TWO CAPTAINS WILL NOT SINK THE SHIP: EVALUATION OF BIO-BASED BUNKER FUEL PRODUCTION AND DISTRIBUTION LOGISTICS IN BRAZIL

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ABSTRACT: Marine transport is the most cost-effective mode of international long-distance transportation. Hence, marine transportation is responsible for an expressive demand for fossil fuels that results in around 3% of global CO_2 emissions. Nowadays, this industry face challenges to reduce the GHG and air pollutant emissions of their ships. Rules and regulatory parameters to drastically reduce emissions from marine transport activities have been set. Thus, the utilization of alternative biofuels in marine transportation has caught the attention of the sector. Therefore, this study aims to assess the Brazilian potential to produce marine biofuels (biobunkers). For this purpose, the applied methodology includes the characterization of biofuel production pathways, the assessment of costs-effectiveness of the readiest pathways according to the Brazilian conditions. Further, a life cycle analysis (LCA) and the evaluation of biofuel production and distribution logistics in Brazil were performed. Preliminary results reveal that production costs are still higher than conventional marine fuels. The biofuels produced from soybeans and forest residues can reduce significantly the life cycle GHG emissions. The localization of biomass in countryside areas may hamper its production and distribution. However, the country's well-established biofuel infrastructure and the high availability of biomass resources may favor biobunker production near coastal areas.

Keywords: biofuel, biomass to liquid (BtL), life cycle assessment (LCA), oil crops, residues.

1 INTRODUCTION

The ocean-going ships consume a large amount of petroleum derived fuels. Today, the sector is responsible for over 3% of anthropogenic GHG emissions, with a perspective to grow by a factor of 2 to 3 by 2050 [1], [2]. The IMO's MEPC (Marine Environment Protection Committee) adopted in April 2018 an initial strategy on the reduction of GHG emissions from ships consistent with the Paris Agreement temperature goals. IMO has already set regulations to reduce air pollutants emissions from international shipping, especially the sulphur and nitrous oxides (SOx and NOx, respectively). To comply with these regulations the sector will have to shift to more refined fuels, such as Very Low Sulphur Fuel Oil (VLSFO) and Ultra Low Sulphur Fuel Oil (ULSFO). However, additional refining steps may increase CO_2 emissions and add extra operational costs [3].

In a technical context, some options can reduce GHG emissions in the sector, since decreasing shipping activity is very unlikely in a globalized economy. To reach IMO's goals, the maritime industry will have to optimize operations and capacity utilization, improve energy efficiency promptly and change towards low or zero carbon fuels. Increasing energy efficiency is a way to reduce shipping carbon intensity, however it may not be enough given the expected growth for the sector in the next decades. Then, the introduction of alternative fuels such as liquefied natural gas (LNG), methanol and biofuels are crucial for the next years [1], [4].

Given the need to develop low-carbon solutions for the maritime transport sector, it is expected that the alternative fuels, mainly the renewable ones, have an increase share in the upcoming decades. Biofuels represent an important option to simultaneously reduce the fossil fuel dependence, GHG emissions and air pollutants. As maritime fuels have low specifications requirements and higher viscosity, they are submitted to less refining steps than other transportation fuels. This represents an opportunity to produce biobunker fuels that would not require many specification processes, reducing its production costs [5]. Also, in view of the sector well established operational structure and long lifespan of ships the drop-in fuels are the most feasible alternatives.

Different alternative fuels 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 the front runner options. For Otto or dual fuel engines with ignition pilot, the options are the liquefied natural gas (LNG), methanol, liquefied biomethane (Bio-LNG), liquefied biogas (LBG) and biomethanol [6].

In this context, Brazil may be considered a potential producer of biobunkers, given the high availability of resources throughout the country at a relatively low cost and large scale production of ethanol and biodiesel biofuels. The major concerns regarding the use of biofuels in shipping transport is the uncertainties associated with safety, continued reliability, fuel price and supply guarantee. The performance of biofuels in ship engines is not well understood yet and thus, a significant amount of testing and standardization needs to be established so that appropriate drop-in biofuels are developed [5].

Furthermore, there are important questions related to the sustainability of bioenergy production in large scales. Major concerns are related to the GHG and air pollutants emissions, however, for the biofuels, land use changes, loss of biodiversity, the competition with food production and other uses for bioenergy production should be considered [7]. To this end, the life cycle assessments (LCA) are performed, including all lifetime stages of a product from the extraction of raw material, through processing, manufacturing, distribution, use, disposal and recycling [8]. From the LCA, the avoided emissions of a novel technology can be determined.

Studies already performed in the literature discuss about different alternatives to reduce the maritime transport sector emissions. The ECOFYS report from 2012 presents a review of potential biofuels for shipping assessing their technical, organizational and market limitations [7]. Gilbert (2014) explored the co-benefits created by mitigation measures that could reduce sulphur and carbon dioxide emissions [9]. Brynolf et al (2014) performed an LCA to compare methane and methanol as marine fuels in the Northern Europe, considering natural gas and biomass as raw materials [10]. Moirangthem et al. (2016) developed an overview of the marine sector including, fuel specification analysis, its emission related issues and the introduction of alternative fuels [11]. 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 [12]. Finally, Gilbert et al (2018) performed a LCA for alternative fuels for shipping with respect to six emissions species that contribute for the global warming and local air pollution [13].

