sustainability indicator is partially equivalent to FT-diesel. However, the H2 used for e-diesel production requires huge amounts of high purity water.

Thus, e-diesel is considered to have an average performance in local sustainability (score 3).

- e-methane

Likewise, bio-LNG, electromethane has significant reductions in SO_x and PM emissions. However, the water consumption in electrolysis for green H2 production undermines fuel evaluation in this indicator.

Thus, the electro-LNG is evaluated with an average performance in local sustainability (score 3).

- e-methanol

Methanol combustion in diesel engines produce low emissions of air pollutants. However, considering the green H_2 utilization it should be penalized for huge water requirements.

Thus, electromethanol is evaluated with an average performance in local sustainability (score 3).

1.9 Global sustainability

1.9.1 Group 1 - Liquid distilled biofuels

- SVO

Biofuels in general have high potential to reduce GHG emissions when used as fuels. SVO may reduce up to 57% of GHG emissions compared to HFO (ECOFYS, 2012a). Furthermore, SVO produced in Brazil from soybeans may reduce up to 86% of GHG emissions(CARVALHO; PORTUGAL-PEREIRA; SZKLO, 2019).

However, biofuels production may have indirect impacts on land use. Indirect impacts may induce changes in land use and/or deforestation (PORTUGAL-PEREIRA; KOBERLE; SCHAEFFER, 2016). Such concerns are more evident in the case of soy and palm-based biofuels (SSI, 2019). The relationship between land use and production of agro-energy and biofuels is extremely complex, being influenced by endogenous and exogenous variables (RATHMANN; SZKLO; SCHAEFFER, 2010, 2012).

Notwithstanding, only integrated assessment models (IAMs) are able to foresee the combined impacts of food, energy and materials demand on land use.

Thus, SVOs have average performance in global sustainability indicator (score 3).

- Biodiesel

Biodiesel potential to reduce GHG emissions strongly depends on feedstock, process, location of production and fuel distribution. Studies show that biodiesel may reduce GHG emissions from 19% (from palm oil) to 83% (residual oil) (ECOFYS, 2012a). Limitations in biodiesel content in fuel blends reduce its potential to reduce GHG emissions expressively. Also, as biodiesel uses SVO as feedstock, it may lead to direct and indirect impacts on land use (see 4.1.1.9) and increase GHG emissions. Nevertheless, the use of renewable alcohols in the transesterification process may contribute positively to its environmental performance.

In this context, similarly to SVO, biodiesel has an average performance in global sustainability (score 3).

- HVO

HVO potential to reduce GHG emissions depends on the type of feedstock and production location. Kass et al. estimate that HVO can reduce approximately 70% of GHG emissions compared to fossil alternatives (KASS et al., 2018). Stengel et al. estimated that HVO produced from animal fat and rapeseed reduces emissions by 40% and 20%, respectively (STENGEL; VIUM, 2015). Additionally, Carvalho et al. estimates that HVO-diesel produced in Brazil from soybean oil may reduce GHG emissions by up to 66% (CARVALHO; PORTUGAL-PEREIRA; SZKLO, 2019). Also, HFO production has the same challenges associated with global sustainability than SVO (see section 4.1.1.9).

In this way, HVO is evaluated with a medium performance in global sustainability (score 3).

- HDPO

HDPO potential to reduce GHG emissions depends on the type of feedstock and production location. The possibility of using residual biomass increases the fuel potential to reduce emissions. No data detailing life-cycle emissions for HDPO use in maritime transport were found. However, studies indicates that HDPO-diesel might reduce GHG emissions by 50% to 72% using corn straw and poplar as feedstock (IRIBARREN; PETERS; DUFOUR, 2012; PETERS; IRIBARREN; DUFOUR, 2015; VIENESCU et al., 2018).

Thus, HDPO is evaluated with good performance in the global sustainability indicator (score 4).

- FT-diesel

FT-diesel potential to reduce GHG emissions depends on the feedstock and production location. LCA for FT-diesel produced in Sweden using forest residues indicate that it can reduce from 75% to 100% of GHG emissions compared to HFO (BENGTSSON; FRIDELL; ANDERSSON, 2012). Other studies indicate that FT-diesel produced from forest residues may reduce GHG emissions in approximately 94% compared to HFO (KASS et al., 2018). Finally, LCA results of FT-diesel produced in Brazil from forest residues indicate a reduction of 98% in GHG emissions (CARVALHO; PORTUGAL-PEREIRA; SZKLO, 2019).

In this way, FT-diesel was evaluated with very good performance in global sustainability (score 5).

- ATD

Life-cycle analysis found in literature shows that GHG footprint for middle distillates produced from sugarcane ethanol are 92% lower than fossil middle distillates (STAPLES et al., 2014). However, considering land use changes emissions may have significant impact in fuel mitigation potential results (LAPOLA et al., 2010; PLEVIN et al., 2010).

Therefore, ATD was evaluated with a good performance in this indicator (score 4).

1.9.2 Group 2 – Alcohol and liquefied gases

- Bio-LNG

Although emissions during operation are lower than conventional marine fuels, downstream emissions may reduce bio-LNG GHG mitigation potential. Even so, it may reduce GHG by 30% compared to LSHFO (GILBERT et al., 2018). However, methane slip may negatively affect the fuel global sustainability, as methane has a GWP (Global Warming Potential) 28 times higher than CO_2.

Therefore, bio-LNG was evaluated with a median performance in global sustainability (score 3).

- Biomethanol

Biomethanol life cycle GHG emissions estimates are, on average, 85% lower than conventional fuels (BALCOMBE et al., 2019). Even so, its perfomance in this indicator is inferior to alternatives such as green hydrogen, e-diesel and electromethanol.

Thus, biomethanol was evaluated with a good performance in global sustainability (score 4).

- Bioethanol

Several studies assess the impacts of ethanol GHG emissions. A study published by EMSA reveals that the life-cycle emissions for ethanol produced from Brazilian sugarcane are well below than U.S corn ethanol, LNG and marine diesel (ELLIS; TANNEBERGER, 2015).

Thus, ethanol is evaluated with a good performance in the global sustainability indicator (score 4).

1.9.3 Group 3 - Hydrogen, ammonia and e-fuels

- Green H2

Hydrogen use in fuel cells or ICE does not emit GHG. In addition, as green H_2 is produced by electrolysis from renewable sources of electricity, no GHG emissions occur in fuel production stage.

Thus, green hydrogen is evaluated with a very good performance in global sustainability (score 5).

- Green NH3

Ammonia use in ICEs or fuel cells does not produce GHG emissions. In addition, green ammonia production is entirely based on renewable electricity (for water electrolysis, N_2 production and Haber-Bosch synthesis).

Therefore, green ammonia is evaluated with a very good performance in global sustainability (score 5).

- e-diesel

As e-diesel is produced from green hydrogen, it produces very low GHG emissions. In addition, e-diesel production in large scales would foster the development of carbon capture technologies.

Therefore, electrodiesel is evaluated with a very good performance in global sustainability (score 5).

- e-methane

As for e-diesel, life-cycle GHG emissions of electro-LNG are very low. Also, its production the development of negative emission technologies. Even so, the carbon intensity of e-LNG tends to be higher than other e-fuels, due to handling, transport and storage activities and the possibility of fugitive CH_4 emissions.

In this way, electro-LNG is evaluated with a median performance in global sustainability (score 3).

- e-methanol

Considering that e-methanol is produced from recycled CO_2 and hydrogen from renewable sources, its production and use has almost no GHG emissions. Furthermore, its development may promote CO_2 capture technologies.

Thus, e-methanol is evaluated with a very good performance in global sustainability (score 5).

Appendix B

B.1 Methodological assumptions

S2Biom project biomass potential classes

Table B 1: Biomass potential classes in S2Biom project

Types of potential assessed in S2Biom study		Parameters and models used
Technical potential	Represents the maximum quantity of residues potentially available assuming minimum technical constrains.	Crop and yields derived from CAPRI model. Residue yield factors assumed in CAPRI[a] model were derived from (SCARLAT; MARTINOV; DALLEMAND, 2010). EFISCEN[b] model was used to assess the technical potential of forest biomass.
Base potential	Discounts from the technical potential the fraction of residues needed to stabilize the soil organic carbon (SOC) content and considers additional constraints for residue and stump extraction.	MITERRA[c]-Europe model was used to calculate the soil organic carbon (SOC) balance at regional level in Europe and provided the input data for the RothC[d] model that assessed the soil carbon dynamics. Constrains on forest biomass supply were based in (VERKERK et al., 2011).
User-defined potential	Discounts from the technical or base potential the residues used in current practices, competing uses and additional constrains[e].	CAPRI model estimate competing uses by using factors for agricultural straw use by animals provided by (SCARLAT; MARTINOV; DALLEMAND, 2010). Regarding primary forest biomass, competing uses are associated with roundwood production for material use (DEES et al., 2017).

Notes:

[a]CAPRI: Common Agricultural Policy Regionalised Impact. Global agricultural sector model with focus on EU28, Norway, Turkey, and Western Balkans, that links a supply module and a market module.

[b]EFISCEN: European Forest Information SCENario model is a large-scale forest model that projects forest resource development on regional to European scale.

[c]MI-TERRA: Model that calculates GHG emissions, SOC stock changes and nitrogen emissions from agriculture on a deterministic and annual basis.

[d]Roth C: Rothamsted Carbon Model assesses the turnover of organic carbon in non-waterlogged topsoils considering the effects of soil type, temperature, moisture content and plant cover.

[e] Site productivity, soil and water protection, protected forest areas, soil bearing capacity and roundwood production for material.

Collection and transportation costs of biomass for each region

Table B 2: Collection and transport costs of biomass considered for each region and crop.

	C_{cb} or P_{SVO} (US$/GJ)	C_{tb}[d] (US$/GJ.km)	References
Brazil			
Sugarcane straw	0.57	0.006[c]	(CARVALHO et al., 2019; ROOZEN, 2015; SILVA, 2017)
Soybean straw	0.75		
Maize stover	0.83		
Wheat straw	0.98		
Eucalyptus residues	0.64		
Pinus residues	0.60		
Forest Extraction residues	0.52		
Total residues[a]	0.70		
Soybean oil	20.2	0.02[c]	
Cotton oil	21.7		
Peanut oil	36.3		
Sunflower oil	18.9		
Mamon oil	32.9		
Corn oil	44.6		
Total oil[b]	20.2		
Europe			
All crops (Crop residues, forest residues and total residues[a])	S2biom road-side supply costs files	0.012	(DAIOGLOU et al., 2016; S2BIOM, 2017b)
South Africa			
Sugarcane straw	0.60	0.030	(BATIDZIRAI et al., 2016)
Wheat straw	0.60	0.030	
US			
Forest Residues_1	0.81	0.010	(U.S. DEPARTMENT OF ENERGY, 2011)
Forest Residues_2	0.81		
Forest Residues_3	0.81		
Forest Residues_4	0.81		
Forest Residues_5	0.81		
Corn Residues_1	1.06		
Corn Residues_2	1.06		
Corn Residues_3	1.06		
Wheat Residues_1	1.06		
Wheat Residues_2	1.06		

Notes:
a: Total residues considers all crops resources available in the area. Collection and transport costs was based on average values for main crops in the region.
b: Total oil considers all SVO resources available in the area. Collection costs was based on average values for main SVO in the region.
c: Transport costs were calculated based on equations for transport costs of biomass residues available in (CARVALHO et al., 2019).
d: Consider the distance between each regional division inside the 100 km area and the hotspot (determined in the georeferenced analysis).

