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EVALUATION OF THE BRAZILIAN POTENTIAL FOR PRODUCING AVIATION BIOFUELS THROUGH CONSOLIDATED ROUTES

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AVALIAÇÃO DO POTENCIAL BRASILEIRO PARA PRODUÇÃO DE BIOCOMBUSTÍVEIS DE AVIAÇÃO A PARTIR DE ROTAS CONSOLIDADAS

Francielle Mello de Carvalho

Fevereiro/2017

Orientadores: Alexandre Salem Szklo

Joana Portugal Pereira

Programa: Planejamento Energético

A indústria da aviação estabeleceu metas ambiciosas para reduzir o consumo de combustível, não só para reduzir os custos, mas também para reduzir as emissões de gases de efeito estufa (GEE). Tais metas incluem melhorias na eficiência, crescimento neutro em carbono a partir de 2020 e expressivas reduções na pegada de carbono até 2050. Uma das estratégias estabelecidas para atingir esses objetivos é o desenvolvimento de combustíveis alternativos sustentáveis, também conhecidos como *biojet*. O Brasil pode ser considerado um potencial produtor de *biojet* devido às condições edáfoclimáticas favoráveis, que fazem do país um grande produtor agrícola. Além disso, o país possui elevada disponibilidade de recursos e uma vasta experiência na utilização de biomassa para a produção de biocombustíveis. Nesse sentido, esta dissertação apresenta um estudo de caso para avaliar o potencial da produção de *biojet* no Brasil. Para tal, alguns indicadores como disponibilidade de matéria-prima, performance ambiental e efetividade de custo para rotas de produção selecionadas foram avaliados. Os resultados mostraram que o país tem um potencial expressivo de bioenergia que está favoravelmente concentrado próximo às principais localidades de manuseio de combustível no país. Ainda assim, as reduções nas emissões de gases de efeito estufa (GEE) no ciclo de vida atingiram 94% para uma das rotas selecionadas, em comparação com o combustível convencional. No entanto, as principais rotas de produção exigem altos investimentos de capital ou despesas com matéria-prima, resultando em altos custos nivelados para os combustíveis.

Abstract of Dissertation presented to COPPE/UFRJ as a partial fulfillment of the requirements for the degree of Master of Science (M.Sc.)

EVALUATION OF THE BRAZILIAN POTENTIAL FOR PRODUCING AVIATION BIOFUELS THROUGH CONSOLIDATED ROUTES

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The aviation industry has set ambitious goals to reduce fuel consumption not only to reduce costs but also to reduce greenhouse gas (GHG) emissions. These goals include energy efficiency improvements, a carbon neutral growth from 2020 on and expressive reductions in carbon footprint by 2050. One of the strategies established for achieving these goals is the development of alternative sustainable fuels, also known as biojet fuels. Brazil may be considered a potential producer of biojet fuel given its favorable edaphoclimatic conditions that makes the country a major agricultural producer. Furthermore, the country has a high availability of resources and a vast experience in biomass utilization for biofuels production. In this sense, this dissertation presents a case study for assessing the potential of biojet fuel production in Brazil. To this end, some indicators as feedstock availability, environmental performance and the cost-effectiveness of selected production routes were evaluated. Results has shown that the country has an expressive bioenergy potential that is favorably concentrated near the main localities of fuel consumption and handling in the country. Still, reductions in life cycle GHG emissions reached 94% for one of the selected routes, compared to the conventional jet fuel. However, the main production routes require high capital investments or feedstock expenses leading to high levelized fuel costs.

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1. Introduction

Aviation industry consumes around 1.5 billion barrels of kerosene per year through 1,397 air companies that serve 3,864 airports through a network of several million kilometers (ATAG, 2014). In 2015, the world's airlines transported 3.5 billion people and 51 million metric tonnes of cargo through a fleet of 26,000 aircraft averaging 100,000 flights a day over a global network of 51,000 routes. This industry also contributes with the global economy with $2.7 trillion of GDP (IATA, 2016). This industry strongly depends of fossil fuels due to lack of alternatives to airplanes that travel great distances (CANTARELLA et al., 2015). Jet fuel is produced from crude oil and according to the U.S. Department of Energy (DOE's) Bioenergy Technologies Office, 4 gallons[1] of jet fuel are produced from one oil barrel (EIA, 2013a; WANG; TAO, 2015). In 2014, aviation fuels represented 6.9% of the world refinery output, totalizing approximately 340 million m^3 (IEA, 2016). In this year, the jet fuel production in Brazil was around 6.1 million m^3, representing almost 2% of world refinery output (ANP, 2015). As air transport is a growing industry, it is expected that the demand for air transport doubles by 2034 (IATA, 2016).

Jet fuel represents an important share of operational costs of companies. Approximately one third of these costs are spent on jet fuel: 33%, which is up from 13% in 2001. The uncertainties related to oil prices fluctuation hamper management and planning activities. These fluctuations are directly related to volatility in oil prices, caused by distinct factors. Furthermore, aviation is responsible for about 2% of anthropogenic CO_2 emissions (CREMONEZ et al., 2014). Worldwide, flights produced 781 million tonnes of CO_2 in 2015, while humans produced globally over 36 billion tonnes of CO_2. For this reason, the reduction in fuel consumption is extremely important to ensure the profitability of air companies and to reduce impacts on climate changes.

Historical trends indicate that a modern aircraft are around 80% more fuel efficient than 40 years ago. Since then, aviation industry has been measuring its technical progress according to aircraft and engine efficiency. These were achieved through modifications in aircraft design together with incremental annual improvements to engine design and operation (ATAG, 2010a). Efficient improvements have seen a halving of fuel

[1] 4 gallons are equivalent to approximately 15L (1 gallon = 3.48 L).

consumption per tonne kilometer travelled. Current operations generate around 50% less CO_2 per kilometer compared to the same flight back in 1990 (ENVIROAERO, 2016). This progress has also been promoted by improved operational practices such as weight reduction, more efficient flight procedures and reduced auxiliary power units usage, together with improvements in air traffic management (ATM) and airport infrastructure.

Within this context, the International Air Transport Association (IATA) defined ambitious goals to reduce fuel consumption not only to reduce costs but also to reduce greenhouse gases (GHG) emissions (CANTARELLA et al., 2015). These goals include fuel efficiency improvements of 1.5% per year up to 2020, carbon neutral growth from 2020 on, and reductions of 50% of carbon footprint by 2050 in relation to 2005 levels (IATA, 2013). To accomplish these objectives, the industry relies on a four-pillar strategy based on efficiency gains, improvements in air traffic management, alternative fuels and market-based measures. Efficiency gains tend to be incremental, as modern aircrafts are quite efficient. Furthermore, as air traffic improvements and efficiency gains have potential to reduce emissions, these measures are insufficient to offset the expected growth for the aviation sector (MAWHOOD et al., 2014). Hence, the development of alternative jet fuels (hereafter biojet) has become crucial in the next years.

Through the International Civil Aviation Organization (ICAO) governments took an important step in agreeing on an efficiency standard for commercial aircraft in February 2016. After the approval by the ICAO Council, the standard will apply from 2020 and ensure that CO_2 emissions from new aircraft do not exceed a limit defined which is defined according to the size and weight of aircraft. In September of 2016, during the 39^{th} ICAO Assembly, governments developed a proposal for a Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) that was supported by industry. However, this proposal should be adopted by the assembly, formed by the ICAO's 191 member states, to come into force (IATA, 2016). Additionally, according to the IATA's 2016 Annual review, a considerable progress in the context of alternative fuels was achieved in 2015-2016:

- United Airlines became the first US operator to launch scheduled commercial biofuel-powered flights out of Los Angeles International Airport.
- In April 2016, KLM airlines benefited from the Oslo airport's new hydrant biofuel supply system to promote 80 biofuel flights on its Cityhopper service.

- Air New Zealand and Virgin Australia start a partnership to find opportunities for developing biofuels locally.
- Boeing launched project of sustainable fuels research and development with Aeromexico and the Mexican government and started a partnership with Japanese aviation stakeholders to develop a roadmap for biofuel flights for the 2020 Tokyo Olympic Games.
- The first IATA Alternative Fuel Symposium (AFS) happened together with the IATA Aviation Fuel Forum in Mexico in November 2015. It brought together airline customers and alternative fuel suppliers to discuss opportunities to remove barriers to biojet development.

Recent studies have supported land use for bioenergy production in some regions of the world, without compromising other uses such as food production and preservation of the ecosystem (CANTARELLA et al., 2015; CORNELISSEN; KOPER; DENG, 2012; PRIELER; FISCHER; VAN VELTHUIZEN, 2013). Brazil may be considered one of these localities given its large experience in biomass utilization for energy purposes and the high availability of resources throughout its territory. The country has the attractive combination of available land already cleared for agricultural use, vigorous agriculture sector, a large amount of legally-protected native vegetation and strong conservation laws (CORTEZ et al., 2014). The country is a major producer and exporter of several agricultural commodities such as sugar, soybeans, coffee, wood products, meat, among others. The extensive territory with favorable edaphoclimatic conditions enables sufficient agricultural production in terms of both quantity and variety for use as feedstock for biofuel conversion (CORTEZ et al., 2014). Still, Brazil has a long experience in producing biofuels with sugarcane ethanol and biodiesel programs. In 2014, Brazil produced 3.4 Mm^3 of biodiesel (77% from soybean and 20% from tallow) and 28.8Mm^3 of ethanol (ANP, 2015). These characteristics make the country a potential producer for advanced fuels, such as biojet.

A large variety of feedstock can be used including sugars, lignocellulosic biomass, vegetable oils and agricultural and forestry residues. Although different plant species can be used for bioenergy production, those that are widely cultivated with high yields are more likely to support a biojet fuel industry in the near future. Sugarcane and soybeans have already a well-established production chain in the country, as they are used for ethanol and biodiesel production. Eucalyptus forestry is highly efficient due to favorable climate conditions and investment in research and thus, has the highest hardwood yields and lowest production costs in the world (ABRAF, 2013; RISI, 2015).The utilization of oil crops is also interesting due to Brazilian large experience in biodiesel production. Additionally, the large supply of crop residues such as straw, sugarcane bagasse and forestry residues besides its low costs, make them an attractive feedstock. There is a huge potential for bioenergy production from agricultural and agro-industrial residues that are currently not recovered. This promising feedstock could be collected and processed to generate bioenergy, instead of being left on the farmland where it decomposes, releasing GHG emissions (PORTUGAL-PEREIRA et al., 2015). Municipal solid waste, tallow and used cooking oil (UCO) are also options to biofuel production, not only to recycle products that would otherwise require costly disposal, but also because they avoid food security concerns (CORTEZ et al., 2014). Another non-food crop feedstock include industrial waste residues, which are inherently low value, do not affect land use or compete with food. However, some of these residual feedstocks are not available in large amounts or even are disperse, which means that their conversion would not benefit from scale economies and might suffer from logistic costs.

Notwithstanding, as important as the availability of feedstock, is their capacity of being harnessed for fuel production according with sustainability requirements. For this reason, when evaluating energy sources, the whole production chain should be considered to verify its real potential to achieve environmental benefits and to detect its disadvantages. 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 (ELGOWAINY et al., 2012). Achieving this type of analysis is relevant for biofuel production, since its production process requires energy from fossil fuels, whether in the form of fertilizers, pesticides and machinery for agricultural and industrial phases, or for transportation of intermediate and distribution of final products. From the LCA, the avoided emissions of a novel technology can be determined. In addition, indirect effects of agricultural expansion for fuel production are relevant concerns in the biofuels debate. This is the case of indirect land use changes (iLUC) and competition with food producing. For this reason, the adoption of instruments and policies are fundamental to ensure a sustainable expansion of biofuels feedstock production.

Some studies found in the literature are related to the production of aviation fuels. At the national level, Cantarella et al. (2015) assessed the potential feedstock in Brazil to supply biojet fuel production. Cortez et al. (2014) performed a national assessment of the technological, economic and sustainability challenges and opportunities regarding the development and commercialization of sustainable aviation biofuels in Brazil. Their technological roadmap process was divided into the work fronts of feedstock, refining technologies and logistics. (CREMONEZ et al., 2014) discussed the current scenario and prospects for the use of aviation biofuels in Brazil including the main technologies used, their potential and the impacts generated by their use. (MORAES et al., 2014) assessed the sustainability challenges for biofuels production and discussed the main barriers faced by different classes of feedstock to meet sustainability requirements. Finally, Cremonez et al. (2015) sought to identify the major environmental, economic and social impacts arising from biojet fuel production in Brazil. On the subject of production routes, Guell et al. (2012) identified, described and discussed the most promising and suitable technological pathways and biomass resources for biojet fuel production in Norway. The Pearlson (2011) thesis quantified the economic costs and environmental impacts of producing fuels from hydroprocessed of renewable oils (HRO) process. Elia et al. (2013) introduced a process synthesis framework for the conversion of hardwood biomass to liquid transportation fuel such as gasoline, diesel and jet fuel. Finally, regarding GHG emissions and fossil fuel consumption, Elgowainy et al. (2012) and Stratton et al. (2010) performed a LCA of alternative jet fuels, while Bailis et al. (2010) performed a LCA from biojet produced from *jatropha curcas* cultivated in Brazil. However, these studies present limitations that this work attempted to reach. Such limitations are related to the isolated and qualitative scope of each work that approached different aspects regarding biojet fuel without considering the real specificities of its production in a determined place. For this reason, the present work presents an relevant and original analysis regarding biojet fuel, since it performs an specific case study for its production in Brazil.

In order to perform a specific case study for Brazil, the main objective of this work is to evaluate the technical and economic potential for biojet fuel production in the country, identifying the cost-effectiveness of different technological routes and assessing the competitive opportunities for a Brazilian growing market of this fuel. For this purpose, this analysis comprises distinct steps in order to develop indicators such as the feedstock availability, the techno-economic feasibility and the environmental impact of fuel production and use. Together these assessments are useful to identify areas with major potential to implement biojet production sites in the country. In this way, the specific objectives include:

- Determine the bioenergy potential from agricultural, agro-industrial and forestry residues in Brazil and assess its concentration throughout the country.
- Perform a life cycle assessment (LCA) to evaluate the environmental performance of biojet fuels produced in the country from selected feedstock.
- Estimate capital and operational costs of biojet fuel according to different production routes.

This dissertation is structured in 7 chapters, including the introduction. Chapter 2 presents the main aspects of aviation fuels such as their production process, chemical composition and requirements for specification. Further, this chapter presents the current context of aviation industry and the aspects regarding production and logistics in Brazil. Chapter 3 describes different technological pathways for biojet fuel production. Chapter 4 presents the methodology applied and the database used. Chapter 5 reveal the work findings and its discussion. Chapter 6 contains the final remarks, conclusions and suggestion for future works. Finally, chapter 7 presents the references used as basis for the dissertation.

2. Jet fuel

Aviation gas turbines are powered by liquid petroleum fuels, obtained by the refining process and known as jet fuel or aviation kerosene. Petroleum refining is a process of separating many compounds present in the crude petroleum through the atmospheric and vacuum fractional distillation process. The crude oil is heated and its compounds boil at different temperatures producing gases, which are later condensed into liquids, naphtha that is the lowest boiling fraction compound, and distillate that corresponds to the second fraction of about 33% of the crude oil input. The distillate is further processed in the distillate hydrotreater to become kerosene and special solvents (LIU; YAN; CHEN, 2013). In Brazil, jet fuel is entirely produced by straight run distillation, followed by chemical treating or hydroprocessing. The chemical treating processes, known as Merox and Bender, and the hydrotreating aim to remove sulfur compounds, reduce acidity and stabilize the fuel (PETROBRÁS, 2014). Figure 1 shows the production scheme of jet fuel in Brazil.

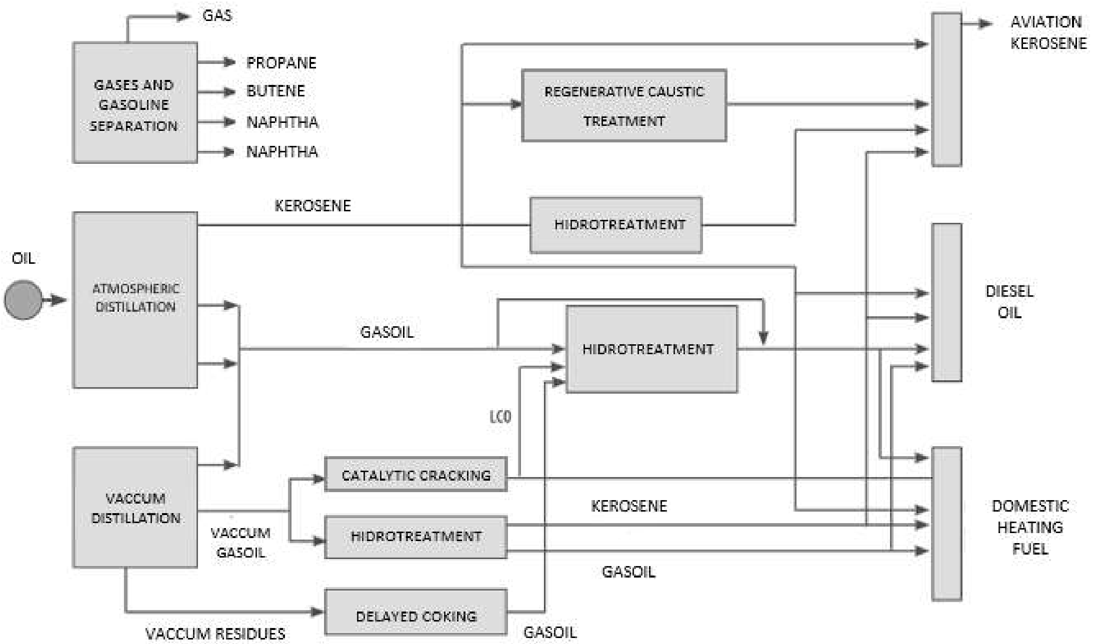

Figure 1: Jet fuel production scheme in Brazilian refineries
Adapted from (PETROBRÁS, 2014)

Aviation kerosene is a multi-component fuel with a carbon chain length of C8-C16, which has been developed from lamp oil. It is composed typically by groups of paraffins, naphtenes or cyclo-paraffins and aromatics, with olefins being present in small amounts. Approximately 70-85% of fuel is made up of paraffins, which include normal straight chain, branched chain isoparaffins and cycloparaffins (naphtenes). The composition of paraffinic compounds is variable according to the type of oil processed in refineries. The aromatics, unsaturated cyclic hydrocarbons containing one or more six carbon ring structures, are present at least by 25%. The fuel also contains trace amounts of sulfur, nitrogen and oxygen, heteroatoms associated with hydrocarbon compounds from the raw crude oil.

2.1 Fuel composition

As mentioned above, aviation fuels are characterized and controlled by specifications, based more upon usage requirements than upon the detailed chemistry of the fuels. Some performance parameters, for example, set limits on particular hydrocarbons such as aromatics and olefins (CRC, 1983). The system requirements include parameters such as fluidity, combustion properties, corrosion protection, fuel stability, contaminant limits, additives, and others.

The jet fuel is formed by four types of compounds, grouped into: paraffins, cycloparaffins or naphthenes, aromatics and olefins. The fuel components are described in the sub-sections below.

2.1.1 Paraffins

Paraffins and cyclopraffins are the major components of jet fuel. Paraffins are chains of carbon fully saturated with hydrogen. They may be straight-chain or branched-chain molecules, enabling a very stable structure that do not readily reacts with materials which they come in contact with. They have a high heat release per mass unit and cleaner burner than other hydrocarbons due to their high hydrogen-to-carbon ratio (CRC, 1983).

Cycloparaffins are hydrocarbons with a saturated ring structure. They have higher density than normal paraffins, but lower hydrogen-to-carbon ratio, what diminishes their heat release per unit of mass. They are also stable and clean burning (CRC, 1983). The main advantage is that they reduce the freeze point of the fuel, a vital parameter for high altitude flights (SIMON; RYE; WILSON, 2011).

2.1.2 Olefins

Olefins are hydrocarbons similar to paraffins, but are unsaturated and so, have lower hydrogen-to-carbon ratio. Among all classes of hydrocarbons they are the most reactive, which make them capable of reacting with diverse materials. This feature gives them a high instability that are not widely found in the crude oil, but may be formed in the refinery processes. In order to reduce the formation of gums and polymers ensuring the useful life of fuels in storage and its thermal stability, its content in the final fuel is limited to 5% (CRC, 1983).

2.1.3 Aromatics

Aromatics are hydrocarbons formed by a six-carbon fully unsaturated ring structure that may be coupled to form polynuclear aromatics. They have higher heat content per unit of volume, but a lower heat content per mass unit than the paraffins. Its content in the final fuel is limited to 20-25% by volume, due to its tendency to form combustor coking and smoke in burning and to its contribution to high luminosity flames. On the other side, a minimum aromatic content is required due to material compatibility, as fuel comes in contact with large range of metals, polymers and elastomers. They also tend to cause swelling effects ion rubbers and sealants, preventing possible leakages in the fuel system.

2.1.4 Non hydrocarbon compounds

Sulfur and Sulfur compounds

In general, all crude oils contain sulfur compounds that can be in the form of free sulfur, mercaptans, sulfides, disulfide and thiophenes. Free sulfur can cause corrosion of metals in the systems, while mercaptans can deteriorate some types of synthetic rubbers. The amount of these compounds are controlled by specification limits, while the other sulfur compounds are constrained by the total sulfur content limits (CRC, 1983).

Gums and gum forming compounds

Gums are compounds with high molecular mass formed by hydrogen, carbon, oxygen and generally sulfur and nitrogen. They may be produced in storage in the presence of air and its formation can be accelerated by the exposure to sunlight, high temperatures and concentration of sulfur compounds. They can cause filter plugging and sticking of fuel valves and controls and plugging of metering orifices. Fuel specifications limits the amounts of gums in the fuel (CRC, 1983).

Water-soluble materials

Some materials like alcohol, sodium soaps, among others, can contribute to corrosion in the fuel system, filter clogging, poor water/fuel separation and poor performance of filter separators. The fuel specifications have a water tolerance test in order to control these hazards (CRC, 1983).

Naphthenic acid

Naphthenic acids are derived from the crude oil. They can cause corrosion with aluminum and magnesium in the presence of water, rapidly reacts with zinc to form compounds that are soluble in the fuel and form surfactants, which can cause free water to remain in suspension. There is no direct method of limiting its amount in the specifications, but the total acidity and the water separation index can indirectly control this contaminant (CRC, 1983).

Additives

The additives are used to improve the properties of fuel and to avoid particular problems, such as corrosion and formation of gums. Only officially approved additives are permitted and its amount its controlled by specifications (CRC, 1983). Table 1 describes the additives used in jet fuel, based in CRC (1983).

Table 1: Additives used in jet fuel

Additive	**Function**
Antioxidants	Prevent the formation of gums and peroxides. Peroxides can be found in heavily hydrotreated fuels, which requires the addition of antioxidants.
Metal deactivators	React with soluble copper and other metal compounds, preventing problems with filter-blockage. Its addition of is allowed in all fuels.

Icing inhibitors	Prevent the formation of ice from water coming out of solution at low temperatures and from water condensing in fuel tank. They can be used as a barrier to microbiological growth.
Corrosion inhibitors	Diminish the formation of rusting in pipelines and storage tanks and improve lubricity.
Static dissipator additives	Raise the electrical conductivity of the fuels, thus preventing the formation of static charges.

2.2 Fuel requirements

The property requirements for jet fuel developed together with improvements on engines and catalytic cracking process in refining. As well as most outputs of refining process, jet fuel is a mixture of different hydrocarbons and the analytical techniques cannot fully identify its entire individual components. For this reason, jet fuel specifications and requirements are commonly defined in terms of required performance (Bauen et al.,2009). The most relevant performance characteristics are described below.

2.2.1 Energy content

The energy content of the fuel have a significant impact on the aircraft performance due to the limited volume available to store the fuel and the mass of the fuel that can be carried. The energy content of different hydrocarbon species is different, varying the composition of jet fuel and therefore, its energy content. For this reason, the standards define a minimum heat of combustion (BAUEN et al., 2009).

2.2.2 Freeze point

Aircraft can operate for long periods at high altitudes, where air temperature can be very low. As main fuel tanks in modern aircrafts are located in the wings, it is important that the fuel remains pumpable even at very low temperatures. For this reason, the standards define a maximum allowable freezing point (BAUEN et al., 2009).

2.2.3 Thermal stability

Besides being burned by aircraft engines, the fuel has the function to cool the engine lubrication oil and other engine components. At high temperatures, some components of the fuel can undergo chemical reactions, resulting in the formation of gums and insoluble coke particulates, which can deposit in the system compounds, reducing or blocking the fuel flow. It can also clog fuel injection nozzles or small cooling holes in the turbine, increasing the maintenance frequency. To avoid this situations, the standards define a performance test to evaluate the deposits formation in the fuel (BAUEN et al., 2009).

2.2.4 Viscosity

Fuel viscosity affects the spray pattern coming out of the fuel nozzle and in the size of droplets. The droplet size may cause incomplete combustion and prejudice the engine relight at altitude, while the spray pattern can result in the sub-optimal combustion of the fuel and create unequal temperature distributions, damaging the combustor or turbine downstream. In order to avoid these problems, the standards define a maximum allowable fuel viscosity (BAUEN et al., 2009).

2.2.5 Combustion characteristics

The aromatic compounds of the fuel tend to form small carbonaceous particles that may cause harmful effects on engine performance. These particles can increase wall temperatures at the combustor, be deposited on engine internal surfaces, erode downstream engine component and be emitted as visible smoke. These effects can damage the combustor, disrupt the air flow or clog cooling holes. Additionally, the presence of sulfur results in the emission of particulates that affects air quality. To minimize these problems, the standards define maximum allowable concentration of aromatics in the fuel (BAUEN et al., 2009).

2.2.6 Lubricity

The fuel is responsible for lubricating moving parts in the fuel system and engine controls like fuel pumps, fuel controls and hydraulic engine controls. The presence of trace amounts of sulfur, oxygen, nitrogen and aromatics defines the ability of fuel to be a good lubricant. As the lubricity cannot be measured based on chemical properties, the standards define requirements that the fuel must meet (BAUEN et al., 2009).

2.2.7 Material compatibility

Jet fuel is exposed to a wide range of materials, like metals, coatings and elastomers. Fuel components like organic acids or sulfur compounds may cause corrosion of metals. In order to avoid this problem, the specifications limits the total acidity of fuel and the concentrations of its compounds. A corrosion test is also specified. The presence of aromatics in the fuel cause the swelling of aircraft elastomers. For this reason, there is a concern in industry that the use of alternative fuels that do not contain aromatics can lead to leaks in the fuel systems (BAUEN et al., 2009).

2.2.8 Safety properties

The most relevant fuel properties regarding safety are its flash point and electrical conductivity. The flash point is defined as the lowest temperature at which fuel vapors if ignition source is applied. The conductivity of jet fuel is extremely low, meaning that this static charge dissipates slowly and can potentially build up. Enough static charge development can result in a spark, leading to an explosion if the mixture of air and fuel vapor above the fuel is in the flammable range. To minimize the risks of explosion in fuel handling and tanks, the standards defines requirements of minimum flash point and electrical conductivity (BAUEN et al., 2009). The Table 2 summarizes the fuel requirements.

Table 2: Jet fuel requirements. Based on Bauen et al. (2009)

Requirement	Reason	Specification
Energy content	Affects aircraft range	Minimum energy density
Freeze point	Impacts upon ability to pump up fuel at low temperature	Maximum allowable freeze point temperature
Thermal stability	Coke and gum deposits can clog or foul fuel system and nozzles	Maximum allowable deposits in standardizes heating test

Viscosity	Impacts ability of fuel nozzles to spray fuel and of engine to relight at altitude	Maximum allowable viscosity
Combustion characteristics	Creation of particulates in combustor and in exhaust	Maximum allowable sulfur and aromatics content
Lubricity	Impacts upon ability of fuel to lubricate fuel system and engine controls	Maximum allowable amount of wear in standardized test
Material compatibility	Fuel comes in contact with large range of metals polymers and elastomers	Maximum acidity, maximum mercaptan concentration, minimum aromatic content
Safety	To avoid explosion in fuel handling and tanks	Minimum fuel electrical conductivity and minimum allowable flash point

2.3 Fuel certification

There are three standards for certifying aviation fuel: ASTM D1655, International Air Transport Association Guidance Material (Kerosene Type), and the United Kingdom Ministry of Defense, Defence Standard (DefStan) 91-91 (WANG; TAO, 2015). ASTM Specification D7566 (Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons), which targets alternative jet fuels, lists the fuel properties and criteria required to control the production and quality of a renewable fuel for aviation safety (WANG; TAO, 2015). In Brazil, the fuel specification is established by the National Petroleum Agency (ANP) according to PANP n.137 – 01/08/2000 (AUGUSTO; NOGUEIRA, 2002). These specifications control the chemical composition of these fuels and its requirements include characteristics like pour point, combustion properties, corrosion protection, stability, contaminant and additives content, among others.

In commercial aviation there are two types of fuels used, which differ basically in the freezing point: (i) Jet-A (used mainly in the USA) is -40°C and (ii) Jet A-1 (used worldwide) is -47°C (ROSILLO-CALLE et al., 2012). As jet fuel supply arrangements have become more complex, involving co-mingling of product in joint storage facilities, a number of fuel suppliers developed a document known as the Aviation Fuel Quality Requirements for Jointly Operated Systems (AFQRJOS[2]) for the Jet A-1 (SHELL, [s.d.]). The AFQRJOS embodies the most stringent requirements of the British Ministry of Defence Standard DEF STAN 91-91 and ASTM Standard Specification D1655 (JIG, 2012).

In Brazil, there are two types of aviation fuels produced and commercialized: QAV-1, similar to Jet A-1 and QAV-5, for military use. The main difference between them is major restrictions associated to the presence of lighter compounds to ensure safety in product handling and storage (PETROBRÁS, 2014).

Table 2 shows the specifications for jet fuel in Brazil. The table contains the physicochemical characteristics listed in the ANP resolution. It indicates the fuel characteristics and lists its components, which are classified according to minimum and maximum levels allowed. The method used for testing each component is also shown.

[2] Agip, BP, ChevronTexaco, ExxonMobil, Kuwait Petroleum, Shell, Statoil and Total recognize this checklist as the basis of their international supply of virtually all civil aviation fuels outside North America and former Soviet Union (SHELL, [s.d.]).

Table 3: Jet fuel (QAV-1) specifications in Brazil

TABELA I - ESPECIFICAÇÃO DE QUEROSENE DE AVIAÇÃO - QAV-1 (1)

CARACTERÍSTICA	UNIDADE	LIMITE	MÉTODOS	
			ABNT NBR	ASTM
APARÊNCIA				
Aspecto	-	claro, límpido e isento de água não dissolvida e material sólido à temperatura ambiente	Visual	Visual D4176 (Procedimento 1)
Cor (2)	-	Anotar	14921	D156, D6045
Partículas contaminantes, máx. (3)	mg/L	1,0	-	D5452
COMPOSIÇÃO				
Acidez total, máx.	mg KOH/g	0,015	-	D3242
Aromáticos, máx. ou	% volume	25,0	14932	D1319
Aromáticos totais, máx. (4)	% volume	26,5	-	D6379
Enxofre total, máx.	% massa	0,30	6563	D1266, D2622
			14533	D4294, D5453
Enxofre mercaptídico, máx. ou,	% massa	0,0030	6298	D3227
Ensaio Doctor (5)	-	negativo	14642	D4952
COMPONENTES NA EXPEDIÇÃO DA REFINARIA PRODUTORA (6)				
Fração hidroprocessada	% volume	anotar	-	-
Fração severamente hidroprocessada	% volume	anotar	-	-
VOLATILIDADE				
Destilação (7)	ºC		9619	D86
P.I.E. (Ponto Inicial de Ebulição)		anotar		
10% vol. recuperados, máx.		205,0		
50% vol. recuperados		anotar		
90% vol. recuperados		anotar		
P.F.E. (Ponto Final de Ebulição), máx.		300,0		
Resíduo, máx.	% volume	1,5		
Perda, máx.	% volume	1,5		
Ponto de fulgor, mín.	ºC	40,0 ou 38,0	7974	D56, D3828
Massa específica a 20ºC (8)	kg/m3	771,3 - 836,6	7148	D1298
			14065	D4052
FLUIDEZ				
Ponto de congelamento, máx	ºC	- 47	7975	D2386 (9), D5972, D7153, D7154
Viscosidade a -20ºC, máx.	mm2/s	8,0	10441	D445
COMBUSTÃO				
Poder calorífico inferior, mín.	MJ/kg	42,80	-	D4529, D3338 D4809
Ponto de fuligem, mín. ou	mm	25,0	11909	D1322
Ponto de fuligem, mín. e	mm	19,0		
Naftalenos, máx.	% volume	3,00	-	D1840
CORROSÃO				
Corrosividade ao cobre (2h a 100ºC), máx.		1	14359	D130
ESTABILIDADE				
Estabilidade térmica a 260ºC (10)			-	D3241
queda de pressão no filtro, máx.	mm Hg	25,0	-	-
depósito no tubo (visual)	-	< 3 (não poderá ter depósito de cor anormal ou de pavão)	-	-
CONTAMINANTES				
Goma atual, máx. (11)	mg/100 mL	7	14525	D381
Índice de separação de água, MSEP (12)			-	D3948
com dissipador de cargas estáticas, mín.	-	70		
sem dissipador de cargas estáticas, mín.	-	85		
CONDUTIVIDADE				
Condutividade elétrica (13)	pS/m	50 - 600	-	D2624
LUBRICIDADE				
Lubricidade, BOCLE máx. (14)	mm	0,85	-	D5001
ADITIVOS (15)				
Antioxidante (16)	mg/L	17,0 - 24,0	-	-
Desativador de metal, máx. (17)	mg/L	5,7	-	-
Dissipador de cargas estáticas, máx. (18)	mg/L	5,0	-	-
Inibidor de formação de gelo (19)	% volume	0,10 - 0,15	-	-
Detector de vazamentos, máx. (20)	mg/kg	1,0	-	-
Melhorador da lubricidade		(21)	-	-

Source: Petrobrás (2014)

2.4 Aviation industry

The aviation industry consumes around 1.5 billion barrels of Jet A-1 fuel annually through 1,397 airlines serving 3,864 airports. If this industry were a country, it would rank 21st place in the world in terms of gross domestic product (GDP), generating US$664 billion per year (ATAG, 2015).

This industry highly depends on liquid fossil fuels due to lack of alternatives to aircrafts that fly long distances. Data from U.S Energy Information Administration (EIA) indicate a jet fuel production in 2012 of 5.4 million barrels per day in the world (EIA, 2013b). The traffic and fleet forecasts developed by the Forecasting and Economic Analysis Support Group (FESG) of the International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection (CAEP) indicates an annual growth[3] of 4.8% in passenger and freight traffic for the 2020-2030 period, 4.2% in 2030-2040 and 3.7% in 2040-2050[4] (ICAO, 2013). However, economic and political events over the last years have affected some of the fundamentals for growth. The uncertain developments in the global economy may dampen this demand forecast for air transport (IATA, 2015).

Air transportation was growing rapidly in Brazil, but in the recent years, the economic downturn in the country directly affected the demand for aviation services (ANAC, 2014). In 2012, jet fuel consumption in Brazil were 125 thousand barrels per day, representing 2.3% of the world (EIA, 2013b). According to the Annual Air Transport report released by the National Agency of Civil Aviation (ANAC), in 2014, 13 Brazilian companies provided air services in Brazil, 4 of them for freight transport, while among the 84 foreign companies, 25 were for freight transportation (ANAC, 2014). In the end of this year, Brazilian companies owned a freight of 549 airplanes, most of them manufactured by Boeing and Airbus. In 2014, 1.1 million flights were carried out for Brazilian and foreign companies, considering total domestic and international operations (ANAC, 2014). Regarding economic aspects, in 2009, aviation contributed with R$32 billion to Brazilian GDP and employed about 684 thousand people. In addition, it is estimated that there are a further 254 thousand people employed through activities promoted by aviation (CORTEZ et al., 2014; OXFORD ECONOMICS, 2014).