In order to perform a specific case study for Brazil, this study aims to evaluate the technical and economic potential for biobunker production in the country, identifying the cost-effectiveness of different technological routes and assessing the opportunities for a Brazilian growing market of this fuel. To this end, the technological development of production routes, levelised costs of production, GHG emissions and fuel logistics are evaluated.

This paper is structured as follows. Section 2 explains the methodology applied and the tools used. Section 3 presents the case study. Section 4 presents the results found in the assessment. Finally, section 5 presents the final considerations and suggestions for future work.

2 METHODOLOGY

This study aims to identify the competitive opportunities for Brazil to produce biobunker fuels. To this end, this work was performed in four stages that assess the maturity stage of technological routes, the levelised costs of production, the GHG emissions and biomass and fuel logistics in the country. Figure 1 represents schematically the methodology applied.

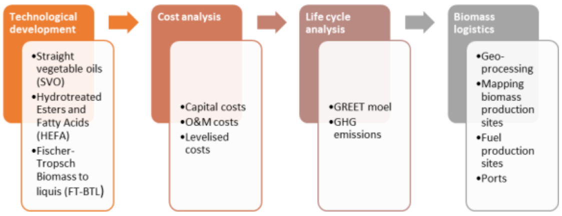

Figure 1: Methodological steps.

Initially, promising technological routes to produce biobunker fuels are described and their technological development assessed. The routes of drop-in biobunker fuel alternatives were selected according given their technological maturity and to the Brazilian potential feedstock. The pathways chosen were: (i) SVO from soybeans, (ii) FT-BTL from forest residues, (iii) HEFA from soybeans.

Next, an assessment of the production costs for the selected routes was performed. The capital costs (CC), operation and maintenance costs (O&M) and fuel levelized costs (LCOF) (1) were determined. The individual components of the biofuel plant that determine its costs are feedstock, water, operations, electricity, charges associated to capital cost among others. The total plant investment includes equipment costs and indirect costs. The O&M costs are formed by fixed (FOM) and variable (VOM) costs. In the case of SVO, fuel cost is assumed to be the soybean oil average price of 2017, therefore, the CC, O&M and LCOF were not determined [14].

For HEFA and FT-diesel, different plant capacities were considered. The procedures and assumptions undertaken to estimate CC and O&M costs were based on [15] and [16], respectively. Monetary values were adjusted to 2017 year according to GDP deflators given by [17]. The LCOF was determined assuming that the total capital investment would be incurred in the construction period. A discount rate of 12% per year was considered based on a study from Oxera Consulting Ltd. [54].

The third step is a LCA performed in GREET (Greenhouse gases, Regulated Emissions and Energy use in Transportation) model for accounting the GHGs emissions for the selected biobunker production routes. The model was developed by Argonne National Laboratory and allows the modeling of life cycle energy use and emissions associated with a wide range of transportation technologies, which include the fuel production pathways and their use on on-road vehicles, aircrafts and marine vessels. The results obtained are the GHG emissions in a CO_2 equivalent (CO_2e) basis. Functional unit chosen is grams per tonne kilometer (g/t.km). The emissions were compared to conventional bunker fuels: residual oil, marine distillate, low sulphur marine fuels.

The final step was a georeferencing and spatial analysis that aimed to identify areas with great biomass potential and analyze their proximity to strategic locations of feedstock handling, bunker fuel production and consumption. Thus, it was possible to identify the challenges biomass handling and biofuel production and distribution until their final use. The maps were designed through the software QGIS (version 3.6.2).

3 APPLICATION

3.1 Marine fuels and Biofuel Pathways

The marine fuels, commonly known as bunker fuels, are produced in oil refineries and their characteristics are determined by the crude oil quality and/or by the refinery scheme used. Bunker fuel is typically distinguished in residual or distillate fuel. The residual fuel is called heavy fuel oil (HFO) and the distillates is called marine gas oil (MGO). Blends with residual and distillate fuels are known as intermediate fuel oil (IFO) or marine diesel oil (MDO)[18].

Since 1987, the requirements for fuels used in diesel engines and boilers in the shipping industry are specified by IMO through the international standard ISO 8217 ("Petroleum products – Fuel (class F) – Specifications of marine fuels"). Also, the standard ISO 8216 specifies different categories of maritime fuels. The latest edition of ISO 8217 launched in 2017 included new specifications of fuels and blends with biofuels [19]. The fuels currently specified are not only hydrocarbons from crude oil but also from oil sands and shale; hydrocarbons from synthetic or renewable sources similar to distillate fuels, and blends with FAME (2) [20].

As aforementioned, different options of biofuels can be considered to the maritime transport sector. This work selected SVO from soybeans, HEFA from soybeans and

FT-BTL from forest residues as biofuels for the further analysis because these are drop-in alternatives based on consolidated technological processes. In the sections below, the technological development and the main advantages and disadvantages of each are presented.

3.1.1 SVO

The use of SVO represent an interesting alternative of fuel for diesel engines. The vegetable oils are largely produced in the world. According to the most recent data of the Food and Agricultural Organization of the United Nations (FAO), 173.3 million tonnes of vegetable oils were produced in the world in 2014. In the same year, Brazil produced 8.5 million tonnes of vegetable oil, of which approximately 88% is soybean oil [21]. The utilization of non-food crops may reduce impacts related to competition with food chains and land use change, while residual oils, such as waste cooking oils (WCO) (3), have the advantages of low costs and is beneficial for the environment, as WCO have significant disposal problems [22].