Table B 3: Prices and factors for each region

Inputs				
	Labour costs factor (ILO, 2020)	**Electricity ($US\$_{2018}$/MWh)[b]** (IEA, 2018b)	**Natural gas (US$/m3)** (GLOBAL PETROL PRICES, 2018)	**Make up water (US$/t)** (GLOBAL WATER INTEL, 2020; GLOBAL WATER SECURITY, 2020)
USA	1.00	70	0.23	4.3
South Africa	0.26	63	0.42	1.3
Brazil	0.52	117	0.53	1.6
Europe	0.83[a]	170	0.37	3.9
Co-products				
Co-products	**Jet fuel (US$/t)** (INDEXMUNDI, 2018b)	**Naphtha (US$/t)** (TRADING ECONOMICS, 2018)	**LPG (US$/t)** (INDEXMUNDI, 2020)	
All regions	709.3	536.2	455.7	

Notes:
a: Average from Portugal, Netherlands, France, Norway, Croatia, and Spain salaries.
b: Electricity is also a co-product in some routes

Table B 4: Costs for each transport mode

	Biochar transport costs (US$/t.km)			Biofuel transport costs (US$/t.km)			
	Road	Rail	IWW	Road	Rail	IWW	Pipeline
Brazil	0.09 (CASTRO, 2020)	-	-	0.09 (FRETEBRAS, 2020; TRANSPETRO, 2020)	-	-	5.55[a] (TRANSPETRO, 2020)
South Africa	0.21 (DEPARTMENT OF ENVIRONMENTAL AFFAIRS SOUTH AFRICA, 2015)	-	-	0.21[a] (DEPARTMENT OF ENERGY SOUTH AFRICA, 2020a, 2020b)	-	-	-
Europe	0.14 (ZIMMER et al., 2017)	0.05 (HOEFNAGELS et al., 2014)	0.01 (HOEFNAGELS et al., 2014)	0.22 (DE JONG et al., 2017)	0.02 (DE JONG et al., 2017)	0.007 (DE JONG et al., 2017)	0.02[c]
USA	0.10	0.04	0.01	0.23	0.02[b]	0.007[b]	0.02[c]

	(MAI-MOULIN et al., 2019)	(HOEFNAGELS et al., 2014)	(GONZALES; SEARCY; EKŞIOĜLU, 2013)	(BROWN et al., 2013)	(DE JONG et al., 2017)	(DE JONG et al., 2017)	(DE JONG et al., 2017; STRATA, 2017)
Tortuosity factor							
			Road		1.27		(SULTANA; KUMAR, 2014)
			Rail		1.79		(KIM; DALE, 2015)
			Inland Waterway		1.60		(PEARLSON, 2011)

Notes:
[a] A conservative estimate was adopted, and same value as reported for biochar transport was considered.
[b] Same transport costs as EU
[c] Calculated with a factor that correlates rail and pipeline transport for US. Same relation assumed for EU costs

Technological production routes yields

HVO

Table B 5 presents a summary of the yields, main inputs and outputs and parameters adopted for the HVO plant. This study considered hydrogen on-site production from natural gas (PEARLSON, 2011).

Table B 5: HVO yields

HVO		References
Inputs		
Vegetable oil (kt/yr)	132.7	(PEARLSON, 2011)
Natural gas (m^3/yr)	467.5	
Electricity (MWh/yr)	34,176.7	
Water (m^3/yr)	104,454.7	
Outputs		
Diesel (kt/yr)	90.4	(PEARLSON, 2011)
Propane (kt/yr)	5.6	
LPG[a] (kt/yr)	2.1	
Naphtha (kt/yr)	2.4	
Jet fuel (kt/yr)	17.0	
Biobunker yield		
Mass basis	0.68	
Energy basis	0.76	

Note:
[a]Liquefied Petroleum Gas

ATD

Table B 6 presents the plant scale, main inputs, outputs, and yields for biobunker production from ATD pathway. Part of the electricity produced in the 2G-ethanol production supplies the plant demand and the rest is exported. A fraction of the bio-alcohol produced feeds an in-site hydrogen production facility.

Table B 6: ATD yields

ATD	Inputs	Outputs	References
Bio-alcohol production			
Lignocelullosic biomass (kt/yr)	720.0		(CERVI et al., 2021; JONKER et al., 2015)
Ethanol (kt/yr)		158.4	
Electricity (MWh)		92,135.6	
Biobunker production[a]			
Ethanol (kt/yr)	158.4		(PECHSTEIN; KALTSCHMITT, 2019)
Ethanol used for H_2 production[b] (kt/yr)	6.3		
Diesel		52.3	
LPG		2.9	
Gasoline		17.1	
Jet fuel		22.8	
Biobunker yield[c]			
Mass basis		0.12	
Energy basis		0.27	

Note:
[a] Water is also produced in ethanol dehydration.
[b] A small fraction of ethanol (3.8%) is used for H2 production. Even though it reduces product yield, it would decrease fossil inputs requirements (e.g., natural gas).
[c] Diesel output per biomass input.

HDPO

Table B 7 presents the plant scale, main inputs, outputs, and yields for HDPO pathway. Plants scales were based in typical hydrotreatment unities in oil refineries (GUEDES et al., 2019) and cost data obtained from (JONES et al., 2013).

Table B 7: HDPO yields

HDPO	Inputs	Outputs	References
Pyrolysis			
Ligonocelullosic biomass (kt/yr)	620.5		(JONES et al., 2013)
Natural gas (Mm^3/yr)	34.0		
Electricity (MWh/yr)	76287.8		

Make up water (kt/yr)	338.8		
Bio-oil (kt/yr)		384.71	
Biobunker production			
Bio-oil (kt/yr)	384.7		(GUEDES et al., 2019; JONES et al., 2013)
Diesel (kt/yr)	92.6		
Gasoline (kt/yr)	75.8		
Biobunker yield[a]			
Mass basis		0.15	
Energy basis		0.34	

Note:
[a] Hydrogen for hydroprocessing (hydrotreating and hydrocracking) is produced via steam reforming of fast pyrolysis off-gases. Additional natural gas is used to obtain sufficient hydrogen for the plant.
[b] Diesel output per biomass input

FT-BTL

Table B 8 presents the plant scale, main inputs, outputs, and yields for FT-BTL pathway.

Table B 8: FT-BTL yields

FT-BTL	Inputs	Outputs	References
Decentralized configuration			
Torrefaction			
Lignocellulosic biomass (kt/yr)	213.0		(CASTRO, 2020)
Torrefied biomass (kt/yr)		170.4	
Biobunker production			
Biochar (kt/yr)	88.3		(CASTRO, 2020; JAMES et al., 2019; TAGOMORI; ROCHEDO; SZKLO, 2019)
Diesel (kt/yr)		10.9	
Gasoil (kt/yr)		1.1	
LPG (kt/yr)		3.4	
Naphtha (kt/yr)		4.3	
Biobunker yield[a]			
Mass basis		0.06	
Energy basis		0.12	
Centralized configuration			
Biobunker production			
Lignocellulosic biomass (kt/yr)	949.0[b]-326.5[c]		[65,96,98,99] (CASTRO, 2020; PORCU et al., 2019; TAGOMORI;
Diesel (kt/yr)		48.5[b] - 21.8[c]	
Gasoil (kt/yr)		4.8[b] - 2.1[c]	
LPG (kt/yr)		15.1[b] - 6.8[c]	
Naphtha (kt/yr)		19.1[b] - 8.6[c]	

ROCHEDO; SZKLO, 2019; WORLEY; YALE, 2012)

	Biobunker yield[a]
Mass basis	0.06[b] - 0.07[c]
Energy basis	0.13[b] -0.16[c]

Notes:
[a] Diesel and gasoil output per biomass input
[b] Entrained flow gasifiers scale
[c] Fluidized bed gasifiers scale

B.2 Biomass hotspots, potential, costs, and infrastructure

B.2.1 Maps of biomass hotspots and potential

B.2.1.1 BRAZIL

Agricultural and forest residues

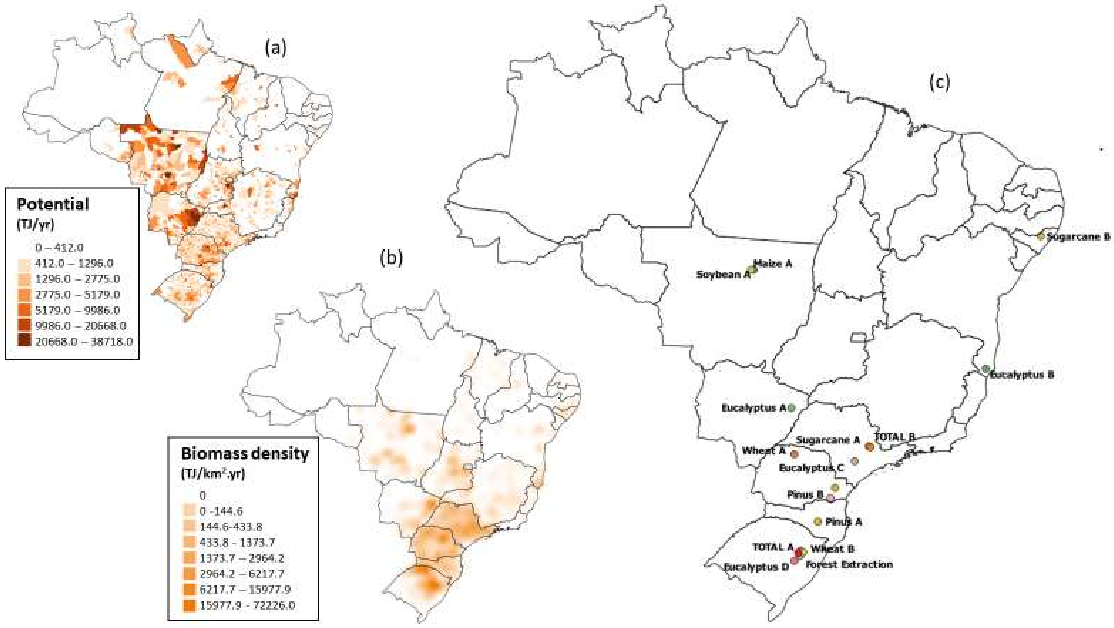

Figure B 1: Brazil residues potential for each municipality, kernel maps and hotspots