[3] Average annual growth rate of revenue tonne-kilometres [RTK].
[4] Estimates from the Most Likely Scenario (Central Forecast).

Aviation industry measures its technical progress by aircraft efficiency and engines. The historical trends in improving efficiency levels show that modern aircrafts are about 80% more fuel efficient than 40 years ago, due to step changes in materials and design coupled with incremental improvements to engine design and operation. Figure 2 shows fuel efficiency gains in the industry over time. Fuel efficiency is a critical factor for aviation given that fuel is one of the highest costs of an airline operation and that oil prices are volatile. There is also environmental issues related to fossil fuel depletion and GHG emissions (ATAG, 2010b), as detailed in following sections.

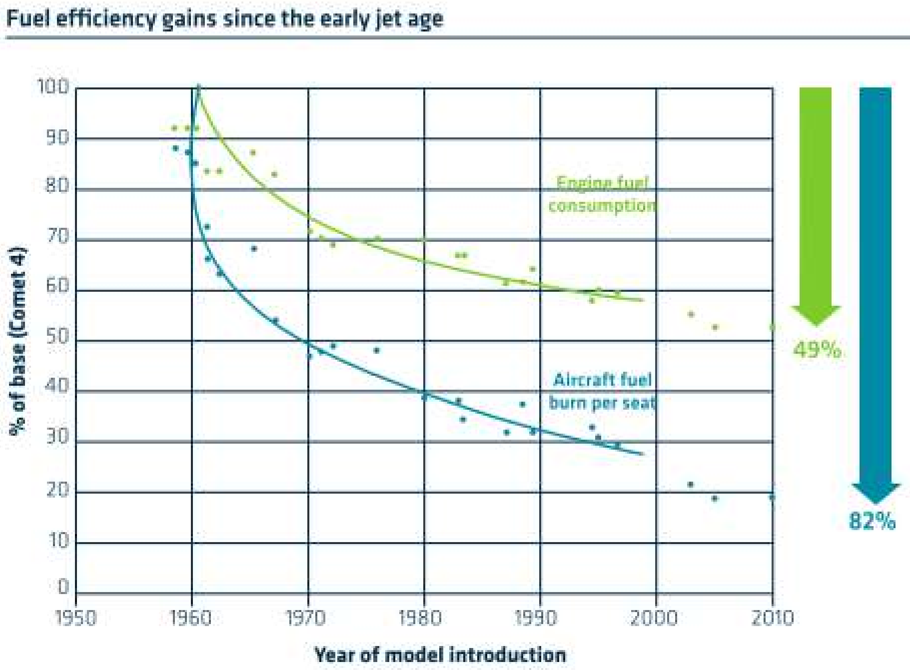

Figure 2: Aviation fuel efficiency gains
Source: ATAG (2010)

Fuel represents the most important operational cost for airline companies. World average fuel corresponds to about 34% of operational costs. However, in Brazil, it comes to represent around 40% of operational costs (CORTEZ et al., 2014). It occurs because the fuel pricing used in Brazil is linked to the cost of importing jet fuel from the US Gulf Coast. Thais is, the fuel pricing is set up as if 100 percent of the fuel were imported, adding artificial expenses to the cost of fuel. However, 75% of the fuel that is supplied to Brazilian airlines is produced domestically (CEDERHOLM, 2014; PEARSON, 2014). As mentioned above, besides the high share of fuel costs, the uncertainty in oil prices promotes difficulties for companies to plan and manage. Figure 3 shows the benchmark crude oil and aviation kerosene prices in the past years according to U.S Energy Information Administration data (EIA, 2016a, 2016b).

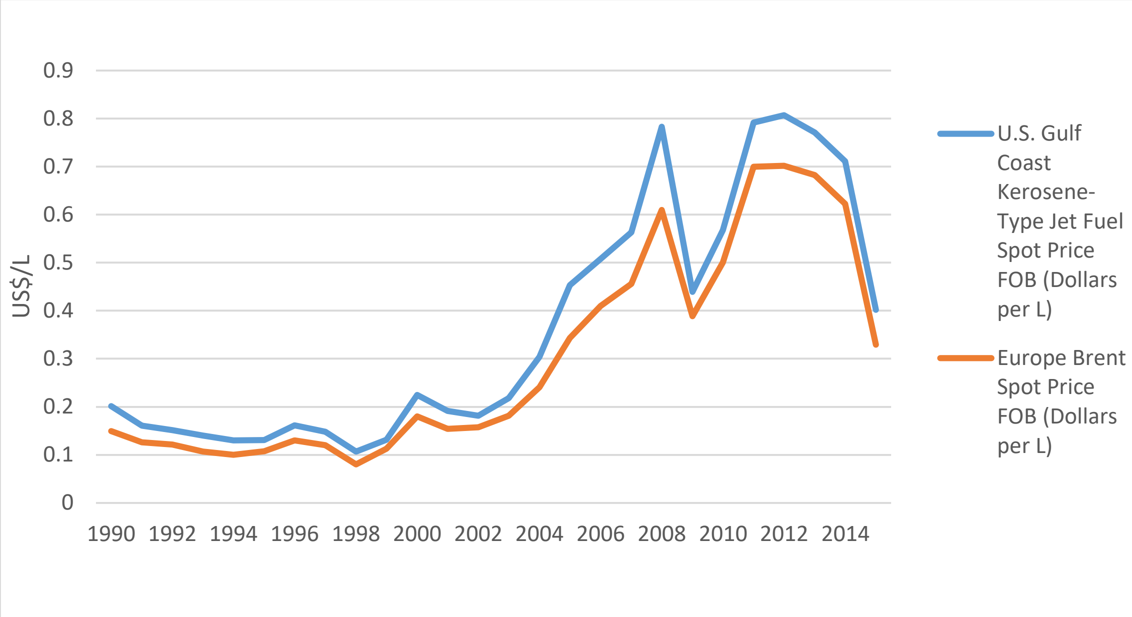

Figure 3: Aviation kerosene and oil prices

Nowadays the aviation sector contribution to global anthropogenic GHG emissions is minor, when compared to other transport modals. Worldwide, flights produced 770 Mt of CO_2 in 2015, equivalent to 2% of humans emissions (ATAG, 2016). Despite the minor impact, the perspectives indicate a growth in the sector in the next years, which will lead to increased emissions (ROSILLO-CALLE et al., 2012). For this reason, the aviation industry (IATA) announced in 2009 its commitment to mitigate aviation GHG emissions by adopting the following goals: fuel efficiency improvements of 1.5% per year from 2009 to 2020, achieve carbon neutral growth in 2020, reducing net CO_2 emissions in 50% by 2050 compared to 2005 levels. In order to reach these goals, the aviation industry established a four-pillar strategy, based on:

- Investments in technology, like more efficient airframe, engines and equipment, sustainable biofuels and new energy sources;
- Efficient operations;
- Effective infrastructure by improving air routes, air traffic management and airport procedures;
- Economic measures, like carbon offsets and global emissions trading.

Short-term options to reduce air travel emissions are limited. Modern aircraft are already highly fuel-efficient and so, technological improvements tend to be incremental.

Further, since commercial aircraft have a lifetime of around 25 years, the diffusion of improvements across global fleet tends to be slow (LEE; LIM; OWEN, 2013; MAWHOOD et al., 2015). Notwithstanding, advances in air traffic management and engine efficiency have the potential to reduce emissions, this is not sufficient to offset increases in demand and the aviation industry growth. Therefore, the majority of emissions reductions will have to come from alternative sustainable biofuels.

2.5 Brazilian aviation kerosene production and logistics

The aviation fuel trading chain is composed by three agents, which have the responsibility of assuring the fuel supply in the country. These agents are the fuel producer, importer and distributor. Figure 4 shows the supply scheme of the fuel. In Brazil, the refineries that produce jet fuel are all own by Petrobras, the Brazilian oil company. Although the production is dominated by one company, the distribution is made by three companies, through 191 bases and 6 terminals. The aviation fuel import is all made by Petrobras through three port terminals (Itaqui/MA, Suape/PE and São Sebastião/SP) (ANP, 2014).

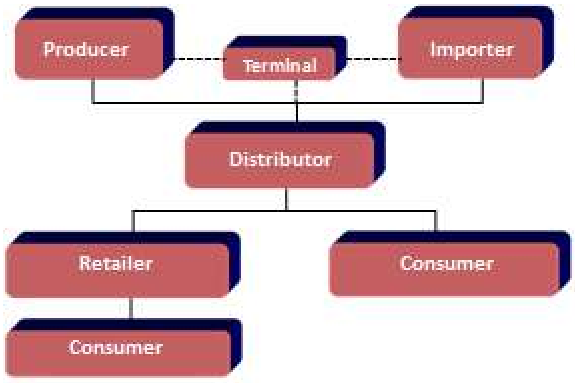

Figure 4: Aviation kerosene supply scheme in Brazil
Adapted from (ANP, 2014)

Brazil has 17 refineries, which processed 2.4 billion barrels per day in 2014 (ANP, 2015). Thirteen of them belong to Petrobras and they represent 98.2% of the country's total refining capacity. The Southeast refineries concentrate together 61.7% of the storage capacity of petroleum and 67.2% of the national storage capacity of oil products (ANP, 2015). Also, in 2014, the production of oil products was 130.2 million m^3, of which approximately 6.1 million m^3 were aviation kerosene.

Actually, from the 17 refineries in the country, 9 produce aviation kerosene: REDUC (RJ), REFAP (RS), REGAP (MG), REMAM (AM), REPAR (PR), REPLAN (SP), REVAP (SP), RLAM (BA), RPCC (RN). All of them belong to Petrobras. REVAP (SP) was the main producer in 2014, with 33.5% of the total aviation kerosene produced in the country (ANP, 2015). Figure 5 presents the location of refineries that produce aviation kerosene in Brazil and Table 4 shows the kerosene production of each refinery in 2014.

Figure 5: Refineries producing aviation kerosene

Table 4: Aviation kerosene production of each refinery

Aviation kerosene production in 2014 (m^3)	
REDUC (RJ)	1,324,235
REFAP (RS)	240,199
REGAP (MG)	773,814
REMAN (AM)	174,251
REPAR (PR)	325,485
REPLAN (SP)	809,688
REVAP (SP)	2,034,941
RLAM (BA)	283,731
RPCC (RN)	112,770
Total	5,977,621

Source: (ANP, 2015)

The sales of jet fuel in 2014 totaled 7.5 million m^3. The consumption of this fuel showed the following distribution among the country regions (Figure 6): North, 397 thousand m^3 (5.3% of total); Northeast, 1.1 million m^3 (14.4% of total); Southeast, 4.7 million m^3 (62.7% of total); South, 552.1 thousand m^3 (7.4% of total), Midwest 758.7 thousand m^3 (10.2% of total). The concentration of consumption in the southeast region occurs due to the presence of the main airports of the country, and also because this region is the principal origin and destiny of international flights. The state of São Paulo registered the highest consumption of aviation kerosene (40.6% of total), followed by Rio de Janeiro (17.0% of total) and the Federal District (7.3% of total) (ANP, 2015).

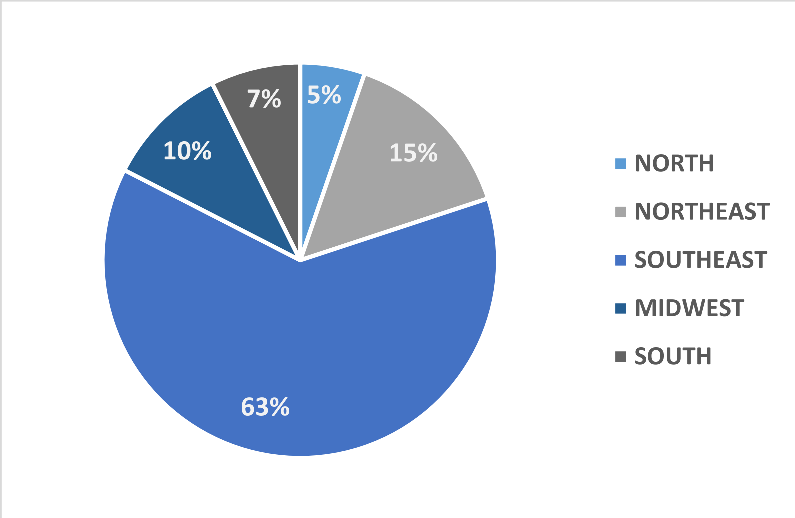

Figure 6: Jet fuel consumption per region in Brazil

As seen above, jet fuel consumption in Brazil is higher than its production, resulting in an annual deficit of 1.4 million m^3. For this reason, importation is necessary to meet the fuel demand. In 2014, the total aviation kerosene imported was 1.5 million m^3, mostly from Kuwait (72.6%). The total amount of fuel exported was 20 thousand m^3 (ANP, 2015).

Although Petrobras is responsible for all jet fuel production, its distribution to the consumer market is made by three companies: BR (Petrobras Distributor), Shell (Raízen fuels) and Air BP Brazil. The fuel supply to the distributors can be accomplished in two ways, according to the structure of the airports. The first is related to airports that have an aircraft supply unit (UAA/PAA) connected directly with refineries through pipelines. This is the case of Garulhos airport in São Paulo and Galeão airport in Rio de Janeiro, connected with the REVAP and REDUC refineries, respectively. The second corresponds to the airports with no connections with refineries through pipelines. In this case, the distributor company receives the fuel from refineries in their bases through pipelines or cabotage. Then, after delivered in the bases, the fuel is transported by trucks to the distributors bases in the airports and then delivered to fuel the airplanes (PALAURO, 2015).

2.5.1 Jet fuel logistics in Brazilian regions

Among the five Brazilian regions, only Midwest, which do not have an oil refinery, is completely dependent of jet fuel supply from other regions. North region's jet fuel demand is met by one refinery production and cabotage supply from other regions.

Pipelines, inland waterway and road transport are the modals used to distribute the fuel. In Northeast region, the demand is attained by two refineries production, cabotage supply and import. There, the fuel is distributed by road transport and cabotage. Southeast region is the major jet fuel producer in the country and its demand is met by four refineries production, cabotage supply and import. Southeast is also responsible for supplying all Midwest jet fuel demand by road transport. Within the southeast region, pipelines and road transport distribute the fuel. In the South, the demand is attained by two refineries production and the fuel is distributed by road transport.

The aviation kerosene supply in the North region comes from REMAN production, responsible for meeting 40% of regional demand and is complemented by cabotage to REMAN and Miramar port in Belém (PA). In Amazonas state (AM), the fuel distribution starts with pipeline transfer from REMAN to two primary bases in Manaus (AM), from which the fuel is transferred by inland waterway transport to 8 PAAs (two of them in the states of Roraima (RO) and Pará (PA)), by road transport to one PAA (in Roraima state) and to the Manaus airport (ANP, 2014). In Pará state (PA), the fuel received by cabotage by the two primary bases of Belém (PA) is transferred by road transport to Belém airport and to 8 PAAs, three of them in the states of Maranhão (MA), Amapá (AP) and Tocantis (TO) that belongs to the Northeast region. In Rondônia state (RO), the fuel that comes from Manaus (AM) is transferred from the base of Porto Velho (RO) by road transport to the city airport and to 3 PAAs. Figure 7 shows the logistics in the North region.

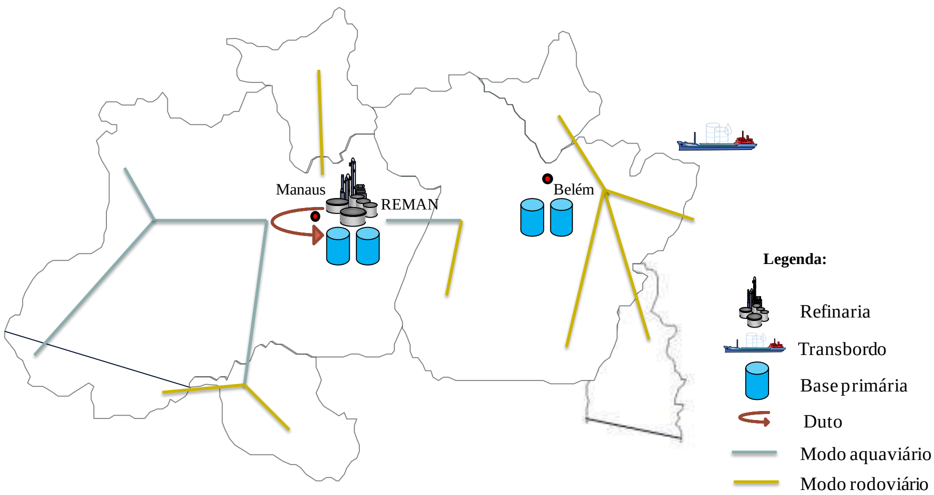

Figure 7: Aviation kerosene logistics in the North region
Source: ANP (2014)

In the Northeast region, the production of aviation kerosene is made by two refineries, and as it is insufficient to attain the demand, cabotage and import represent 62% of fuel supply. Suape (PE) and Itaqui (MA) ports are mostly for import, while the Mucuripe (CE) port is mostly a cabotage point. In the Bahia state (BA), the Madre de Deus terminal is a cabotage point, whose volume is added to the RLAM production. The fuel is supplied by road transport by the producer and importer. In the state of Maranhão (MA), the importation in Itaqui port is received by the primary base of São Luís (MA), transferred to São Luís airport and to PAA of Teresina (in the state of Piauí), from which is also transported to another PAA in Piauí. In Ceará state (CE), the cabotage in the Mucuripe port is drained from the Fortaleza's primary bases to Fortaleza airport and to 1 PAA. In the Rio Grande do Norte state (RN), the RPCC production is transferred from the primary base of Guamaré (RN) to the airports of Natal (RN) and João Pessoa (PB). In the Pernambuco state (PE), jet fuel imported in Suape port is transferred from the primary base of Ipojuca to the airports of Recife (PE), Maceió (AL), João Pessoa (PB) and to two airclubs. In Bahia state (BA), the cabotage and RLAM production are transferred from the two primary bases of São Francisco do Conde to 4 PAA, to Aracajú (SE) and Salvador (BA) airports, and from this to two PAAs. Figure 8 illustrates the logistics in Northeast region.

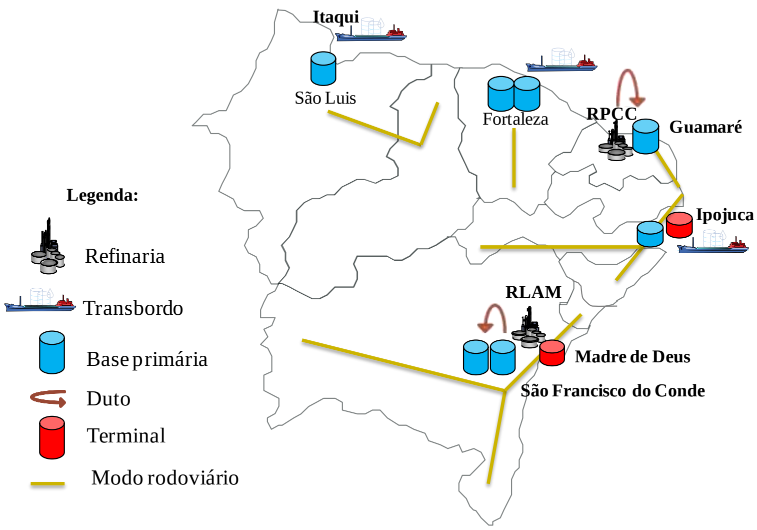

Figure 8: Aviation kerosene logistics in the Northeast region
Source: ANP (2014)

Figure 9 shows the fuel logistics in the Southeast region. The two largest Brazilian airports, Guarulhos and Galeão, are connected through pipelines to refineries, as earlier stated. The third, fifth sixth and seventh busiest airports of the country are also located at southeast region. Furthermore, the Brasília airport, the fourth largest airport, located in the Federal District, is fed by the southeast production. In view of the characteristics, dependency and the connection of these fluxes, the analysis of jet fuel logistics in the Southeast and Midwest regions cannot be separated (ANP, 2014).

In 2014, the aviation kerosene production in REGAP (MG) and REDUC (RJ) was 27% bigger than the demand of the states of Minas Gerais (MG) , Rio de Janeiro (RJ) and Espírito Santo (ES) (ANP, 2015). Besides that, REGAP delivers about half of its production to the Federal District (ANP, 2014). In the state of Minas Gerais, the fuel distribution chain begins in the primary base of Betim, which expands REGAP production by truck transport to the airports of Confins (MG) and Pampulha (MG), to 5 PAAs and to Brasília airport in the Federal District. In the state of Rio de Janeiro, REDUC production is sent to the primary base of Galeão airport (RJ) through pipelines. Thenceforth, the fuel is transferred by road transport to Santos Dumont Airport (RJ), to 8 PAAs, one of them in the state of Minas Gerais, and to Vitória airport, in the state of Espirito Santo (ES) (ANP, 2014).

In São Paulo state, the fuel demand is supplied by the production of 2 refineries: REPLAN and REVAP. The São Sebastião Port is responsible for the greatest volume of import received in the country, allowing São Paulo to attend its demand, to make transfers to Midwest region and, with the exceeding, to perform cabotage operations to another regions (ANP, 2014). São Paulo has a pipeline network that connects refineries to terminals and basis; however, the transfer to Midwest region is realized by truck transport. The REVAP production is sent to the primary base in Guarulhos airport (SP) through pipelines and from this airport, the fuel is transferred by road transport to airports and PAAs in 12 locations. The production of REPLAN starts from Paulínia primary base to airports and PAAs of 32 localities in São Paulo state and in the states of Midwest region (ANP, 2014).

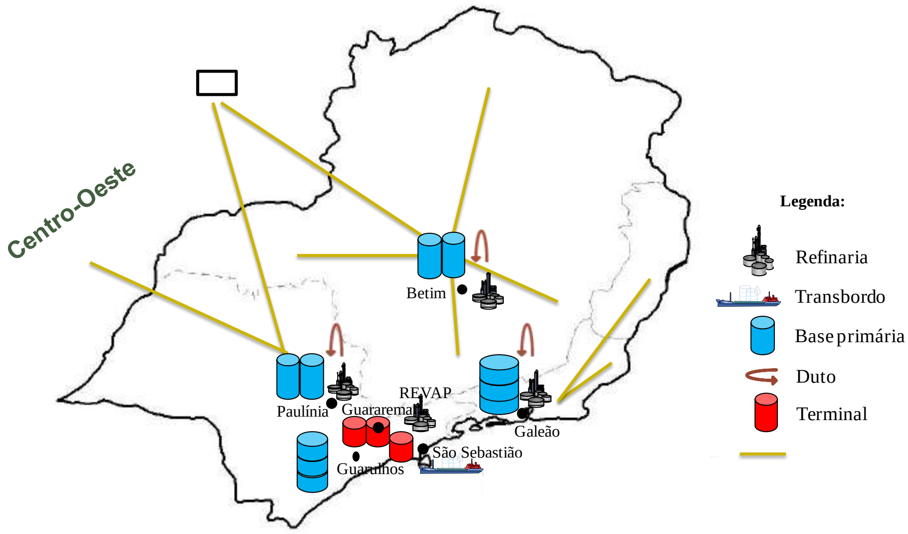

Figure 9: Aviation kerosene logistics in Southeast and Midwest regions
Source: ANP (2014)

In the South region, jet fuel is transferred from the refineries (producers) by road transport. Figure 10 shows the aviation kerosene logistics in the South region. In Paraná state (PR), the production of REPAR is transferred from the primary base of Araucária (PR), to the airports of São José dos Pinhais and Curitiba (PR), to 6 PAAs, 2 of them in Santa Catarina state, and to Florianópolis airport (SC). In the state of Rio Grande do Sul, the production of REFAP is transferred from the primary bases of Canoas (RS) and Esteio (RS) to the airport of Porto Alegre (RS), to 6 PAAs, one of them in Santa Catarina state, and to Florianópolis airport (SC). From this airport, the fuel is also transferred to another PAA (ANP, 2014).

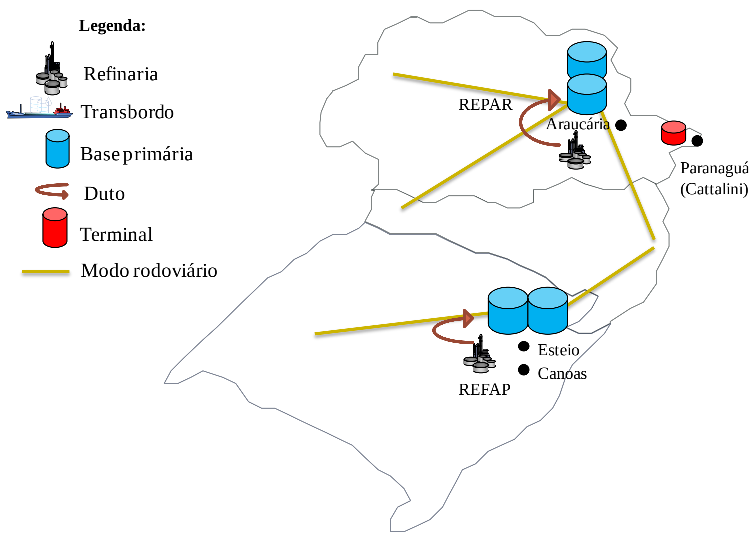

Figure 10: Aviation kerosene logistics in South region
Source: ANP (2014)

Then, it is noteworthy the relevance of Northeast and Southeast regions, whose terminals receive jet fuel imported in the country. The imported jet fuel is responsible for the marginal supply in the country. The southeast region is also responsible for supplying jet fuel to Midwest by truck transport. It is also important to emphasize the relevance of truck transport in the country, as the majority of the jet fuel distribution is made by road.

3. Biojet fuel

Sustainable biomass-derived fuels for aviation can offer a solution to environmental problems related to the fossil fuel depletion and to the vulnerability of the sector towards the oil price volatility. In this way, biofuels for aviation represent an attractive option due to the opportunity to reduce GHG emissions, the necessity to reduce fossil fuel dependence and the availability of renewable sources. The aviation industry aims to develop sustainable "drop-in" biofuels, which means, biofuels that use the same supply infrastructure and that do not require changes in aircraft engines (CORTEZ et al., 2014). In the case of aviation industry, the "drop-in" concept is relevant due to the globalization of demand, stricter conditions of use and safety standards.

Nowadays, different technological pathways convert biomass into alternative fuels to replace jet fuel. Diverse technological processes can be used and the technology chosen highly depends on the type of biomass. Conversion routes include processes like hydrotreatment, Fischer-Tropsch (F-T) synthesis, pyrolysis, liquefaction, enzymatic hydrolysis, fermentation, among others.

3.1 Biojet fuel production routes

The most common routes to produce biojet are hydroprocessing of vegetable oils and biomass gasification followed by Fischer-Tropsch synthesis. Up until now, biojet fuel from hydro-processing technologies using vegetable and waste oils are approved by ASTM International and ready for large scale development. Biojet fuels from Fischer-Tropsch (F-T) synthesis, known as synthetic paraffinic kerosene (FT-SPK), and from fermentation route known as synthetizes iso-paraffins (SIP), are also certified by ASTM and approved for blends up to 50% as 10% (molar basis), respectively, with the conventional jet fuel (MAWHOOD et al., 2014). Other routes have been developed at commercial scale and testes in pilot flight, but are yet to be certified by ASTM, as in the case of conversion of alcohols to jet fuel. Also, jet fuel produced from sugars through fermentation and catalytic conversion have been developed in joint ventures by biofuel and oil companies. Additionally, the conversion through pyrolysis process have not yet been approved by ASTM but it is been developed by several companies and research institutes (WANG; TAO, 2015).

To evaluate the biojet fuel development options, it is important to have an understanding of all the conversion pathways. In the present study, the pathways were classified into four groups according to the type of feedstock and based on Wang and Tao (2015). The following subsections describe the conversion processes of each group, appointed by: (1) alcohol-to-jet (ATJ), (2) oil-to-jet (OTJ), (3) gas-to-jet (GTJ) and (4) sugar-to-jet (STJ).

3.1.1 Alcohol to Jet

The Alcohol to Jet (ATJ) pathway is a conversion pathway that produces jet fuel from biomass via an alcohol intermediate (MAWHOOD et al., 2014), such as methanol, ethanol, butanol and long-chain fatty alcohols. The process is also named alcohol oligomerization (WANG; TAO, 2015). ATJ developers are looking forward to develop drop-in fuels, which include synthetic paraffinic kerosene (ATJ-SPK) and synthetic paraffinic kerosene with aromatics (ATJ-SKA).

This process does not involve the use of microorganisms or special enzymes for fermentation, since it begins with alcohol that has already been produced through fermentation. The conversion process is basically made of four steps: dehydration, oligomerization, distillation and hydrogenation (HARI; YAAKOB; BINITHA, 2015). All steps necessary to convert alcohol to jet fuel are based on processes that are currently used at commercial scale in the petrochemical industry, reducing scale up risks. It is a catalytic process that is capital efficient and scalable, and the process does not require external hydrogen and hydroprocessing (ICAO, 2011). Furthermore, the pathway is considered very economical since the feedstocks are not much expensive[5] and the process does not require large amounts of energy (HARI; YAAKOB; BINITHA, 2015). Figure 11 shows the main steps of ATJ process.

Figure 11: Main steps in the alcohol-to-jet process.
Based in (GUELL et al., 2012)

[5] Although Hari et al (2015) indicated that the feedstocks are low cost, this is not certain, since alcohols have other uses either as energy sources or as inputs for chemical reactions. This means that they have an opportunity cost.

Using ethanol as feedstock, the dehydration step produces ethylene, which follows to the catalytic oligomerization step producing linear α-olefins. This process delivers a wide range of hydrocarbons. The olefins are distillated producing diesel- and jet- range fuels and light olefins. Light olefins (C4-C8) are recycled back to the oligomerization step and jet fuel range products (C9-C16) are submitted to hydrogenation producing alkanes, which are appropriated for renewable jet fuel (WANG; TAO, 2015).

Starting with n-butanol, the dehydration step produces 1-butene and the residual 2-butene formed is isomerizes to 1-butene. Next, the oligomerization step produces olefins in C8-C32 range, which follows to the hydrogenation process. The resulting paraffins in C12-C18 range can be blended to jet fuel. Alternatively, n-butanol can be dehydrogenated in a catalytical process, producing ketones in C5-C11 range. These ketones can be deoxygenated, producing paraffins similar to jet, gasoline and diesel components (WANG; TAO, 2015).

Beginning with iso-butanol, the dehydration process produces a mixture of isobutene, 1-butene and 2-butene, which are converted to olefins through oligomerization process. To increase diesel and jet fuel yields, the C8 olefins can be distilled and sent to one additional dimerization process. Alternatively, the C8 olefins can be either converted into C6H32 through dimerization or reacted with butenes to produce C12 olefins, increasing C12 and C16 and the jet-range products (WANG; TAO, 2015).

Although there are a wide variety of alcohols that can be used as a feedstock for the production of biojet fuels, ethanol and isobutanol are the most suitable ones. They can be produced from a wide variety of biomass feedstocks and technological pathways, such as fermentation and enzymatic hydrolysis. Figure 12 shows the entire chain for ATJ pathway.

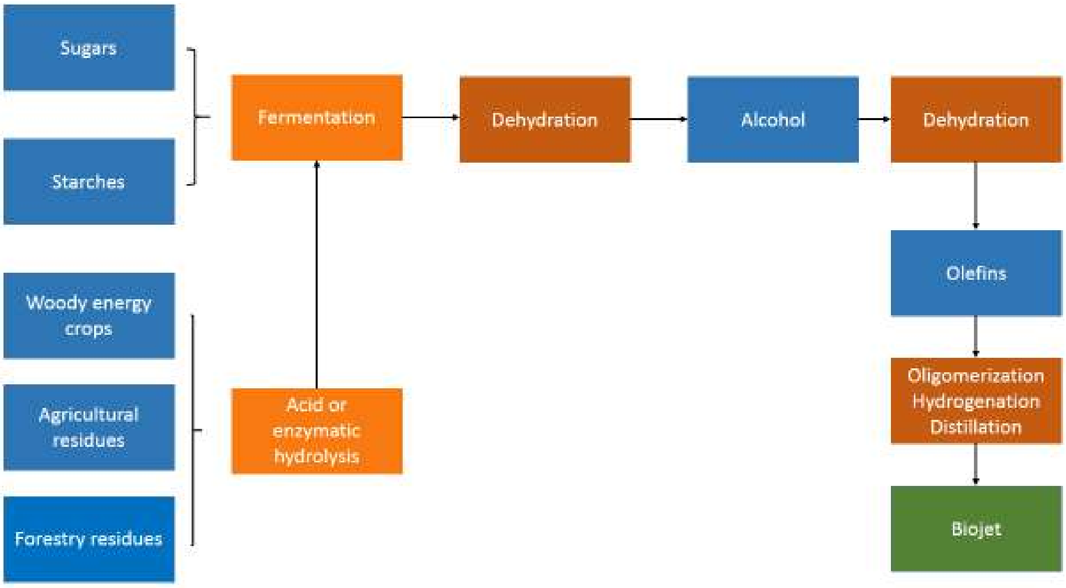

Figure 12: Biomass feedstocks and technological pathway for the ATJ route.
Based on (GUELL et al., 2012)

The feedstock can be divided in three groups: sugars, starches and lignocellulosic biomass. Sugars obtained from plants like sugarcane, for example, can be converted into alcohols through a fermentation process using yeasts or other microorganisms. On the other hand, starches from corn, cassava, and potatoes, for exemple, have to be hydrolyzed before the fermentation process to produce fermentable sugars. The lignocellulosic biomass, such as wood, agricultural and forestry residues, have to be subjected to more severe hydrolysis before the fermentations. It is necessary because the sugars are stored in cellulose and hemicellulose structures, which are more resistant than starches (GUELL et al., 2012).

The conversion of alcohols into jet-fuel, as main product, also produces significant amounts of diesel. Other by-products are obtained in the alcohol production. The unfermented residues left by the fermentation of sugars and starches can be converted into a product that may be sold as animal feed or converted into power or other bio-materials (GUELL et al., 2012). Furthermore, the fermentation process releases biogenic CO2 that can be captured and sold to other industries. Also, the residual cellulose and the non-fermentable lignin left by the conversion of lignocelullosic biomass in alcohols can be used for power generation or steam (GUELL et al., 2012). These residues can also be used to produce fuels by thermochemical processes, and the suitable pathways will be described in this study.

The Table 5 provides a summary of strengths and challenges related to the ATJ pathway.

Table 5: ATJ strengths and challenges.

Strengths	Challenges
All steps necessary to convert alcohol to jet-fuel are based on processes currently used at commercial scale in petrochemical industry	Brazil has a long tradition in producing ethanol from sugarcane, which is currently used as automotive fuel, making ethanol a high cost feedstock
Large feedstock flexibility: sugars, starches and forestry and agricultural residues (lignocelullosic biomass)	
ATJ-SPK contains aromatics and thus it does not require blends with the conventional jet fuel	There is limited experience with alcohols other than methanol/ethanol and with optimizing the process for the production of jet fuel
The process requires small amounts of external hydrogen	
The fermentation of biomass to alcohols are high selective reaction, leading to high conversion of desired products	

Adapted from (GUELL et al., 2012)

3.1.2 Oil to Jet

Bio-oils can be converted to biojet fuels through three pathways: hydroprocessing, known as hydrotreated renewable jet (HRJ) or Hydrotreated Esters and Fatty Acids (HEFA); Catalytical hydrothermolysis and Fast pyrolysis, known as Hydrotreated Depolymerized Cellulosic Jet (HDCJ). HEFA and CH processes use triglyceride-based feedstocks, but the free fatty acids (FFAs) are produced differently by propane cleavage of glycerides and by thermal hydrolysis, respectively. The bio-oil used in HDCJ pathway is obtained by pyrolysis of biomass feedstock. Up until now, only HEFA pathway have been approved for blending and have a defined specification by ASTM (WANG; TAO, 2015).