SVO can be used in ships composing blends with the conventional fuel or replacing them integrally. Given their higher viscosity and boiling point, they may require preheating to avoid buildup of deposits in the engine and lubrication problems [5]. This implies constant monitoring of the biofuel temperature to maintain adequate viscosity level, ensuring optimal engine injection and efficient atomization and combustion. However, in tropical areas with warmer temperatures, the SVO viscosity is reduced and they can be directly used [7].

Recently, the shipping Danish company Norden has tested vegetable oil as fuel and is confident in offering it regularly to clients that aims to handle their supply chain in a more sustainable way [23].

3.1.2 HEFA

The hydrotreatment of refined vegetable oil and fats produces biofuels known as HEFA (hydrotreated esters and fatty acids). It is an alternative to produce diesel from bio-oils in addition to the esterification process that produces biodiesel. The hydrotreating is a process currently used in petroleum refineries that produces hydrogen-saturated straight-chain paraffin-rich hydrocarbon liquids [24]. The fuel produced is free of aromatics, oxygen and have high cetane number (4). Also it offers reduced NO_x emissions and better stability conditions for storage and cold flow properties if compared to biodiesel [25].

The process begins with a catalytic hydrogenation of bio-oil to remove oxygen and other components. Then, the hydroisomerization step breaks down the long hydrocarbon chains, improving its cold flow properties. The produced fuel is in the diesel range, however, the hydroisomerization process can be adjusted to increase the production of lighter hydrocarbons, such as kerosene [26]. Figure 2 represents the HEFA diesel production steps.

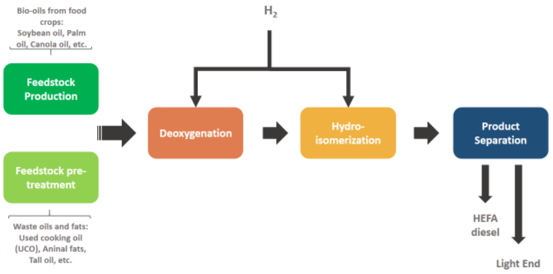

Figure 2: HEFA diesel production process. Adapted from [26].

At present, the HEFA pathway is a mature technology that is commercially available at large scales [27]. Several companies are currently producing HEFA diesel. In 2017, the annual operational capacity of the world's HEFA facilities accounted for approximately 4.3 billion liters [27]. Neste Oil has plants in Finland, Singapore and Rotterdam with an annual production capacity of 3 million tonnes using different bio-oils and waste animal fats [25], [28]. Other producing companies include Diamond Green Diesel (Louisiana), REG (Geismar, Louisiana) and ENI (Italy).

Eni was the first company that retrofitted a conventional refinery into a biorefinery, the Venice bio-refinery, which produces high quality fuels from organic raw material. Since 2014, the unit is capable of storing 360,000 tonnes of vegetable oil, of which 15% is purified UCO. In 2021, the company plans to increase its processing capacity to 560,000 tonnes of vegetable oil, resulting in a renewable diesel production of around 420,000 tons per year. In addition, the completion of another biorefinery in Gela (Sicily) is expected for the next years with a processing capacity of 750,000 tonnes of vegetable oil and a production of 600,000 tonnes of renewable diesel [29]. Also, the company led the Flota Verde project in partnership with the Italian Navy to develop biofuel for naval vessels. The fuel produced is composed by at least 50 percent of renewable diesel and had no effect on the performance or thermodynamic properties of ships propulsion engines or generators [30].

3.1.3 FT-BTL

The FT-BTL pathway produces fuels through biomass gasification followed by FT synthesis. The alternative biofuel for diesel produced is known as FT-diesel. The process begins with the pretreatment of biomass to increase its energy density and to reduce its humidity and particle size. The higher energy density of the feedstock improves the gasifier operation and facilitates the biomass logistics [31]. Then, the pre-treated biomass follows to the gasification step, carried out at high pressure, temperature and with a controlled volume of oxygen. The gasification step produces the syngas, formed mainly by a mixture of carbon monoxide (CO) and hydrogen (H_2) that is conditioned to remove impurities and adjusted to the appropriate H_2:CO ratio. Next, the syngas undergoes to the FT synthesis, a process that uses a series of catalytic reactions to produce liquid hydrocarbons. Finally, common process in oil refineries such as hydrocracking, hydroisomerization and fractionation are applied to produce high quality fuels [32]. One advantage of this pathway is the possibility to use different types of biomass, with little pre-treatment other than moisture control. The

Figure 3 shows the production steps of FT-diesel [33].

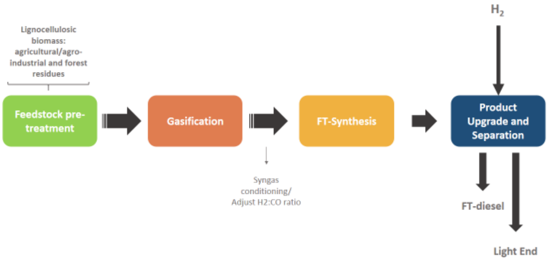

Figure 3: FT-diesel production process.