Vegetable oil

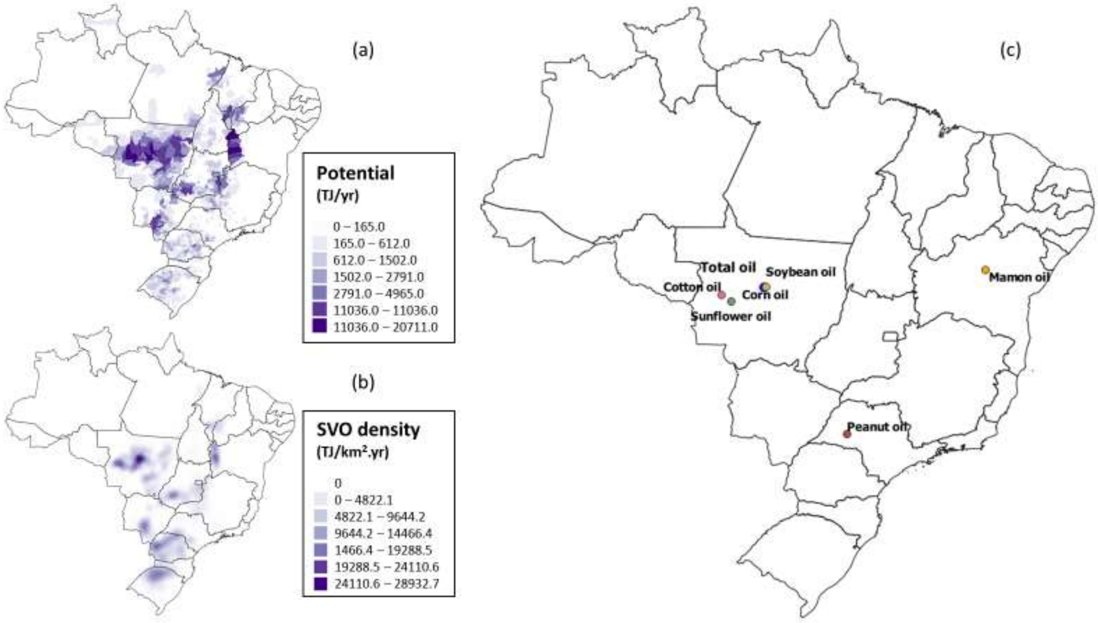

Figure B 2: Brazil SVO potential for each municipality, kernel maps and hotspots

B.2.1.2 Europe

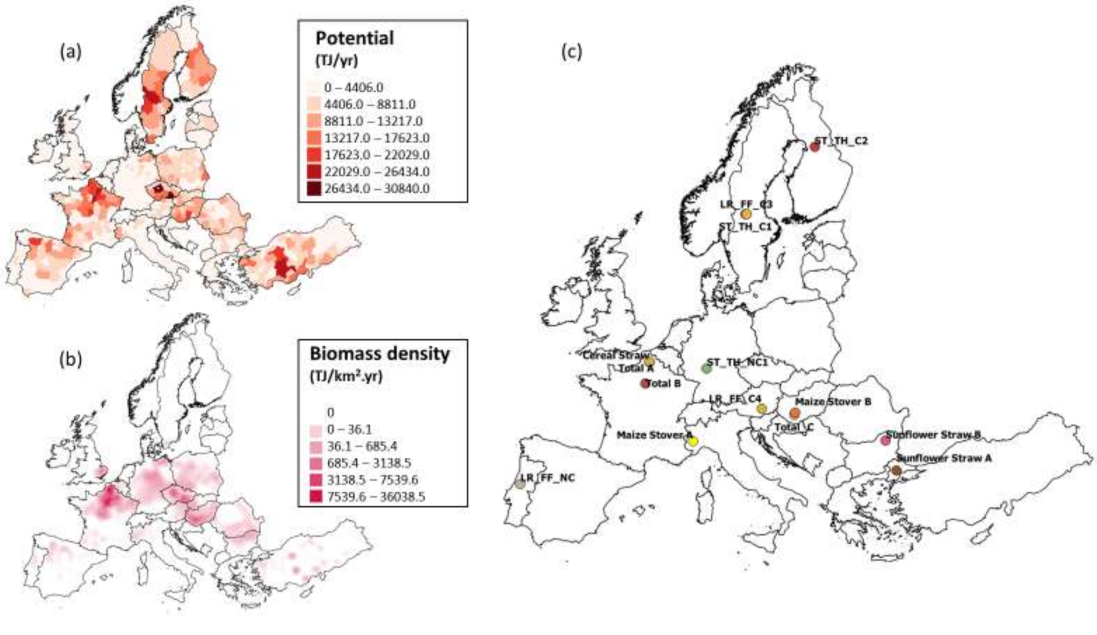

Figure B 3: Europe potential for each municipality, kernel maps and hotspots

B.2.1.3 U.S.

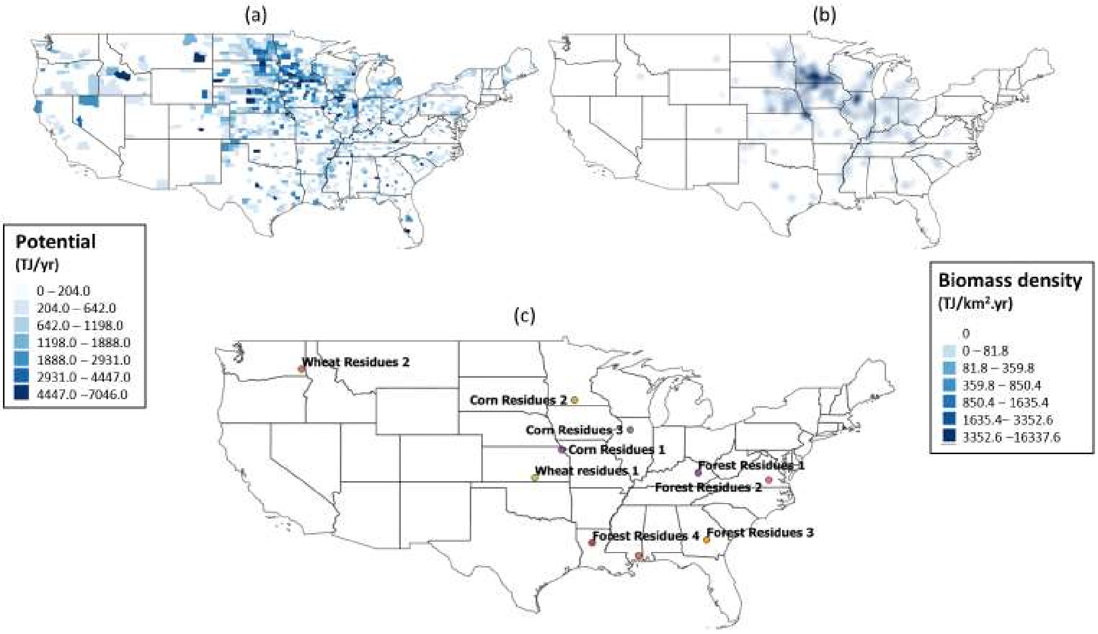

Figure B 4: US potential for each municipality, kernel maps and hotspots.

B.2.1.4 South Africa

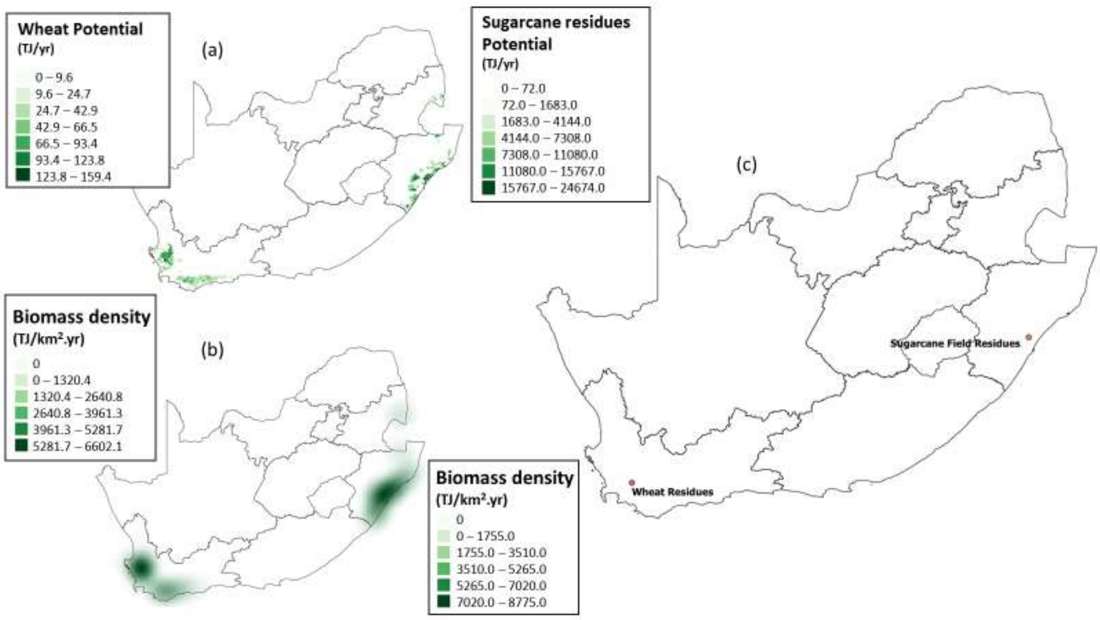

Figure B 5: South Africa potential for each municipality, kernel maps and hotspots.

B.2.2 Biomass residues and vegetable oil potentials for each hotspot

Table B 9: Biomass residues and vegetable oil potentials

Hotspot	Potential (PJ)
BR_Sugarcane A	118.4
BR_Sugarcane B	43.2
BR_Soybean A	71.1

BR_Soybean B	59.5
BR_Maize A	34.1
BR_Maize B	14.1
BR_Wheat A	5.8
BR_Wheat B	3.1
BR_Eucalyptus A	66.6
BR_Eucalyptus B	49.1
BR_Eucalyptus C	52.2
BR_Eucalyptus D	59.2
BR_Pinus A	60.5
BR_Pinus B	32.6
BR_Forest Extraction	3.5
BR_Total A	196.5
BR_Total B	153.6
BR_Soybeanoil	8.6
BR_Cottonoil	1.6
BR_Peanutoil	0.6
BR_Sunfloweroil	0.2
BR_Mamonoil	0.03
BR_Cornoil	2.6
BR_Totaloil	12.9
EU_Cereal Straw	89.8
EU_Maize Stover A	25.7
EU_Maize Stover B	53.2
EU_Sunflower Straw A	12.1
EU_Sunflower Straw B	18.2
EU_LR_FF_NC	18.2
EU_LR_FF_C3*	15.1
EU_LR_FF_C4	17.1
EU_ST_TH_NC1	25.8
EU_ST_TH_C1	19.5
EU_TOTAL_A	111.4
EU_TOTAL_B	129.4
EU_TOTAL_C	131.5
SA_Sugarcane straw	17.0
SA_Wheat Residues	10.2
US_Forest Residues 1	35.0
US_Forest Residues 2	28.3
US_Forest Residues 3	25.0
US_Forest Residues 1	20.3
US_ Forest Residues 5	13.2
US_Corn Residues 1	31.4
US_Corn Residues 2	58.1
US_Corn Residues 3	49.1
US_Wheat Residues 1	16.8
US_Wheat Residues 2	17.8

B.2.3 Maps of hotspots and existing infrastructure.