3.1.2.1 Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene

The Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK) was certified as jet fuel in July 2011 by ASTM for blends up 50% with conventional jet fuel, as earlier mentioned. The hydroprocessing is a common process in conventional oil refineries to remove oxygen and undesirable components like nitrogen and sulfur. The process involves the deoxygenation, desulfurization and denitrogenation of oils through catalytic hydrogenation, producing hydrogen-saturated straight-chain paraffin-rich hydrocarbon liquids. The complete deoxygenation ensures a production of a renewable jet fuel similar to the conventional one, with good storage stability and maximum specific energy. In order to meet jet fuel specifications, the fuel should have good cold flow properties and high flash point. Therefore, hydroisomerization and cracking reactions are needed to shorten down the hydrocarbon chains and to obtain highly branched molecules (GUELL et al., 2012). The isomerization process transforms the straight-chain hydrocarbons into branched structures, reducing the freeze-point to meet the jet fuel specifications. The hydrocracking reactions results in the production of lighter liquids and gas products (WANG; TAO, 2015). The product is a synthetic paraffinic kerosene (SPK) with carbon chain in the range of C9-C15 (PEARLSON). The hydrotreating process produces around 50-70% jet fuel and the remaining products are mainly diesel, with fractions of propane, naphtha and LPG (GUELL et al., 2012). It is noteworthy that naphtha can be submitted to a catalytic reforming process producing, among other products, aromatics and hydrogen. Aromatics are suitable to compose a complete biojet blend, while hydrogen is necessary for hydrotreating processes.

The feedstock required for the process are natural oils and fats rich in triglycerides and free fatty acids. Bio-oils are produced from oil crops and microalgae, which involves cultivation, drying and extraction steps or can be ready-available, as in the case of used cooking oils or tallow. A large number of oil crops can be used. First generation feedstock includes oil crops already used for food or animal feed, such as soybeans, palm oil, rapeseed, among others. The utilization of non-food crops, like jatropha, camelina and halophytes, which can be grown on marginal land, may reduce impacts related to fuel competition with food chains and land use change. Microalgae used as feedstock has advantages over common oil crops of, including higher oil content, CO_2 recycling due to their CO_2 uptake from the atmosphere and minimal impacts on biodiversity and land use change (GUELL et al., 2012). Residual oils have the advantages of low costs, however their impurities and heterogeneity difficult pre-treatment stage and their disperse localization increases collecting costs. Overall, dedicated feedstock are generally expensive related to fossil materials, but their costs can be shared with other co-products. Figure 13 shows the HEFA-SPK production from biomass feedstocks.

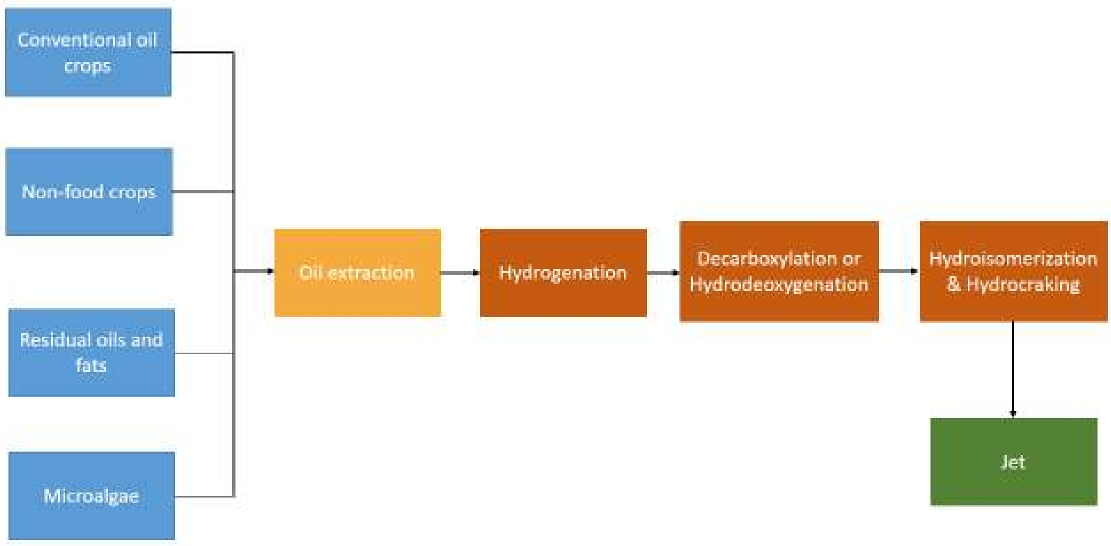

Figure 13: Biomass feedstocks and technological pathway for the HEFA pathway. Based on (GUELL et al., 2012) *and* (WANG; TAO, 2015)

The hydrotreatment process for biojet production has co-products like, renewable diesel, propane, naphtha and LPG and a wide range of by-products such as pesticides, bio-plastics, animal feed, among others, that improve the market economics (GUELL et al., 2012).

The conversion of vegetable oils in hydrocarbons is already a commercial process. However, the high cost of feedstock compared to fossil materials, may be a barrier to its development in large scales. The integration of the plant with conventional oil refineries could reduce the hydrogenation costs (CORTEZ et al., 2014). The Table 6 provides a summary of strengths and challenges related to the ATJ pathway.

Table 6: HEFA strengths and challenges.

Strengths	Challenges
Wide range of feedstock can be processed	High feedstock prices

Life cycle emissions significantly lower than fossil fuels	Feedstock availability (Competition with biodiesel producers for the same feedstock)
Very pure and high quality product with a chemical composition similar to conventional jet fuel	
Possibility of using used cooking oils or tallow as feedstock, diminishing its costs	External hydrogen required in large amounts
Investment costs considered to be low	

Based on (GUELL et al., 2012) *and* (CORTEZ et al., 2014)

3.1.2.2 Catalytical hydrothermolysis

The Catalytical Hydrothermolysis (CH) process is a pathway developed and patented by Applied Research Associates, Inc. (ARA) to produce renewable aromatic drop-in fuels, called ReadiJet and ReadiDiesel. The CH process converts oils directly into high-density aromatic, cycloparaffin or isoparaffin hydrocarbons, which are ideal for drop-in jet and diesel fuels (READIFUELS, 2013). The process comprises reactions like cracking, hydrolysis, decarboxylation, isomerization and cyclization, which are responsible to convert triglycerides into a mixture of straight chain, branched and cyclic hydrocarbons. The products of CH are sent to decarboxylation and hydrotreating processes in order to remove oxygen and saturate the molecules. These two processes form hydrocarbons in C_6-C_{28} range like n-alkanes, iso-alkanes, cyclo-alkanes, and aromatics, which after a fractionation step produce naphtha, jet fuel and diesel. The renewable jet fuel produced meets the ASTM and military specifications and has excellent combustion quality, cold flow properties and stability (WANG; TAO, 2015).

The entire process is also called biofuels isoconversion (BIC), developed by ARA and Chevron Lummus Global (CLG) based on the CH process patented by ARA and CLG's market-leading hydroprocessing technologies. The advantages of the process are: the compatibility with a wide range of oils, waste oils and fats and greases, requiring no pretreatment other than filtering; the production of 100% drop-in fuels and very short resident times, which means a small footprint and low capital cost (ARA, 2016). Figure 14 shows the steps of the process.

Figure 14: Biofuel isoconversion process through catalytic hydrothermolysis

3.1.2.3 Hydrotreated depolymeryzed celullosic jet

The Hydrotreated depolymeryzed celullosic jet (HDCJ) is a process that involves fast pyrolysis of oils followed by an upgrade to produce a mixture of liquid fuels compatible with conventional fuel infrastructure and engine technologies. Depending on the process used, the products may be classified as SPK. However, given the high aromatic content, the fuel is limited by ASTM jet fuel specifications.

The fast pyrolysis is performed under moderate temperatures (~500°C) and short residence times in the reactor to maximize the oil yield. The process involves rapid decomposition of biomass under specific thermal conditions in the absence of oxygen (ELGOWAINY et al., 2012). As a result, biomass decomposes to generate mostly gases, vapors, and char. After cooling and condensation, a liquid with a heating value that is approximately half of that characterizing petroleum-derived oil, known as pyrolysis oil is formed (GUELL et al., 2012). The oil obtained is unstable due to high oxygen and water content and has high acidity. Thus, an upgrading step is needed. Pyrolysis oil is stabilized by oxygen and water removal and acidity reduction through hydrotreating process. It should be noted that the upgrading step can be performed in a dedicated plant or co-fed in oil refineries (ELGOWAINY et al., 2012; GUELL et al., 2012). Further, hydroprocessig (hydrocraking) is needed to produce fuels in the desired range. Additional hydrogen is also needed for the hydrocraking process and may come from an external source or internal source (ELGOWAINY et al., 2012). The co-feeding of pyrolysis oil in oil refineries for upgrading may be an feasible option for renewable jet fuel production to reduce costs, due to the significant amounts of hydrogen , an expensive input, that would be required (GUELL et al., 2012). Finally, the liquid products follows to separation step. Figure 15 shows the main steps related to HDCJ production.

Figure 15: Main steps in the HDCJ process.
Based on (ELGOWAINY et al., 2012; GUELL et al., 2012)

Feedstock for the fast pyrolysis process are lignocelullosic biomass as sugarcane bagasse, corn stover, agricultural and forest residues. The process does not requires any biomass pretreatment (WANG; TAO, 2015).

The pyrolysis and subsequent upgrading processes can be self-sufficient with regard to heat and electricity requirements. The pyrolysis produces other combustible co-products, such as fuel gas, which is a mixture of carbon monoxide and methane and bio-char that can be used in a combined heat and power unit. These co-products may satisfy the heat and power requirements of biomass drying and grinding steps and bio-oil upgrading processes (ELGOWAINY et al., 2012).

Several companies are working on the development of the pyrolysis technology, which is at the pilot and/or commercial scale (GUELL et al., 2012; IRIBARREN; PETERS; DUFOUR, 2012). UOP and Ensyn launched a joint venture named Envergent Technologies, which offers a practical and commercially proven path to renewable energy. The process is called RTPTM Technology (ENVERGENTTECH, 2016). Dynamotive, announced in 2009, the production of renewable diesel and gasoline through a secondary upgrading step of pyrolysis oil, and that early testing of bench scale products indicates a fraction of around 30% of jet fuel in the products (GUELL et al., 2012).

3.1.3 Gas to jet

Gas can be coverted to biojet fuels through two pathways: Fischer-Tropsch synthesis, known as FT-BTL (Fischer-Tropsch Biomass-to-liquids) and gas fermentation.

3.1.3.1 FT-BTL

The process known as FT-BTL produces fuels through biomass gasification followed by Fischer-Tropsch synthesis. The aviation biofuel produced, named FT-SPK (Fischer-Tropsch Synthetic Paraffinic Kerosene) was approved for certification by ASTM in 2009 for blend up to 50% due to its paraffin content (GUELL et al., 2012).

The process begins with biomass pre-treatment, which aims to elevate its density by reducing particle size and humidity. It is suitable to facilitate feedstock logistics and to ensure a reliable and continuous feeding, due to the heterogeneous nature of biomass. Torrefaction and pyrolysis processes are the main technologies used for biomass pre-treatment. Torrefaction converts biomass into a solid higher quality fuel through its submission to moderate conditions (200-300°C) in an inert atmosphere for short residence times. This process allows the destruction of biomass fibrous structure and increases its energy content. The fast pyrolysis thermally decomposes biomass in the absence of oxygen, moderate temperatures (~500°C) and very short residence times. The liquid produced has high energy density, known as pyrolysis oil. Other products include coal and fuel gases, that can be used for heating purposes (GUELL et al., 2012). The pre-treated biomass follows to the gasification step that occurs under high pressure and temperature with a controlled volume of oxygen. It produces the syngas, formed by a mixture of carbon monoxide (CO) and hydrogen (H2). Up until now, many types of gasifiers have been developed. Fluidized bed and entrained flow gasifiers are considered the most suitable technologies for biofuel production, however, another technologies as plasma gasification and hydrothermal gasification are gaining interest (GUELL et al., 2012).

The syngas should be conditioned to remove CO_2 and impurities (MAWHOOD et al., 2014). After conditioning and the adjustment of H_2:CO ratio, the gas follows to Fischer-Tropsch process that produces liquid hydrocarbons through a series of catalytic reactions (WANG; TAO, 2015). In the process, the syngas reacts in the presence of a metal catalyst (commonly iron, cobalt or nickel) (MAWHOOD et al., 2014). The resulting products are a mixture of saturated hydrocarbons, totally free of sulfur, nickel, nitrogen, vanadium, asphaltenes and aromatics, typically found in mineral oils (TIJMENSEN et al., 2002). Conventional refinery processes such as hydrocraking, hydroisomerization and fractioning can be applied to adjust products in high quality fuels, with low sulfur and aromatics content (WANG; TAO, 2015). As described in the HEFA route, the hydrocracking/isomerization process is used to produce hydrocarbons with shorter chains that, after submitted to a separation step, produce jet fuels, diesel and lubricants. Figure 16 shows the main steps in the FT-SPK production.

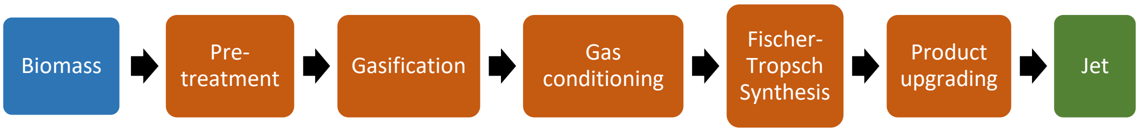

Figure 16: Main steps in the FT-SPK process.
Based on (GUELL et al., 2012)

Feedstock for FT-BTL pathway include lignocellulosic biomass such as woody energy crops, agricultural, agro-industrial and forestry residues, and waste. However, the feedstock characteristics affects the quality of syngas produced, the efficiency and the type of gasifier used. A significant amount of the forest products have a well-established market so the production of fuels should come from low value materials such as forest residues, that do not have any market presently (GUELL et al., 2012). For the same reason agricultural residues should also receive attention.

The main co-products obtained in the FT-SPK process are diesel and naphtha. As mentioned before, naphtha can be submitted to a catalytic reforming process to produce aromatics and hydrogen, forming a 100% biojet fuel blend and supplying feedstock to hydrotreating processes. In addition, gasification and FT synthesis produce heat, electricity and chemicals such as hydrogen and methanol. Potential chemical include naphtha, paraffins and lubricants. The co-products may increase the overall process efficiency. The system configurations determine the co-products obtained influencing the production costs of FT-SPK (GUELL et al., 2012).

The FT synthesis is currently applied at a commercial sale for the production of fuel from fossil resources, like coal and natural gas. Companies such as Sasol, Shell and Total are involved in FT fuels projects. As regards to FT-BTL, the projects are already in pilot or demonstration scale. NSE Biofuels, Enerkem, Rentech, Solena and Bioliq are companies involved in the production of FT-BTL fuels (GUELL et al., 2012). Table 7 summarizes the strengths and challenges regarding FT-SPK pathway.

Table 7: Strengths and challenges for FT-SPK pathway.

Strengths	**Challenges**

Wide range of products can be produced	Biomass gasification requires optimization
Feedstock flexibility	High capital costs
High carbon conversions	Catalysts deactivations due to impurities
Low operation costs	

3.1.3.2 Gas fermentation

Another alternative for producing renewable fuels for aviation is the fermentation of syngas to produce liquid biofuels. The biomass derived syngas can be obtained from lignocellulosic feedstock as described for FT-BTL route. After cooled, the syngas can be fermented by acetogenic bacterias, producing a mixture of alcohols such as ethanol and butanol. These alcohols are converted to jet fuel through the processes described in ATJ route, which includes steps of dehydration, oligomerization, distillation and hydrogenation (WANG; TAO, 2015). Figure 17 shows the steps involved in gas fermentation pathway to produce biojet fuel.

An interesting point of this pathway is that it can convert municipal and industrial organic waste, besides energy crops and typical agricultural residues. Also, this pathway is capable of producing more products than the conventional biochemical or thermodinamical pathways. The process requires lower temperature and pressure and less expensive enzymes (WANG; TAO, 2015).

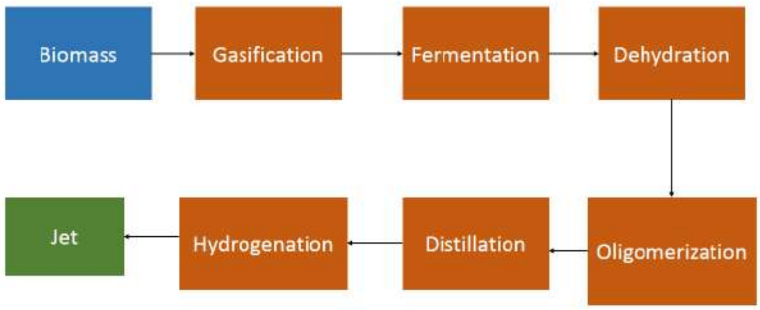

Figure 17: Main steps in gas fermentation route to produce biojet. Based on (WANG; TAO, 2015).

3.1.4 Sugar to Jet

Liquid transportation fuels can be produced through biological or catalytic conversion of sugars. The Sugar to Jet (STJ) pathway is divided into catalytic upgrading of sugars to hydrocarbons also known as aqueous phase reforming (APR) and direct sugar to hydrocarbons (DSH), which is the fermentation route known as fermentation to jet (FTJ).

3.1.4.1 Catalytic Upgrading of Sugars

In the catalytic process the lignocellulosic biomass should be firstly pretreated and hydrolysed to the extraction of carbohydrate fractions which are subsequently dissolved in water (MAWHOOD et al., 2014). The process requires certain purification levels and sugar concentration to convert the sugars into hydrocarbons through the aqueous phase reform (WANG; TAO, 2015). Thence, the second step aims to reduce the oxygen content of the solution and involves reaction like: reforming to produce hydrogen, dehydrogenation of alcohol and hydrogenation of carbonyls, deoxygenation, hydrogenolysis and cyclisation (MAWHOOD et al., 2014). The APR products include hydrogen, carbon dioxide, alcohols, ketones, aldehydes, alkanes, organic acids and furans (BLOMMEL; CORTRIGHT, 2008; WANG; TAO, 2015). The hydrogen produced can support the following hydrotreating process before APR and the hydro-refining processes after APR. The lighter alkanes (C1-C4) can be sent to a combustor producing heat for the process (HELD, 2009; WANG; TAO, 2015).

Three alternative secondary steps have been identified to convert the APR products into jet fuel range hydrocarbons. The first route is acid condensation, which is responsible to convert the oxygenates into alkanes, isoalkanes and aromatics with a zeolite ZSM-5 catalyst. It is performed through the dehydration of oxygenates to alkenes, oligomerization of alkenes to heavier alkenes, cracking, cyclization and dehydration of heavier alkenes to aromatics, alkene isomerization, and hydrogen-transfer to form alkanes. The heavier species can be distilled and blended into jet fuels (BLOMMEL; CORTRIGHT, 2008; DE KLERK; NEL; SCHWARZER, 2007; GOGUEN et al., 1998; WANG; TAO, 2015). The second route is the direct catalytic condensation over multi-functional solid base catalysts, whose products are mostly in jet fuel range (KING;

KELLY; STITT, 2003; WANG; TAO, 2015). Finally, the third route converts the APR oxygenates to alkanes and alkenes through dehydration and hydrogenation-dehydration reactions. The alkenes follow to oligomerization to produce jet fuel (GÜRBÜZ; DUMESIC, 2013; GÜRBÜZ; KUNKES; DUMESIC, 2010; WANG; TAO, 2015).

Virent's Bioforming platform is a process that converts sugars into hydrocarbons. The Bioforming technology combines Virent's proprietary APR technology with catalytic steps similar to petroleum refining. The four main steps of Virent's technologies are: pretreatment or fractionation, hydrogenation, aqueous phase reforming done under moderate temperatures and pressures and acid catalyzed dehydrations/condensations (NABC, 2011). Figure 18 shows the schematic catalytic upgrading of sugars to hydrocarbons, based on Virent's process.

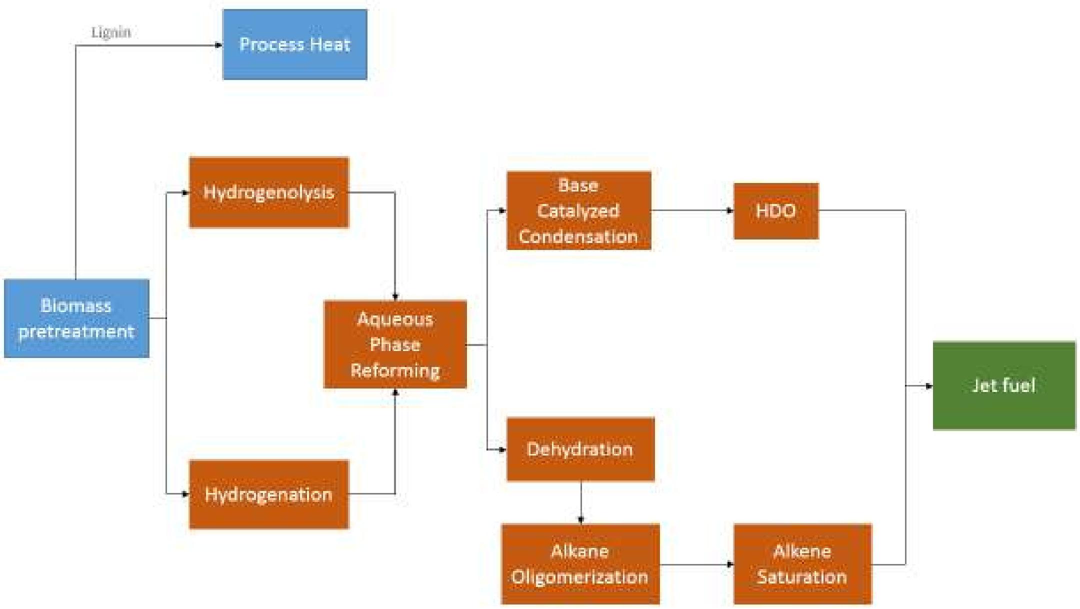

Figure 18: Main steps in catalytic upgrading of sugars to jet fuel. Adapted from (NABC, 2011)

Feedstock suitable for this process is soluble plant sugars, obtained from sugar, starch or lignocellulosic feedstocks like sugarcane, sugar beet, maize, corn stover, grasses, wood, among others (MAWHOOD et al., 2014; NOVELLI, 2011). As well as in the FT-SPK and HEFA-SPK, the fuel produced by APR route can not be directly used as jet fuel, due to its low aromatics content and so should be blended for use in aircraft (NOVELLI, 2011). However, the Bioforming process can produce also synthetic aromatic kerosene (SAK). In this way, a fully renewable aviation fuel can be produced by blending SPK and SAK products (VIRENT, 2016a).

The main co-products of this process are gasoline and diesel biofuels, obtained through fractionation of final products. Bio-derived chemicals as para-xylene for polyethylene-terephthalate-saturated polyester polymers are also produced. Further, processes that recover and recycle unreacted species can obtain more co-products, improving process economics. However, the separation processes can be technically challenging (WANG; TAO, 2015).

The catalytic upgrading of sugars to hydrocarbons are considered to be at the R&D and pilot stages of development and Virent is the unique organization that has reached and advanced stage of jet fuel development (MAWHOOD et al., 2015).

The process has the advantage of being energy efficient. It allows for efficient system heat integration along with reduced energy inputs as it produces hydrocarbon products that are naturally separated from water. The energy efficiency of the processes allows for reduction in carbon life cycle emissions with more biomass options and lower input costs (VIRENT, 2016b).

3.1.4.2 Direct Sugar to Hydrocarbons or Fermentation to Jet

The Direct Sugar to Hydrocarbons (DSHC) or fermentation to jet (FTJ) routes produce alkane-type fuels through aerobic fermentation. As in the catalytic upgrade described above, biomass feedstock undergoes pre-treatment and is submitted to an enzymatic hydrolysis, releasing sugars and removing solid materials (WANG; TAO, 2015). Unlike in the production of biochemical cellulosic ethanol, after enzymatic hydrolysis, the hydrolysate is clarified using a filter press in order to remove insoluble solids as lignin residues. Furthermore, differently from anaerobic processes like the ethanol fermentation, most hydrocarbon conversion pathways are aerobic. The residues removed from the process, which are rich in lignin, are potential source of fuels and co-products. After the solids removal, the stream may be sent to the biological conversion (NREL, 2013). The fermentation can be proceed in fed-batch or continuous reactors using genetically modified microorganism. The different process schemes requires different optimum sugar concentrations. The necessity to maintain aerobic condition via continuous aeration is one of the major challenges to the economic scale up of this process. Moreover, aeration is usually costly to implement due to high costs with air compressors and powerful motors (NREL, 2013). Finally, the resulting products are sent to a phase separation stage. Their conversion to jet fuel can be performed via hydroprocessing (WANG; TAO, 2015). Figure 19 shows a scheme of the main step of FTJ route.

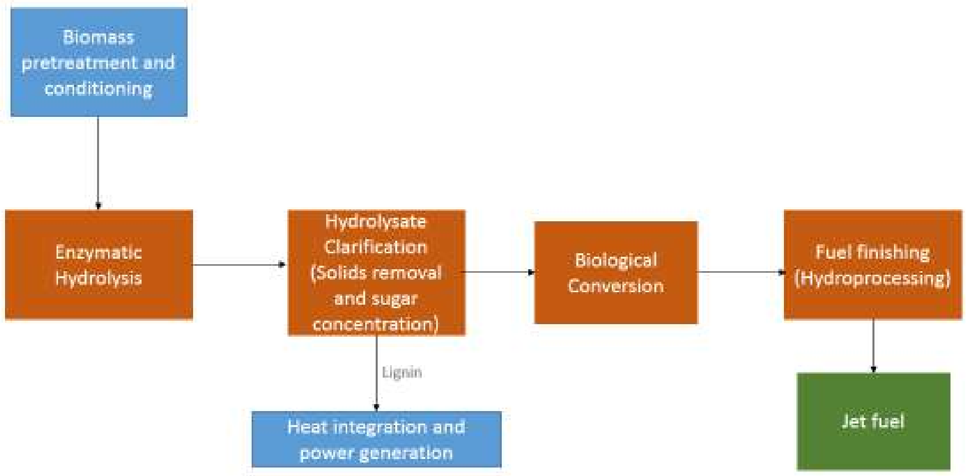

Figure 19: Main steps in the FTJ route.
Adapted from (NREL, 2013)

The feedstock suitable for this process are mainly lignocellulosic sugars. The processes was developed by Amyris and LS9. The development of FTJ route is being led by a joint venture between Amyris, an American biotechnology company, and Total, a French oil company. Their technology named Biofene produces the isoprenoid farnesene, used as the basis for petroleum replacement products. The first commercial plant is localized in Brotas, Brazil, and has been operational since 2012 (MAWHOOD et al., 2015). In 2012, Amyris successfully demonstrated the renewable fuel in a flight when an aircraft operated by Azul Airlines flew in Brazil (AMYRIS, 2016). In 2014, the Biofene jet fuel was certified for blends up to 10% with petroleum-derived jet (MAWHOOD et al., 2015).

The lignin-rich residues removed from the process may be a potential source of fuel and co-products. However, it is necessary the development of cost-effective technologies to convert this non-sugar components into value-added co-products or fuel precursors (NREL, 2013).

The FTJ pathway leverages prior experience in biochemical conversion technologies, as in the case of sugar production from cellulosic biomass. The utilization of genetically engineered microorganism has the advantages of producing fuel components with high yields and value, improving economic viability. However, conversion costs associated with the aerobic fermentation step are considered the main challenges to process scale up (NREL, 2013).

4. Methodology

This study applies a methodology to assess the potential for biojet production in Brazil by identifying the competitive opportunities for a growing market in the country. For this purpose, this analysis comprises distinct steps in order to assess the availability of feedstock, the techno-economic feasibility and the environmental impact of fuel production and use. Together these assessments are useful to identify areas with major potential to implement biojet production sites in the country.

4.1 Feedstock availability

This section exposes the methodology adopted to evaluate the available potential of primary bioenergy from agricultural, agroindustrial and forestry residues. The biomass potentials can be classified according to their theoretical, geographic, technical, economic and sustainable potentials. For example, the basis to estimate the theoretical biomass potential are the biophysical and agro-ecological factors that affect the biomass growth and extension and its residues production (ANGELIS-DIMAKIS et al., 2011). Even though this is the highest level of potential, it is limited by natural, climatic and environmental constrains, as agricultural residues are important to the biome regulation. The geographic potential is the theoretical potential limited by the availability of resources at geographical locations. The technical potential represents the fraction of the environmentally sustainable potential available under technological possibilities, logistics restrictions and competition for non-energy uses (PORTUGAL-PEREIRA et al., 2015). The economic potential represents the technical potential at cost levels considered competitive (ECOFYS, 2008). The sustainable potential, on the other side, is a deeper assessment that evaluates the amount of biomass available considering the socio-economic and ecological impacts of its use in energy projects (ANGELIS-DIMAKIS et al., 2011). Figure 20 exposes the characteristics of biomass potentials mentioned above. This study quantified the technical potential of biomass residues from sugarcane, rice, soybeans, wheat, maize, eucalyptus and pinus. Sugarcane and soybeans were chosen due to their current utilization for energetic purposes in the country. The another crops were chosen due to their relevant planted area, potential for expansion and high residue to product ratio.

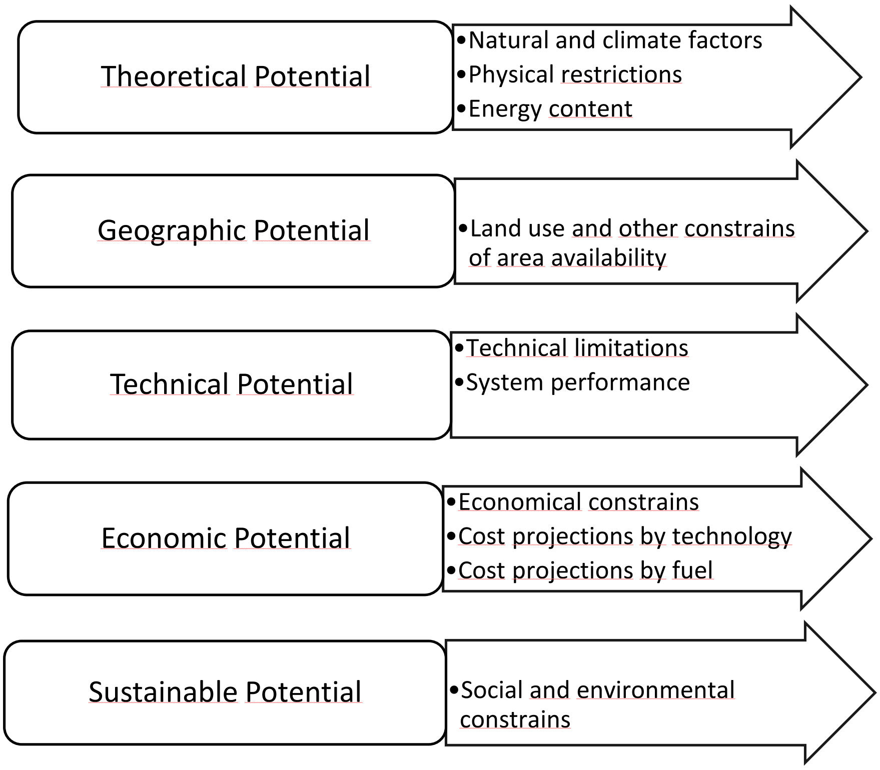

Figure 20: Different potential of biomass resources classifications
Adapted from PORTUGAL-PEREIRA ET AL. (2015) ECOFYS (2008)

The methodology adopted to estimate the residues production by agricultural and agro-industrial practices was based in the indirect quantification of the residues produced, since to this point, there is no information available for the residues produced in farming and harvest stages. Then, considering the technical constrains described above, this study follows a bottom-up analysis to determine the technical potential of bioenergy from agricultural and forestry residues as follows:

$$RP_j = \sum A_i . P_i . RPR_{j,i} . ESR_j . AR_j . LHV_j$$

Where:

RPj: residue potential

Ai: planted area of crop i (ha.year^{-1})

Pi: productivity of crop i (tonne.ha^{-1})

RPRj,i : residue of j to product i ratio

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

ARj: availability rate of residue j (%)

LHVj: low heating value of residue j ($MJ.kg^{-1}$)

Data of agricultural harvested area (A_i) and crop productivity (P_i) was obtained in the database of the Brazilian Institute of Geography and Statistics (IBGE), under the Municipal Agricultural Survey (PAM) for all Brazilian municipalities in 2014. It should be noted that the planted and harvested area have different concepts. Sometimes agricultural areas are planted but not harvested and so, the crop remains on the field. In this study, it is assumed that the entire planted area is harvested.

Table 8 presents the planted area and total production for the selected crops in the year of 2014. In 2015, sugarcane and soybeans were the most significant crops in terms of planted area and production, accounting together to about 56% of total agricultural area in the country (IBGE, 2016). Other crops as rice, maize and wheat correspond to smaller planted areas of approximately, 20,500 ha.

Table 8: Planted area and productivity of the crops selected

Crop	Planted area (ha/year)	Total product (t/year)
Sugarcane	10,438	737,156
Rice	2,341	12,176
Soybeans	30,274	86,761
Maize	15,342	79,878
Wheat	2,835	6,262

The residue-to-product ratio (RPR) varies considerably according to the biophysical characteristics of species and to the edaphoclimatic conditions of the agricultural fields (BHATTACHARYA et al., 2005). Evidences suggest that residue yields increase up to a certain level and then remain constant after that (BENTSEN; FELBY; THORSEN, 2014). Since there is no specific data regarding residues production by Brazilian crops, an average factor from data collected in literature and presented in Portugal-Pereira (2015) was adopted.

The environmental sustainable rate (ESR) represents the part of the residues that should remain in the agricultural fields in order to regulate the ecosystem by protecting the soil against erosion, retaining soil humidity and recycling the nutrients lost in the harvest process. This factor varies according to the crop analyzed and to the climate and soil conditions. As in the case of RPR, specific data of ESR is not available for Brazilian conditions. Thus, as proposed in Portugal-Pereira et al. (2015), the conservative value of 30% for removal rate was considered.

Further, the available rate of residue (AR) represents the competition with other non-energy uses and logistic constrains. In other words, it represents the availability of residues for energy purposes. For the rice, soybeans, maize and wheat crops, it was assumed full availability of residues, as they are mostly left in the fields with no utilization.

However, regarding sugarcane, a coefficient that express the fraction of its residues that are not headed for burning and are available for energy use was adopted. Traditionally, before the harvest, sugarcane straw is burned to clean the fields and facilitate the harvesting operations. As this practice is responsible for local pollutants and GHG emissions, the Brazilian government determined the gradual reduction of the burning practice by 2021. However, the deadline for burning reductions depends of the land declivity. Areas with higher declivity have longer deadline periods. In this context, based on Portugal-Pereira et al. (2015), this study assumed that 65% of sugarcane straw is available for energetic uses, taking into account the rate of farmland that is harvest mechanically with no open air burning.