Up until now, the FT-BTL process has been demonstrated in small scale pilot plants. Large scale application has not been under operation yet. Notwithstanding, some projects are currently being developed to scale up its production. The BioTfuel project developed by the French company Total with other five partners is designed to convert lignocellulosic biomass into advanced biofuels like renewable diesel and biojet. The project demonstration deadline is in 2020 [34]. Fulcrum Bioenergy and Sierra Biofuels are developing the waste-to-energy project that aims to produce renewable transportation fuels from organic material recovered from municipal solid waste (MSW). The project has started its phase 2 of construction in 2018 and the commercial operations are expected to begin in the first quarter of 2020 [35]. In May 2018, the company Velocys received an allowance to start the production of Fischer-Tropsch reactors for the Red Rock Biofuels (RRB) biorefinery that will be placed in Oregon, USA. The biorefinery is projected to produce annually 15 million gallons of renewable fuels [36]. The project represents part of RRB’s portfolio of biorefineries to convert waste and woody biomass into renewable diesel and jet fuels [37].

3.2 Cost analysis

3.2.1 HEFA-diesel

The energy consumption, yields and parameters adopted for HEFA pathway operations are presented in Table I. It was considered that the units receive refined soybean, therefore the agricultural steps of its production and refining are not included.

The FOM costs were based in literature heuristics and interviews presented in Pearlson (2011) [15] (Table II). The VOM costs include expenses with catalyst, electricity, natural gas, water and feedstock. The present work considered hydrogen production in site from natural gas and soybean oil as feedstock. Table III presents the prices used to estimate VOM costs.

Table I: Yields, energy consumption and parameters for HEFA diesel production. Based on Pearlson (2011).

Inputs	
Soybean oil (t)	1.47
Hydrogen (m3)	6.29
Natural gas (GJ)	0.12
Electricity (MWh)	0.52
Makeup water (m3)	1.16
Products	
Diesel (t)	1.00
Propane (t)	0.06
GLP (t)	0.02
Naphtha (t)	0.03
Kerosene (t)	0.19
Carbon Dioxide (t)	0.08
Parameters	
Construction time (years)	3
Plant lifetime (years)	20

Notes:
(a) Not pioneer plants built from traditional and well-established petrochemical plant and equipment [15].
(b) Plant built near refineries. Reduced infrastructure costs such as building roads, offices, laboratories and distribution terminals.
(c) Optimistic construction time. The average time for complex refining projects of 5 years [38].

Also, the biomass transportation costs were determined using the Equation 1 below. The equation was obtained from a linear regression analysis using data from SIFRECA [39].

$$C_T = 14.40\ (\text{US\$/t}) + 0.56\ (\text{US\$/t.km})\ .\ d \quad \text{(Equation 1)}$$

Where:
C_T: Transportation costs (US$/t)
d: Biomass transport distance (km)

Table II: Parameters considered for HEFA-diesel FOM costs.

FOM	
Insurances	0.5% of Investment
Taxes[a]	5.0% of Investment
Maintenance	5.5% of Investment
Miscellaneous supplies	0.2% of Investment
Staff and operation[b]	0.4-0.7% of Investment
Contingency	10% of subtotal

Note:
a,b: Values adapted for Brazilian reality.

Table III: Parameters and prices considered to estimate HEFA diesel VOM costs.

VOM		
Inputs	**Prices**	
Catalyst	0.2-0.5 $/L of fuel produced	[15]
Electricity	124.52 US$/MWh[a]	[40]
Natural gas	15.96 US$/GJ	[41]
Soybean oil	776 US$/t	[14]

Notes:
[a] **Industrial tariff in Brazil.**

3.2.2 FT-diesel

The inputs and energy consumption and parameters considered to estimate FT-diesel costs are presented in Table IV. As the feedstock chosen is residual biomass with no defined use, it was assumed that the costs for its acquisition were zero, except for its collection.

It was assumed that the O&M costs correspond to 10% of the plant total investment [42]. The VOM costs were determined from the inputs prices presented in Table V and from the transportation costs of biomass. Transportation costs were determined by Equation 2 given by Hoffman et al. (2013), using data from SIFRECA [43], [44].

The FOM costs were then obtained discounting the VOM from the total O&M costs.

$$C_T = 5.62 \text{ (US\$/t)} + 0.04 \text{ (US\$/t.km)} \times d \quad \text{(Equation 2)}$$

Where:
C_T: Transportation costs (US$/t)
d: Biomass transport distance (km)

Table IV: Yields, energy consumption and parameters for FT- diesel production.

Inputs	
Biomass[a] **(t)**	5.19-4.99
Water (t)	0.82
Electricity (MWh)	0.28-0.39
Outputs	
Diesel (t)	1
Gasoline (t)	0.31
LPG (t)	0.01
Parameters	
Construction time (years)	3
Plant lifetime (years)	25

[a] **Dry matter**

Table V: Prices considered to estimate FT-diesel VOM costs.

VOM		
Inputs	**Prices**	
Biomass	-	-
Water	3.53 US$/t	[45]
Electricity	124.52 US$/MWh[a]	[40]

Note:
[a] **Industrial tariff in Brazil.**

3.3 LCA

The GREET model was used to assess life cycle fossil fuel consumption and GHG emissions. The fuel life cycle called well-to-hull (WTH) represents a combination of the well-to-pump (WTP) and pump-to-hull (PTH) stages. The WTP stage comprises the exploration and recovery activities from the well to fuel production and the subsequent transportation to the pump, while the fuel combustion during marine vessel operation constitutes the PTH stage.