B.2.3.1 Brazil

Biomass residues

Figure B 6: Biomass residues hotspots and infrastructure in Brazil

Vegetable oils

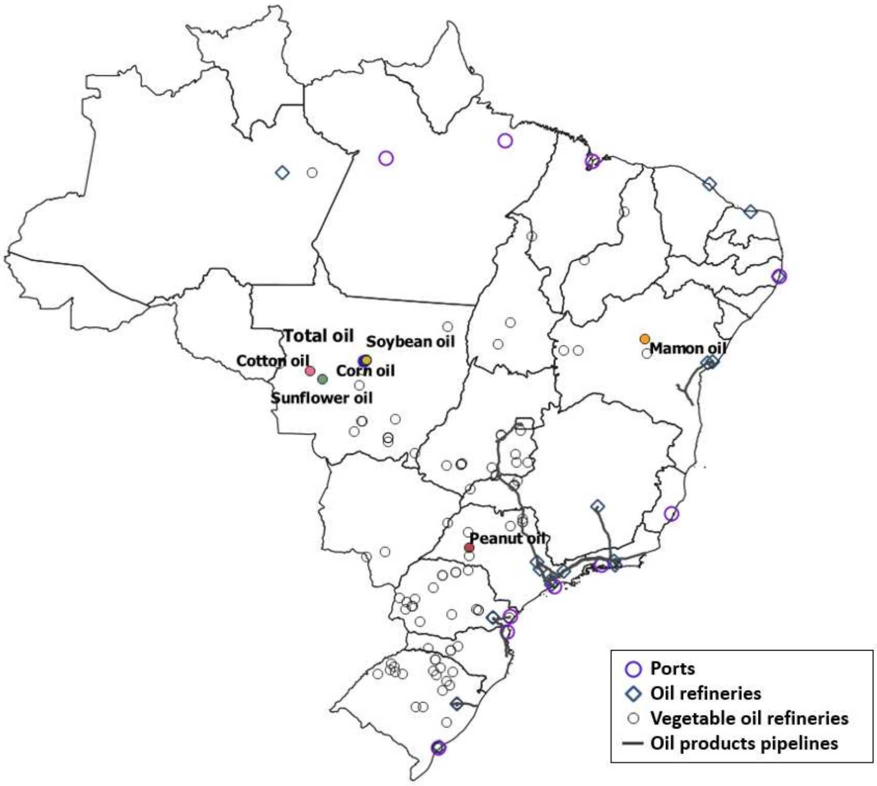

Figure B 7: SVO hotspots and infrastructure in Brazil

B.2.3.2 Europe

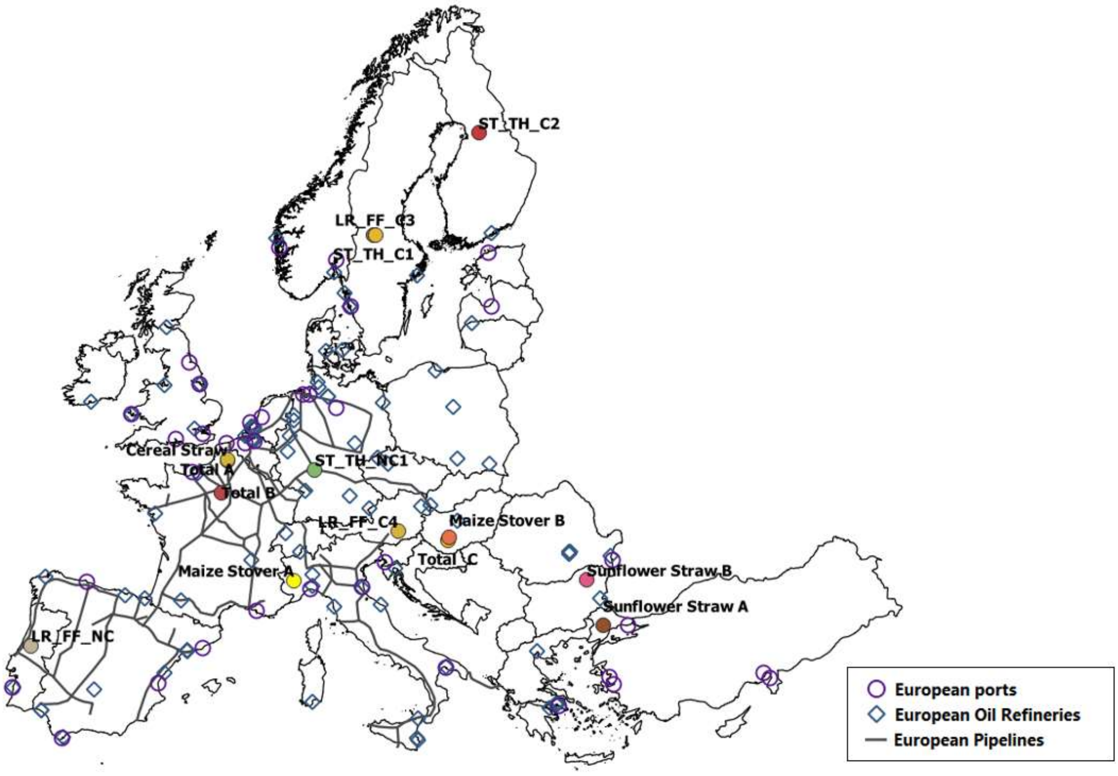

Figure B 8: Biomass residues hotspots and infrastructure in Europe

B.2.3.4 US

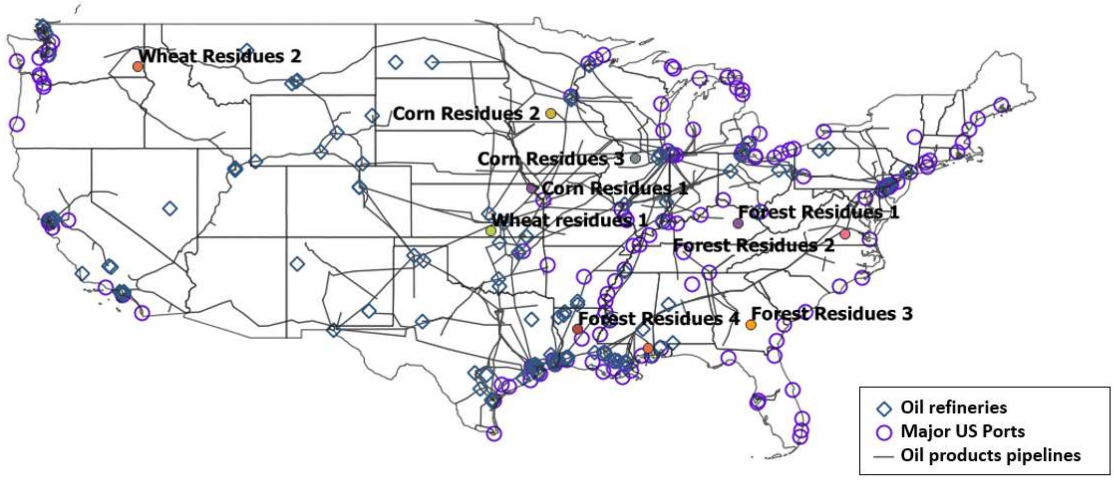

Figure B 9: Biomass residues hotspots and infrastructure in the US

B.2.3.5 South Africa

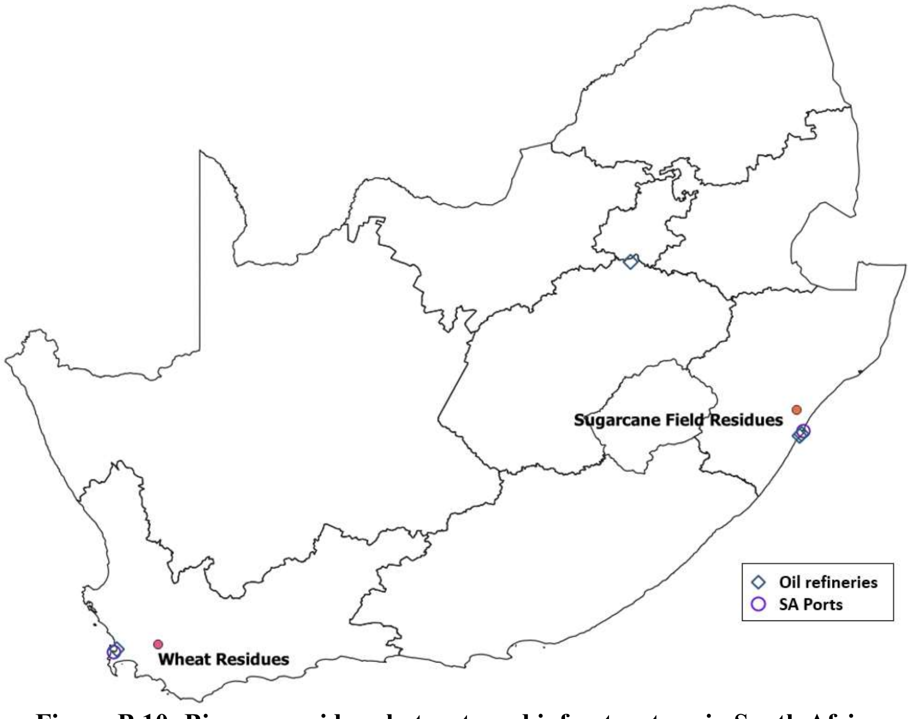

Figure B 10: Biomass residues hotspots and infrastructure in South Africa

B.2.4 Distance of hotspots to the nearest terminal

Table B 10: Hotspots distances to the nearest terminal

Hotspot	Nearest Port	Distance (km)
BR_Sugarcane A	Santos	157.7
BR_Sugarcane B	Suape	160.7

BR_Soybean A	Santarem	901.7
BR_Soybean B	Rio Grande	288.8
BR_Maize A	Santarem	902.0
BR_Maize B	Paranagua	76.5
BR_Wheat A	Paranagua	408.9
BR_Wheat B	Rio Grande	282.1
BR_Eucalyptus A	Paranagua	637.0
BR_Eucalyptus B	Vitoria	267.2
BR_Eucalyptus C	Santos	179.8
BR_Eucalyptus D	Rio Grande	219.7
BR_Pinus A	São Francisco do Sul	209.1
BR_Pinus B	São Francisco do Sul	98.4
BR_Forest Extraction	Rio Grande	219.7
BR_Total A	Rio Grande	269.8
BR_Total B	Santos	148.1
BR_Soybeanoil	Santarem	1019.5
BR_Cottonoil	Santarem	1022.1
BR_Peanutoil	Santarem	1131.3
BR_Sunfloweroil	Santarem	1153.6
BR_Mamonoil	Paranagua	402.0
BR_Cornoil	Suape	744.1
BR_Totaloil	Santarem	1021.9
EU_Cereal Straw	Dunkirk	85.9
EU_Maize Stover A	Genova	97.0
EU_Maize Stover B	Trieste	358.6
EU_Sunflower Straw A	Ambarli	128.7
EU_Sunflower Straw B	Constanta	167.9
EU_LR_FF_NC	Sines	237.7
EU_LR_FF_C3	Oslo	237.7
EU_LR_FF_C4	Trieste	174.9
EU_ST_TH_NC1	Hamburb	339.5
EU_ST_TH_C1	Oslo	232.5
EU_TOTAL_A	Dunkirk	90.2
EU_TOTAL_B	Le Havre	187.2
EU_TOTAL_C	Trieste	347.2
SA_Sugarcane straw	Durban	44.9
SA_Wheat Residues 1	Cape Town	76.0
US_Forest Residues 1	Huntington Tri-State	132.5
US_Forest Residues 2	Virginia	126.1
US_Forest Residues 3	Brunswick	172.9
US_Forest Residues 1	Central Louisiana Regional Port	59.1
US_Forest Residues 5	Pascogoula	49.6
US_Corn Residues 1	Kansas City	93.5
US_Corn Residues 2	Saint Paul	142.5
US_Corn Residues 3	Chicago	160.0
US_Wheat Residues 1	Tulsa	205.4
US_Wheat Residues 2	Everett	397.9

B.2.5 Feedstock costs

Table B 11: Feedstock costs for each hostpot

Hotspot	Cf (US$/GJ)
BR_Sugarcane A	0.98
BR_Sugarcane B	1.01
BR_Soybean A	1.16
BR_Soybean B	1.10
BR_Maize A	1.24
BR_Maize B	1.28
BR_Wheat A	1.41
BR_Wheat B	1.35
BR_Eucalyptus A	0.95
BR_Eucalyptus B	0.94
BR_Eucalyptus C	0.99
BR_Eucalyptus D	1.01
BR_Pinus A	0.93
BR_Pinus B	0.99
BR_Forest Extraction	0.76
BR_Total A	1.12
BR_Total B	1.12
BR_Soybeanoil	20.6
BR_Cottonoil	24.3
BR_Peanutoil	37.2
BR_Sunfloweroil	22.0
BR_Mamonoil	34.3
BR_Cornoil	45.0
BR_Totaloil	20.8
EU_Cereal Straw	3.62
EU_Maize Stover A	2.96
EU_Maize Stover B	2.23
EU_Sunflower Straw A	2.00
EU_Sunflower Straw B	2.04
EU_LR_FF_NC	2.04
EU_LR_FF_C3	4.57
EU_LR_FF_C4	3.78
EU_ST_TH_NC1	3.44
EU_ST_TH_C1	4.91
EU_TOTAL_A	3.94
EU_TOTAL_B	3.97
EU_TOTAL_C	2.46
SA_Sugarcane straw	1.74
SA_Wheat Residues	0.92
US_Forest Residues 1	1.40