For sugarcane bagasse, an availability factor was also attributed, since part of this residue is used to generate process heat and electricity. Nowadays, approximately 70% of sugarcane plants use the bagasse only for heat and power generation for own consumption. In these cases, only 8-10% of bagasse is available for energetic use (DIAS et al., 2012; MACEDO; SEABRA; SILVA, 2008; SANTOS, 2013). This study considered an availability factor of 10% for sugarcane bagasse. Regarding rice husk, it was assumed an availability of 30% as part of this residue is used for energy generation in the mills (DIAS et al., 2012).

The low heating value (LHV) of the residues was obtained in literature and an average value was adopted as proposed in Portugal-Pereira (2015). Table 9 shows the data of RPR, AR and LHV used for each crop residue.

Table 9: Characteristics of evaluated residues

Residue	**RPR**	**AR (%)**	**LHV (MJ/kg)**
Sugarcane straw	0.22	65%	18.62
Sugarcane bagasse	0.22	10%	19.81
Rice straw	1.54	100%	17.22
Rice husk	0.26	30%	17.08
Soybeans straw	2.01	100%	20.09
Corn stover	1.53	100%	18.67
Wheat straw	1.55	100%	19.54

Activities in the forest industry are divided in silviculture (or forestry) and extraction of native forests. Forestry activities include the development and reproduction of forests to produce timber and other products, and to promote environmental protection (IPEA, 2012). On the other side, the forest extraction involves the tree cutting in native forests for its management.

Wood residues come not only from cutting and peeling activities, but also from the subsequent steps for manufacturing wood products. Forestry products are currently used as energy sources, firewood for charcoal and steel industries, and as feedstock for furniture, paper and pulp, black liquor and building industries, among others. This study considers the residues produced up until the production of basic product, like charcoal, wood chips, sawn wood or wood sheets through processes known as mechanical or primary processes. Figure 21 shows the production chain of forestry and wood sector.

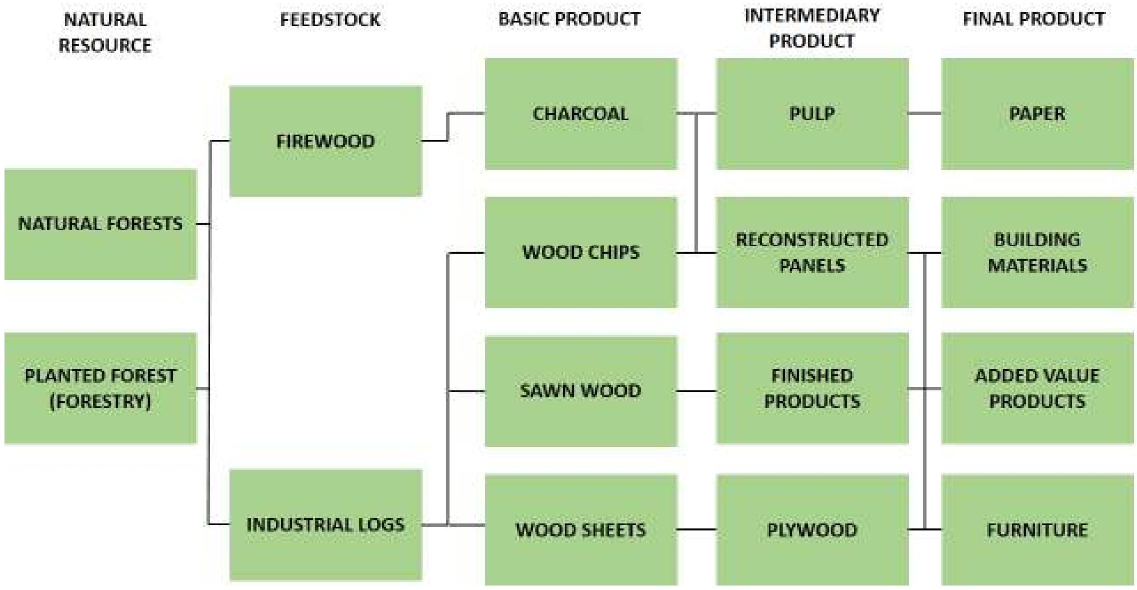

Figure 21: Production chain of forestry and wood sector.
Source: STCP (2011)

Residues from forest harvesting are timber and other forest products that remain with no defined used due to technological or market limitations (IPEA, 2012). Usually, residues are defined as all the organic material, excepting stem, including wood chips, branches, leaves, stump, roots and bark (SFB, 2011). The utilization of logs and roots is not usual due to the difficult exploration and possibility of soil damages. Residues from harvesting activities in forests are twigs and branches, superior and broken parts of the trees and stumps that have not reached a minimum height for commercialization. The amount of forest residues ranges from 10% to 20% in planted forests and from 60% to 70% in the natural forests (CANTO, 2009). However, leaving a fraction of organic material in the fields is required to maintain soil quality and increase fertility. As most part of nutrients are concentrated in the leaves, leaving only them in the fields may be advantageous. Another possibility to replace the nutrients that are removed with the residues harvesting is the application of chemical fertilizers or ashes from the cultivation (CANTO, 2009). In this way, this study considered a lower limit for the residues availability, indicating that half part of residues should remain in the fields, and an upper limit, indicating that all residues are exploited. Thus, the range of residues available in the forestry sector varies from 5% to 10% and from 30% to 70% in the extractive industry.

The wood residues from the primary processes of forest sector may be classified in sawdust, shavings and firewood or wood chips (IPEA, 2012). The primary process is the initial transformation of wood logs producing residues, whose characteristics vary according to the log diameter, size and its final use, for example. The STCP (2011) study shows that in the mechanical processing of wood there is an initial loss of 45% to planted forests and of 18% to natural forests. These losses are included in the estimates of residue production (STCP, 2011).

For the residues quantification, a methodology used in a study from IPEA for assessing residues availability was adopted (IPEA, 2012). Data of forestry production and extraction in 2014 from IBGE was used (IBGE, 2014). The production data from IBGE refers to charcoal, firewood and sawlog. To the residue quantification, it was considered all log production and it was assumed that for firewood production, the whole tree is harnessed (IPEA, 2012).

It is noteworthy that this study has not considered current data of wood residues. Wood chips and sawdust can be used in cables and packages production if they are not sent to energy uses. Wood shavings have been used in intensive chicken farming in Brazil. Thus, great part of the residues produced are being used and have a market price. On the other hand, studies show that a huge amount is sent to composting and may cause negative environmental impacts (IPEA, 2012).

The methodology described above enabled the quantification of the bioenergy technical potential of each municipality in Brazilian territory. Moreover, the spatial localization and concentration of this bioenergy is important to enable its recovery and utilization. In this way, a GIS analysis was applied in order to identify geographical areas with great biomass potential and analyze their proximity to strategic locations of feedstock handling, jet fuel production and consumption. To this end, after the technical potential was calculated for each municipality, it was allocated to the shape files with municipalities divisions obtained from IBGE. Thus, it was possible to identify for each crop and municipality its bioenergy potential, in TJ/year. It was assumed a uniform energy density for each municipality, being this a limitation of this study. Figure 22 shows the total bioenergy potential for Brazilian municipalities. The total biomass potential estimated in Brazil is 3,931,807 TJ/year. Regions with major potential are South and Southeast, accounting for 1,288,131 and 1,095,003 TJ/year, respectively. Crops with major potential in the country are soybeans and sugarcane, totalizing 1,050,091 and 1,033,683 TJ/year, respectively.

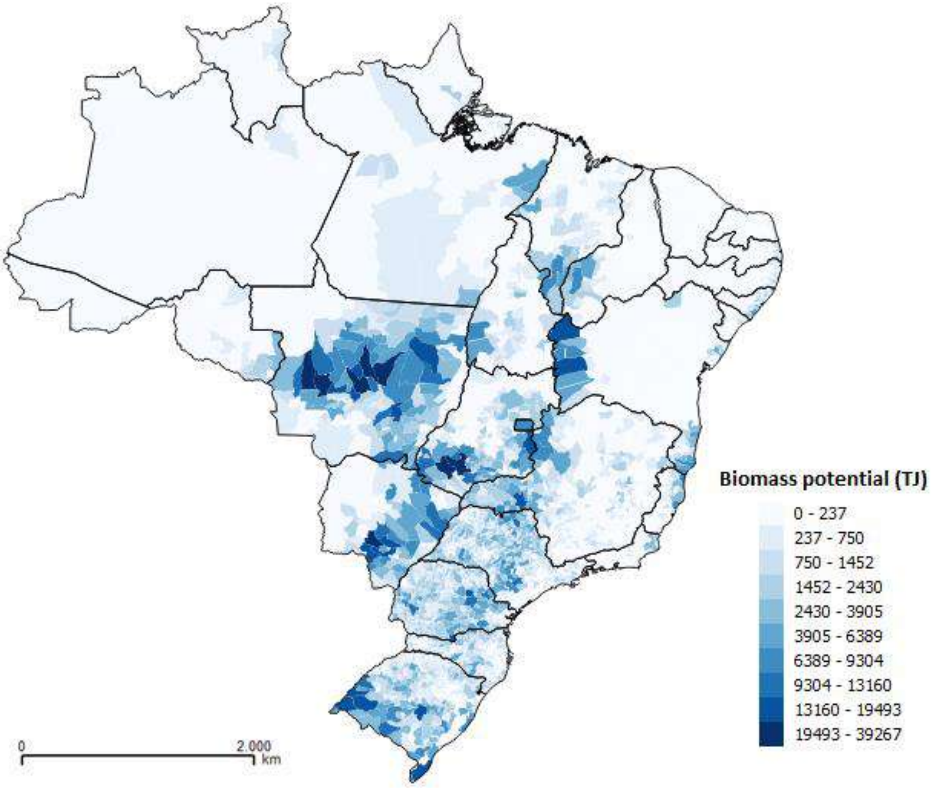

Figure 22: Bioenergy potential from selected biomass residues in Brazilian territory

The next step was the construction of kernel maps from the shape files containing the bionergy potentials. In geoprocessing technologies, the kernel map represents a statistical method to estimate density curves. In this method, each one of the potentials is weighted by a distance to a central point. In other words, Kernel map is a tool for geographic analysis of behavior patterns. Through interpolation methods, these maps show the punctual intensity of potentials in all regions analyzed. To construct the maps, files in raster format were generated from the shape files by defining the municipalities' centroids as the central points and a distance of 100 kilometers. This value represents an optimistic estimate for biomass transportation, representing twice the distance recommended by Hoffmann et al. as an economically feasible radius to transport biomass for energy purposes. Constructing kernel maps is a useful way to assess the residues potential without limiting them to defined areas, such as municipalities.

Next, important locations for fuel production, distribution and utilization, such as refineries that produce jet fuel, terrestrial and waterways terminals of fuel handling and main airports of the country were mapped (Figure 23) in order to help determining suitable areas for biojet fuel production. Also, biodiesel and etanol plants and soybean oil refineries were mapped (Figure 24) to identify areas with existing infrastructure for feedstock and fuel logistics.

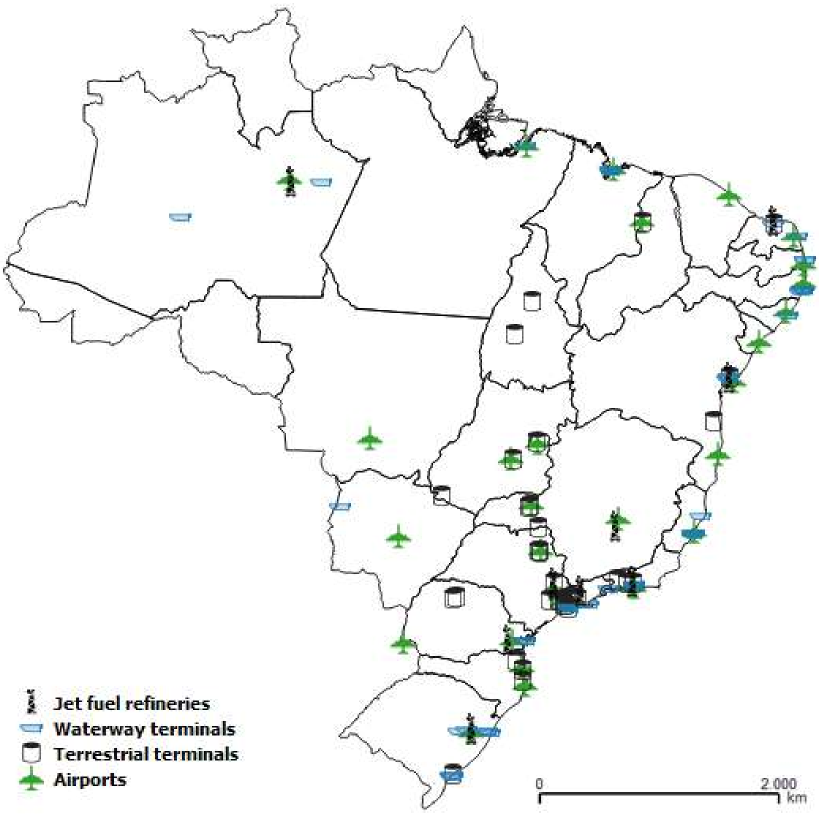

Figure 23: Jet fuel refineries, distribution terminals and main airports in Brazil

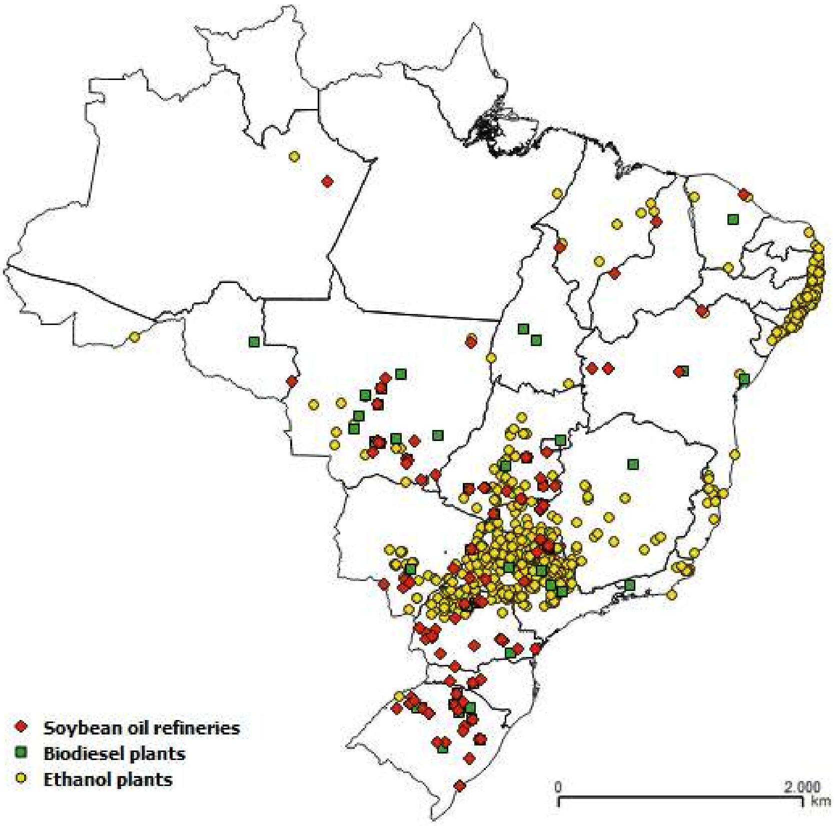

Figure 24: Biodiesel and ethanol plants and soybean oil refineries in Brazil

4.2 Life cycle assessment

The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model (Version 1 2015) was used to assess life cycle fossil fuel consumption and GHG emissions from diverse biojet fuel production pathways. This analysis includes all steps in a products life, from the raw material extraction to further processing, manufacture, distribution, use and storage or recycle. The fuel life cycle, also named well-to-wake (WTW) represents a combination of the well-to-pump (WTP) and pump-to-wake (PTW) stages. The WTP stage comprises the exploration and recovery activities from the well to fuel production and the subsequent transportation to the pump. On the other hand, the combustion of fuel during aircraft operation constitutes the PTW stage. Figure 25 and Figure 26 shows the WTW cycles for conventional jet fuel and biojet fuel production, respectively. The GREET model is a useful tool to evaluate the production chain of advanced fuels and has the advantages of providing results in well-to-pump (WTP) and pump-to-wake (PTW) phases, including local pollutants and water consumption data, being adjustable by the user and free access. The HEFA and FT-BTL routes were selected and the life cycle results for each one were compared with the conventional jet fuel.

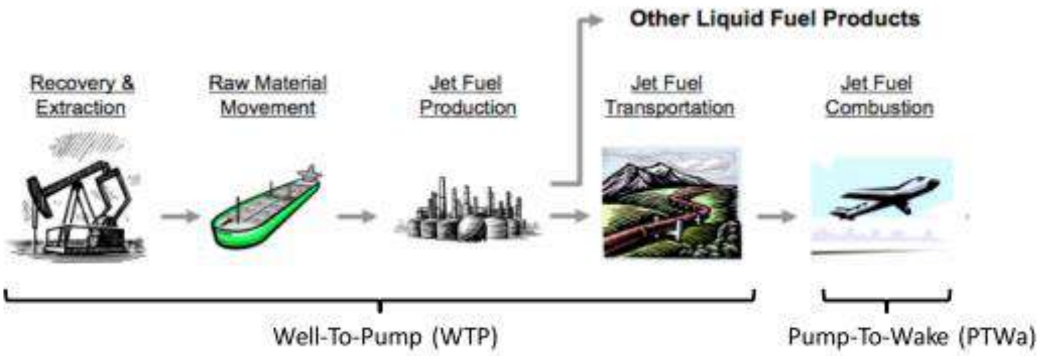

Figure 25: WTW cycle for conventional jet fuel production
Source: Elgowainy et al. (2012)

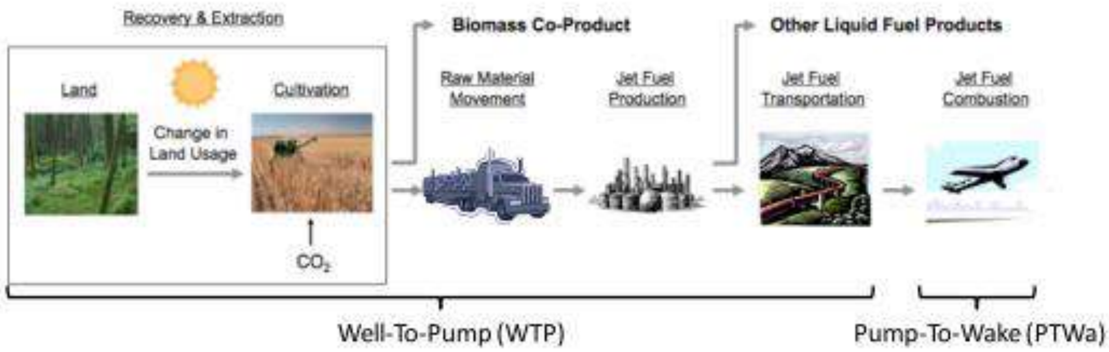

Figure 26: WTW cycle for biojet fuel production
Source: Elgowainy et al. (2012)

Tailored assumptions according to Brazilian conditions were inputted in GREET. Inputted parameters include application of fertilizers, pesticides, herbicides and energy consumption in the agricultural stages and land use change emissions (LUC). For HEFA route, data regarding the soybean farming in Brazil and LUC emissions in Brazilian savannah were considered. As for FT-BTL route the feedstock considered is a residual biomass, no farming energy and fertilizer use were considered. Other inputs include the electricity generation matrix in the country and the fuel yield per feedstock input. It is noteworthy that although Brazilian diesel contains 7% of biodiesel, this study considered the utilization of 100% diesel in the analysis.

Functional units adopted for LCA results were MJ for GHG emissions and fossil fuel consumption. The model allows the user to choose an aircraft type to display the results. The Large Twin Aisle (LTA), a type of passenger aircraft like Boeing 747 and Airbus A380 was selected. Although these aircrafts are not representative of the Brazilian aviation fleet, in future advanced aircrafts with innovative engines are more likely to be used for biojet blendings. The energy allocation method was chosen for all pathways modelled in this analysis, as this LCA is about an energy product. Activities regarding biojet fuel distribution were not considered in this analysis. Results include data of energy consumption and GHG emissions for the biofuel and conventional fuel WTW cycles. The model also gives the results for each fuel production stages mentioned above, WTP and PTW. The results obtained are compared to biojets studied in literature and biodiesel from Brazil and EU.

The petroleum derived jet fuel life cycle begins in the activities of oil recovery in oil fields, follows to the refining process and ends in the fuel consumption by aircraft. Activities related to fuel transportation and infrastructure are not included in the model. The oil recovery activity has as a co-product an associated gas consisted mainly of methane (CH_4), one of the main GHG which has a global warming potential (GWP_{100}) 25 times higher than the CO_2, considering a period of 100 years (FORSTER et al., 2007). The associated gas is burned and vented in the oil recovery process. This study considered these emissions in the fuel life cycle, even though the burning practice is limited in Brazil, corresponding to approximately only 3.9% of the gas production (ANP, 2016a).

For the HEFA biojet fuel, the life cycle begins in the soybeans production in the agricultural fields, as the feedstock chosen in this study for this route is the soybean oil. Soybean production in Brazil highly depends of land availability, fertilizer and pesticides use, fuel for transportation, machinery and electricity (PRUDÊNCIO et al., 2010). The agricultural activities include cultivation, farming, fertilizer (N, P_2O_5, K_2O), $CaCO_3$ for soil acidity reduction, herbicides and pesticides application, diesel consumption and electricity. The nitrogenous fertilizers contribute to GHG emissions due to the N_2O emissions from nitrogen mineralization in the soil (LOKESH et al., 2015). The intense mechanization requires high diesel consumption in the soybean agricultural stages. In this study, data from fertilizer, pesticides, herbicides and energy for soybean oil extraction were obtained by an average value in the studies of literature (CAPAZ, 2009; CAVALETT; ORTEGA, 2010; ROCHA et al., 2014). Data regarding diesel consumption and electricity were obtained in the agricultural census (IBGE, 2006).

The LUC due to biomass production is a critical point in life cycle assessments. This work considered only direct land use changes that occur within the agricultural boundaries of the system as, for example, the replacement of the natural soil cover for energy crops. If these crops induce to an initial carbon loss as a result of the soil cover replacement, a carbon debt is created (BAILIS; BAKA, 2010). In this work, only the direct land use changes in Brazilian savannah were considered. The associated GHGs emissions were calculated from the emission factors from IPCC (IPCC, 2006) for savannah substitution to soybean cultivation under conventional tillage. Also, according to Prudêncio et al. (2010), there is a factor of 3.4% of soil transformation for soybean production in Brazilian savannah (PRUDÊNCIO et al., 2010). It represents an extrapolated factor that indicates the portion of land transformation from savannah to soybean production. The uncertainties associated to this factor may affect the LCA results, once these values may be higher for marginal areas of soybean expansion. Table 10 contains the inputs given for soybean agricultural stage in GREET.

Table 10: Input data for agricultural stage of soybean production used in GREET

Soybeans			
			Source
Productivity	3	t/ha	(CONAB, 2016)
Fertilizers			
Nitrogenous	0.32	g/kg soybean	(CAPAZ, 2009; CAVALETT; ORTEGA, 2010; ROCHA et al., 2014)
P2O5	12	g/kg soybean	
K2O	23.10	g/kg soybean	
CaCO3	138	g/kg soybean	
Farming energy	2.08	MJ/kg soybean	(IBGE, 2006)
Oil extraction energy	0.86	MJ/kg soybean	(CAPAZ, 2009; CAVALETT; ORTEGA, 2010; ROCHA et al., 2014)
LUC emissions	2568.40[6]	g CO_2e/kg soybean	(IPCC, 2011), (PRUDÊNCIO et al., 2010)

The following step in HEFA fuel production is the hydroprocessing of soybean oil. This technology is already well developed and commercially available. Emission in this stage is related to the hydrogen production, used in the hydrotreatment and hydrocracking processes. The GREET model is based on the UOP process for hydrodeoxigenation of renewable oils (Figure 27). Figure 28 shows the life cycle stages for HEFA jet fuel production from soybeans.

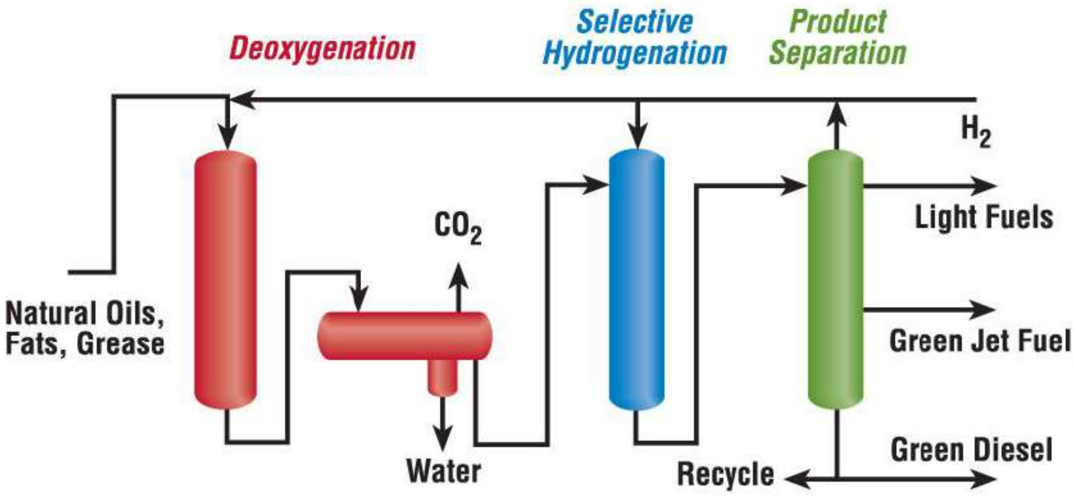

Figure 27: UOP jet fuel production process from natural oils and fats
Source: Honeywell (2015)

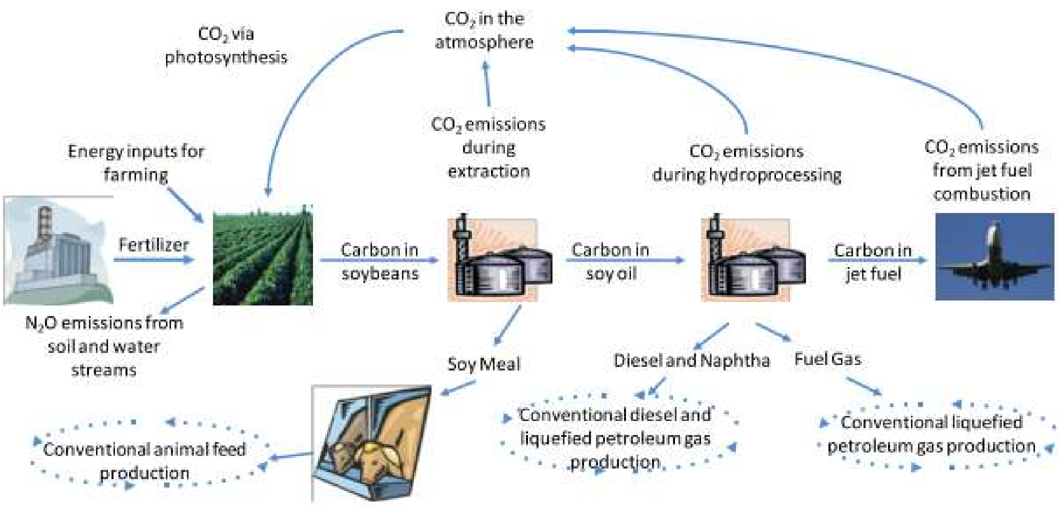

Figure 28: Life cycle stages of HEFA jet fuel production from soybeans
Source: Elgowainy et al. (2012)

The FT-BTL biojet life cycle begins in the agricultural phase of biomass. Once this study considered residual biomass as feedstock for the FT-BTL pathway, no energy use and emissions associated with farming and collection of biomass were considered.

The following step is the conversion of biomass in jet fuel through the Fischer-Tropsch synthesis. In this process, biomass is fed into a gasifier to produce syngas. The CO_2 in syngas may be vented or captured and sequestered. In addition, unconverted syngas can be recycled for further FT synthesis or exported for electricity generation (ELGOWAINY et al., 2012). This study did not consider CO_2 capture or export. Finally, to produce jet fuel, additional hydrocracking and a higher rate of syngas recycling are needed, increasing hydrogen and power requirements for the plant. As in the HEFA biojet case, hydrogen production may be responsible for increasing emissions in the fuel production. Figure 29 shows the life cycle stages of FT-BTL jet fuel production.

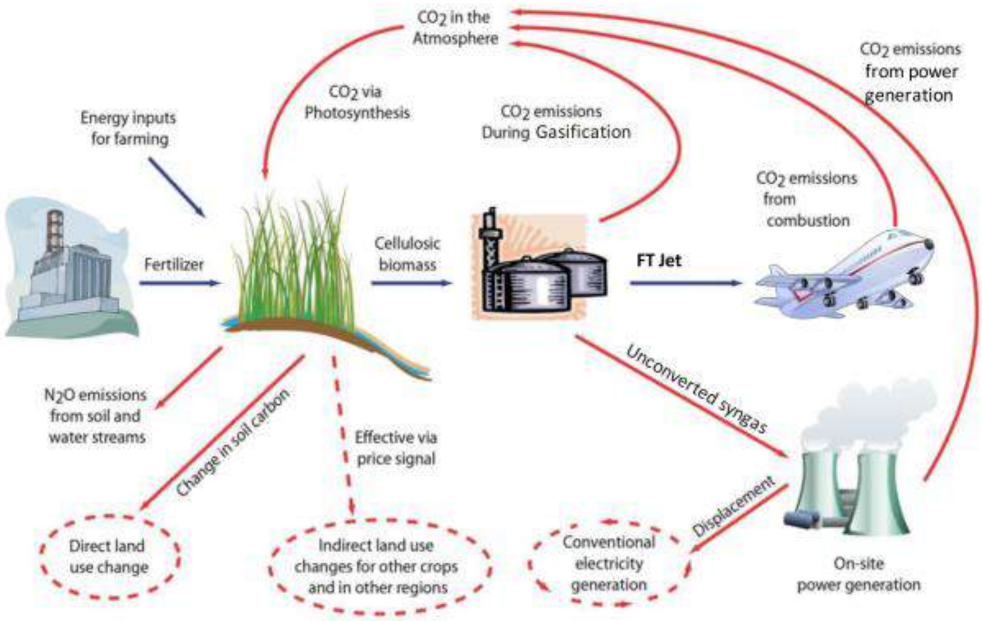

Figure 29: Life cycle stages for FT-BTL jet fuel production from biomass
Source: (ELGOWAINY et al., 2012)

The GHG emissions during operation are associated with fuel combustion in aircraft. Major emissions are CO_2 and water vapor, as well as methane (CH_4) and N_2O, contributing with global climate changes. Water vapor was not accounted in the GHG emissions in GREET. Emissions were normalized to a CO_2 equivalent basis using the global warming potential metric considering a time horizon of 100 years (GWP_{100}). The GWP_{100} values used are 25 and 298 for methane and N_2O, respectively. The utilization of GWP has been debated in literature (FUGLESTVEDT et al., 2010; O'NEILL, 2000; ROTMANS; DEN ELZEN, 1992; SMITH; WIGLEY, 2000) mainly because GWP is simply a direct indicator of climate change under a restrictive set of assumptions

(DORBIAN; WOLFE; WAITZ, 2011). Also, according to FUGLESTVEDT ET AL. , GWPs are reliable for calculations of long-lived gases, but problems and uncertainties increase for short-lived components. Other emissions influencing both local air quality and climate change are nitrous oxides (NO_x), sulfur oxides (SO_x), particulate material with 10 micrometers or less (PM_{10}). The volatile organic compounds (VOC) and carbon monoxide (CO) impact air quality (ELGOWAINY et al., 2012). Even though these pollutants have significant and detrimental effects in regional air quality and climate, they are beyond the scope of this study.

4.3 Techno-economic feasibility of biojet production routes

This section presents the description of capital and operational costs estimates for implementing production units of biojet in Brazil. Given the technological maturity and approval by ASTM specifications, two pathways for biojet production, described in Chapter 3, were selected: the Fischer-Tropsch Biomass-to-liquids (FT-BTL) and Hydroprocessed Esters and Fatty Acids (HEFA). In the case of HEFA route, the existence of a well-established industry of biodiesel production, which uses the same feedstock, also contributed to its selection.

For each pathway, different plant capacities were considered in the cost estimates. For HEFA route three plant capacities were evaluated: 2000 (A), 4000 (B) and 6000 (C) barrels per day[7] (PEARLSON, 2011). For FT-BTL pathway four plant sizes were considered: 800 (A), 1,000 (B), 2,500 (C) and 10,000 (D) barrels per day (ELIA et al., 2013). Parameters used in the levelized costs estimates are shown in Table 11.

Table 11: Parameters considered in HEFA and FT-BTL cost estimates.

Parameters	**HEFA**			**FT-BTL**			
Operating hours (hours/year)[a]	8,000			8,000			
Installed processing	(A) 348,531	(B) 697,061	(C) 1,045,592	(A) 127,190	(B) 158,987	(C) 397,468	(D) 1,589,873

[7] The plant capacity refers to the total amount of fuel produced.

capacity (L/day)[b]	

[a] Feedstock (soybean oil) has a storage period of 13 days (PEARLSON, 2011).

[b] Liters of biojet per day.

4.3.1 HEFA methodological description

This sub-section describes the procedures and assumptions made to estimate the capital and operational costs associated with HEFA biojet production, based on the study conducted by Pearlson (2011). Monetary values were adjusted to 2014 year according to GDP deflators given by the U.S. Department of Commerce (BEA, 2016).

As mentioned above, in the case of HEFA pathway, three different plant sizes were evaluated. The processing unities considered for each plant are:

- Feedstock reception and pre-treatment: Storage of vegetable oils. It is assumed that refined, deodorized and bleached oils are purchased from suppliers.
- Hydrodeoxigenation: Hydrotreating is responsible for oxygen removal, double bonds saturation and propane backbone of triglycerides cleavage by reaction with hydrogen in the presence of a catalyst.
- Selective isomerization and catalytic cracking: Reduction of freezing point, obtaining products in the desired range.
- Heat integration for steam generation and cooling water: Heat removal during the exothermic processes like hydrotreating and isomerization.
- Gas cleanup and recycle: Separation of liquid and gaseous products and separation and recycle of oxygen to deoxygenation process.
- Hydrogen production: A hydrogen plant is necessary to guarantee the amount required. Steam reforming of methane was considered in this analysis[8].
- Product separation through atmospheric distillation
- Products storage and blending

[8] As mentioned in HEFA route description (Chapter 3.1), the reforming of naphtha is an alternative to produce aromatics and hydrogen (catalytic reforming) or only hydrogen (steam reforming).

Feedstock chosen was soybean oil and, once the units receive the refined oil, the agricultural steps of its production and refining are not included. Table 12 presents a summary of the energetic consumption and yields for HEFA pathway operations.

Table 12: Inputs and products profile for HEFA pathway. Based in (PEARLSON, 2011)

Inputs	
Soybean oil (t)	2.02
Hydrogen (t)	0.08
Natural gas (GJ)	45.04
Electricity (MWh)	0.71
Products	
Biojet (t)	1
Propane (t)	0.09
GLP (t)	0.12
Naphtha (t)	0.14
Diesel (t)	0.47

Table 13 below contains the most relevant parameters to the economic evaluation of biojet production. It was considered a construction time of 3 years[9] and lifetime of 20 years (PEARLSON, 2011). The feedstock price is also shown.

Table 13: Parameters considered in the economic analysis.