Tailored assumptions according to Brazilian conditions were inputted in GREET. These include data for fertilizers, pesticides and herbicides use, and energy consumption in agricultural stages. Only the direct-land use change emissions (LUC) were considered. Functional unit chosen was MJ. The energy allocation method was selected, based on the EC directive on biofuels sustainability criteria, which indicates that the energy allocation method is the most appropriate, predictable over time and minimizes counter-productive incentives [46][46], [47]. Distribution activities were not considered. The results obtained are compared to the fossil marine fuels, HFO and MGO.

The life cycle of fossil marine fuels starts in the oil recovery activities, follows to the refining process and ends in fuel combustion in marine vessels. Fuel transportation and infrastructure activities are not included in the model.

For the HEFA diesel, the soybean production in the agricultural fields is the first step of its life-cycle. Data for fertilizer, pesticides, herbicides, energy for soybean oil extraction and diesel and electricity consumption were obtained from Rocha et al. (2014) and Raucci et al. (2015) [48], [49]. The LUC derived from biomass production is critical in LCA. This work considered only the direct land use changes in Brazilian savannah (*cerrado*) and its GHGs emissions were determined by the emission factors from IPCC [50]. Table VI contains the inputs given for soybean agricultural stage in GREET.

Table VI: Input data for agricultural stage of soybean production used in GREET.

Soybeans			
			Source
Productivity	3.4	t/ha	[51]
Fertilizers			
Nitrogenous	2.0	g/kg soybean	
P_2O_5	23.0	g/kg soybean	
K_2O	24.5	g/kg soybean	
$CaCO_3$	129.8	g/kg soybean	[48]
Farming energy	8.6	MJ/kg soybean	[48]
Oil extraction energy	0.82	MJ/kg soybean	[49]
LUC emissions	49.2	g CO_2e/kg soybean	[50]

Then, the final step in HEFA diesel production is the hydroprocessing of soybean oil. In this stage, emissions are associated with the hydrogen production. The GREET model considers the UOP process for hydrodeoxigenation of renewable oils.

For the FT-diesel, the agricultural phase of biomass is the first step of the life-cycle. No energy use and emissions associated with farming and collection of biomass were considered, as residual biomass was chosen as feedstock. In the fuel production stage, CO_2 is formed along with syngas in gasification. The CO_2 may be vented or captured and sequestered, however, CO_2 capture or export was not considered. Finally, the required hydrotreatment and syngas recycling increase the hydrogen and power consumption. As in the HEFA pathway, the hydrogen production may increase emissions in the fuel production step.

During marine vessels operation (PTH stage), the GHG emissions are derived from fuel combustion in marine engines. In terms of quantity and global warm potential, carbon dioxide is the most important GHG emitted by ships. Emissions in large ships typically come from the combustion in the main engines for propulsion, in ancillary engines for power production and in boilers for steam production [52].

3.4 Biomass logistics

The final step of this study enabled the localisation of great biomass potential areas and analyse their proximity to strategic locations of feedstock handling, bunker fuel production and consumption. The georreferencing analysis was performed in QGis software (version 3.6.2). First, areas with great biomass potential were identified. The methodology applied was based in Portugal-Pereira et. al (2015) that quantified the bioenergy potential from biomass residues of each municipality in Brazilian territory [53]. The technical potential calculated for each municipality was allocated to shape files with municipalities divisions obtained from IBGE. A uniform energy density for each municipality was assumed. Thence, it was possible to identify for each municipality its energy potential from biomass residues. The spatial localization and concentration of bioenergy is important to enable its recovery and conversion into biofuels.

In this work the sugarcane, eucalyptus and soybean crops were chosen. Sugarcane is one of the major agricultural crops produced in the country and has a well-established production chain, as it is used for ethanol production. Eucalyptus forestry is highly efficient, has high hardwood yields and low production costs given the favorable climate conditions and investments in research [54], [55]. Also, as forest residues was the feedstock chosen for the FT-diesel life-cycle analysis in GREET, the localization of biomass residues from eucalyptus in the country was appropriate. Soybean is the major agricultural crop produced in Brazil and is the feedstock for producing soybean oil, considered in this study as a fuel alternative for ships (SVO) and as feedstock for HEFA-diesel production. Also, the localization of soybean oil production and utilization areas is important. Thus, the soybean oil refineries and biodiesel production plants in Brazil were mapped.

Finally, important locations of bunker fuel production and utilization, such as petroleum refineries and the main ports of the country, were localized in order to evaluate the biofuel logistics through the integration of biomass production and fuel supply sites.

4 RESULTS AND DISCUSSION

4.1 Cost analysis

4.1.1 HEFA-diesel

The main findings for HEFA diesel are shown in Table VII, which also contains the LCOF of each plant capacity. Figure 4 shows the LCOF divided into Capital, FOM and VOM costs and compare the LCOF with MDO prices of 2017 for the three plant sizes [56]. The VOM costs are the major contributor to HEFA pathway LCOF. Feedstock represent from 73% to 83% of the total O&M costs, varying from plant A to plant C. Notwithstanding, technology scale gains can be achieved for the plants with higher capacities. Figure 5 shows only the capital and FOM costs for a better observation of the technological scale gains. For plant B, a reduction of 35% in capital costs comparing to plant A is observed, while for plant C this reduction is of 46%. Results for all plant sizes were far superior than the MDO average price of 2017.