US_Forest Residues 2	1.47
US_Forest Residues 3	1.58
US_Forest Residues 1	1.55
US_Forest Residues 5	1.42
US_Corn Residues 1	1.57
US_Corn Residues 2	1.67
US_Corn Residues 3	1.60
US_Wheat Residues 1	1.63
US_Wheat Residues 2	1.63

B.3 Technoeconomic analysis

B.3.1 Number of plants

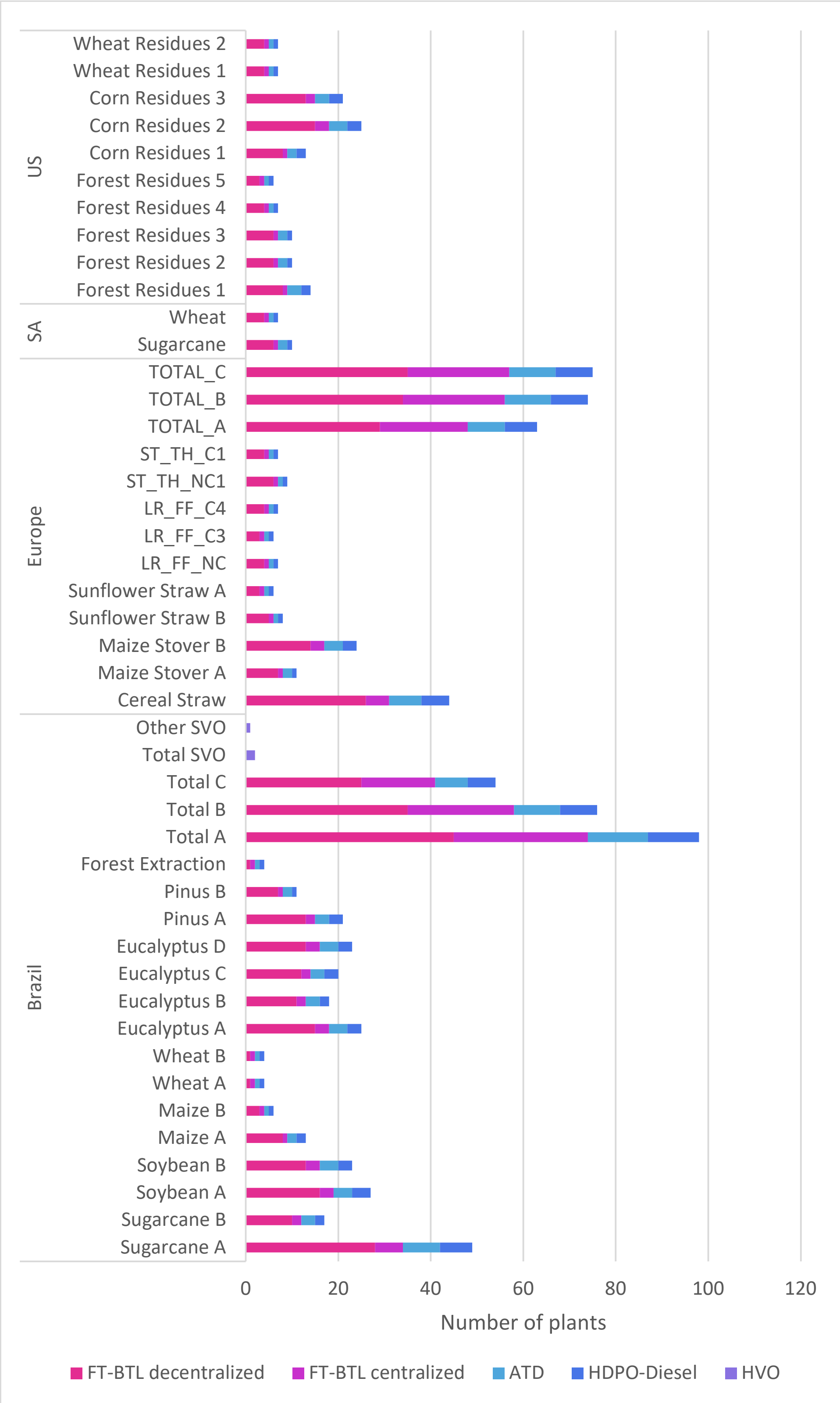

Figure B 11: Number of plants for fuel conversion technologies in each hotspot

B.3.2 LCOF

Table B 12: LCOF for different fuel conversion technologies in each hotspot

Region	Hotspots	LCOF (US$/GJ)					
		FT-BTL decentralized	FT-BTL centralized	ATD	HDPO-Diesel	HVO	SVO
Brazil	Sugarcane A	53.0	27.3	40.3	28.0	-	-
	Sugarcane B	53.0	27.4	40.3	28.1	-	-
	Soybean A	53.1	30.9	39.5	27.3	-	-
	Soybean B	53.1	30.4	39.5	27.1	-	-
	Maize A	53.1	29.0	40.3	29.5	-	-
	Maize B	53.1	30.1	39.3	30.6	-	-
	Wheat A	53.2	40.4	62.1	39.9	-	-
	Wheat B	57.7	44.7	92.6	49.6	-	-
	Eucalyptus A	53.0	27.2	40.4	26.5	-	-
	Eucalyptus B	53.0	27.6	40.4	26.4	-	-
	Eucalyptus C	53.0	27.6	40.4	26.6	-	-
	Eucalyptus D	53.0	27.8	40.4	26.7	-	-
	Pinus A	53.0	27.7	40.4	24.6	-	-
	Pinus B	53.0	28.2	40.4	20.8	-	-
	Forest Extraction	59.6	36.9	108.5	38.9	-	-
	Total A	53.1	22.7	40.6	26.9	-	-
	Total B	53.1	22.7	40.6	26.9	-	-
	Total C	53.1	22.8	40.6	28.4	-	-
	Total oil	-	-	-	-	32.3	20.6
	Soybean oil	-	-	-	-	21.9	24.3
	Cotton oil	-	-	-	-	23.6	37.2
	Peanut oil	-	-	-	-	41.5	22.0
	Sunflower oil	-	-	-	-	20.4	34.3
	Mamon oil	-	-	-	-	37.0	45.0
	Corn oil	-	-	-	-	51.0	20.8
Europe	Cereal Straw	72.8	45.9	51.8	41.6	-	-
	Maize Stover A	69.8	39.4	50.1	32.4	-	-
	Maize Stover B	64.8	36.0	47.5	35.6	-	-
	Sunflower Straw B	63.1	37.0	41.7	32.9	-	-
	Sunflower Straw A	62.9	38.9	46.9	37.2	-	-
	LR_FF_NC	64.8	35.2	43.4	29.9	-	-
	LR_FF_C3	85.0	56.1	56.3	39.5	-	-
	LR_FF_C4	78.9	49.5	51.7	36.1	-	-
	ST_TH_NC1	76.2	45.4	45.8	31.7	-	-
	ST_TH_C1	87.7	57.9	54.5	38.2	-	-
	TOTAL_A	77.4	35.7	53.8	40.4	-	-
	TOTAL_B	77.6	35.8	53.9	40.5	-	-
	TOTAL_C	66.8	27.5	48.4	36.0	-	-
SA	Sugarcane	48.3	22.8	40.6	38.8	-	-

	Wheat	44.5	25.1	36.4	42.6	-	-
US	Forest Residues 1	58.9	27.2	43.2	28.6	-	-
	Forest Residues 2	59.4	27.8	43.4	28.9	-	-
	Forest Residues 3	60.3	28.7	43.9	29.2	-	-
	Forest Residues 4	60.0	28.4	43.7	29.1	-	-
	Forest Residues 5	59.0	28.5	43.2	30.8	-	-
	Corn Residues 1	59.2	27.6	43.5	28.8	-	-
	Corn Residues 2	60.0	25.6	43.9	29.1	-	-
	Corn Residues 3	59.4	25.3	43.7	28.9	-	-
	Wheat Residues 1	59.7	28.3	43.8	29.0	-	-
	Wheat Residues 2	56.7	28.1	43.8	29.0	-	-

B.3.3 Fuel transportation mode for each hotspot

Table B 13: Fuel transportation mode chosen for each hotspot.

Region	Hotspot	Transport mode	
		FT-BTL decentralized	FT-BTL centralized, ATD, HDPO and HVO
Brazil	Sugarcane A	Road	Pipeline
	Sugarcane B, Soybean A, Soybean B, Maize A	Road	
	Maize B	Road	Pipeline
	Wheat A, Wheat B, Eucalyptus A, Eucalyptus B, Eucalyptus C, Eucalyptus D, Pinus A, Pinus B, Forest Extraction, Total A, Total B, Total C	Road	
	Total SVO, Soybean oil, Peanut oil, Cotton oil, Mamon oil, Corn oil	-	Road
South Africa	Sugarcane, Wheat	Road	
Europe	Cereal Straw	Road	
	Maize Stover A, Maize Stover B, Sunflower Straw A, Sunflower Straw B, LR_FF_NC, LR_FF_C3, LR_FF_C4, ST_TH_NC1	Rail	
	ST_TH_C1, TOTAL_A	Road	
	TOTAL_B	IWW	
	TOTAL_C	Rail	
US	Forest Residues 1, 2 and 3	Rail	
	Forest Residues 4 and 5	Road	
	Corn Residues 1	Road	Pipeline
	Corn Residues 2 and 3, Wheat Residues 1 and 2	Rail	

B.3.4 Fuel total costs

Table B 14: Total biobuker cost for different fuel conversion routes in each hotspot

Region	Hotspots	TOTAL COSTS (US$/GJ)					
		FT-BTL decentralized	FT-BTL centralized	ATD	HDPO-Diesel	HVO	SVO
BR	Sugarcane A	53.7	27.4	40.4	28.1	-	-
	Sugarcane B	53.7	27.8	40.7	28.5	-	-
	Soybean A	57.2	32.4	40.9	28.7	-	-
	Soybean B	54.4	31.0	40.1	27.7	-	-
	Maize A	57.2	30.5	41.7	30.9	-	-
	Maize B	53.5	30.3	39.4	30.7	-	-
	Wheat A	55.0	41.1	62.8	40.6	-	-
	Wheat B	60.6	45.8	93.1	50.1	-	-
	Eucalyptus A	55.9	28.3	41.5	27.6	-	-