Parameters	
Construction time (years)	3
Plant lifetime (years)	20
Soybean oil prices (US$/t)[10]	776

The hydrotreating plants analyzed are not pioneer plants and it is assumed that they will be built from traditional and well-established petrochemical plant and equipment. These plants require less efforts in engineering, acquisitions, building and have an optimized operation, reducing their costs (PEARLSON, 2011). It is also assumed that the plant is built near refineries, reducing infrastructure costs such as building roads,

[9] Optimistic approach. For Brazilian reality, values may be higher.
[10] Data source: (INDEXMUNDI, [s.d.])

offices, laboratories and distribution terminals. For this reason, an optimistic construction time was adopted, if compared to the average time for complex refining projects of 5 years (NOGUEIRA DE OLIVEIRA et al., 2015). Delays in construction and project implementation are not considered, as this assessment regards to a small/medium project size.

Table 14 lists the process equipment and other expenses included in the plant investment. The capital costs (CAPEX) can be divided in ISBL (Inside battery limits), which include expenses like acquisition and installation of process and ancillary unities, and OSBL (Outside battery limits), which include storage and basic processes utilities. Additional costs include the external costs arising from the associated infrastructure, such as the construction of roads. The special costs include project management, offices, among others. Additionally, a contingency of 15% for ISBL, OSBL, external and special costs subtotal was considered (PEARLSON, 2011). Scaling and localization factors were applied to adjust regional differences in the expenses.

Table 14: Equipment and other expenses included in HEFA plant investment

Capital costs
ISBL
Hydrotreating
Isomerizer
Hydrogen production (Reforming)
Saturated gas plant
OSBL
Feed storage
Liquid products storage
Gaseous products storage
Cooling water tower
Special costs
Contingency
Scalability
Location factor

The operation and maintenance costs are composed by fixed and variable costs. Fixed costs (FOM) include the expenses that do not depend on the production levels, unlike the variable operational costs (VOM), that depend on the production levels. Fixed costs include insurances, taxes, maintenance and salaries. In the study of Pearlson (2011), used as reference, the fixed costs were based in literature heuristics and interviews. Table 15 shows the assumptions made to estimate the fixed costs.

Table 15: Assumptions made in fixed costs estimate.

Fixed costs	
Catalyst	0.2-0.5 $/L of fuel produced
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

Source: Pearlson (2011)

Insurances and taxes represent around 0.5% and 5.0% of the plant total investment. Taxes include the financial cost plus the basic remuneration of the credit institution and the interest rate risk (BNDES, 2016). Maintenance costs were estimated around 5.5% of the plant total investment. Miscellaneous supplies costs are low, representing around 0.2% of the total investment and they include purchase of chemicals, drinking water, among others. As the units assessed in this study for biojet production do not have the complexity of an oil refinery, for example, a reduced number of staff was considered (PEARLSON, 2011). It was assumed an equip containing 12 employees which salaries were assumed according to Brazilian reality (EXAME, 2016). These values were converted and related to the total fuel production, resulting in a cost of 0.2 to 0.8 dollars per liter of fuel produced.

Variable costs are directly influenced by the production levels. These costs include expenses with catalyst, electricity, natural gas, water and feedstock. Catalysts need periodical replacements or regenerations. Expenses with catalysts were estimated according to standard parameters for hydrotreating processes. Electricity is used to power pumps, compressors and electrical appliances. Natural gas is a fuel for heating and feedstock for processes like hydrogen production by steam reforming. This study also considered the hydrogen production in site and soybean oil as feedstock (Table 16). The biomass transportation costs were evaluated from a linear regression analysis using data available in SIFRECA website (SIFRECA, 2016). The analysis results in the equation 1 below (Eq. 1) and is a function of the amount of biomass transported and the distance travelled.

Table 16: Prices of production supplies that compose the variable costs analysed for HEFA plant

Inputs	**Prices**	
Catalyst	0.2-0.5 $/L of fuel produced	(PEARLSON, 2011)
Electricity	102.93 US$/MWh[a]	(ANEEL, 2012)
Natural gas	15.96 US$/GJ	(FIRJAN, 2011)
Soybean oil	776 US$/t	(INDEXMUNDI, [s.d.])

Notes:

[a] Industrial tariff

$$C_T = 14.40\left(\frac{US\$}{t}\right) + 0.56\left(\frac{US\$}{t.km}\right) x\ Distance\ (Eq. 1)$$

4.3.2 FT-BTL methodological description

This sub-section describes the proceedings and assumptions made to estimate capital and operational costs for FT-BTL route to produce biojet fuel based on the study of Elia et al. (2013). Values were adjusted for 2014 according to GDP deflators given by the U.S. Department of Commerce (BEA, 2016) and adapted to Brazilian conditions.

As mentioned before, four plant capacities were studied for FT-BTL route to produce biojet fuel. These plants contain the following process unities:

- Biomass handling: the analyzed feedstock is residual forest biomass in wood chips form. This feedstock should be pretreated prior gasification. Biomass is firstly screened and then follows to a grinder to reduce particles sizes. Next, the drying process reduces humidity so the feedstock can feed the process.
- Syngas production from biomass: Conversion of pre-treated residual forest biomass in fluidized bed gasifiers pressurized with oxygen.

- Syngas conditioning: Removal of acid gases, nitrous compounds and fractions of CO_2.
- Hydrocarbon synthesis via Fischer-Tropsch: The FT unities operates with high pressures and use cobalt catalysts, aiming to maximize the production of medium distillates.
- Hydrocarbon upgrade: Initially the water-soluble oxygenates are removed from the stream, which follows to a separator to remove the aqueous phase from the residual steam and from any liquid hydrocarbon. Then, hydrocarbons are sent to a fractioning column and further hydroprocessing.
- Light gases recycle
- Hydrogen and oxygen production: Hydrogen demand may be attained by pressure-swing adsorption or water electrolysis. The oxygen produced in electrolysis along with the oxygen obtained in air separation unit (ASU) are used to satisfy the plant requirement.

Table 17 resumes the inputs and energy consumption for FT-BTL route.

Table 17: Inputs and energy consumption for FT-BTL biojet production.

Inputs	
Biomass[a] (t)	5.36
Water (t)	0.82
Electricity (MWh)	0.3-0.5
Outputs	
Biojet	1
Gasoline[11]	0.32
[a] Dry matter	

Table 18 presents the main parameters for the economic analysis of biojet production. It was considered a construction period of 3 years and a lifetime of 25 years (ELIA et al., 2013). As the feedstock considered is a residual biomass with no defined use, it was assumed that there are no costs for its acquisition, except for its collection.

[11] As mentioned in FT-BTL route description (Chapter 3), the reforming of naphtha (or gasoline) is an alternative to produce aromatics and hydrogen (catalytic reforming) or only hydrogen (steam reforming).

Table 18: Parameters adopted for FT-BTL cost analysis

Parameters	
Construction time (years)	3
Lifetime (years)	25
Biomass price (R$/m^3)	-

Fuel production costs are based in the individual components of BTL refinery, which includes feedstock, water, charges associated to capital cost, operation and maintenance costs, electricity, among others. The sum of all these costs forms the refinery total cost, which can be offset by co-product selling. The total plant investment includes equipment costs and indirect costs. The plant sections with major contribution to the total investment are biomass handling, syngas production, syngas conditioning, hydrocarbon producing, hydrocarbon upgrading, hydrogen/oxygen production, heat/energy integration and water treatment.

As mentioned before, the operational costs can be divided into fixed and variable costs. Variable costs were estimated from plant inputs prices (Table 19). This study have not considered the biomass costs since it is a residual feedstock. Biomass transportation costs are included in the variable costs. This study followed the methodology proposed by Hoffman et al. (2013) using an equation obtained from a linear regression using data from SIFRECA (SIFRECA, 2011). The equation was adapted, being expressed in U.S dollars (Eq.2). This study considered that the operation and maintenance costs correspond to 10% of the plant total investment (IEA, 2013). Then, fixed costs were obtained by the difference between total O&M costs and variable O&M costs.

Table 19: Prices of production supplies that compose the variable costs analysed for FT-BTL plant

Biomass	-	-
Water (R$/t)	4.54 US$/t	(SABESP, 2012)
Electricity (R$/MWh)	102.93 US$/MWh[a]	(ANEEL, 2012)

Note:
[a] Industrial tariff

$$C_t = 5.62 \left(\frac{US\$}{t}\right) + 0.04 \left(\frac{US\$}{t.km}\right) x\ Distance \quad (Eq.2)$$

Fuel levelized costs were calculated assuming that the total capital investment would be paid in the construction period (three years). The annual fixed and variable O&M costs (FOM and VOM) were adjusted according to the plant lifetime. A study made by Oxera Consulting Ltd. estimated that discount rate would vary from 9% to 13% for biomass-based low-carbon and renewable technologies (OXERA CONSULTING LTD, 2011). Based on that, a discount rate of 12% was used in the calculations. After determining the levelized costs of biojet fuel (LCOF) production for HEFA and FT-BTL pathways, this study evaluated the QAV prices that make the biofuel competitive, according to different CO_2 prices and a fixed biomass transportation distance. Finally, a sensibility analysis was performed. This analysis aimed to evaluate the major contributors to the biojet prices and the inclusion of a carbon tax in QAV prices. The parameters analyzed include the CC, FOM, VOM and a carbon tax represented by CO_2 prices.

5. Results

5.1 Feedstock availability

This section presents the technical potential of biomass from the selected feedstock (as described in chapter 4). As mentioned above, the total biomass potential estimated in Brazil is 3,932 PJ/year. Figure 22 already revealed the spatial distribution of bioenergy sustainable potential of selected agricultural, agro-industrial and forestry residues in 2014. This potential is mainly concentrated in South (33%), Southeast (28%) and Midwest (27%), which contain larger agricultural areas, while North and Northeast regions shows limited bioenergy potential. Figure 30 shows the potential contribution of each region in the country.

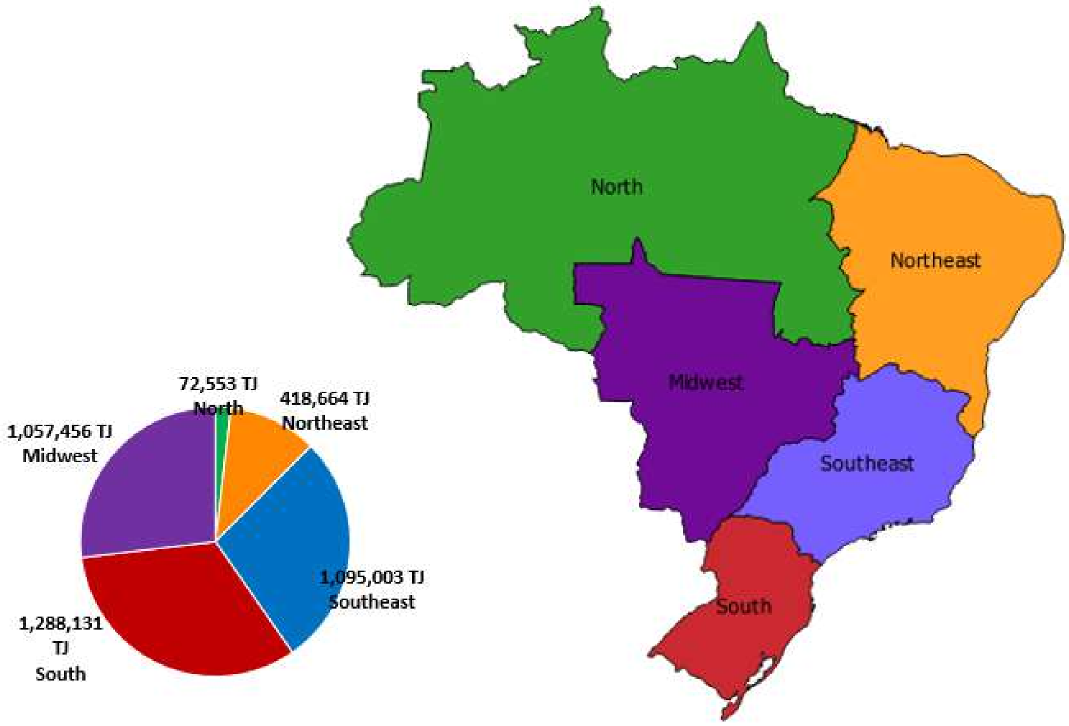

Figure 30: Contribution of each region for country's bioenergy potential.

In North region, biomass residues with higher potentials are produced from forestry extraction (37%) and soybeans (23%). Although forestry extraction residues have least influence in the country's totals, its representativeness in this region is quite significant. In the Northeast, soybeans (25%) and sugarcane (24%) reveal the highest residues bioenergy potentials. In the Southeast, sugarcane residues have the greater potential among all crops (62%), followed by eucalyptus (24%). In South, the region with major potential in the country, soybean (28%) and rice residues (21%) register major contributions. It is noteworthy the influence of rice in the south bioenergy potential even though this crop is not expressive to the country's total potential. Figure 31 shows the potentials divided by regions and crops in the country.

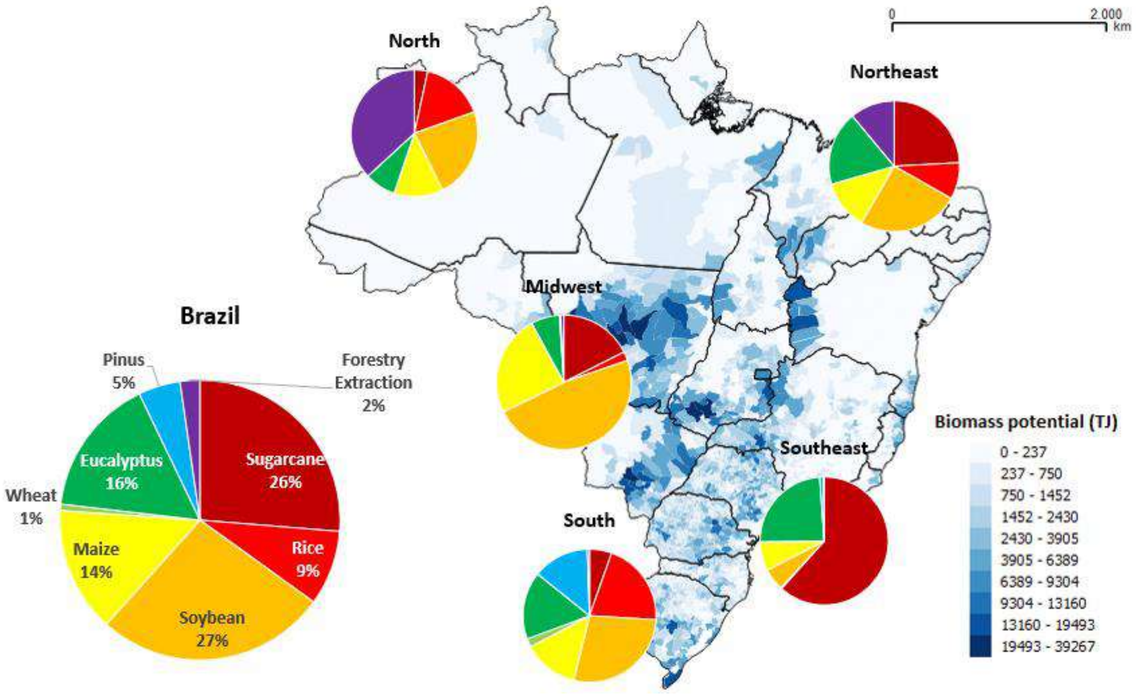

Figure 31: Bioenergy potential for each crop in country's regions.

Regarding the selected crops, soybeans and sugarcane register the major contributions, corresponding together to 53% of the country's potential. The total potential for soybean residues is about 1.5 TJ, which are mostly concentrated in the Midwest region (Figure 32). Sugarcane residues potential totalize 1.0 TJ, being more expressive in the South-Central region of the country (Figure 33).

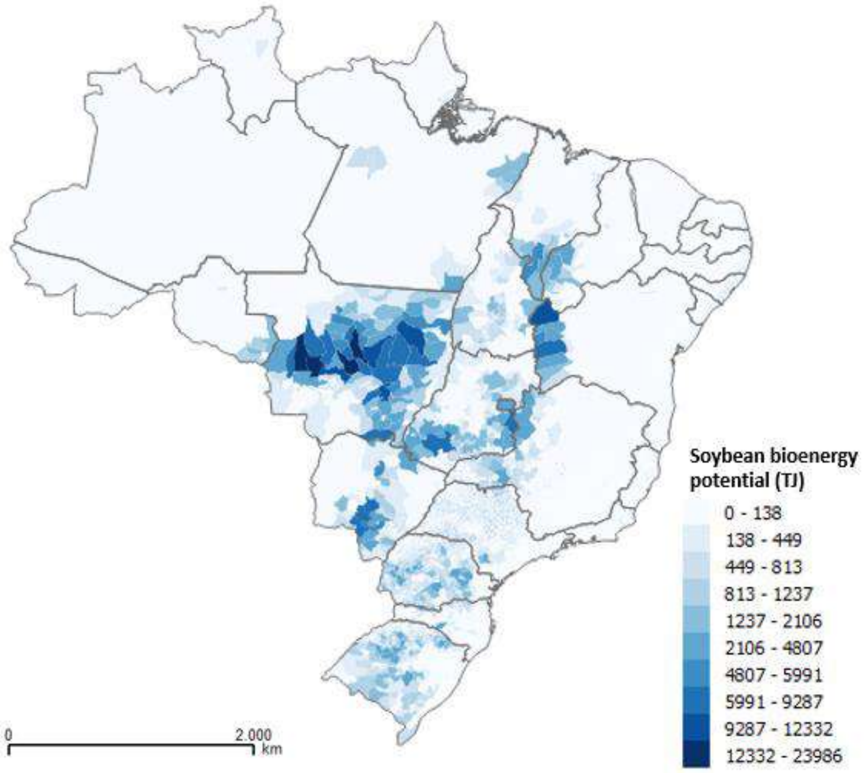

Figure 32: Soybean bioenergy potential distributed for each municipality.

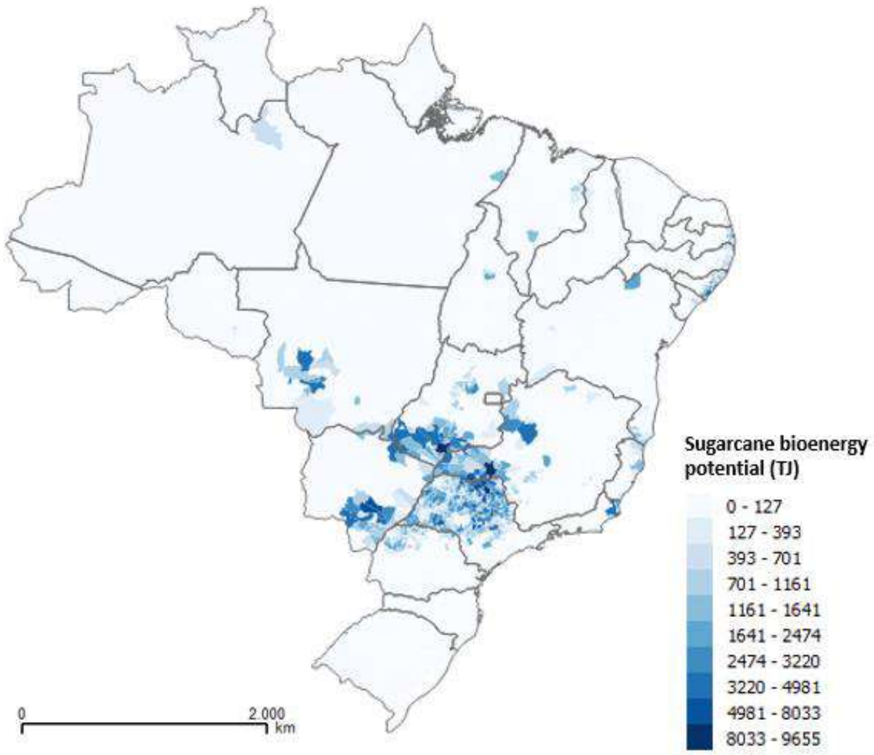

Figure 33: Sugarcane bioenergy potential distributed for each municipality

The eucalyptus residues represent 16% of the country’s potential, followed by maize (14%) and rice (9%). Eucalyptus residues potential is 631 PJ and municipalities with highest values are localized in the state of Mato Grosso do Sul (Figure 34). Residues from maize totalize 568,511 TJ of bioenergy, mostly concentrated in the Midwest municipalities (Figure 35). Rice residues potential is 340,183 TJ and the South region, especially the state of Rio Grande do Sul hosts municipalities with the largest potentials (Figure 36).

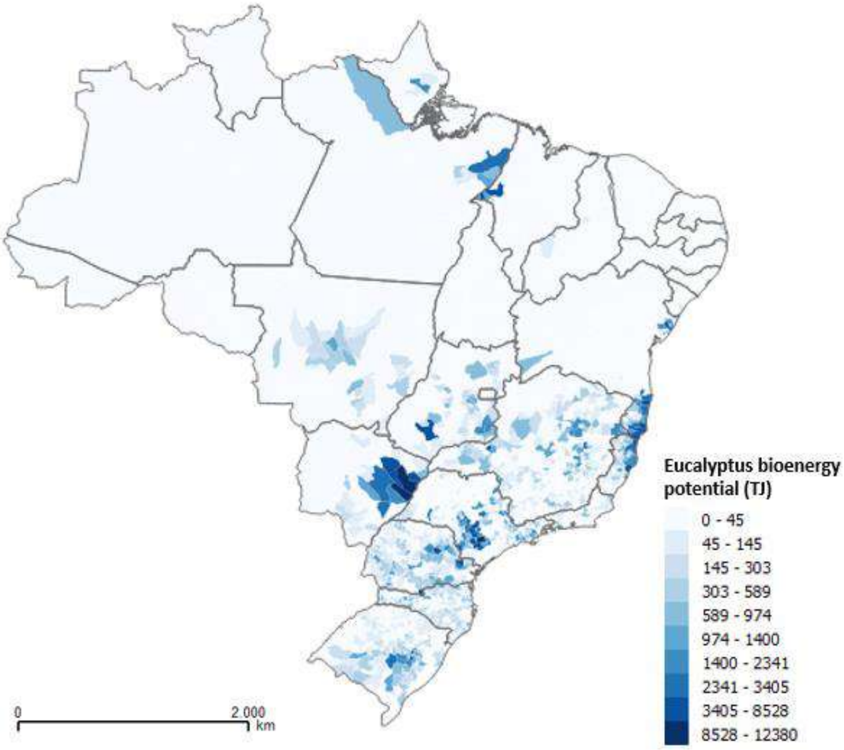

Figure 34: Eucalyptus bioenergy potential distributed for each municipality

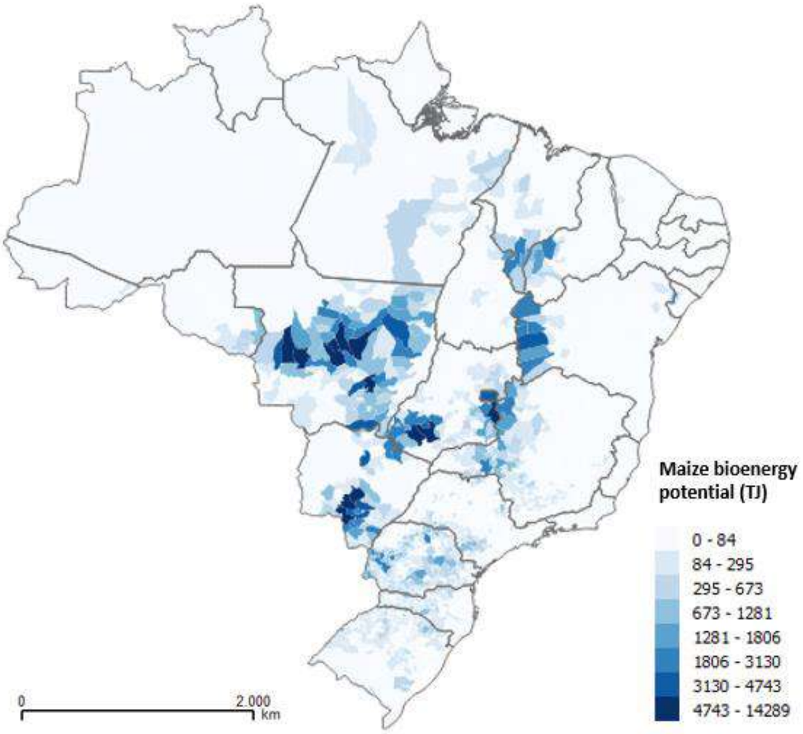

Figure 35: Maize bioenergy potential distributed for each municipality

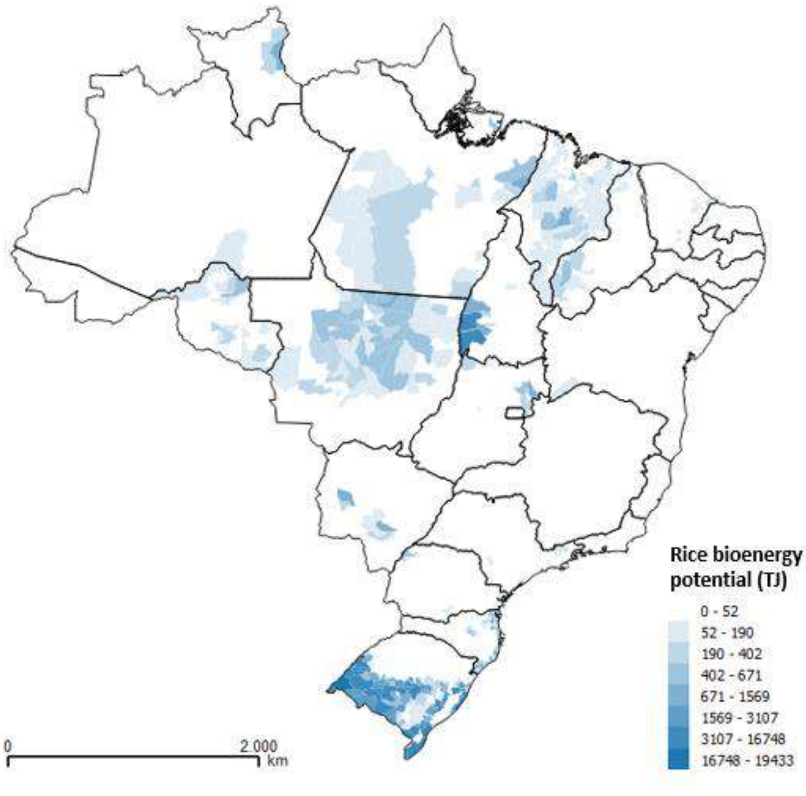

Figure 36: Rice bioenergy potential for each municipality

Crops with less contribution are pinus, forestry extraction and wheat, representing 5%, 2% and 1% of the country's bioenergy potential, respectively. Pinus and wheat residues are mostly concentrated in the municipalities of South region (Figure 37 and Figure 39), while forestry extraction residues are more expressive in the North region municipalities (Figure 38).

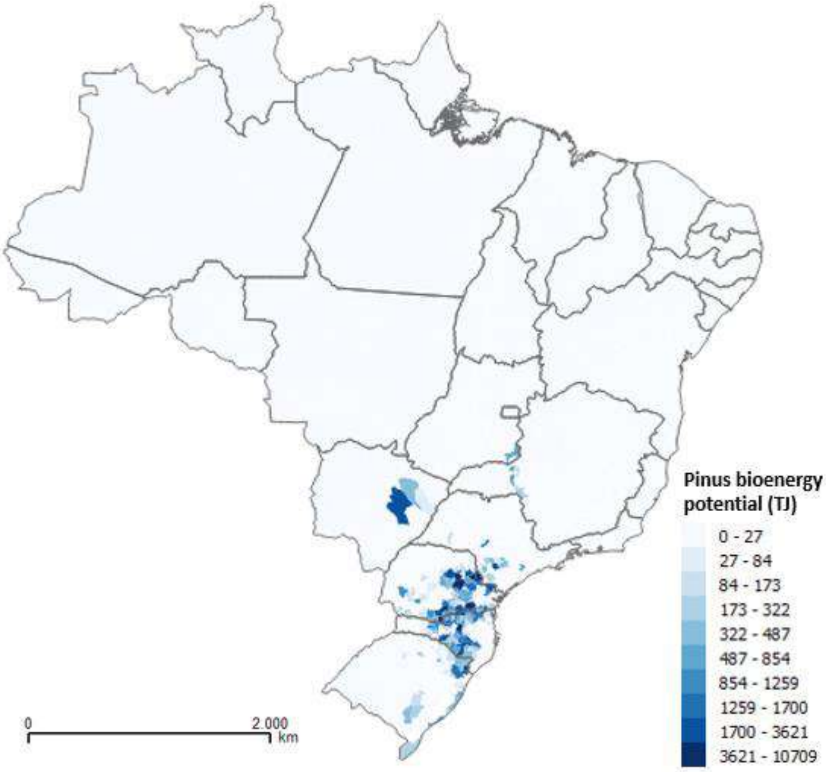

Figure 37: Pinus bioenergy potential for each municipality

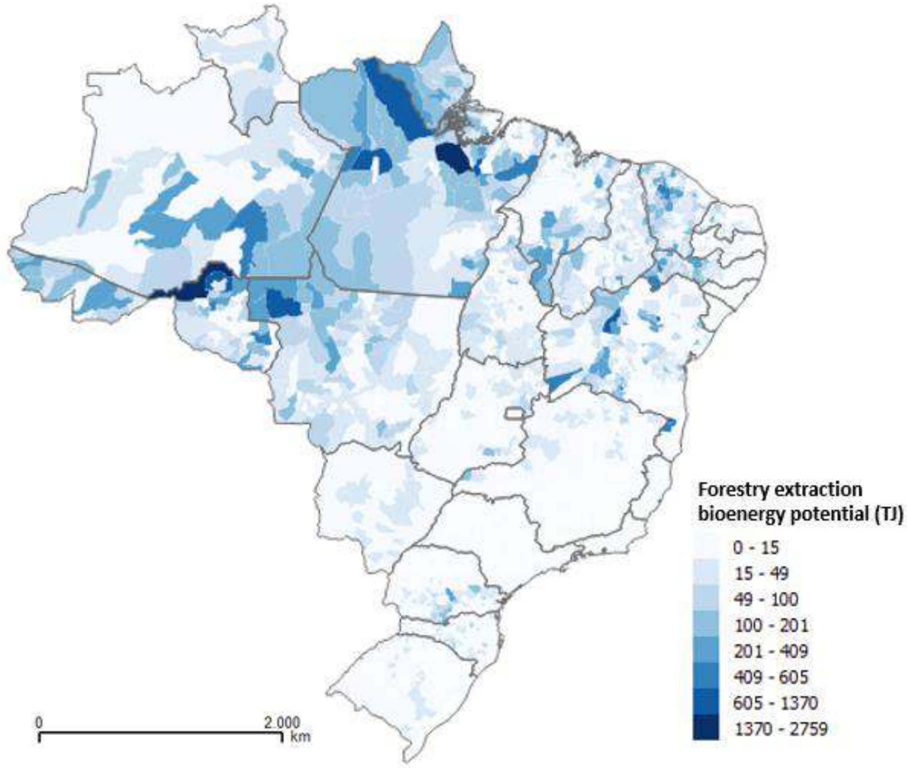

Figure 38: Forestry extraction bioenergy potential for each municipality

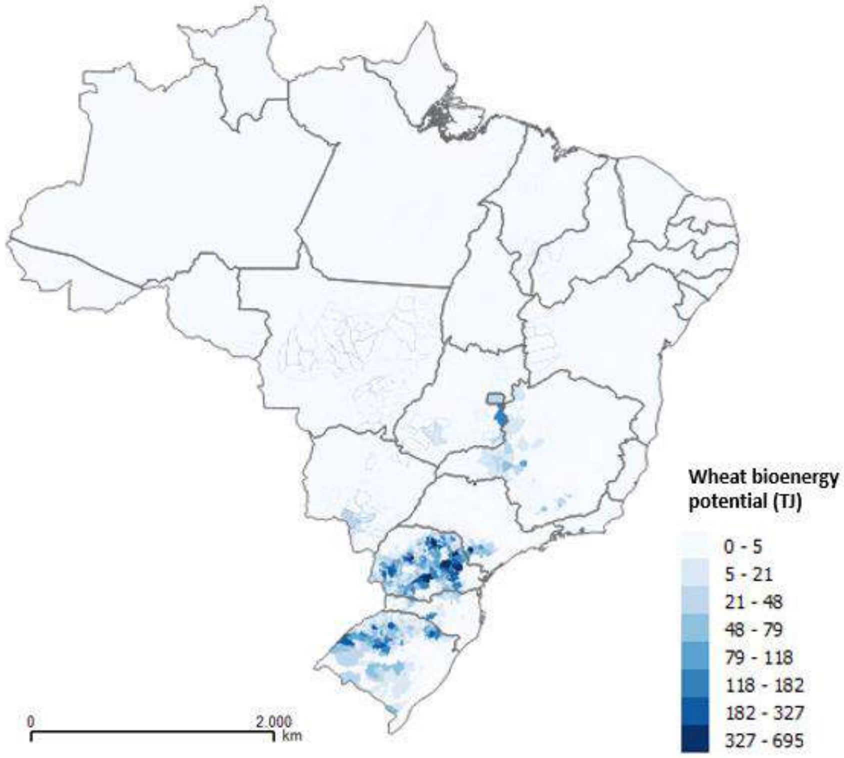

Figure 39: Wheat bioenergy potential for each municipality

The next step was the construction of kernel maps to evaluate bioenergy dispersion in the territory. These maps are useful to assess the bioenergy intensity in the country without restricting it to each municipality. Figure 40 shows the kernel map for the total biomass energy potential from residues in Brazil. Areas with more intense colors represent localities with higher bioenergy potential. Thus, this map emphasizes the significance of southeast and south regions, which concentrate the major bioenergy potential in the country, and especially the significance of São Paulo and Paraná states, which host most of this bioenergy.

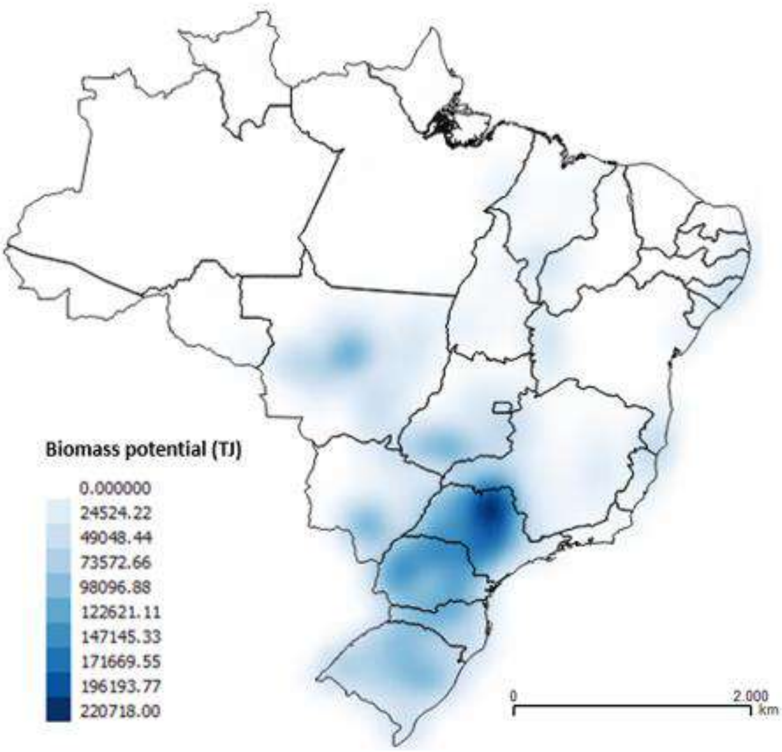

Figure 40: Kernel map for total biomass energy potential

In addition, the kernel maps were generated for each crop analyzed in this study. Figure 41 below, shows the kernel map for bioenergy potential for the agricultural and agro-industrial residues. As well as in the kernel map for total bioenergy potential, this map indicates the energy concentration in the Southeast region, precisely in São Paulo state.