Table VII: HEFA-diesel Capital, Fixed and O&M costs.

HEFA-diesel				
		Plant A	Plant B	Plant C
Capital		65.5	85.7	105.8
Fixed O&M		33.2	46.7	46.8
Variable O&M	Million US$	121.1	242.3	363.4
Production	Million L/yr	116.1	232.1	348.2
LCOF	US$/L	1.41	1.24	1.22

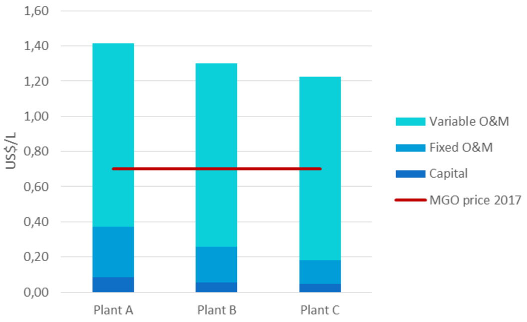

Figure 4: HEFA-diesel capital, VOM and FOM costs compared with MGO prices of 2017.

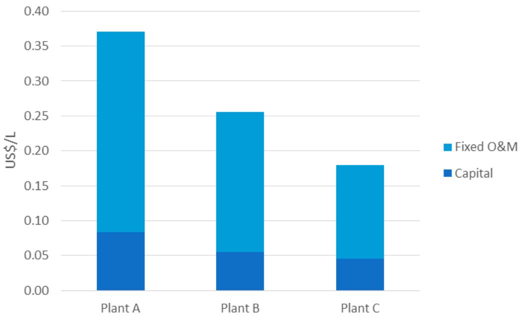

Figure 5: Technology scale gains for HEFA-diesel plants.

The LCOF of the HEFA diesel is far superior than the average MDO price in 2017 (0.70 US$/L), considering the three scales assessed. Technological scale gains and carbon taxes may improve HEFA diesel competitiveness with the conventional fuel. However, the high O&M variable costs pose a major challenge for this technology, since soybean oil is a commodity and its price is not influenced by technological improvements in HEFA technology. The utilisation of residual feedstock, as used cooking oil (UCO) or tallow, would decrease the feedstock expenses. However, additional pre-treatment processes would be required, which may impact capital costs, and testing in ship engines would be necessary.

4.1.2 FT-diesel

Table VIII shows results for Capital, O&M costs and LCOF for each plant capacity of FT-diesel.

Table VIII: FT-diesel capital, O&M and LCOF costs.

FT-BTL					
		Plant A	Plant B	Plant C	Plant D
Capital		147.5	162.9	310.3	884.6
Fixed O&M		13.5	13.8	26.0	67.3
Variable O&M	Million US$	2.8	4.4	9.6	39.7
LCOF	US$/L	0.88	0.77	0.59	0.50

Figure 6 shows the LCOF divided into the capital, VOM and FOM costs and compare with the MDO prices of 2017. Differently from the HEFA-diesel route, for FT-diesel the capital costs are the major contributor to the LCOF and the VOM costs are majorly composed by the biomass transportation costs (39% to 47%). Again, the scale gains are obtained for the plants with higher capacities. Plant D registered a reduction of 41% in capital costs (levelised) compared to plant A. For plant C and B, a reduction of 35% and 14% is observed, respectively. Plants C and D (larger capacities) registered lower LCOF than the 2017 MDO average prices. Plants A and B (lower capacities) had slightly higher LCOF than the 2017 MDO prices.

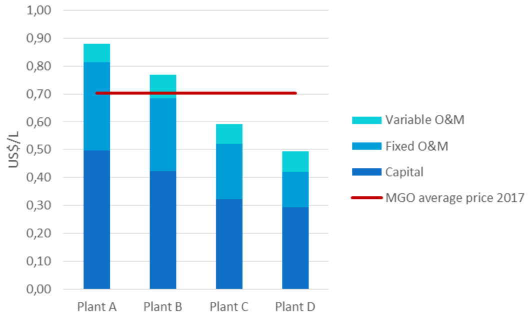

Figure 6: FT-diesel capital, VOM and FOM costs compared with MGO prices of 2017.

For the FT-diesel production, the economic analysis revealed that, for plants with large capacities, the biofuel registered lower LCOF than the MDO average price of 2017. The high capital costs for the FT-BTL plants is mainly associated with the gasification units and represents a challenge for its development. However, Brazil has some advantages regarding this technology, given the high availability of lignocellulosic biomass in the country, which is the most suitable feedstock for the process. Also, the application of carbon taxes may improve the biofuel competitiveness.

4.2 LCA

As expected, FT-diesel, HVO and SVO emit less GHG than conventional marine fuels: residual oil, marine distillate and low sulphur marine distillate. FT-diesel leads to a reduction of 98% in GHG emissions compare to the petroleum-derive marine fuels, while HVO and SVO registered reductions of 66% and 86%, respectively (Figure 7).

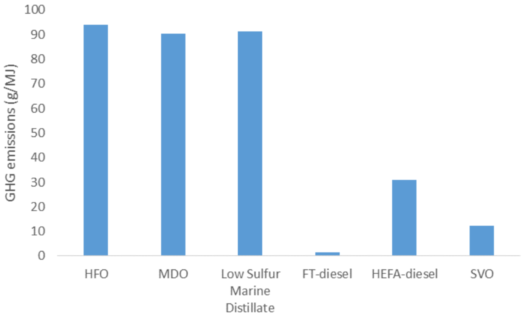

Figure 7: Life cycle emissions from conventional and bio-derived marine fuels.