	Eucalyptus B	54.2	28.1	40.9	26.9	-	-
	Eucalyptus C	53.8	28.0	40.8	27.0	-	-
	Eucalyptus D	54.0	28.2	40.9	27.2	-	-
	Pinus A	53.9	28.1	40.8	25.0	-	-
	Pinus B	53.5	28.5	40.7	21.1	-	-
	Forest Extraction	60.8	37.4	109.0	39.4	-	-
	Total A	60.8	23.5	41.4	27.7	-	-
	Total B	53.7	23.1	41.0	27.3	-	-
	Total C	57.2	24.2	42.0	29.8	-	-
	Total oil	-	-	-	-	34.1	22.4
	Soybean oil	-	-	-	-	23.7	26.1
	Cotton oil	-	-	-	-	25.4	39.0
	Peanut oil	-	-	-	-	43.5	24.0
	Sunflower oil	-	-	-	-	22.4	36.4
	Mamon oil	-	-	-	-	37.8	45.7
	Corn oil	-	-	-	-	52.3	22.1
EU	Cereal Straw	73.5	46.4	52.2	42.0	-	-
	Maize Stover A	70.1	40.1	50.4	32.7	-	-
	Maize Stover B	65.8	38.8	48.4	36.6	-	-
	Sunflower Straw B	63.6	38.3	42.1	33.4	-	-
	Sunflower Straw A	63.3	39.9	47.2	37.6	-	-
	LR_FF_NC	65.5	37.0	44.0	30.5	-	-
	LR_FF_C3	85.7	58.0	56.9	40.1	-	-
	LR_FF_C4	79.4	50.9	52.2	36.6	-	-
	ST_TH_NC1	77.2	48.1	46.7	32.6	-	-
	ST_TH_C1	89.6	59.0	55.7	39.4	-	-
	TOTAL_A	78.2	36.1	54.3	40.9	-	-
	TOTAL_B	77.7	37.1	55.2	41.8	-	-
	TOTAL_C	67.9	30.3	49.3	36.9	-	-
SA	Sugarcane Field Residues	49.9	23.2	41.1	39.3	-	-
	Wheat Residues	47.2	25.6	36.9	42.6	-	-
US	Forest Residues 1	59.6	29.2	45.2	30.6	-	-
	Forest Residues 2	59.7	29.7	45.3	30.8	-	-
	Forest Residues 3	60.6	31.3	46.5	31.8	-	-
	Forest Residues 4	60.3	28.7	44.6	30.0	-	-
	Forest Residues 5	59.3	28.7	43.5	31.1	-	-
	Corn Residues 1	59.8	27.6	43.5	28.8	-	-
	Corn Residues 2	60.3	27.8	46.1	31.3	-	-
	Corn Residues 3	59.8	25.4	46.2	31.4	-	-

	Wheat Residues 1	60.1	26.1	46.9	32.1	-	-
	Wheat Residues 2	58.9	28.6	49.9	35.1	-	-

B.4 Biobunker fuel supply and regional demands

Table B 15: Biobunker fuel supply and regional marine fuel demands

	Biomass potential (PJ)	FT-BTL (A)	FT-BTL (B)	ATD	HDPO	HVO	HFO - Brazil (2018)	HFO - EU (2016)	HFO - US (2018)	HFO - Africa (2018)	HFO - Rotterdam (2018)	HFO - Singapore (2018)	HFO - Fujairah (2018)
BR_Hotspots	791.9	98.6	91.0	200.0	235.6	-	217.3	1526.5	958.3	205.0	385.4	2041.8	369.0
BR_Total A	196.5	25.6	33.0	54.2	63.8	-							
BR_Total B	153.6	19.9	26.2	41.7	46.4	-							
BR_Total C	105.3	13.6	17.4	27.8	33.2	-							
BR_SVO_Hotspots	13.6	-	-	-	-	0.23							
BR_Totaloil	12.9	-	-	-	-	0.22							
EU_Hotspots	294.7	39.0	35.4	77.6	93.5	0.0							
EU_TOTAL_A	111.4	15.2	18.1	28.5	34.4	-							
EU_TOTAL_B	129.4	17.8	21.0	35.6	39.3	-							
EU_TOTAL_C	131.5	18.3	21.0	35.6	39.3	-							
SA_Hotspots	27.1	5.2	5.8	12.4	9.2	-							
US_Hotspots	294.7	36.3	30.3	77.7	84.4	-							

Legend:
FT-BTL (A) – Decentralized configuration (torrefaction as pretreatment)
FT-BTL (B) – Centralized configuration

Table B 16: : Percentage of fuel demand supplied by biofuel production in the hotspots

Biofuel production/Regional marine fuel demand	FT-BTL (A)	FT-BTL (B)	ATD	HDPO	HVO	SVO
/BR demand						
BR_Hotspots	45%	42%	92%	108%	-	
BR_Total A	12%	15%	25%	29%	-	
BR_Total B	9%	12%	19%	21%	-	
BR_Totaloil	-	-	-	-	0.10%	6%
BR_SVO_Hotspots	-	-	-	-	0.11%	6%
/EU demand						
EU_Hotspots	3%	2%	5%	6%		
EU_TOTAL_A	1%	1%	2%	2%		
EU_TOTAL_B	1%	1%	2%	3%		
EU_TOTAL_C	1%	1%	2%	3%		
/Rotterdam demand						
EU_Hotspots	10%	9%	20%	24%		
EU_TOTAL_A	4%	5%	7%	9%		
EU_TOTAL_B	5%	5%	9%	10%		
EU_TOTAL_C	5%	5%	9%	10%		
/Africa demand						
SA_Hotspots	3%	3%	6%	4%		
/US demand						
US_Hotspots	4%	3%	8%	9%		

Appendix C

C.1 Fuel demand information

C.1.1 Projected soybean trade flows from Brazil and U.S. to China

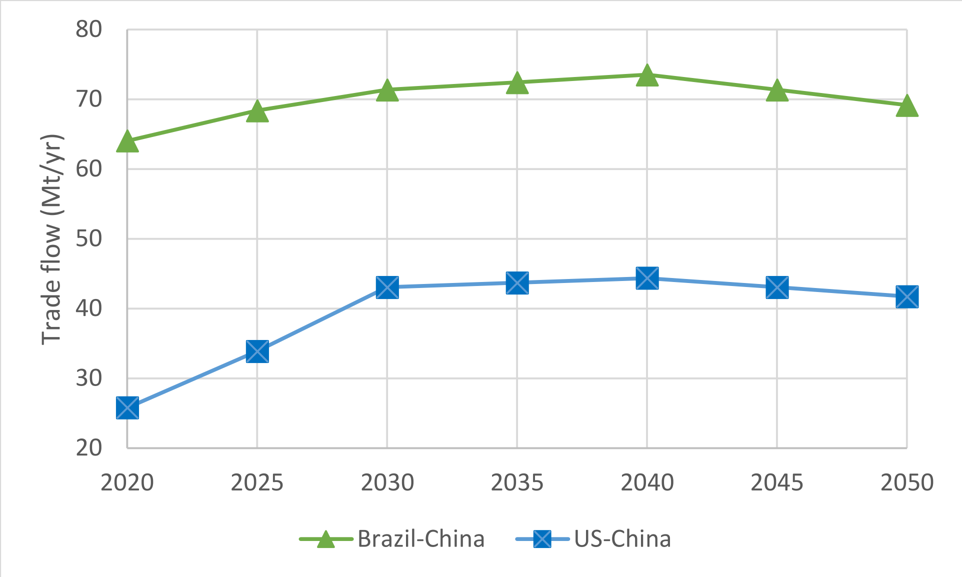

Figure C 1: Projected soybean trade flows.

C.1.2 Specific fuel consumption of the standard ship between 2020 and 2050.

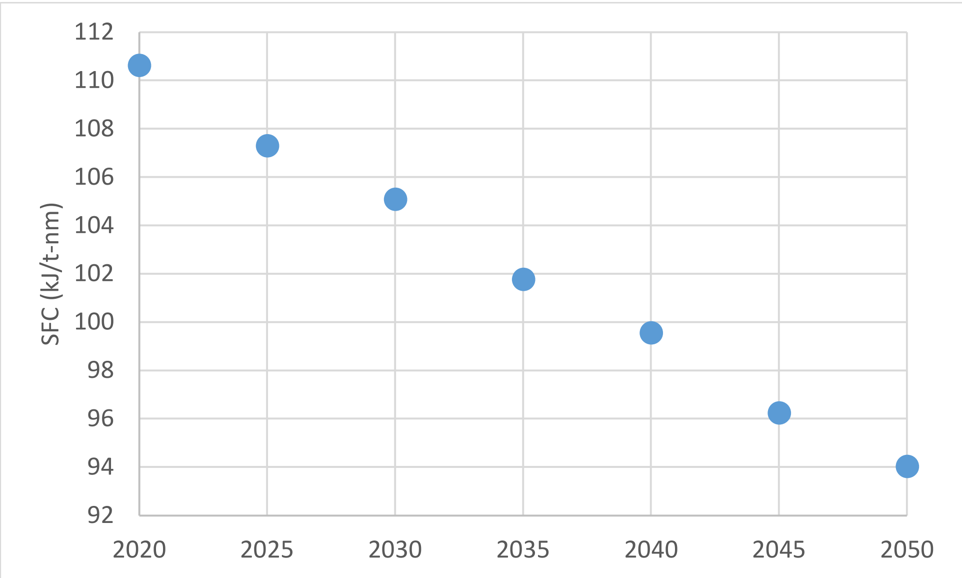

Figure C 2: Specific fuel consumption of the standard ship between 2020 and 2050.

C.2 Biofuel supply

C.2.1 Projection for increase in biomass production from the selected crops from 2020 to 2050.

Table C 1: Projection for increase in biofuel production from 2020 to 2050.

	Biofuel production increase – projections			
Period	**Sugarcane (FAO, 2021)**	**Eucalyptus (EPE, 2018)**	**Residues Mix**	**Forest Residues[a] (COSTANZA, ABT, et al., 2017)**
2020-2025	5%	7.5%	6%	-1.0%
2025-2030	5%	7.5%	6%	-1.0%
2030-2035	2%	7.5%	5%	-1.0%
2035-2040	2%	7.5%	5%	-1.0%
2040-2045	3%	7.5%	5%	-1.0%
2045-2050	3%	7.5%	5%	-1.0%

[a] Decrease of 7.9% between 2010-2050. Thus, the decrease for each 5-year step between 2010 to 2050 would be ~1.0%.

C.2.2 GHG emissions

Table C 2: Abatement cost and avoided emissions for each biofuel pathway in the optimistic and conservative scenarios.

Region	**Hotspot**	**Technology**	**US$/t$CO_2$e**	**Avoided emissions (MtCO2e)**	
				Optimistic	**Conservative**
BRAZIL	Sugarcane	FTBTL	128	1.5	0.9
		ATD	298	3.1	0.7
		HDPO-Diesel	152	2.9	1.9
	Eucalyptus	FTBTL	135	0.7	0.4
		ATD	302	0.5	0.3
		HDPO-Diesel	137	1.6	0.9
	Residues Mix	FTBTL	79	3.1	1.9
		ATD	304	2.9	1.6
		HDPO-Diesel	142	3.1	2.8
U.S.	FR-Louisiana	FTBTL	144	0.2	0.1
		ATD	349	0.2	0.1
		HDPO-Diesel	176	0.3	0.2
	FR-Mississippi	FTBTL	144	0.1	0.1
		ATD	335	0.1	0.1
		HDPO-Diesel	190	0.3	0.2

C.3 Cost and competitiveness assessment of lignocellulosic biofuels

C.3.1 Zero profit price of biofuels (ZPP) according to different carbon price levels

Table C 3: ZPP of lignocellulosic biofuel pathways according to different CO_2 prices.