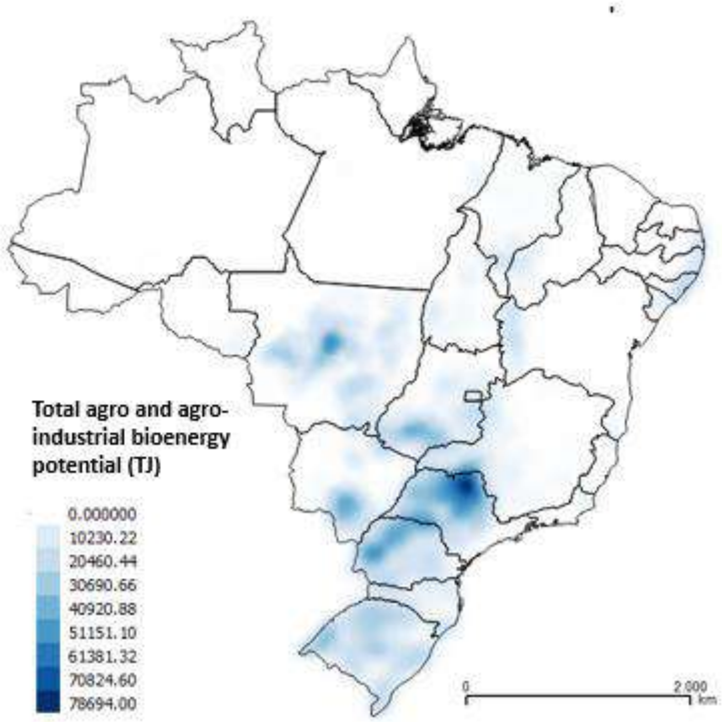

Figure 41: Biomass energy density for agricultural and agro-industrial biomass residues

Analyzing the kernel maps of each crop individually, the same trend of bioenergy concentration is observed as in the case of the maps with bioenergy potential for each municipality presented above. Figure 41 and Figure 42 show the kernel maps for soybeans and sugarcane bioenergy potentials, which indicate an energy concentration in the states of Mato Grosso and São Paulo, respectively. For eucalyptus, Figure 44 shows the energy concentration in the state of São Paulo. For maize, two localities with highest bioenergy potential were identified and they are located in the states of Mato Grosso and Paraná (Figure 45). Figure 46 shows the kernel map for bioenergy potential from rice residues, which is most expressive in the state of Rio Grande de Sul. Figure 47, Figure 48 and Figure 49 show the kernel maps for pinus, forestry extraction and wheat, respectively, which are the crops with less contribution to the total bioenergy potential in the country. Most expressive areas for these crops are the states of Santa Catarina, Acre and Paraná.

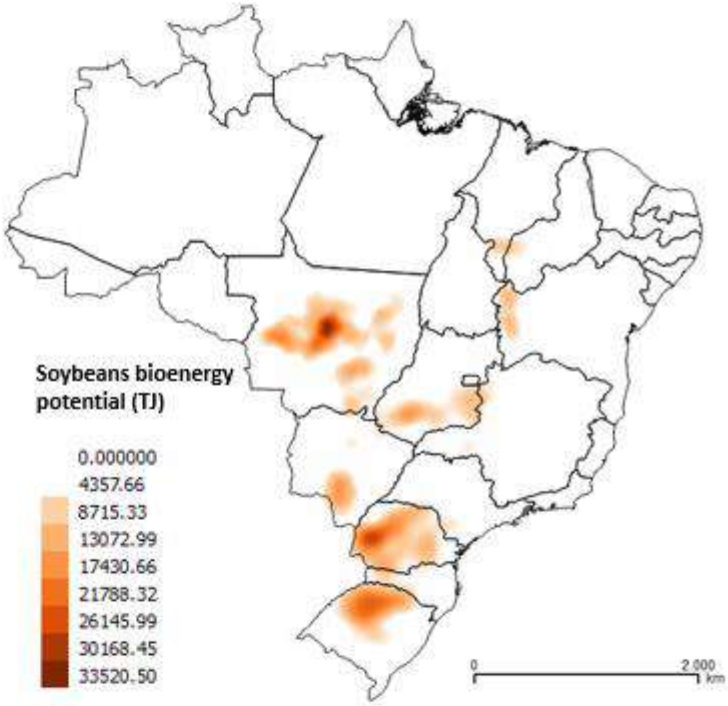

Figure 42: Kernel maps for soybeans bioenergy potential

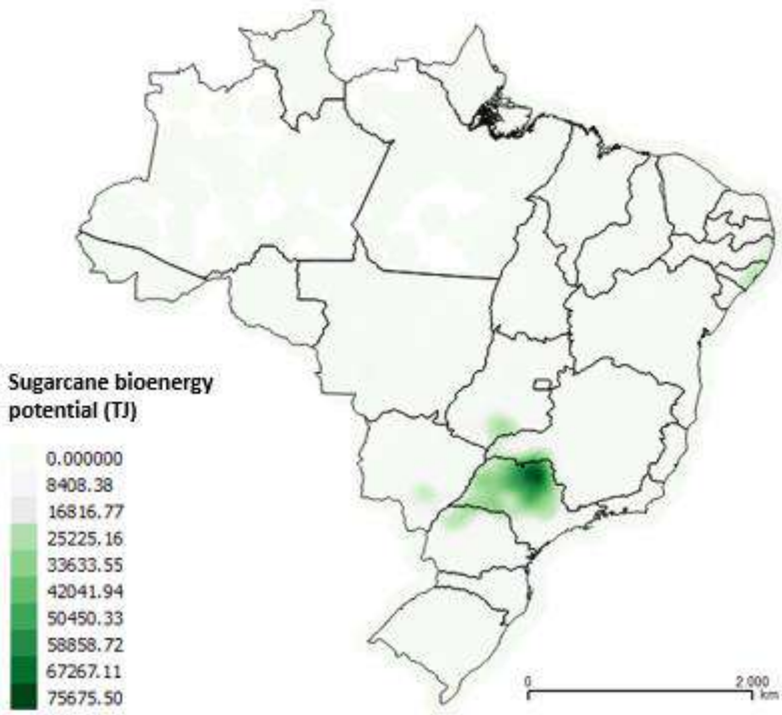

Figure 43: Kernel maps for sugarcane bioenergy potential

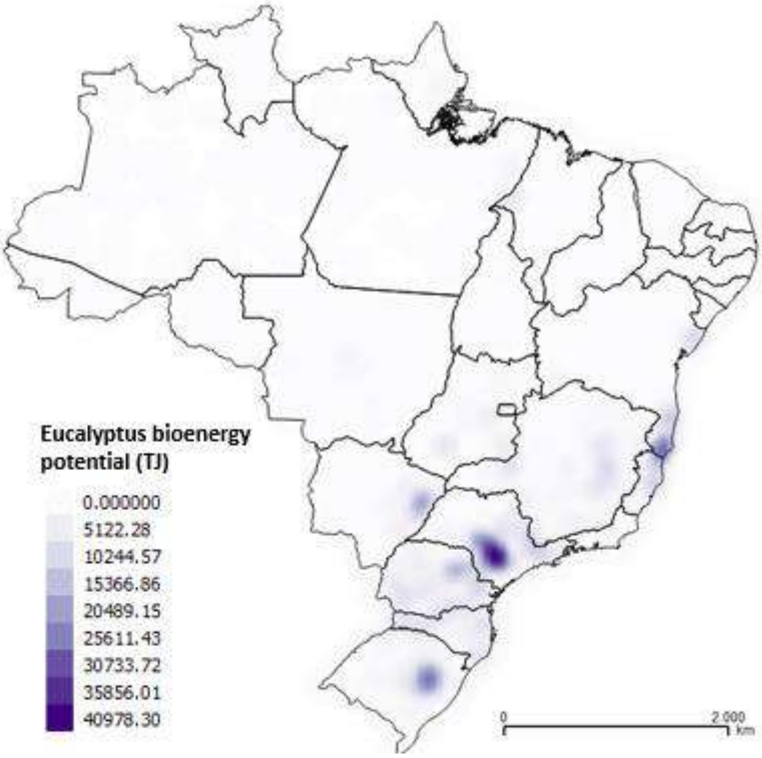

Figure 44: Kernel map for eucalyptus bioenergy potential

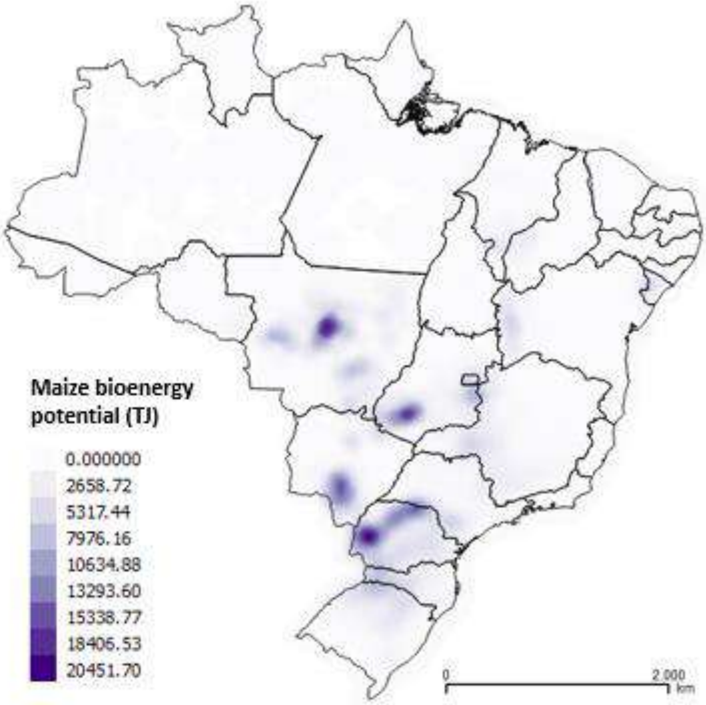

Figure 45: Kernel map for maize bioenergy potential

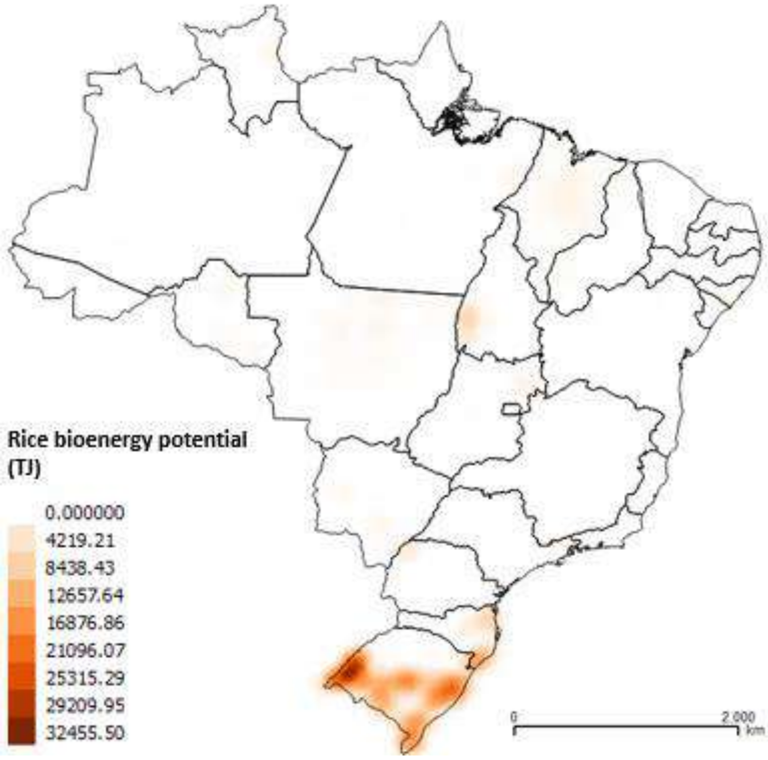

Figure 46: Kernel map for rice bioenergy potential

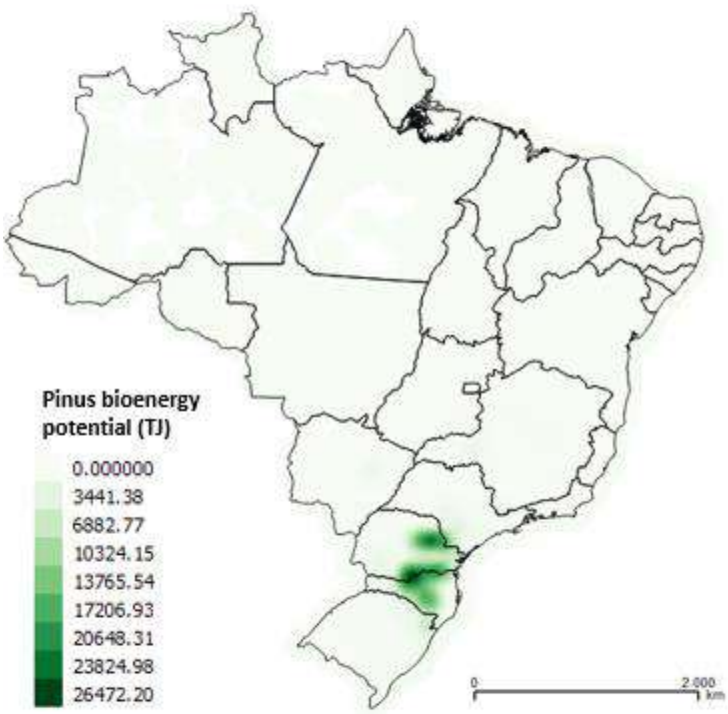

Figure 47: Kernel map for pinus bioenergy potential

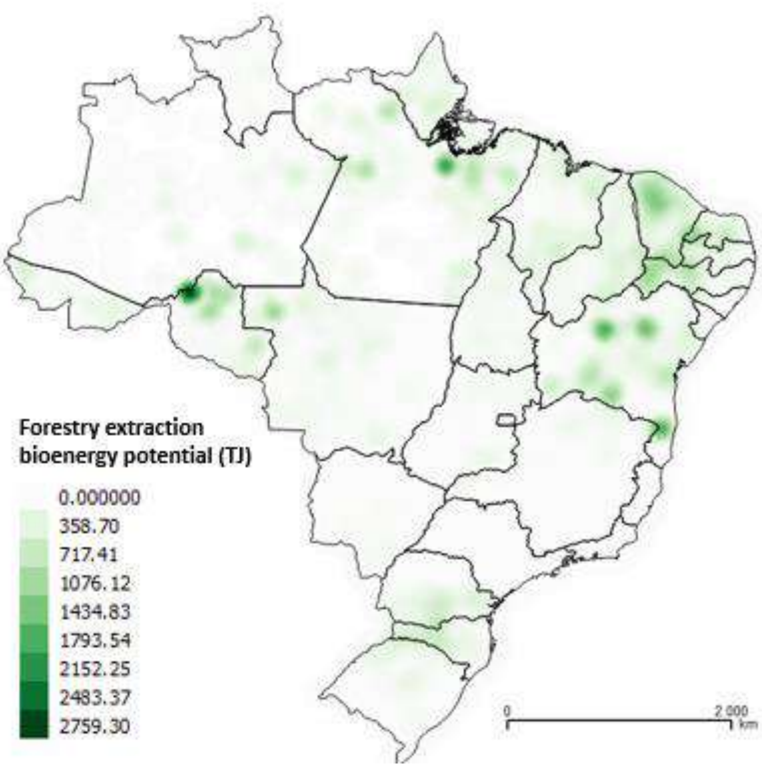

Figure 48: Kernel map for forestry extraction bioenergy potential

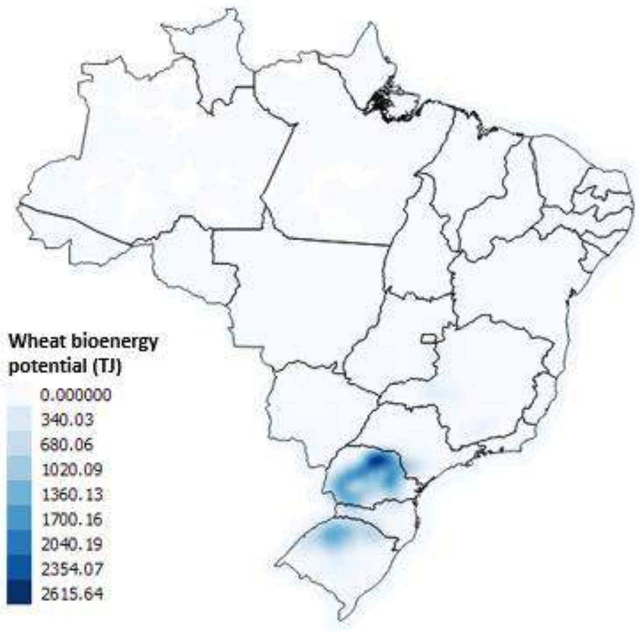

Figure 49: Kernel map for wheat bioenergy potential

The following step had the objective to identify the hotspots of bioenergy. Defining hotspots is useful to determine areas with greater biomass potentials. A radius of 100 km from these points was assumed to delimitate areas with greater potentials and as a distance to biomass transportation. These areas represent localities with major potential for biorefineries establishment. Figure 50 below, shows the procedure performed to determine the energy hotspots (red point) and the potential areas using a radius of 100 km. Next, the Figure 51 reveals the hotspots determined for each crop.

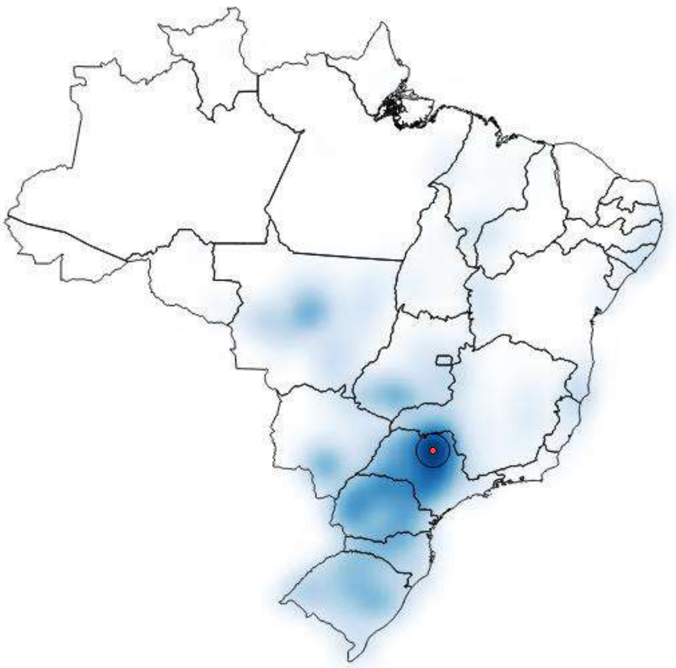

Figure 50: Determination of biomass hotspots

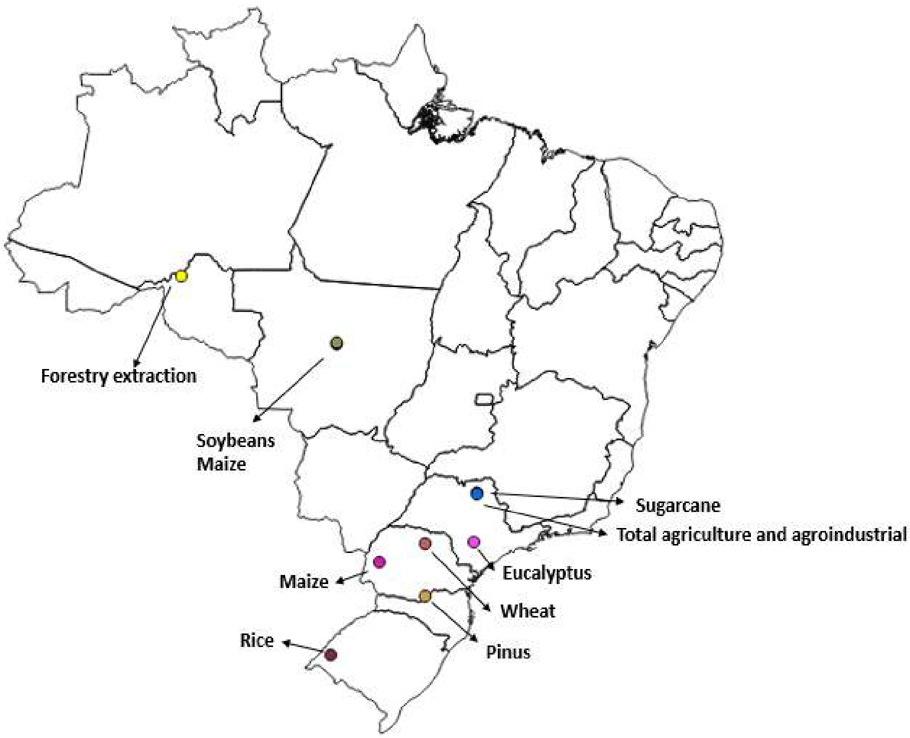

Figure 51: Biomass energy hotspots for each crop

Thereafter, the map above was overlaid by the map containing the Brazilian municipal division, in order to identify which municipalities hosts each hotspot. This step was performed for the total bioenergy potential and for each crop potential. A zoom was made on the map, and the municipalities detected for each case listed (Figure 52). Table 20 shows the municipalities that contain the energy hotspots for each crop.

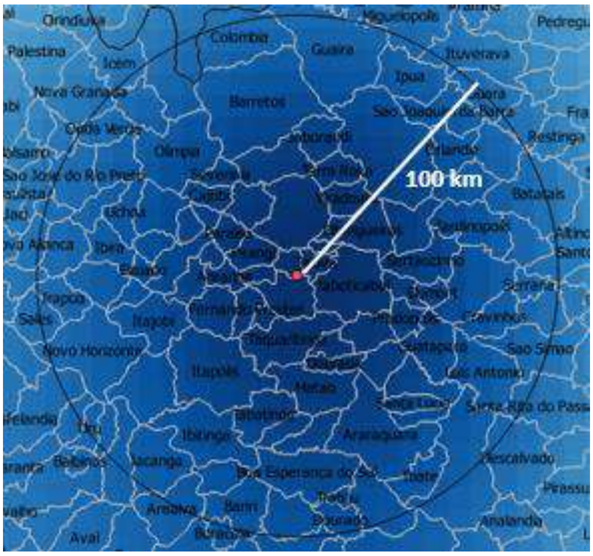

Figure 52: Zoom on kernel map

Table 20: Biomass potential hotspots for each crop

Hotspots			
Crop	**Municipality**	**State**	**Potential (TJ)**
Total	Taiacu	SP	2,202,410
Sugarcane	Morro Agudo	SP	75,676
Soybeans	Sorriso	MT	33,396
Maize	Sorriso	MT	19,359
	Tupassi	PA	20,452
Wheat	Londrina	PA	2,612
Rice	Alegrete	RS	32,455
Eucalyptus	Angatuba	SP	40,978
Pinus	Porto União	SC	26,472
Forestry extraction	Porto Velho	AC	2,759
Total agriculture and agro-industrial	Morro Agudo	SP	78,694

Then, the kernel map of total bioenergy potential containing the hotspot and the area covered by the radius ok 100 km (Figure 50) was firstly overlaid by a layer containing the main localities of jet fuel production, distribution and use (Figure 53). Next, the kernel map was overlaid by layers containing biodiesel and ethanol plants and soybean oil refineries, indicating localities with an existing infrastructure of fuel and feedstock handling in the country (Figure 54). The analysis of these maps reveals the proximity between biomass production and fuel handling and consumption areas in the state of São Paulo.

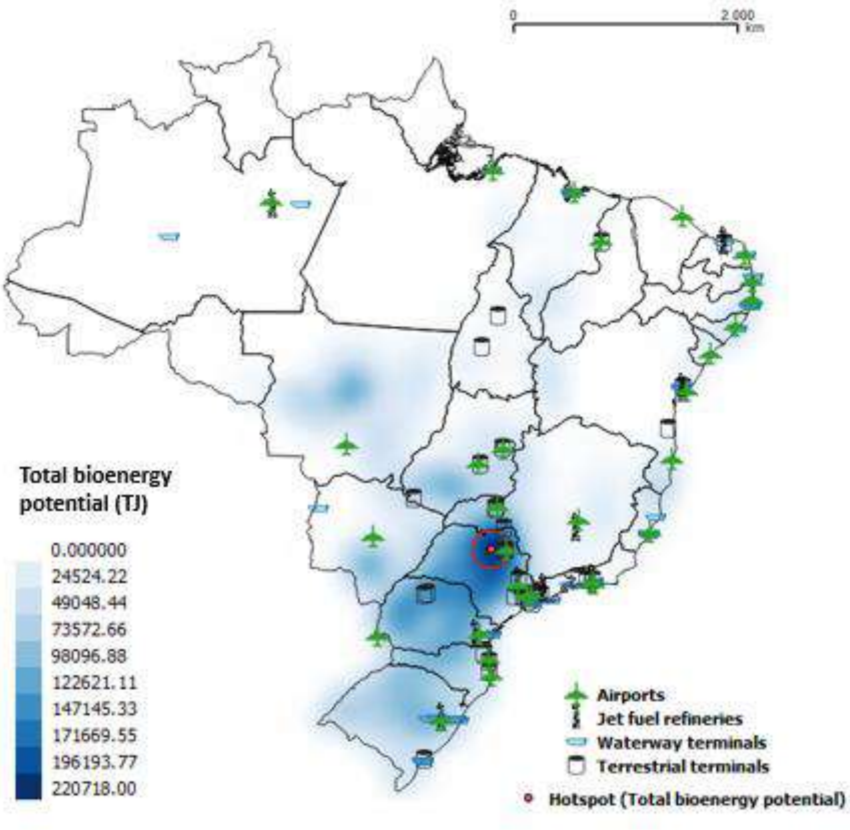

Figure 53: Total bioenergy potential and important localities for jet fuel logistics

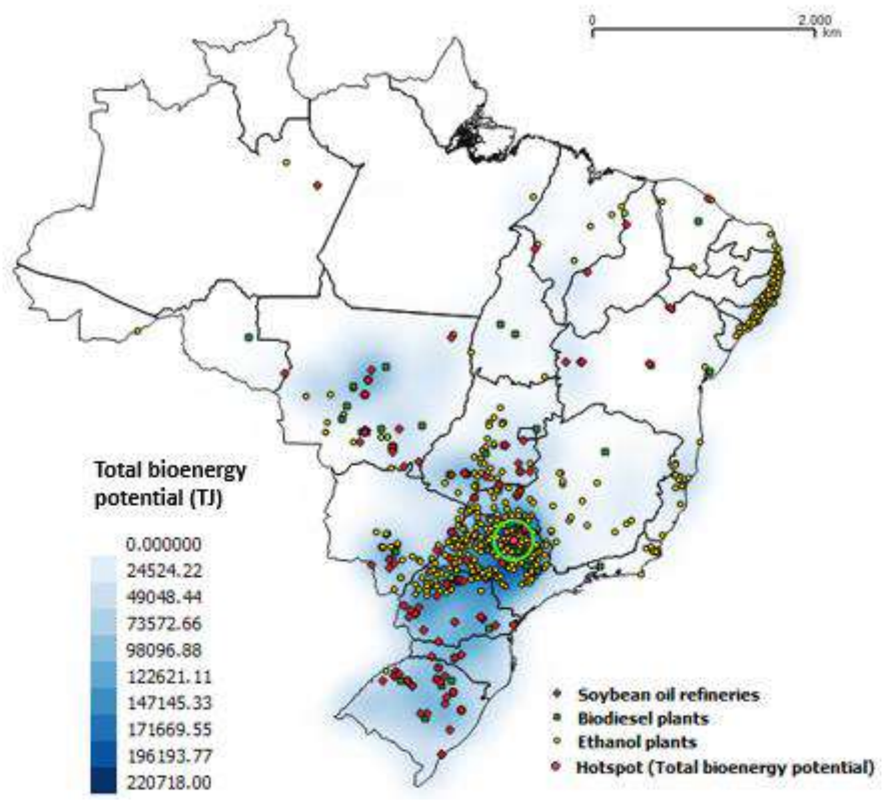

Figure 54: Total bioenergy potential hotspot and localities of biofuels and soybean oil production in Brazil

The same procedure described above was performed for each crop hotspot (Figure 55 and Figure 56). A zoom was made in the area with greater concentration of hotspots, fuel handling and consumption localities for better observation of results (Figure 57 and Figure 58). These results emphasize the relevance of southeast and south regions, especially the São Paulo state, as potential areas for biojet production development in Brazil. The development of biorefineries in these locations would benefit from the proximity to the feedstock and existing infrastructure, reducing logistics issues and transportation costs.

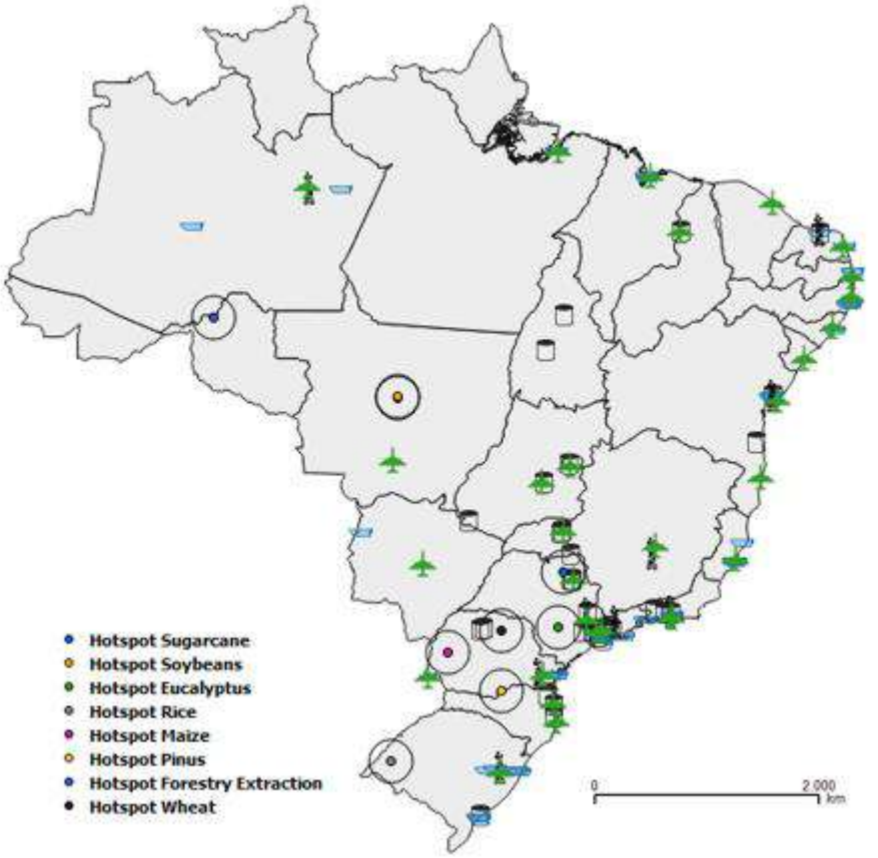

Figure 55: Biomass energy hotspots and important localities for jet fuel logistics

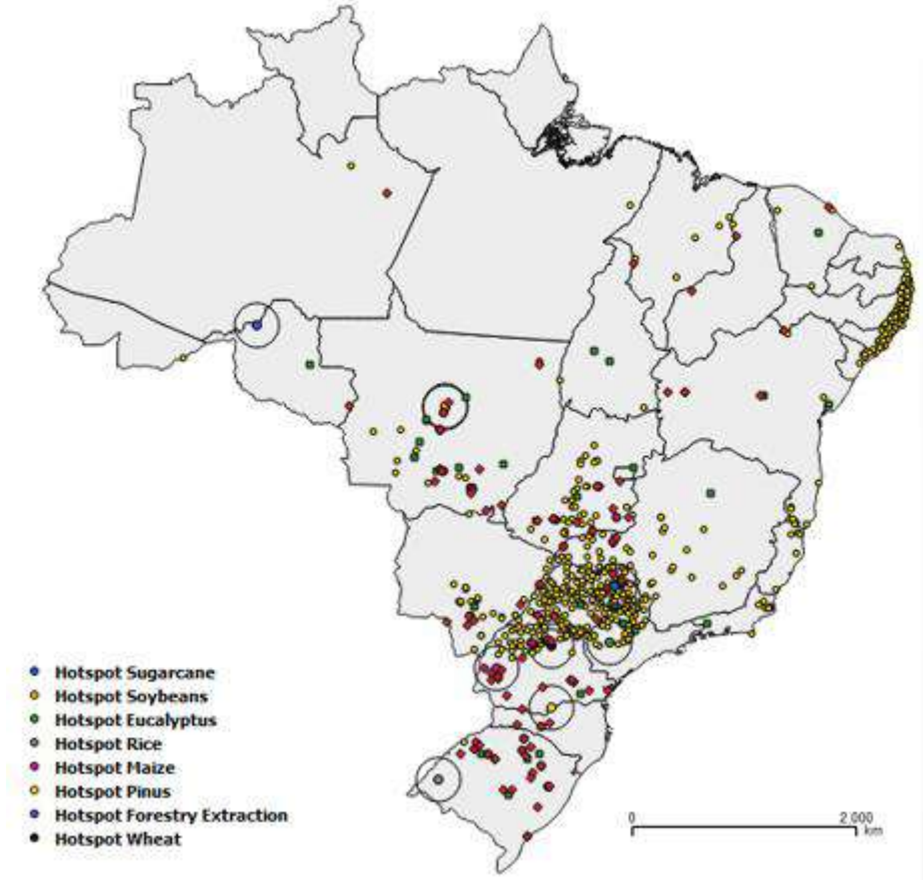

Figure 56: Biomass energy hotspots and localities of biofuels and soybean oil production in Brazil

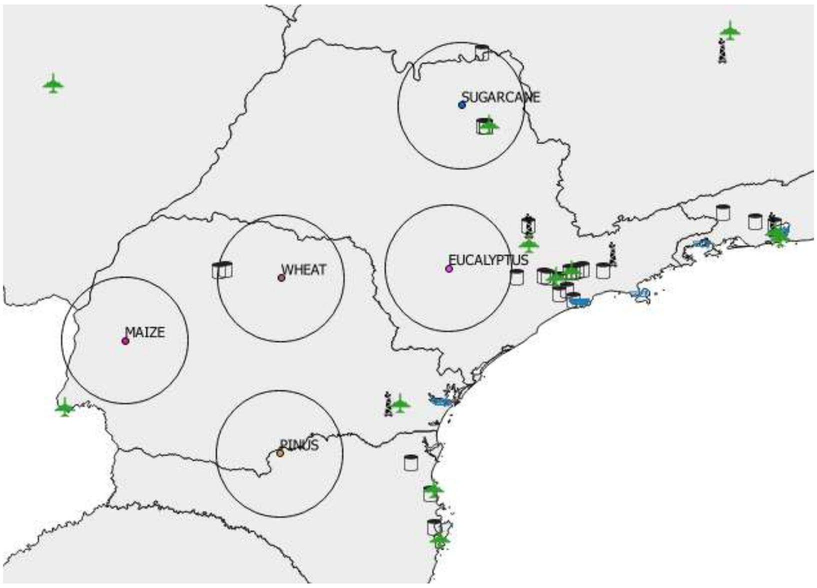

Figure 57: Biomass energy hotspots and important localities for jet fuel logistics in Southeast and South regions

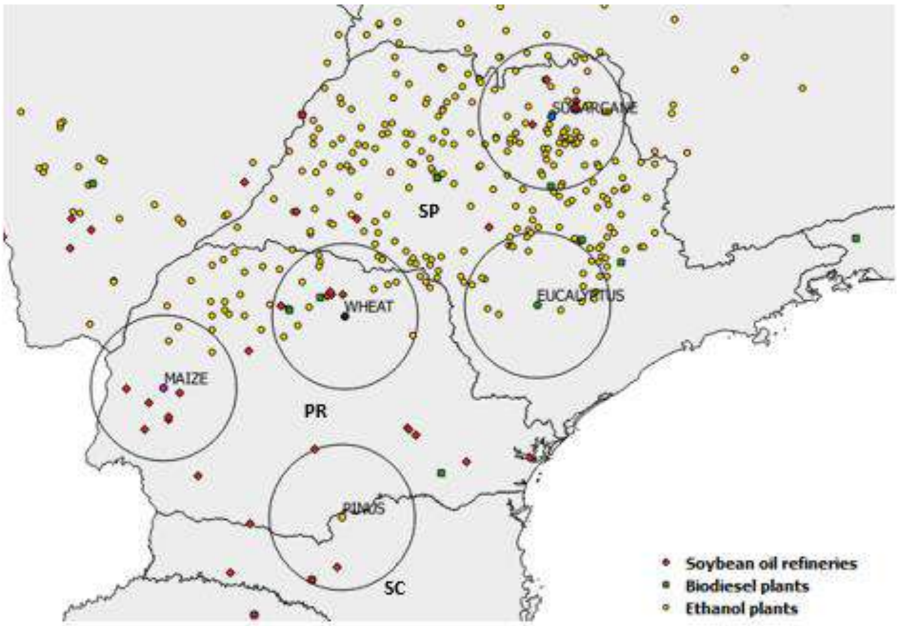

Figure 58: Biomass energy hotspots and localities of biofuels and soybean oil production in Southeast and South regions

On the other hand, results enable considering the establishment of biorefineries in isolated locations that depends entirely of an external fuel supply. This is the case of Brazilian Midwest region that does not have any oil refinery, being its jet fuel demand fully supplied by the Southeast production. The region concentrates the greater bioenergy potential from soybean and maize residues, accounting together for 52,8 PJ. Such potential could be harnessed for local biojet production, providing fuel directly to the Brasilia airport and reducing the external fuel dependence. In this case, the jet fuel supply coming from the southeast region would be addressed to its internal market, reducing necessity of importation. Figure 59 represents a zoom in from Figure 56, which reveals the proximity between soybean and maize hotspots and Brasilia airport. In addition, the production of biojet fuel from vegetable oils through HEFA route is also an option, due to the presence of soybean oil refineries and biodiesel plants, indicating an existing infrastructure in this area. However, the isolated localization adds issues regarding hydrogen supply, a necessary input for HEFA production pathway.