The WTP emissions were negative given the CO2 absorption from atmosphere in the growth phase of biomass even admitting carbon emissions from land use (Figure 8). As GREET does not have the option for modelling the SVO combustion in ship engines, it was considered that their WTP emissions were not negative, but that they compensate the PTH emissions. So the life cycle emissions for SVO are composed only by the WTP emissions. Emissions from HEFA and SVO production are associated with soybean farming and collection, fertilizer and hydrogen use and diesel consumption in the harvest and transportation activities.

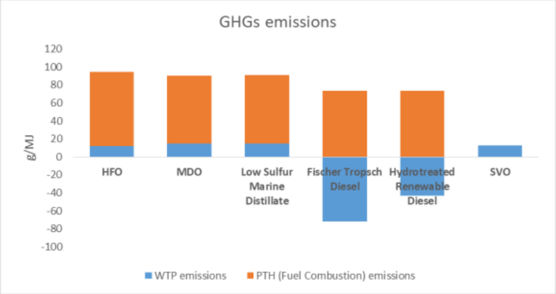

Figure 8: WTH emissions divided in WTP and PTH emissions for the conventional and bio-derived marine fuels

The LCA revealed that all the biofuels considered, HEFA, FT-diesel and SVO, reduce the GHG emissions compared to the conventional bunker fuels. In this way, the country could produce biobunker fuels that reduce the environmental impacts of maritime transportation sector. However, the choice of allocation methods can impact in the LCA results, especially for the fuels produced from vegetable oils, whose production comprises another co-products. Also, its important to highlight that, regarding HEFA-diesel and SVO production, the competition for resources may threat country’s biodiversity and impact their environmental performance. Finally, this analysis did not consider the different qualities of the biobunker fuels produced. Particularly, FT-BTL is a very-high quality fuel that can be easily blended to compose a pool for maritime fuels, without compromising the performance of the ship. This should not be the case of SVO.

4.3 Biomass logistics

The figure 9, 10 and 11 shows the areas with major potential of sugarcane, eucalyptus and soybean residues (and, consequently, sugarcane, eucalyptus and soybean crops) production in the country, respectively, together with soybean oil refineries and biodiesel production plants. The country’s oil refineries and major ports were also mapped.

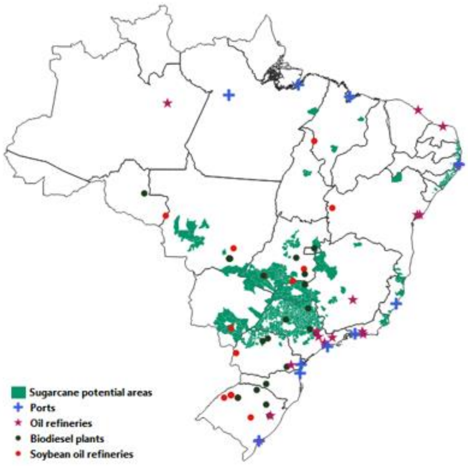

Figure 9: Potential areas of bioenergy from sugarcane and important areas for biofuel production logistics.

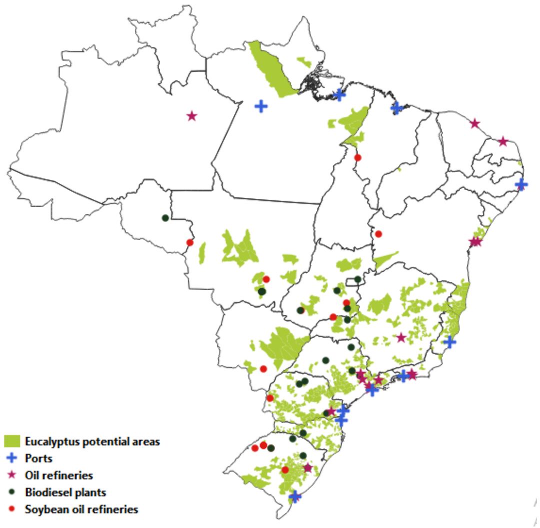

Figure 10: Potential areas of bioenergy from eucalyptus and important areas for biofuel production logistics.

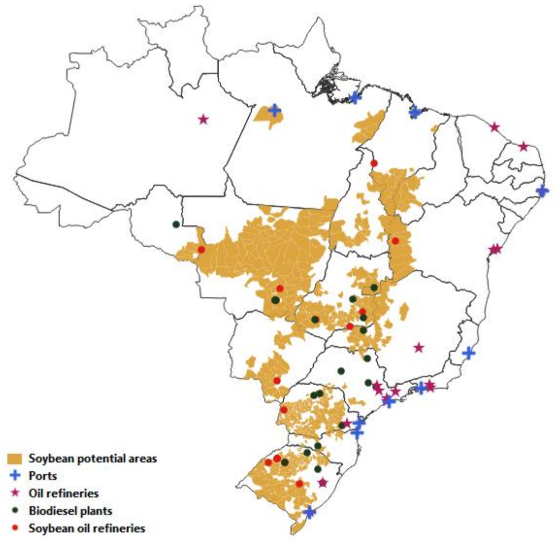

Figure 11: Potential areas of bioenergy from soybean and important areas for biofuel production logistics.