Zero profit price of biofuels			**CO_2 price levels (US$/t$CO_{2e}$)**					
			10	**20**	**50**	**100**	**150**	**200**
BRAZIL	Sugarcane	FTBTL	26.5	25.7	23.1	18.8	14.5	10.3
		ATD	39.6	38.8	36.4	32.4	28.3	24.3
		HDPO-Diesel	27.4	26.6	24.3	20.4	16.6	12.7

	Eucalyptus	FTBTL	27.1	26.3	23.7	19.4	15.1	10.8
		ATD	40.0	39.2	36.8	32.7	28.7	24.6
		HDPO-Diesel	26.2	25.4	23.1	19.3	15.4	11.6
	Residues Mix	FTBTL	22.3	21.4	18.9	14.6	10.3	6.0
		ATD	40.2	39.4	36.9	32.9	28.9	24.8
		HDPO-Diesel	26.6	25.8	23.5	19.6	15.8	11.9
USA	FR-Louisiana	FTBTL	27.8	27.0	24.5	20.3	16.1	11.9
		ATD	43.8	43.0	40.6	36.6	32.7	28.7
		HDPO-Diesel	29.3	28.5	26.3	22.5	18.8	15.0
	FR-Missisipi	FTBTL	27.9	27.1	24.5	20.3	16.1	11.9
		ATD	42.7	41.9	39.5	35.5	31.5	27.5
		HDPO-Diesel	30.3	29.6	27.3	23.6	19.8	16.1

C.4 Freight costs

C.4.1 Optimistic scenario

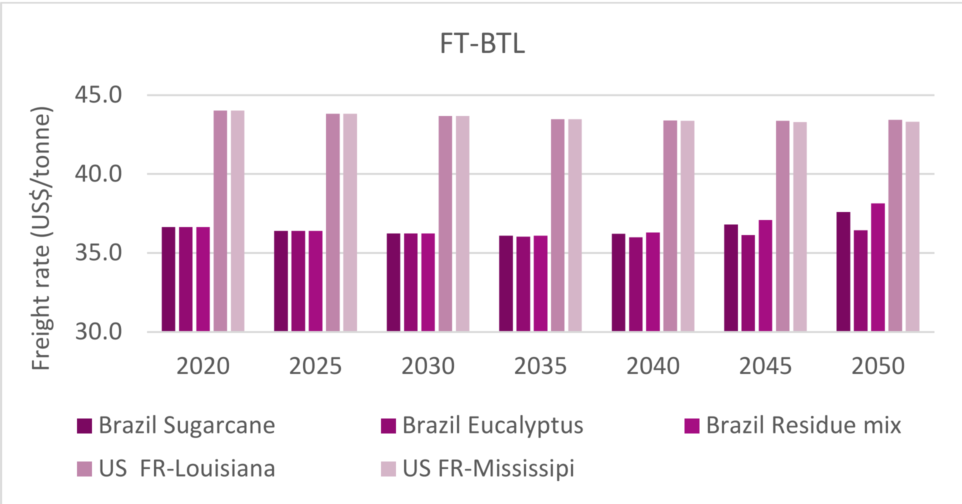

Figure C 3: Freight rates for Brazil and U.S soybean trade routes to China from 2020 to 2050 for the FT-BTL technology in the optimistic scenario.

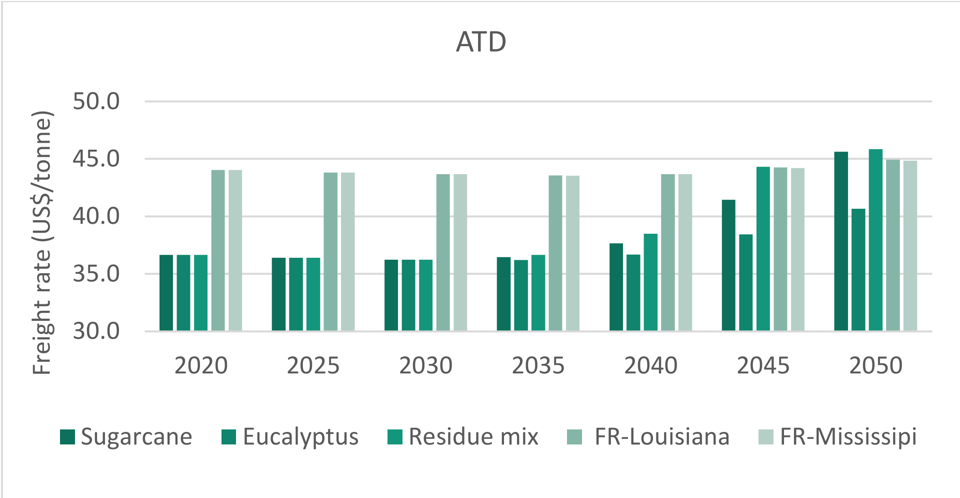

Figure C 4: Freight rates for Brazil and U.S soybean trade routes to China from 2020 to 2050 for the ATD technology in the optimistic scenario.

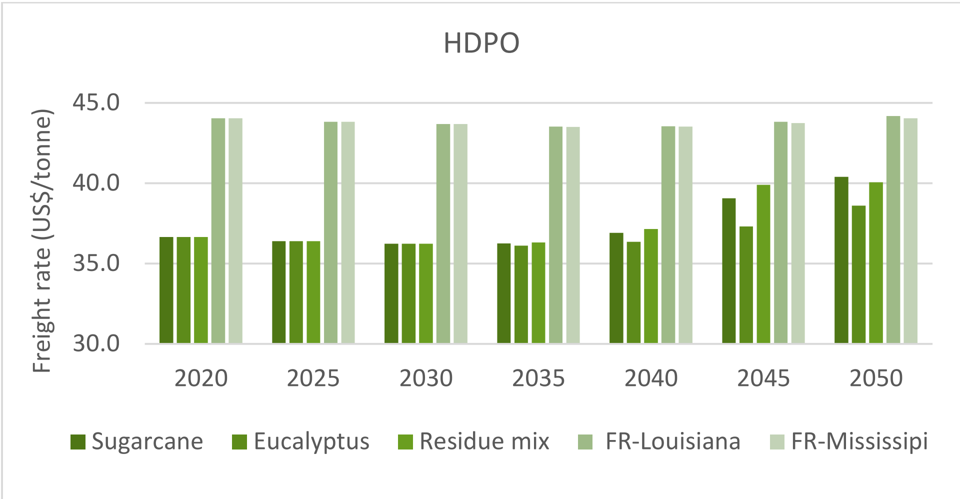

Figure C 5: Freight rates for Brazil and U.S soybean trade routes to China from 2020 to 2050 for the HDPO technology in the optimistic scenario.

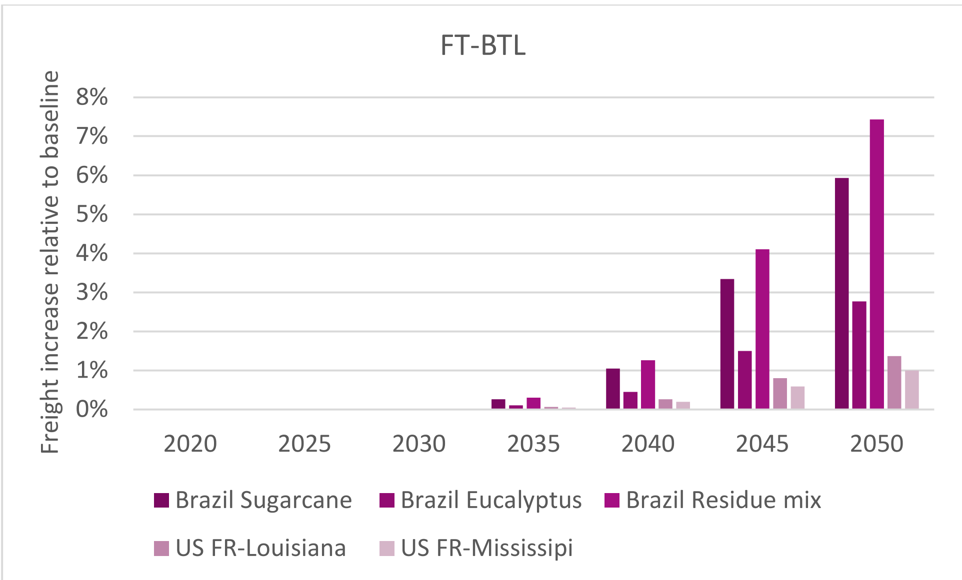

Figure C 6: Freight increase relative to baseline for FTBTL technology in the optimistic scenario from 2020 to 2050

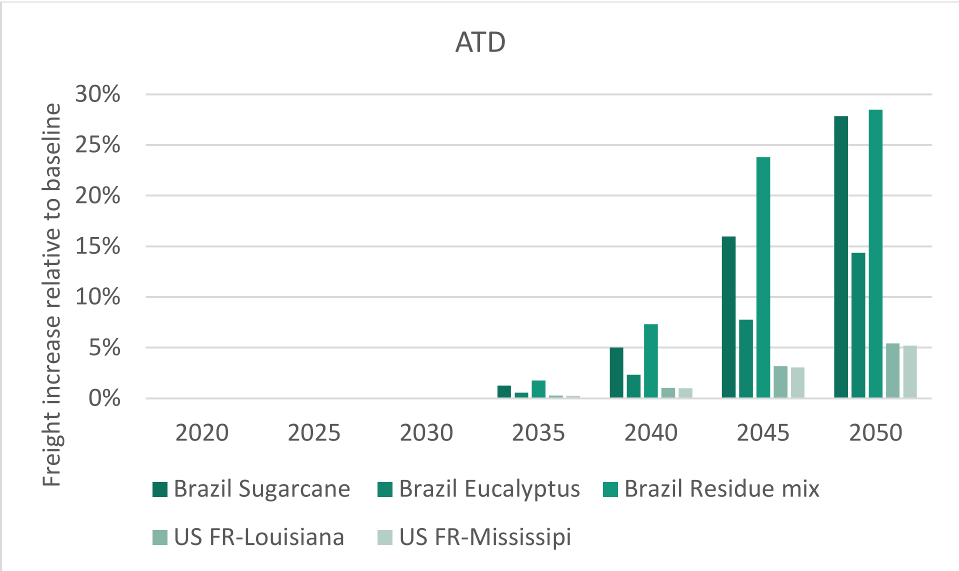

Figure C 7: Freight increase relative to baseline for ATD technology in the optimistic scenario from 2020 to 2050.

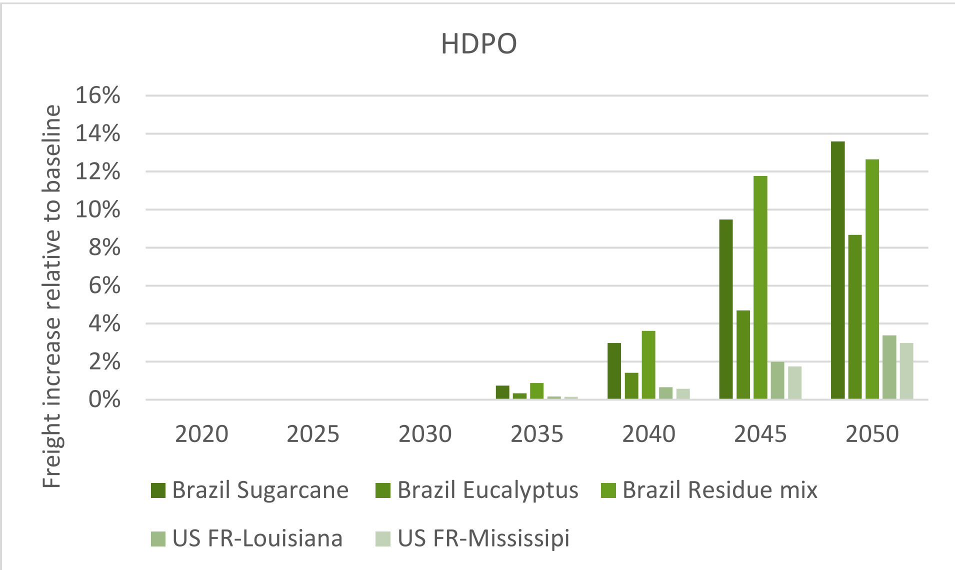

Figure C 8: Freight increase relative to baseline for HDPO technology in the optimistic scenario from 2020 to 2050.