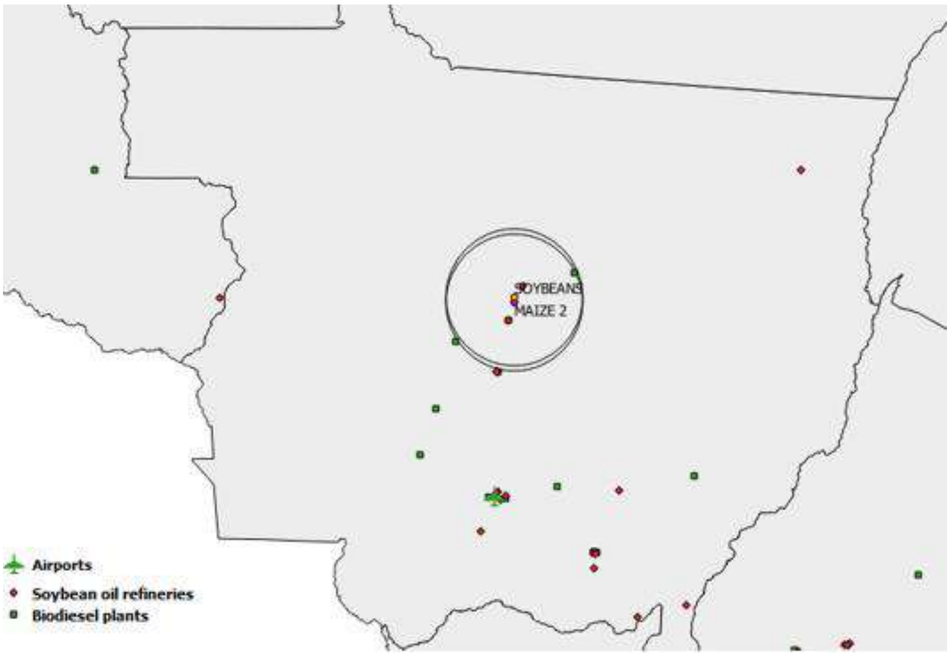

Figure 59: Soybeans and maize energy hotspots and localities of biodiesel and soybean oil production in Midwest regions

5.2 Life cycle assessment results

The results of the environmental analysis performed in GREET model are presented according to the life cycle stages of the fuel. Fuel life cycle is divided in well-to-pump (WTP) and pump-to-wake (PTW) stages, which together form the well-to-wake (WTW) fuel cycle. The WTP stage comprises the exploration and recovery activities from feedstock harvesting to fuel production and transportation to terminals. The PTW stage represents the fuel combustion during aircraft operation. Functional units chosen are MJ for GHG emissions and fossil fuel consumption results. The aircraft model selected was Large Twin Aisle (LTA), a type of passenger aircraft such as Boeing 747 and Airbus A380. The choice of aircraft do not affect the final results.

Results for biojet pathways analyzed in this study indicate important life cycle reduction in GHG emissions and fossil fuel consumption. Biojet from FT pathway from wood residues had lower emissions and fossil fuel consumption than biojet from HEFA pathway using soybeans. FT-SPK shows a reduction of 94% in GHG emissions and fossil fuel consumption compared to the conventional jet fuel, while HEFA biojet from soybeans registered reductions of 52% in GHG emissions and 69% in fossil fuel consumption. Figure 60 shows the results of GHG emissions and Figure 61 shows the results for fossil fuel consumption obtained in GREET for the fuels life cycles.

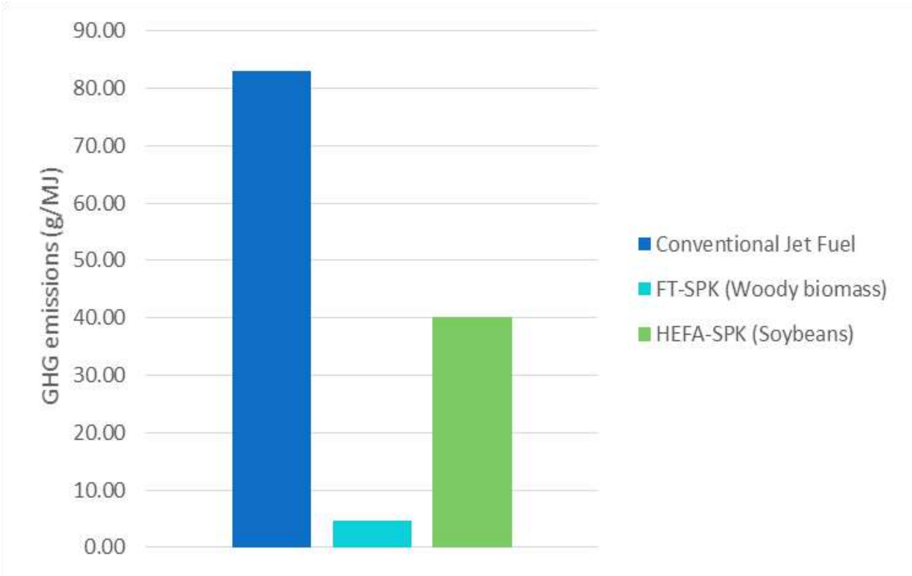

Figure 60: Life cycle or WTW GHG emissions

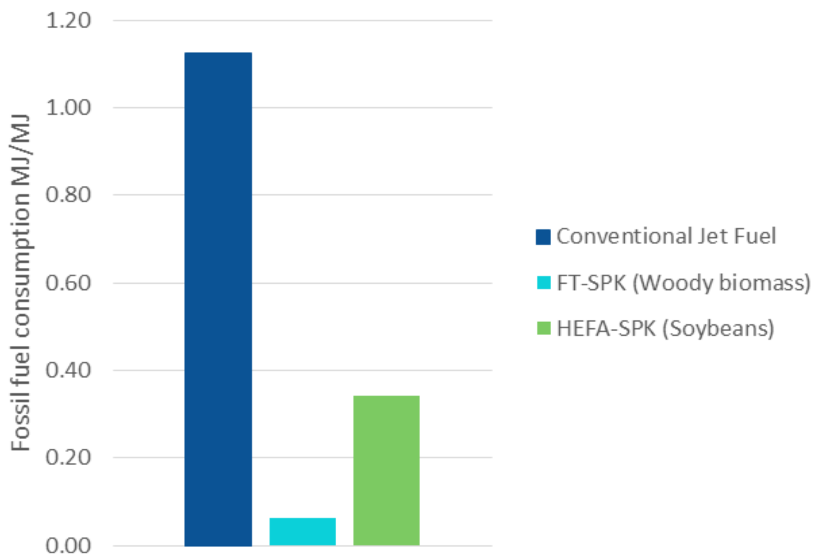

Figure 61: Life cycle or WTW fossil fuel consumption

These results emphasize the potential of biomass residues for biojet production in Brazil, once the feedstock used for FT-BTL pathway are residual woody biomass. Despite being a low-cost feedstock with high availability, they also reduce expressively the GHG emissions and fossil fuel consumption compared to the conventional fuel. Although results for HEFA biojet from soybeans are less significant than for FT from biomass residues, it also contributes with great reductions, if compared to conventional jet fuel. The GHG emissions for this HEFA pathway are mostly associated with soybean farming and collection, fertilizer and hydrogen use for fuel upgrade, while the fossil fuel consumption is related to diesel consumption in harvesting and transportation activities. Moreover, this study considered the direct land use changes, which increase the GHG emissions. However, if the allocation method in GREET is altered in a way that soy oil is considered a sub-product instead of a co-product of soybean production, HEFA results could be improved.

As mentioned above, the WTW results can be divided in WTP and PTW stages. Figure 62 shows the contribution of the WTP and PTW stages to GHG emissions of conventional and alternative jet fuels evaluated in this study, in grams per MJ of fuel. The WTP results for the two alternative jet fuel pathways revealed negative values due to CO_2 absorption from atmosphere in the growth phase of biomass through the photosynthesis process. However, the CO_2 captured during biomass growth can be offset by emissions associated with energy use for biomass farming and collection, fertilizer and nitrogen use in the agricultural stage and fuel upgrading step. As a result, the carbon sequestered in biomass ends up in the fuel and returns to the atmosphere by the fuel combustion in aircraft. Figure 63 shows the contribution of each stage for WTP emissions and the total GHG emissions with the carbon offset. The PTW stage represents the emissions during aircraft operation.

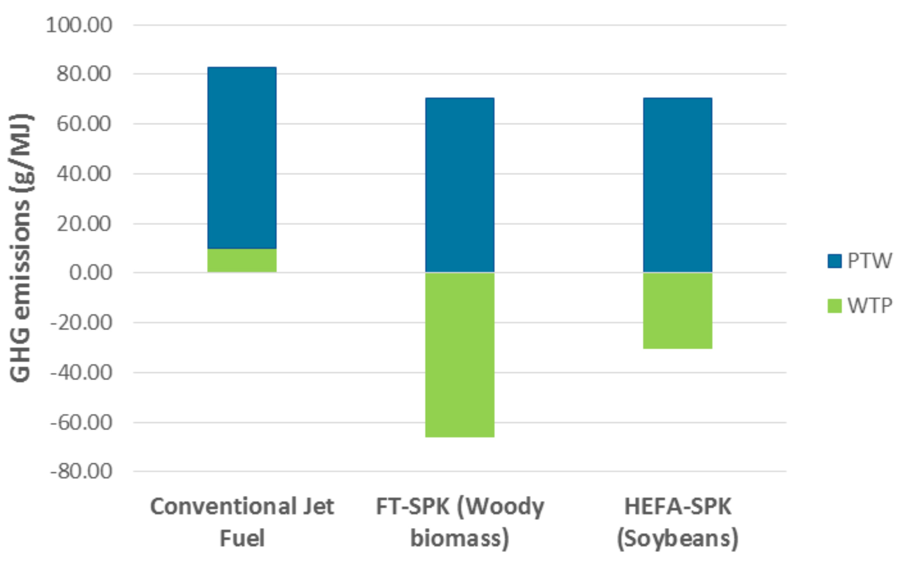

Figure 62: GHG emissions in WTP and PTW stages

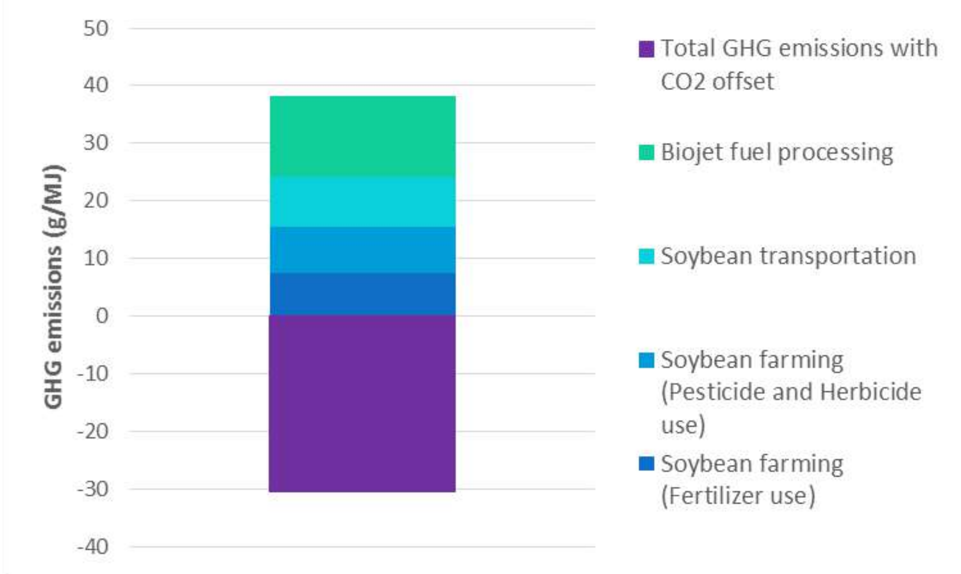

Figure 63: Emissions from different activities in WTP stage and total GHG emissions with carbon offset

The fossil fuel consumption in WTP and PTW stages are shown in Figure 64. The WTP stage of the conventional jet fuel consumes 0.12 MJ of fossil energy per MJ of fuel produced, which is lower than the average of 0.20 MJ/MJ, for the biojet fuels analyzed. The fossil energy consumption for the FT biojet was 0.06 MJ/MJ, while the consumption for HEFA pathway was 0.34 MJ/MJ. Fossil fuel consumption in HEFA pathway is mostly associated with diesel consumption in soybean harvesting and transportation activities. The PTW stage represents the fossil energy consumed during aircraft operation. As there are no fossil energy in biofuels, only the conventional jet fuel registered results for this stage (1MJ/MJ).

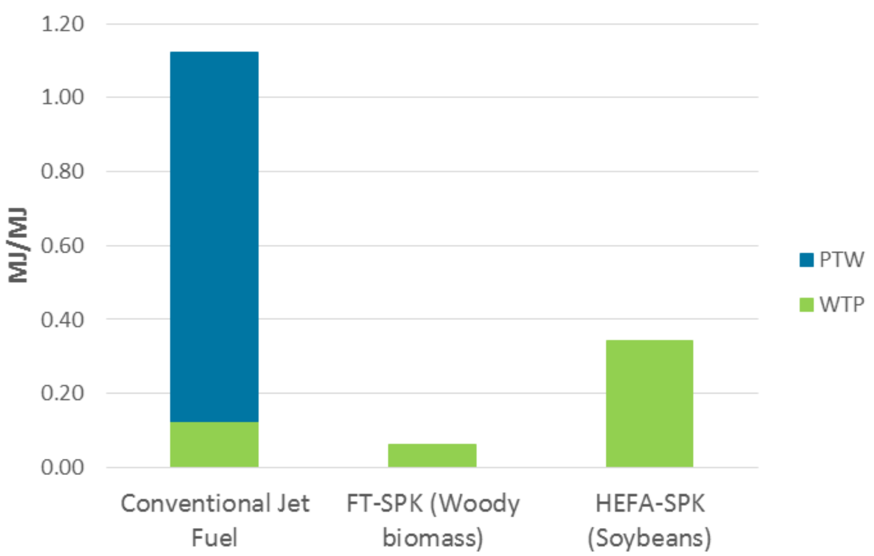

Figure 64: Fossil fuel consumption in WTP and PTW stages

5.3 Techno-economic feasibility of biojet production routes

5.3.1 HEFA-SPK

This section presents the results obtained for the economic analysis of biojet fuel production from HEFA and FT-BTL routes. Data include investment and O&M costs and a sensitivity analysis to evaluate the parameters that contribute most to the biofuel price.

Main results found for HEFA biojet pathway are shown in Table 21, which also contain the levelized costs of fuel (LCOF) obtained for each plant capacity in US$/L.

Table 21: HEFA biojet fuel costs

	HEFA		
	Plant (A)	**Plant (B)**	**Plant (C)**
Plant Capacity (L/day)	348,531	697,061	1,045,592
Capital Costs (US$/yr)	64,976,703	86,635,604	101,074,871
Fixed O&M (US$/yr)	27,625,729	38,795,729	38,814,264
Variable O&M (US$/yr)	220,382,306	440,764,611	661,146,917
LCOF (US$/L)	2.22	2.07	2.05

Results reveal that variable O&M costs are the major contributor to HEFA pathway costs. Annual operational costs for plant (A) totalize US$ 248 million. For plant (B) these costs add up to US$ 480 million, while for plant (C) these values reach US$ 700 million. The O&M costs are mostly related to feedstock purchase (57% to 59%) followed by expenses with natural gas (25%-27%) and electricity (3%). Figure 65 shows the contribution of capital costs, fixed and variable O&M costs to the LCOF. As the variable O&M costs are the main components of fuel production costs, Figure 66 does not include them for a better observation of the technology scale gains. For plant B, results reveal a reduction of 38% in capital costs comparing to plant A, while for plant C this reduction is of 48%.

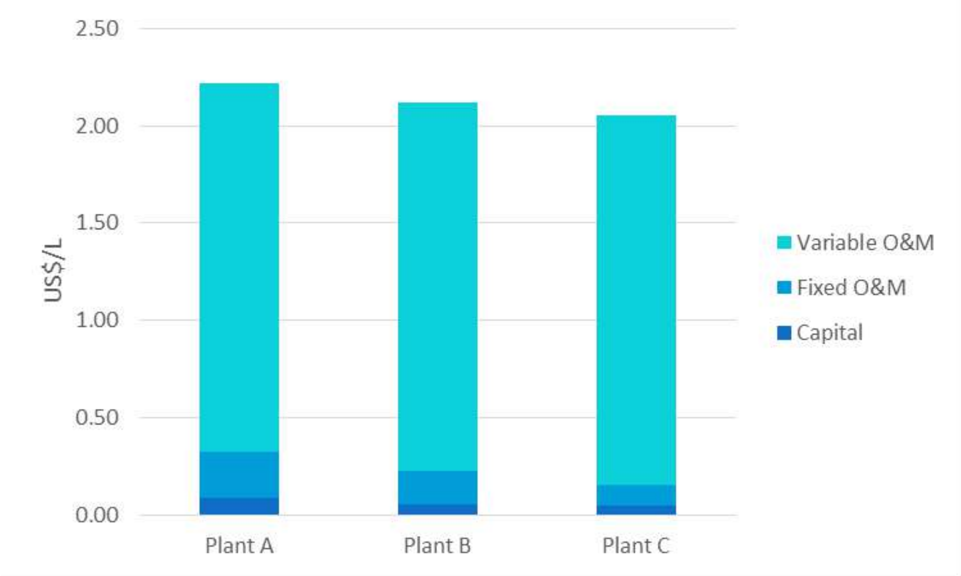

Figure 65: Contributions to HEFA biojet LCOF

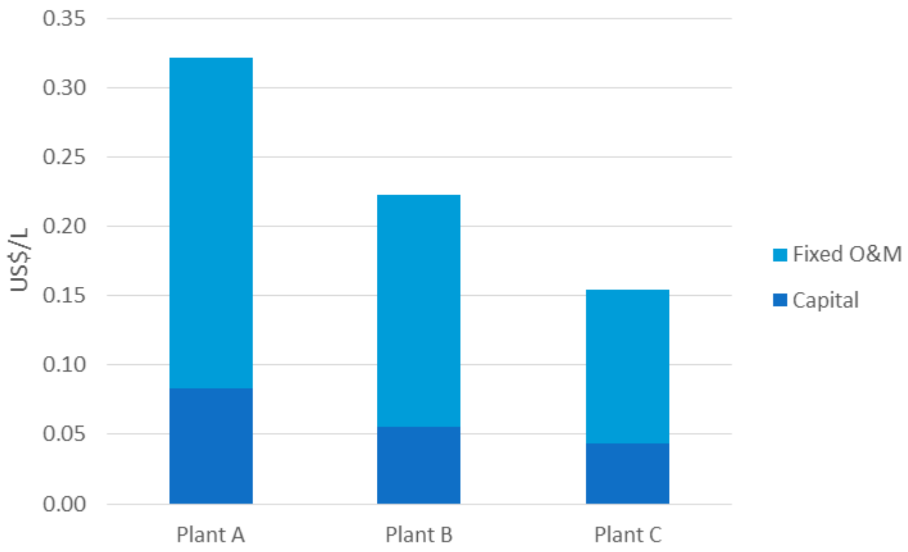

Figure 66: Contributions to HEFA biojet LCOF and technological scale gains.

The HEFA biojet levelized costs obtained for the three plant capacities were far superior than the average jet fuel price in 2014 of 0.71 US$/L (INDEXMUNDI, 2016). In this way, to evaluate the competitiveness of HEFA biofuels, different jet fuel prices were calculated assuming a biomass transport distance of 100 km, different CO_2 prices and the GHG emission obtained in the LCA, whose results are presented in section 5.3. These jet fuel prices represent the prices of the conventional fuel that turns the biofuel competitive. Equation 2 (Eq. 2) shows the calculation made to determine the jet fuel prices. Table 22 above shows the jet fuel prices obtained considering each plant capacity for HEFA biojet production.

$$C_{biojet} - C_{jet} + \$_{CO_2}(E_{biojet} - E_{jet}) + \$_{CO_2} x\, E_{diesel}\, x\, d\, x\, \eta_{biomass} = 0\ (Eq. 2)$$

Where:

C_{biojet}: Biojet fuel levelized cost (US$/l)

C_{jet}: Jet fuel price (US$/l)

$\$_{CO_2}$: Carbon tax or CO_2 price (US$/t$CO_2$)

E_{biojet}: Biojet fuel life cycle emissions (tCO_2e/l)

E_{jet}: Conventional jet fuel life cycle emissions (tCO_2e/l)

E_{diesel}: Diesel emissions by medium and heavy duty trucks (tCO_2e/t.km)

d: Biomass transport distance (km)

$\eta_{biomass}$: Biomass yield (%) (tbiomass/tfuel)

Table 22: Jet fuel determined prices for different HEFA biojet plant capactities.

Biomass transport distance 100 km		**Jet fuel prices (US$/L)**		
		Plant A	**Plant B**	**Plant C**
CO_2 prices (US$/t$CO_{2e}$)	0	2.22	2.07	2.05
	10	2.19	2.05	2.03
	50	2.09	1.94	1.92
	100	1.96	1.81	1.79
	150	1.83	1.68	1.66
	200	1.70	1.55	1.53

The best scenario for the jet fuel price is for a CO_2 price of US$200/t$CO_{2e}$ and considering the plant with greatest production capacity, which leads to a jet fuel price of US$1.53/t$CO_2$. Even in the best case, the jet fuel price is greater than twice of jet fuel 2014 price (US$ 0.71/L). In this way, it is evident that even with technological scale gains and application of mitigation measures such as carbon taxes, the insertion of HEFA biojet fuels in the market would be challenging. To evaluate the difficulties regarding biofuel competitiveness and propose measures to overcome them, this study performed a sensibility analysis to identify the major contributors to the biofuel prices. Variables evaluated include capital costs (CC), variable O&M costs (VOM), CO_2 prices and biomass transport distance. Variations of 10%, 25% and 50% in their values were performed and the three HEFA biojet plant capacities evaluated. Figure 67 shows results for plant capacity A, while Figure 68 and Figure 69 show results for plant capacities B and C.

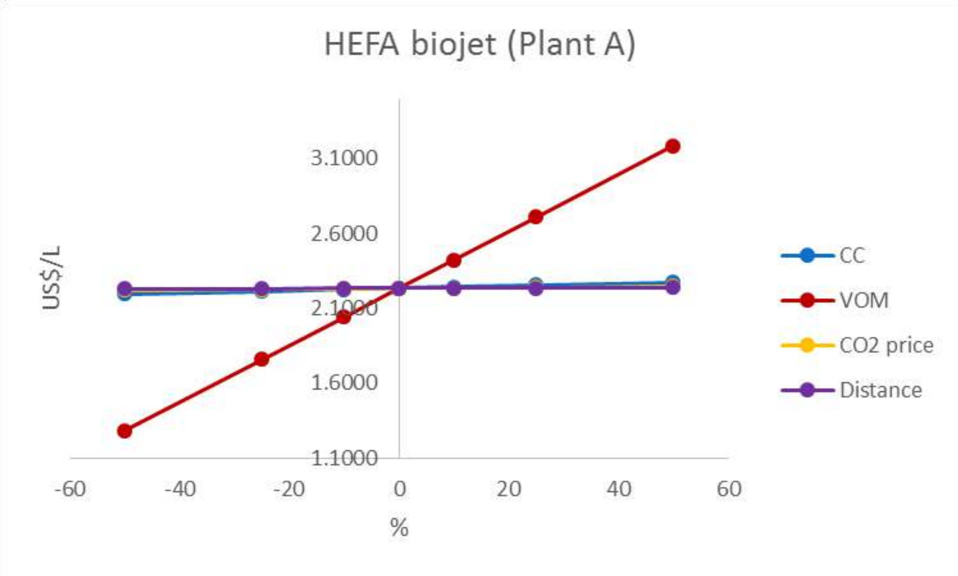

Figure 67: Sensibility analysis for HEFA biojet (plant A)

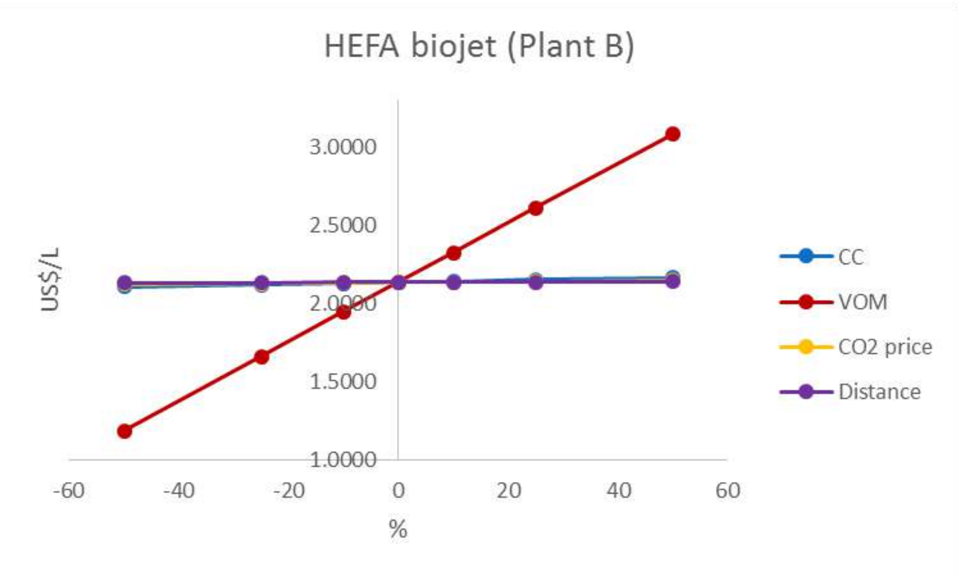

Figure 68:Sensibility analysis for HEFA biojet (plant B)

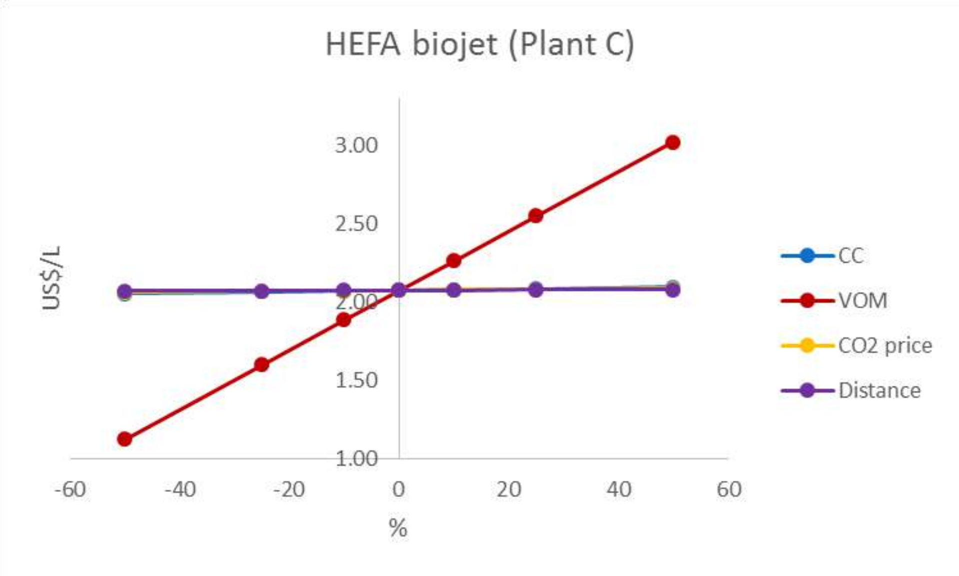

Figure 69: Sensibility analysis for HEFA biojet (plant C)

Results were similar for all plant capacities and the sensibility analysis confirms the influence of variable O&M costs to the biofuel prices. Capital costs, CO_2 prices and biomass transport distance almost did not altered the fuel price. Variable costs for HEFA production are high mostly due to the feedstock price (soybean oil), an edible oil with high added value used also for biodiesel production in the country. Therefore, this poses a major challenge to this technology, since soybean oil price is not directly driven by technological advances in HEFA technology. It can only be indirectly affected through improved performance resulting in less consumption of vegetal oil per biojet produced.

5.3.2 FT-SPK

Regarding FT-BTL pathway, results for capital and O&M costs and levelized costs of fuel (LCOF) for each plant capacity are shown in Table 23 above.

Table 23: FT-BTL jet fuel costs

	FT-BTL			
	Plant A	**Plant B**	**Plant C**	**Plant D**
Plant capacity (L/day)	127,190	158,987	397,468	1,589,873
Capital Costs (Million US$/yr)	148	173	322	834
Fixed O&M (Million US$/yr)	14	15	28	66
Variable O&M (Million US$/yr)	3	4	9	38
LCOF (US$/L) (US$/yr)	0.89	0.82	0.61	0.47

Annual O&M costs for plant A are US$ 17 million, while for plant B, plant C and plant D annual O&M totalize US$ 19 million, US$ 37 million and US$ 104 million, respectively. Majority of variable operational costs are related to biomass transportation (53% to 59%). Figure 70 shows the contribution of capital and O&M costs for the FT-SPK levelized costs. Differently from the HEFA route, for FT-BTL the capital costs are the major influencer in the LCOF. Also, in Figure 70 the scale gains can be clearly observed. In relation to plant A, fuel levelized costs registered a 8% reduction for plant B, 30% for plant C and 45% for plant D. The scale gains become evident by comparing plant A and plant D. The production capacity increases 12 times in plant D in relation to plant A, with a reduction of almost 50% in the fuel levelized cost.

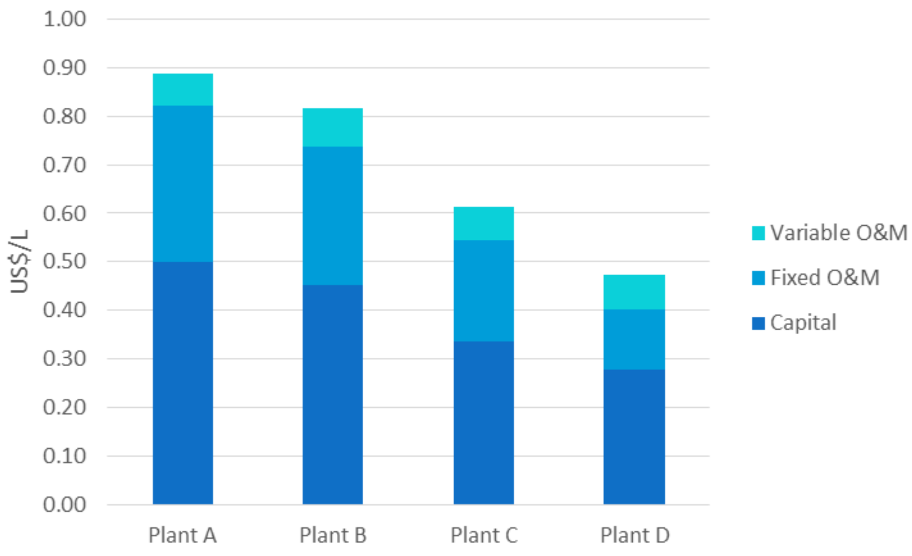

Figure 70: Costs components and technological scale gains for FT-BTL pathway

Results for FT-BTL biojet fuel reveal important technological scale gains. Plants with greater capacities (plant C and plant D) registered lower fuel levelized costs than the 2014 jet fuel average prices of 0.71 US$/L (INDEXMUNDI, 2016). Lower capacity plants (plant A and plant B) had slightly higher levelized costs than the 2014 jet fuel price. However, even with the technological scale gains described above, the jet fuel prices that turns the FT-BTL fuels competitive were determined, as performed for HEFA pathway using equation 2 (Eq. 2). It was assumed a biomass transport distance of 100 km, different CO_2 prices ranging from 0 to 200 US$/t$CO_2$ and the GHG emissions obtained in the LCA presented in section 5.3. Table 24 shows the jet fuel prices achieved according to each plant capacity fof FT-BTL biojet fuel.

Table 24: Jet fuel determined prices for different FT-BTL plant capacities

Biomass transport distance 100 km		**Jet fuel prices (US$/L)**			
		Plant A	**Plant B**	**Plant C**	**Plant D**
CO_2 prices (US$/t$CO_{2e}$)	0	0.89	0.82	0.61	0.47
	10	0.86	0.79	0.59	0.45
	50	0.75	0.68	0.48	0.34
	100	0.62	0.54	0.34	0.20
	150	0.48	0.41	0.21	0.07
	200	0.35	0.27	0.07	-

Determining these jet fuel prices was useful to evaluate the competitiveness of biojet fuel produced by plants with lower capacities. Results in table 24 show that FT-BTL biojet fuel from plant B becomes competitive with a CO_2 price up to US$ 50/tCO_2 that leads to a jet fuel price of US$0.68/L, lower than the 2014 prices. Regarding biojet fuel from plant A, a carbon price between US$ 50-100/tCO_2 makes the biofuel competitive, with a jet fuel price of US$0.62/L, lower than the 2014 price. Therefore, these results indicate that technological scale gains and application of mitigation measures, such as carbon taxes, are capable of promoting biofuel competitiveness in the near future. However, optimization in the technological process is required for large-scale plants, which would also face economic challenges due to high investment costs.