Areas with major sugarcane potential are concentrated in the central and southeast region, far from the coastal areas and near biodiesel production plants. Also, they are distant from almost all country's oil refineries. In this way, the best alternative for producing biobunker fuels from sugarcane residues would be implementing the biofuel plants near the biomass sites that are also close to the infrastructure of biofuel handling, provided by the biodiesel and probably ethanol plants in these locations. However, the biofuel transportation to ports would be challenging, in view of the amount of fuel needed. This would require a large fleet of trucks, which would increase emissions in fuel transportation stage.

For eucalyptus, areas with major potential are more representative in Brazilian Central and South regions. It is expressive in some coastal municipalities and, therefore, close to some of the country major ports. In the Southeast and South regions, it also near oil refineries. This indicates the proximity between biomass sites and the existing infrastructure of maritime fuels production and consumption. However, the amount of bioenergy available from eucalyptus residues may not be enough to encourage the construction of expensive biofuel plants and to produce a significant amount of fuel to be used in the maritime transportation sector.

Finally, the soybean energy potential is mostly located in Brazilian's countryside (Midwest region), far from the oil refineries and coastal areas. As expected, it is close to soybean oil refineries and biodiesel plants. This poses a major challenge for SVO and HEFA-diesel development as alternatives for the maritime transportation. The production of HEFA near of the biomass supply would require development of a new infrastructure for fuel production in countryside areas. Also, the biofuel transportation to ports would be complex, in view of the long travel distances and the amount of fuel required, which may increase significantly its transportation emissions.

5 FINAL REMARKS

This study sought to evaluate the technical and economic potential for biobunker production in the Brazil. Further, the cost-effectiveness of different technological routes were identified and the opportunities for a Brazilian growing market have been assessed. To this end, the applied methodology comprises four stages that aimed to evaluate the technological development of production routes, the levelised costs of production, the GHG emissions and fuel logistics.

Regarding the technological development of production routes, this work considered the utilization of SVO from soybeans, HEFA-diesel from soybeans and FT-diesel from forest residues as biofuels. These pathways are drop-in alternative fuels based on consolidated technological processes.

The results of the economic analysis indicate that the biobunker fuels from HEFA and FT-BTL pathways are yet to be competitive with the petroleum-derived fuels used in ships. Three plant capacities were considered in the cost estimates for the HEFA-diesel production and four plant capacities for the FT-diesel. The FT-diesel plants with greater capacities obtained lower costs among all the bio-based fuels. Results from HEFA-diesel vary from US$ 1.22/l to US$ 1.41/l, while FT-diesel costs vary from US$ 0.88/l to US$ 0.50/l. The costs of HEFA-diesel are mostly driven by feedstock expenses, while for FT-diesel, the capital costs are the major barrier to their development.

The LCA was performed in GREET model to determine the environmental performance of HEFA-diesel, FT-diesel and SVO (from soybean) as marine fuels. Results revealed important reductions in GHG emissions, as all three biofuel alternatives shows significant reductions. FT-diesel achieved a 98% reduction in GHG emissions in comparison with HFO, while HEFA-diesel and SVO registered a reduction of 66% and 86%.

For the biomass and fuel logistics, a georreferencing analysis was performed using QGis software. The results revealed that the concentration of biomass sites in countryside areas may hamper the biobunker fuel development in the country, given the need to transport the fuel over long distances to ports. Also, the large amount of fuel needed for the sector would require a large fleet of trucks and may increase the fuel transportation emissions. However, areas with great biomass potential from eucalyptus were observed in the coastal municipalities of the country. This may encourage the production of bio-based marine fuels in these areas that are also near to some of the major Brazilian ports. In this way, investigating the biomass availability from various crops in these locations and then choosing the most suitable technology for biobunker conversion, may be the best alternative to assess its production feasibility.

In view of the results presented it is noteworthy that Brazil has some advantages to kick off the biobunker fuels production. The high availability of biomass resources, their localization near of important sites of biofuel handling and the country's technical experience in agriculture and biofuel production makes it an attractive location to begin a biobunker fuel industry. Also, using biomass residues as feedstock eliminates concerns regarding food security and land availability.

Despite the efforts to assess the potential of producing biobunker fuels in Brazil, some limitations of the study should be revised in future works to enhance the accuracy of the findings. Some suggestions are listed below:

- The economic analysis relied on a nth of a kind (NOAK) estimate that tends to underestimate the capital costs and overestimate the plant performance.
- Choosing different allocation methods in GREET may significantly impact the results. This study chose the energy-based allocation method.
- Some sustainability indicators like water usage and impacts in biodiversity were not evaluated.
- Considering another biomass alternatives in the spatial analysis and quantifying their energy potential and conversion to biobunker fuels.

6 NOTES

(1) The LCOF represents the lifetime average selling price that would be needed for an investment to breakeven.
(2) Only blends of distillate marine fuels with FAME up to 7% are allowed [19].
(3) WCO should be treated prior their use. Processes like filtration are mostly used [22].
(4) Cetane number indicates the combustion speed of diesel fuel and the compression need for ignition. It is an important factor in to evaluate the quality of diesel fuel. Higher cetane numbers indicate better ignition properties.

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9 LOGO SPACE

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