C.4.2 Conservative scenario

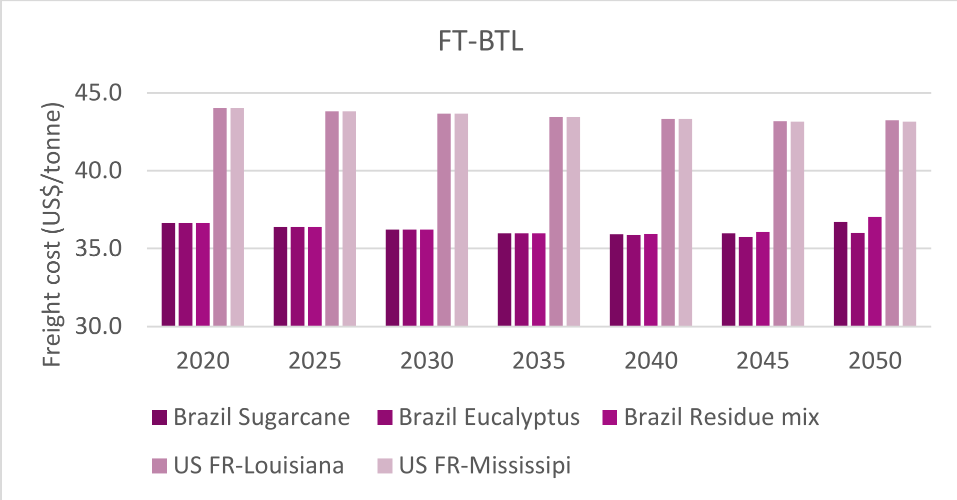

Figure C 9: Freight rates for Brazil and U.S soybean trade routes to China from 2020 to 2050 for the FT-BTL technology in the conservative scenario

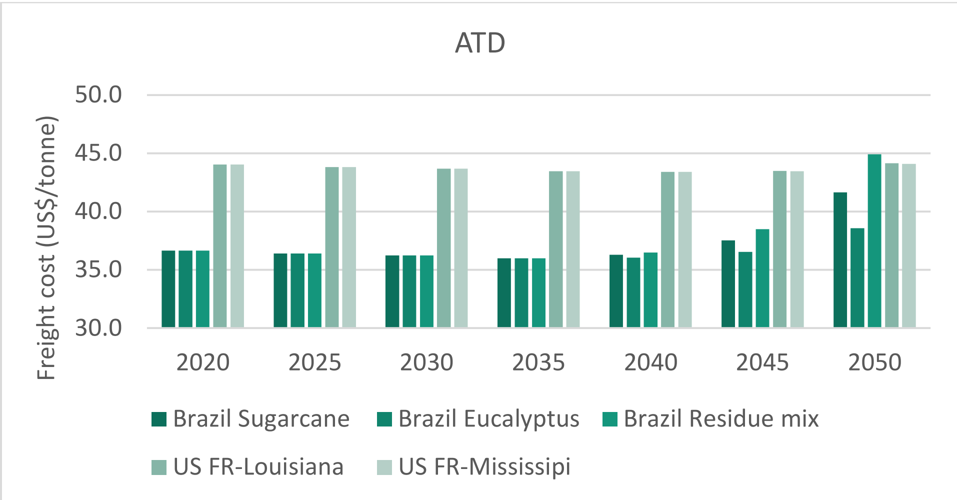

Figure C 10: Freight rates for Brazil and U.S soybean trade routes to China from 2020 to 2050 for the ATD technology in the conservative scenario.

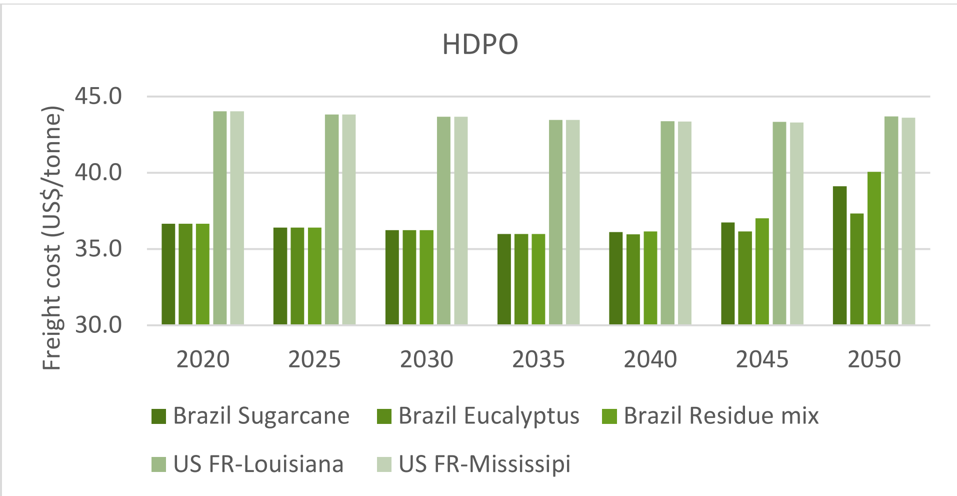

Figure C 11: Freight rates for Brazil and U.S soybean trade routes to China from 2020 to 2050 for the HDPO technology in the conservative scenario.

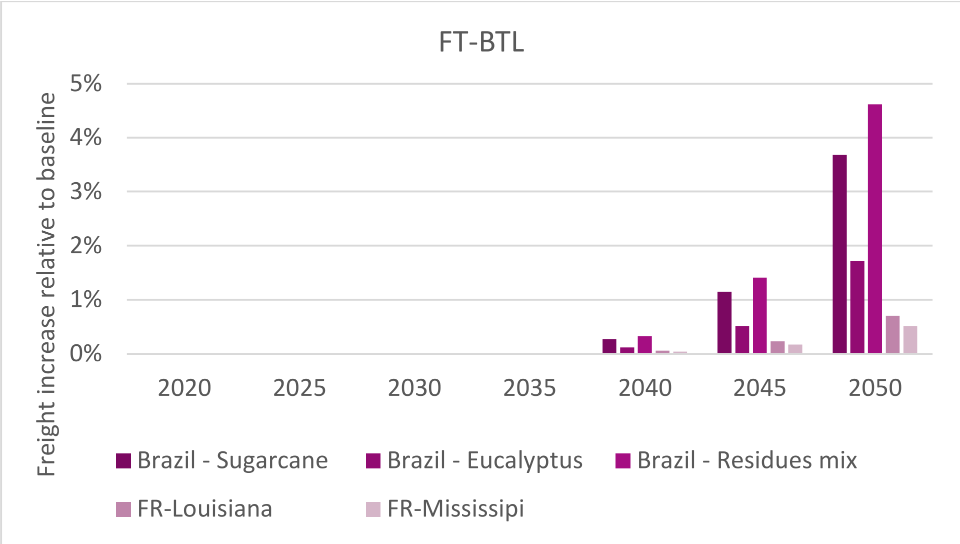

Figure C 12: Freight increase relative to baseline for FT-BTL technology in the conservative scenario from 2020 to 2050.

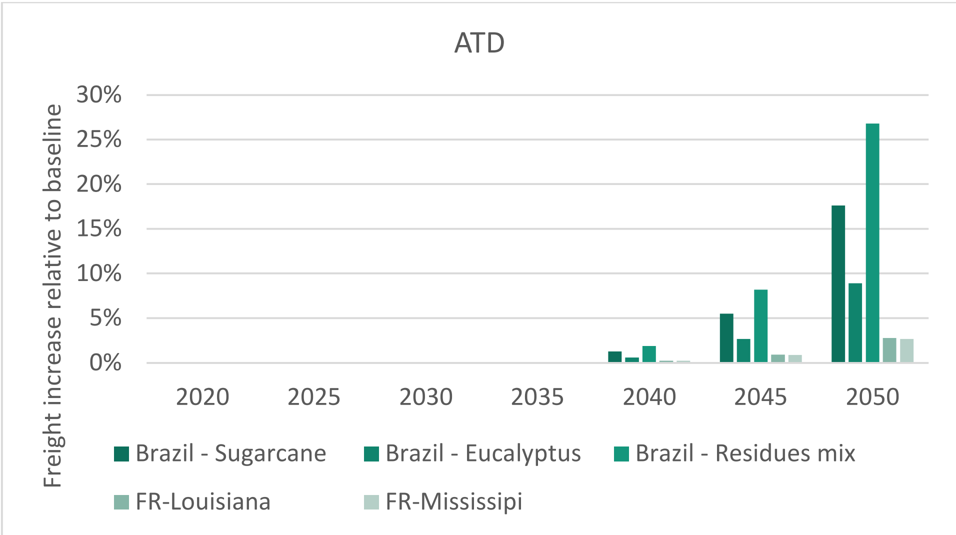

Figure C 13: Freight increase relative to baseline for ATD technology in the conservative scenario from 2020 to 2050.

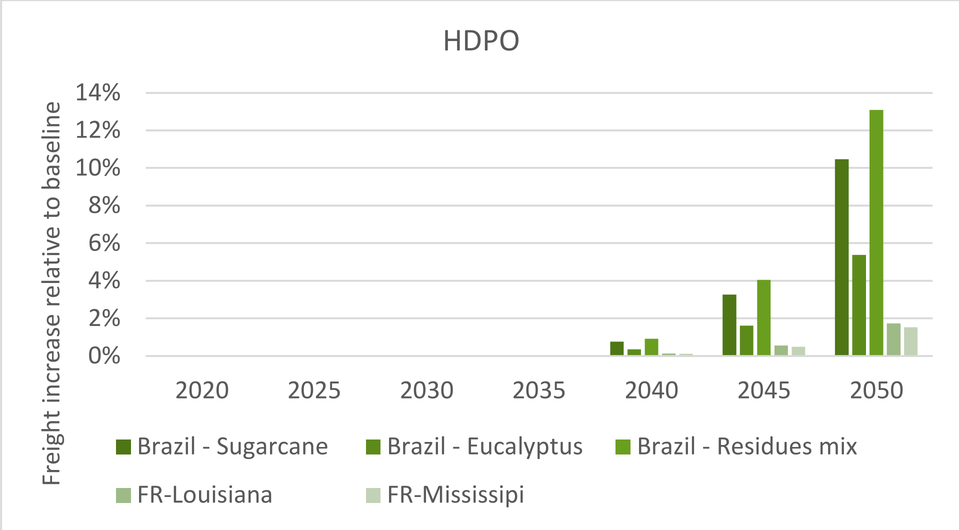

Figure C 14: Freight increase relative to baseline for HDPO technology in the conservative scenario from 2020 to 2050

Table C 4: Fuel share in freight rates in 2050 for all biofuel pathways

Fuel share in freight rates (2050)							
Scenarios		**Optimistic**			**Conservative**		
Route	**Biofuel hotspots**	**FT-BTL**	**ATD**	**HDPO-Diesel**	**FT-BTL**	**ATD**	**HDPO-Diesel**
Brazil (Santos - Qingdao)	**Sugarcane**	24%	38%	30%	23%	32%	27%
	Eucalyptus	21%	27%	24%	21%	24%	23%
	Residues Mix	25%	38%	29%	23%	34%	28%
U.S. (New Orleans - Qingdao)	**FR-Lousiana**	15%	18%	17%	15%	17%	16%
	FR-Missisipi	15%	18%	17%	15%	17%	16%