As for the HEFA pathway, a sensibility analysis was performed to identify most influential factors to the biofuel prices. The same parameters (CC, VOM, CO_2 prices and biomass transport distance) were evaluated from variations of 10%, 25% and 50% in their values. The four plant capacities for FT-BTL biojet fuel production were considered. Figure 71 shows the result for plant capacity A, while Figure 72, Figure 73 and Figure 74 show results for plant B, plant C and plant D, respectively.

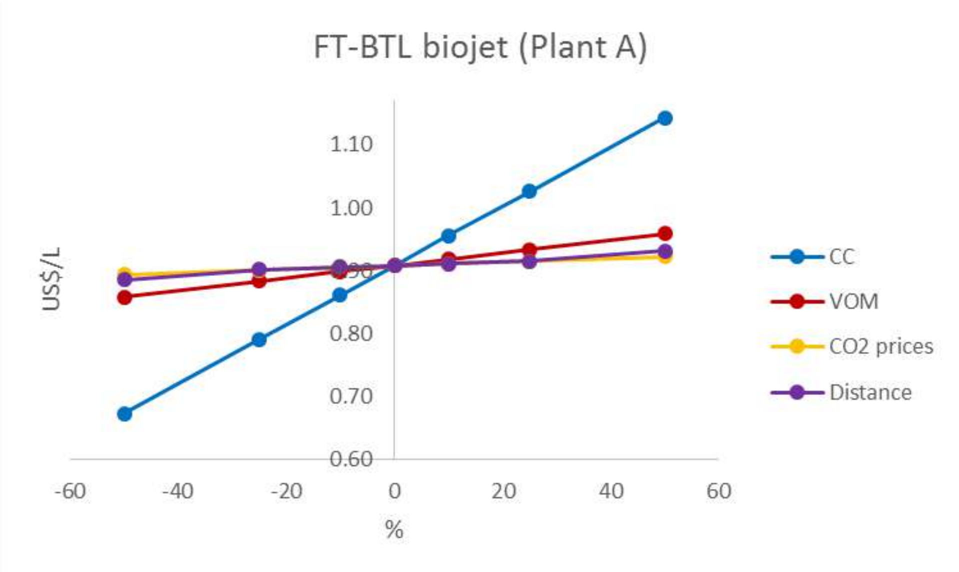

Figure 71: Sensibility analysis for FT-BTL biojet fuel (plant A)

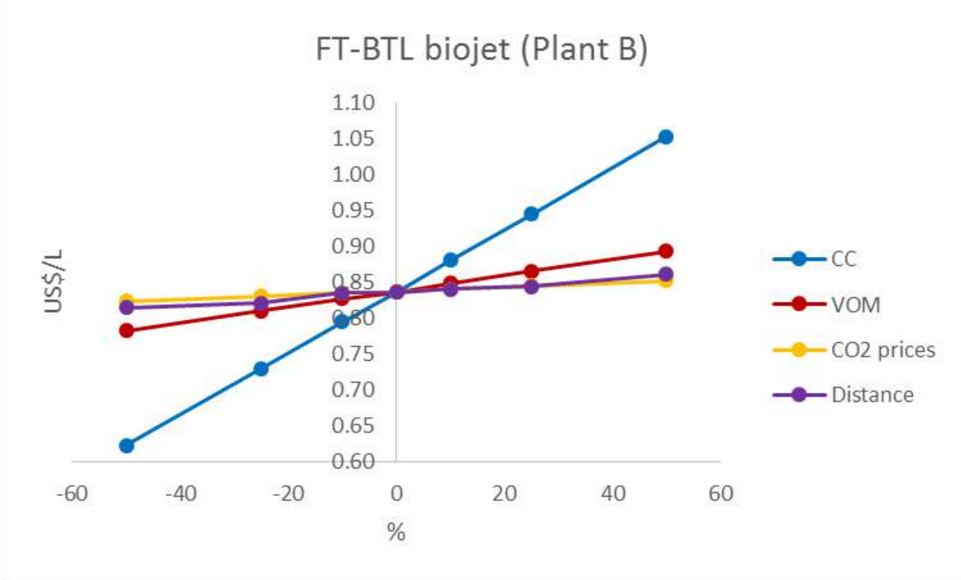

Figure 72: Sensibility analysis for FT-BTL biojet fuel (plant B)

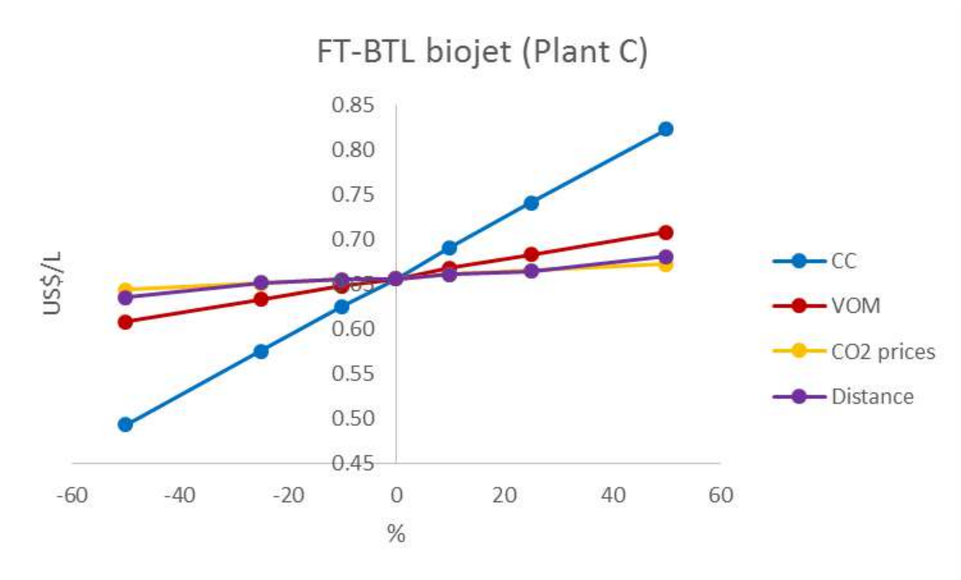

Figure 73: Sensibility analysis for FT-BTL biojet fuel (plant C)

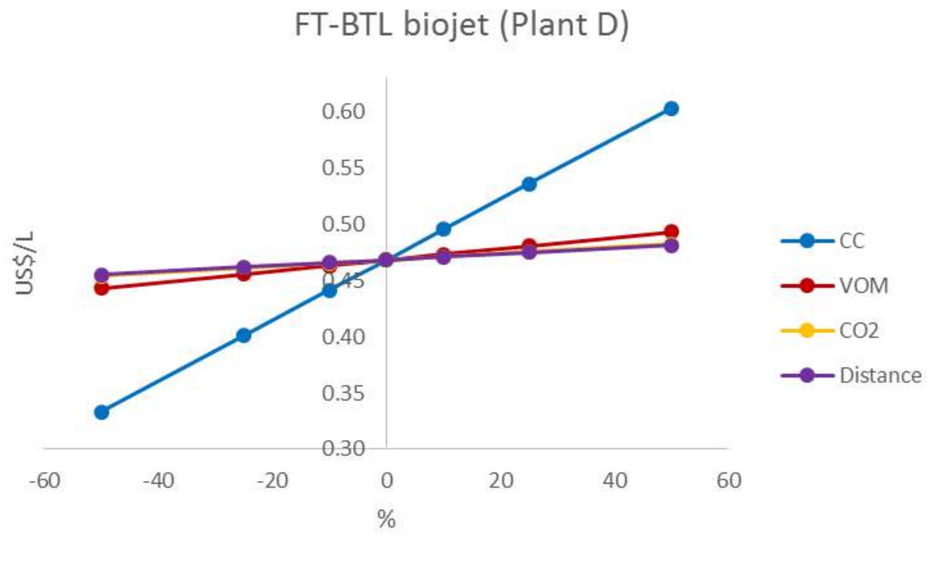

Figure 74: Sensibility analysis for FT-BTL biojet fuel (plant D)

Results for all plant sizes were similar and, differently from HEFA pathway, for the FT-BTL biojet plants the capital costs are the major influencer in the biofuel costs. The application of carbon taxes and the biomass transport distance seem to have minor impact in biojet costs. In this way, the economic analysis revealed that capital costs are the major barrier for FT-BTL biojet development and that the technological improvements are crucial to make larger plants feasible.

The results obtained by the economic and life cycle analysis are useful for determining the abatement costs for each biofuel pathway. Abatement costs were estimated by dividing the fuel levelized cost for the emissions avoided by their use. Lowest GHG abatement costs were found for the FT-BTL pathway, ranging from - US\$ 88.6 /tCO_2 to US\$ 64.4/tCO_2. The LCA has shown that the FT biojet production offers a huge GHG mitigation potential and, for the plants with greater capacity, the abatement costs are negative. For HEFA pathway, abatement costs were bigger, ranging from 871.0 to 979.2 US\$/tCO_2, which is far above the CO_2 prices considered. Although GHG emission reductions for HEFA biojet is lower than for the FT biojet, it still has an expressive mitigation potential. Table 25 shows the abatement costs for HEFA and FT-BTL pathways according to the respective plant capacities.

Table 25: Abatement costs for biojet fuel pathways

Biojet pathways	**HEFA**			**FT-BTL**			
	Plant A	**Plant B**	**Plant C**	**Plant A**	**Plant B**	**Plant C**	**Plant D**
Plant Capacity (L/day)	348,531	697,061	1,045,592	127,190	158,987	397,468	1,589,873
LCOF (US$/L)	2.22	2.07	2.05	0.89	0.82	0.61	0.47
Emissions Reduction (tCO_2/L)	0.002			0.003			
Abatement Costs (US$/$tCO_2$)	979.20	883.87	870.96	64.44	37.95	-36.43	-88.56

5.4 Discussion

This section aims to combine and discuss the results obtained and presented in the previous sections to assess the Brazilian potential of biojet production.

The assessment of feedstock availability revealed an expressive biomass potential in the country, especially in the southeast region and in São Paulo state. The development of biorefineries in these locations would benefit from the proximity to the feedstock and existing infrastructure, reducing logistics issues and transportation costs. The total energy from biomass residues would be more than enough to feed the FT-BTL plants for biojet production. With this total bioenergy, it would be possible to produce an amount of biojet 42% superior than the southeast demand per year. Further, even the bioenergy estimated for each crop in their defined hotspots would be sufficient to feed the conversion plants. Table 26 shows the bioenergy estimated in each crop hotspot and the energy required for each plant capacity for FT-BTL route. Table 27 shows the energy for hotspots located in the Southeast, an estimate of biojet production from each one and a comparison with the jet fuel demand in the region. This comparison indicates that the amount of biojet produced from biomass residues in these localities would be suitable to compose the 50% blends with the conventional fuel. However, these estimates were based in the conversion yields for FT-BTL route based in Elia et al. (2013) that considered forest residues as feedstock. The utilization of other biomass residues would lead to different conversion yields for biojet production. It occurs due to the distinct nature of biomass residues that alter the technical performance of gasification and conversion processes.

Table 26: Bioenergy from biomass residues for each crop and energy inputs for FT-BTL pathway

Hotspots			**FT-BTL**	
Crop	**State**	**Potential (TJ)**	**Biomass input per year (TJ)**	
Total (All crops)	SP	2,202,410	Plant A	1,400
Sugarcane	SP	75,676	Plant B	1,750
Soybeans	MT	33,396	Plant C	4,375
Maize	MT	19,359	Plant D	17,498
	PA	20,452		
Wheat	PA	2,612		
Rice	RS	32,455		
Eucalyptus	SP	40,978		
Pinus	SC	26,472		
Forestry extraction	AC	2,759		
Total agriculture and agro-industrial	SP	78,694		

Table 27: Bioenergy and biojet production with residues in the Southeast region

Hotspots in Southeast Region	**Potential (TJ/year)**	**Biojet production (million L/year)**	**Southeast Jet fuel demand (million L/ year)**	**Biojet production / Southeast jet fuel demand**
Total (All crops)	2,202,410	6,663	4,700	1.49
Sugarcane	75,676	2,289		0.49
Eucalyptus	40,978	1,240		0.26

On the other side, HEFA route would benefit from biomass potential in the Midwest region that concentrates soybean and maize (oilseed feedstocks) bioenergy hotspots and hosts soybean oil refineries and biodiesel plants, indicating an existing industrial infrastructure in this place. In addition, the local concentration of soybean and maize residues would benefit the feedstock supply over the year and diminish issues regarding biomass storage, due to the seasonality of these crops. Figure 75 shows the production profile of these crops over the year and reveals their complementarity.

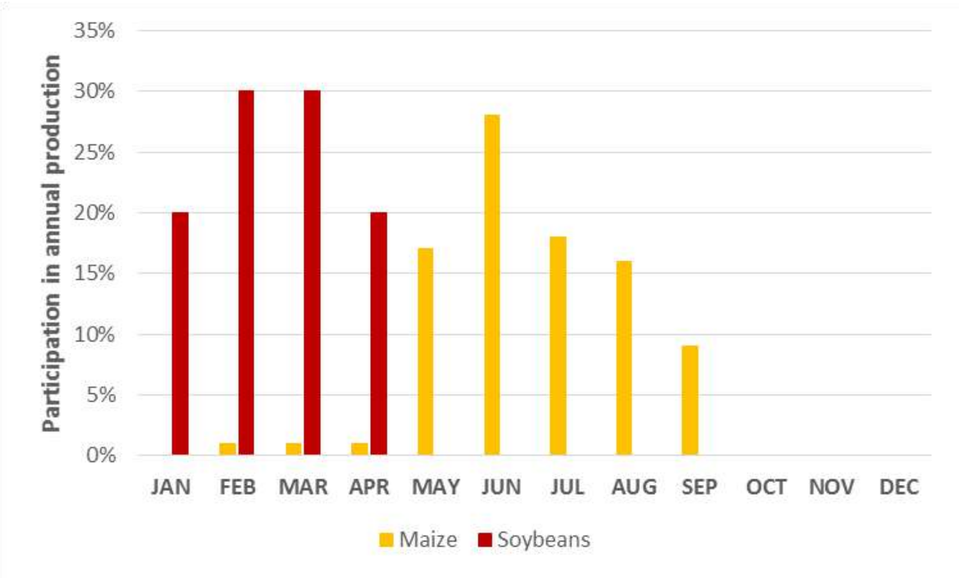

Figure 75: Soybean and maize annual production profile

Further, this study assessed potential localities with an existing infrastructure that would benefit biomass harvesting and logistics, but did not evaluate their specific issues that may alter the fuel production costs. First, the method to collect the biomass residues in the field was not defined. This decision requires the analysis of some variables such as which technology to use, the maximum amount allowed for harvesting, energy consumption, among others. These variables lead to uncertainties on biomass production, which may increase feedstock costs due to premium risk payments to the farmers (OLIVEIRA, 2011). Second, this study did not define in which way the residues would be stored. Biomass storage aims to ensure a continuous supply of feedstock and smooth seasonality. Different storage methods are available and all of them present losses, given different feedstock nature, time and storage conditions (OLIVEIRA, 2011). Finally, the possibility of biomass pretreatment may reduce logistic costs if performed prior to transport and storage. This process aims to produce a higher energy density feedstock, improving the transport and conversion conditions. For this reason, the definition of potential conversion localities was given according to the density of production and the existing infrastructure in the country.

Regarding the life cycle analysis, both HEFA and FT-BTL pathways revealed important reductions in GHG emissions and fossil fuel consumption indicating that the country could produce biofuels that reduce the environmental impacts from aviation. All evaluated biojet routes show a fossil fuel dependence inferior then 1, which reinforces the fact that these fuels are derived from a renewable source. Results obtained in this study were compared with another LCA of biofuels for aviation available in literature. Stratton et al. (2010) and Elgowainy et al. (2012) performed a LCA in GREET model for alternative aviation fuels, while Bailis et al. (2010) analyzed the GHG emissions and LUC from *jatropha curcas*-based jet fuel in Brazil.

Likewise in this study, Elgowainy et al. (2012) found increased fossil fuel consumption in the WTP stage for alternative fuels. In their work, the conventional jet fuel registered a fossil consumption of 0.18 MJ/MJ, while results for FT-BTL and HEFA were 0.70 MJ/MJ and 0.25MJ/MJ. Regarding GHG emissions, results found from Elgowainy et al. (2012) revealed a reduction of 70% and 85% for HEFA and FT-BTL biojet fuels in relation to the conventional fuel, respectively. Stratton et al. (2011) found reductions in GHG emissions of 58% for HEFA from soybeans with no LUC and 80% from FT-BTL from forest residues. In addition, they modelled a scenario considering LUC for soybean production and results indicate an increase of 12% in GHG emissions for HEFA biojet in relation to the conventional jet fuel. The LUC considered was associated with the conversion of grassland to soybean fields, while this study considered LUC from savannah (cerrado) conversion to soybean fields. Bailis et al. (2010) performed a LCA for biojet fuels in Brazil. However, the feedstock chosen for the HEFA pathway was the bio-oil from *jatropha curcas*. The results obtained with no LUC considerations revealed a reduction of 55% in GHG emissions compared to the conventional jet fuel. However, when LUC from savannah conversion to soybean fields were considered, the results indicate an increase of 60% in GHG emissions in relation to the conventional fuel. Table 28 and Figure 76 compare the results for GHG emissions of alternative fuels from the studies cited above and from the present study.

Table 28: GHG emissions for different biojet LCA studies

GHG emissions (g/MJ)		
This study	HEFA (Soybeans) (LUC)	40.09
	FT-BTL (Forest residues)	4.72
Stratton et al (2010)	HEFA(Soybeans) (NO LUC)	37.00
	HEFA(Soybeans) (LUC)	97.80
	FT-BTL (Forest residues)	12.20
Bailis et al. (2010)	HEFA (Jatropha) (NO LUC)	40.00
	HEFA (Jatropha) (LUC)	141.00

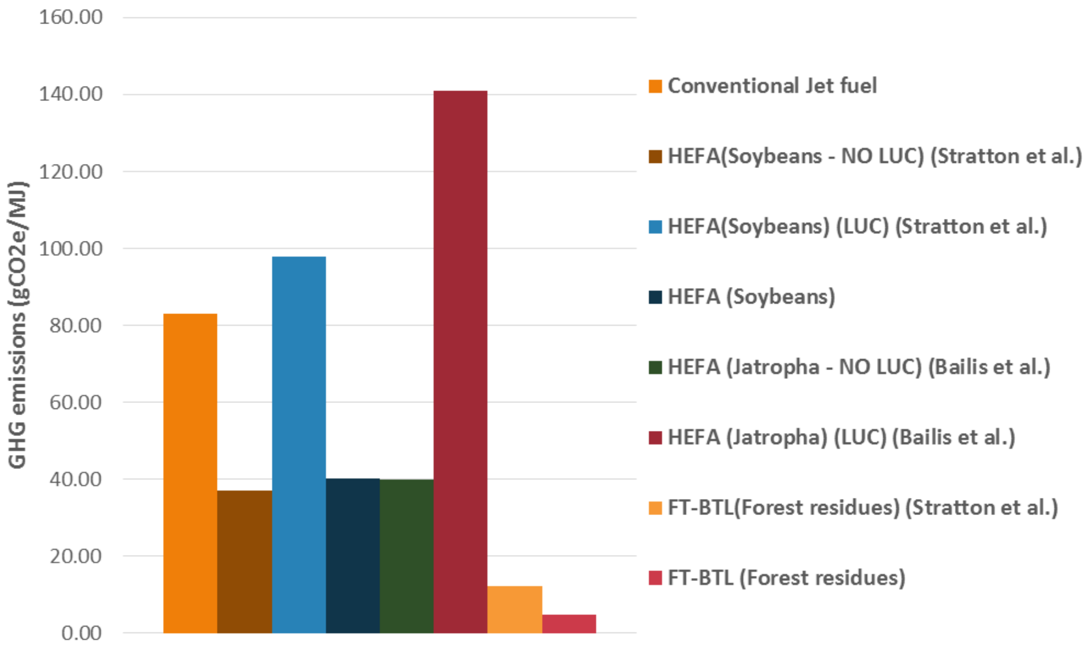

Figure 76: GHG emissions for different biojet LCA studies

The choice of allocation methods in GREET can significantly impact on the LCA results, as discussed in Huo et al. (2008) and Han et al. (2014). For fuels derived from vegetable-oils, the results can be affected by the co-product handling method because: (i) co-products are produced in two separate processes and (ii) a large amount of meals is produced during oil extraction. Since the production of soybean based fuels generates various co-products, including protein soymeal, glycerin and energy products as propane fuel mix and heavy oils, addressing credits for each of them is quite difficult (H. HUO, M. WANG, C. BLOYD, 2008). This study chose an energy-based allocation method as the hydrotreating process coproduce hydrocarbon fuels. The choice of a mass-based-allocation method to deal with co-products would be considered because: (i) an energy-based allocation is not representative for meals, since they are not energy products, and (ii) mass is not subject to fluctuations as in the case of market-based-allocation. The market allocation method is based on the market values of the primary products and co-products and, as these values vary by region and over time and biojet fuel is not already in the market, this method would not be suitable for this analysis (HAN et al., 2014).

Some points regarding the environmental sustainability of the biofuels assessed should be highlighted. First, in relation to HEFA pathway, the competition for resources may compromise its environmental performance and threat country's biodiversity, as soybeans has already important uses in the country. The expansion of soybean cropland and castle pastures, pushed mainly by the higher demand for biofuels (biodiesel), contributes to increase the pressure on the Brazilian savannah (*cerrado*) and the Amazon forest, ensuing in indirect and direct land use changes and impacting climate change (PORTUGAL; KOBERLE; SCHAEFFER, 2016). However, as discussed in Rathmann et al. (2010) and Rathmann et al. (2012), the relation between land use and agro-energy and biofuels production are extremely complex being influenced by endogenous and exogenous variables (RATHMANN; SZKLO; SCHAEFFER, 2010, 2012). Stimulating biojet development would require an expansion in soybean production, either by replacing other crops or expanding to marginal areas, leading to environmental and social impacts. Uncertainties regarding the land use change factors used are explained by the intrinsic complexity in land use dynamics driven by agro-energy production. In principle, arable lands converted to soybean cropland do not lead to direct deforestation, while its production in marginal lands may induce the removal of native soil vegetation. Prudêncio et al (2010) assessed the land use change due to soybean cropland in Brazilian savannah and considered that 3.4% of soybean cropland areas were derived from savannah, without distinguish arable and marginal lands. As GREET model also do not require this kind of distinction, this study used this factor as an average representation of the portion of soybean cropland derived from savannah.

Second, some environmental indicators, such as water footprint, were not assessed. The substitution of fossil fuels by biofuels requires an increase in agricultural production, which requires large fresh water demands. Depending on the location, crop and growing conditions, the water requirements in farming stage vary significantly (GERBENS-LEENES; HOEKSTRA; VAN DER MEER, 2009). This is another reason that makes the utilization of biomass residues so advantageous, as it does not require an increase in agricultural production, besides being highly available in the country. However, for both pathways, additional water is also required in the conversion processes as, for example, reforming reactions and hydrogen production, which increases the water consumption in the biofuel life cycles (BERNDES, 2002).

The economic analysis results indicate that biojet fuels from the HEFA and FT-BTL pathways are yet to be competitive and only the FT-BTL plants with greater capacities reached competitiveness with the conventional jet fuel. However, due to the absence of taxation for jet fuel, an increase in oil prices directly reflects the cost of jet fuel for airline companies (EUROPEAN PARLIAMENT, 2009). This direct correlation becomes evident by analyzing the annual variations in oil and jet fuel prices in the past years. Figure 77 presents the historical European Brent Spot and U.S Kerosene-type jet fuel prices between 2000 and 2015 according to U.S Energy Information and Administration data (EIA, 2016a, 2016b). Jet fuel has seen its mark-up over crude oil prices rising from US$ 0.03/L in 2002 to US$ 0.20/L in 2008. Also, IATA assumes jet fuel prices will remain 24% higher than crude oil prices in the medium-term (EUROPEAN PARLIAMENT, 2009). The fluctuations in oil prices and the high sensitivity of jet fuel prices add uncertainties regarding fuel prices and represent an opportunity for alternative fuels to become more competitive. Also, in view of the agreements already defined by the aviation industry, which is committed to reduce GHG emissions and develop alternative sustainable fuels, the competitiveness must actually take place between the biofuels, so that the most suitable production route is chosen. In this way, the different aspects that challenge each route development should be identified, so that the one with major potential of development according to local conditions is selected.

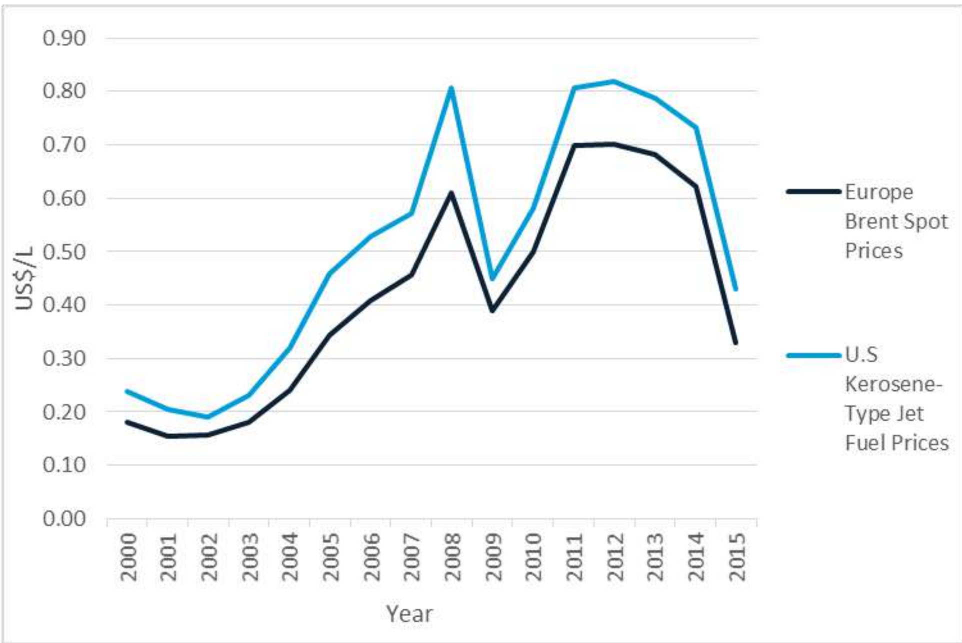

Figure 77: Historical crude oil and jet fuel prices

The HEFA fuel economic analysis revealed high fuel levelized costs, even for plants with large production capacity. The high fuel costs are mainly associated with the feedstock costs, as soybeans oil is a high value product with another competitive uses. Soybean is a valuable commodity and its price is strongly correlated with the amount of protein of soybean meals used in livestock feed. In the last decade, the increased demand for meat, partly driven by emerging economies in Asia, has ramped up the market price of soybeans. Soybean oil itself is just as expensive as jet fuel and other energy uses, for instance for biodiesel production, may also increase its price. In addition, biodiesel use in Brazil will increase to 10 percent in 2019, which would compromise the soybean oil availability (ANP, 2016b; USDA, 2016). The utilization of residual oils and fats, as used cooking oil (UCO) and tallow would diminish issues related to feedstock expenses. However, these feedstocks require additional pre-treatment processes, which may increase the capital costs.

Regarding FT-BTL pathway, for plants with large capacities, the biofuel registered lower levelized costs than the conventional jet fuel. The economic analysis revealed high capital costs, which is the main challenge to its development. The high CAPEX is mainly associated with biomass gasification units, a complex process that requires optimization for large-scale developments. In this way, substantial efforts should be conducted to optimize the process in order to reduce the capital costs. As the most suitable feedstock for this process is lignocellulosic biomass, the utilization of biomass residues, which is a low-cost feedstock with high availability in Brazil, enhance its feasibility in the country.

The economic analysis performed relies on a n^{th} plant estimate or nth of a kind (NOAK), which considers a mature and well-established technology available at commercial scale. This kind of evaluation tends to underestimate the capital costs and overestimate the plant performance if compared with values observed for first-of-a kind plants (FOAK) (DE JONG et al., 2015; MERROW; PHILLIPS; MYERS, 1981; MORRISON et al., 2016). According to de Jong et al. (2015), as biojet fuel production is a novel industry, pioneer plants estimates seem more appropriate to assess the short-term economic feasibility of biojet production pathways. Also, their study considered that the integration between industrial processes would reduce biojet fuel costs. This integration could be established through four degrees based on greenfield, co-locating, retro-fitting and repurposing strategies. Their results found a reduction of 4%-8% for n^{th} plants and 5-8% for pioneer plants by adoption of co-production strategies. For FT-BTL biojet, they found that total capital investment for pioneer plants would be 2.2 times higher than for NOAK plants (DE JONG et al., 2015).

6. Conclusion

This study sought to evaluate the technical and economic potential for biojet production in Brazil and determine potential localities for its production in the country. Further, the competitive opportunities for a growing market have been assessed and the cost effectiveness of different technological routes identified. To this end, indicators like feedstock availability, technological development of production routes, levelized costs of production, dependence on fossil fuels and GHG emissions were developed. The crops considered to determine feedstock potential were soybeans, sugarcane, maize, wheat, rice, eucalyptus, pinus and forest residues. Among different available production routes, the Fischer-Tropsch Biomass-to-liquids (FT-BTL) and Hydroprocessed Esters and Fatty Acids (HEFA) pathway were chosen given their technological maturity and approval by ASTM specifications. Then, their environmental performance were evaluated through a life cycle analysis performed in GREET model.

Feedstock availability analysis revealed that besides being relatively inexpensive, the biomass residues are widely available in the country and totalized an expressive energy potential (3,932 PJ/year). This potential is mainly concentrated in the South, Southeast and Midwest regions, and residues from sugarcane and soybeans showed major contribution among all the crops analyzed. The software QGIS were useful to evaluate the energy distribution in each municipality. The most energy-intensity localities were identified through the construction of kernel maps, which emphasized the significance of South and Southeast regions, especially the São Paulo state that hosts most of this energy. These maps were useful to define the bioenergy hotspots considering each crop individually and the total biomass residues. Their analysis revealed that São Paulo state contains four bioenergy hotspots. Further, it also concentrates important localities of jet fuel production, distribution and use as well as an established infrastructure of feedstock handling for biofuels production. Alternatively, the establishment of biorefineries in isolated locations is also a possibility in the country. This is the case of Midwest region, which concentrates the greater bioenergy potential from soybean and maize residues and depends of external jet fuel supply. Bringing together the results obtained in the feedstock availability analysis, the expressive potential for biojet production in Brazil is confirmed, being São Paulo state the most expressive location for a biorefinery establishment.

The LCA performed in this study revealed important reductions in GHG emissions and fossil fuel consumption, as the two alternative fuels evaluated showed considerable reductions. The best case was for FT pathway from forest residues, with a 94% reduction in GHG emissions and fossil fuel consumption in relation to conventional jet fuel. The HEFA route totalized a reduction of 52% in GHG emissions and 69% in fossil fuel consumption. The GHG emissions from HEFA pathway are mostly associated with soybean farming and collection, fertilizer and hydrogen use for fuel upgrade, whilst fossil fuel consumption is related to diesel consumption in harvesting and transportation activities. Furthermore, both biojet pathways evaluated registered fossil fuel consumption below 1MJ/MJ, which reinforces that these fuels are, in fact, renewables. Comparing the results with other studies that performed a LCA for biojet production in other localities were useful to confirm the advantages for biojet production in Brazil. However, important environmental indicators such as impacts in biodiversity and water usage were not considered, which may compromise the sustainability of these biofuels.

Results of the economic analysis indicate that biojet fuels from the HEFA and FT-BTL pathways are yet to be competitive with the conventional jet fuel, being advantageous only for the FT-BTL route with greater capacities and considering NOAK plants. Levelized costs for FT-BTL biojet vary from US$ 0.47/L to US$ 0.89/L according to four different plant capacities that produce from 42 to 529 million liters per year. Expressive technological scale gains were observed for plants with greater capacities; however, the high capital costs are the major barrier to their development. The application of carbon taxes increases the competitiveness of fuels produced by lower capacity plants. In addition, a great advantage of this pathway is the possibility of using biomass residues as feedstock, a low cost resource widely available in Brazil. Results for HEFA biojet vary from US$ 2.05/L to US$ 2.22/L for plants producing 116 to 348 million liters per year. These costs are mostly driven by feedstock expenses, as soybean oil is a valuable product with another competitive uses. In this way, the utilization of residual oils and fats represent an opportunity to reduce feedstock costs. Even the application of carbon taxes varying from 50 to 200 US$/t$CO_2$ were not enough to make the HEFA biojet competitive. Nevertheless, uncertainties regarding the jet fuel price, which is strongly correlated with the crude oil price, may offer a competitive opportunity for the aviation biofuels. In addition, as the aviation industry is committed with the development of alternative sustainable biofuels, diverse incentives are expected to encourage its development in the near future.

In view of the results presented above, it is remarkable that Brazil has great comparative advantages to establish a growing market for biojet fuel production. The country is capable to produce great amount of biomass residues that provide enough energy to feed biojet fuel production facilities. Assessing the dispersion of these energy resources in the country indicated an expressive concentration in the state of Sao Paulo, which also hosts important localities of fuel production, distribution and consumption as well as feedstock handling. In addition, the country's technical experience in agriculture and industry makes it an attractive environment to begin a biojet fuel industry worldwide. Considering the use of biomass residues for the fuel production eliminates concerns regarding food security and land availability. Further, it should be noticed that there is not an exclusive and ideal feedstock to produce this biofuel in Brazil. This is the reason why this study evaluated the total bioenergy potential from residues of all crops selected. Using a mixture of different feedstock ensures adequate availability and scale production. Furthermore, beyond the great feedstock availability in Brazil, the biofuels produced according to the country's conditions registered expressive reductions in GHG emissions and fossil fuel consumption. In this way, is seems that the most critical feature hampering a growing market for biojet fuel is the economic feasibility for its production. Efforts in R&D are essential to promote the viability of sustainable production pathways, especially the pioneer ones such as the FT-BTL.

Despite the efforts to conduct an accurate analysis of biojet fuel potential in Brazil, this study presents limitations that should be revised in future works to enhance results reliability. First, regarding the evaluation of bioenergy potential, the residue to product ratio and residue removal ratio are site specific and should be adjusted to Brazilian farming characteristics, instead of being assumed according to theoretical values. The density of residues was considered uniform in each municipality when, actually, they are heterogeneously concentrated. The biomass transport distance of 100 km was considered. However, this distance may be affected by logistic and infrastructure limitations. Still, some issues associated with biomass residues harvesting and logistics such as, collection method, storage and pretreatment were not considered. Secondly, limitations of the environmental analysis is that some sustainability indicators like water usage and impacts in biodiversity were not evaluated and the distribution activities of biojet fuels were not considered, which may affect their environmental performance. Also, the choice of different allocation methods in GREET model can improve LCA analysis results. Thirdly, the reforming of naphtha, a co-product of both HEFA and FT-BTL pathways, is a possibility that was not proposed. This process produces hydrogen, which is an essential input for fuel upgrading, and/or aromatics that would be useful to compose a 100% biojet fuel blend. Additionally, the cost estimates for biojet production pathways relies on literature data that are not based in Brazilian conditions, as these technologies are not available in the country yet. These estimates also relies on n^{th} of a kind plant, which may underestimate the capital costs and overestimate its performance. Finally, only two production pathways were assessed. The ATJ and STJ routes may be relevant in view of the fact that the country already has a well-established ethanol production from biomass. Also, considering future changes in urban mobility, in which ethanol may lose its market in the automotive transport, it may be available to feed biojet fuel plants.

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