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Techno-economic and environmental assessment of renewable jet fuel production in integrated Brazilian sugarcane biorefineries

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HIGHLIGHTS

- Integrated biorefineries for year-round production of renewable jet fuel (RJF).
- Assessment of three RJF production routes with ASTM approval.
- On-site H_2 production *via* water electrolysis with bioelectricity from sugarcane.
- HEFA with highest RJF production potential, while FT with best economic indices.
- RJF with > 70% reduction in greenhouse gas emissions in relation to fossil jet fuel.

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ABSTRACT

The use of renewable jet fuel (RJF) in substitution to fossil jet fuel is one of the main initiatives towards the reduction of impacts derived from carbon emissions by airline operations. This study compares different routes for RJF production integrated with sugarcane biorefineries in Brazil. Eight scenarios with sugarcane mills annexed to three ASTM – approved RJF production technologies, i.e. Hydroprocessed Esters and Fatty Acids (HEFA), Fischer-Tropsch Synthesis (FT), and Alcohol to Jet (ATJ), were assessed. Host mills were considered to crush four million tonnes of sugarcane/year and recover straw from the field. In the designed scenarios, HEFA routes processed palm, macauba, or soybean oils, while FT conversion was based on gasification of either sugarcane or eucalyptus lignocellulosic material, and ATJ converted isobutanol or ethanol into RJF. The biorefineries were assessed in terms of both economic and environmental performance, as well as towards their capability of substituting 5% of the consumption of jet fuel in Brazil in 2014 (equivalent to 375 million L/year). Considering the evaluated scenarios, HEFA-based biorefineries yielded the highest RJF production capacities: a single plant processing palm oil could supply 267 million L RJF/year (71% of the defined target). FT biorefineries presented the best economic performances, producing RJF at competitive cost but with a relatively low output. Finally, all conversion technologies were capable of producing RJF with low climate change impacts, with reductions of over 70% when benchmarked against fossil jet fuel. Carbon mitigation targets of the Brazilian aviation sector are further explored in this paper, showing the dimension of the effort in the coming years for fossil jet fuel replacement in commercial flights. The availability of sugarcane and other biomasses in the country makes Brazil a potentially important player for the deployment of large-scale projects with reasonable RJF market prices and reduced CO_2 emissions for both internal and external markets.

1. Introduction

Most scientists around the world agree that climate change is real and that anthropogenic greenhouse gases (GHG) emissions are at the root of this issue. According to recent estimates, airline operations were responsible for 2% of such carbon emissions in 2012 [1]. Among actions established by the aviation sector towards lowering the carbon footprint of the sector, three measures initially set for international

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flights within the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) mechanism stand out: (1) improving fleet fuel efficiency by 1.5% per year until 2020; (2) stabilizing emissions from 2020 onwards through carbon-neutral expansion; and (3) halving carbon emissions in 2050 in comparison to 2005 levels [2]. Since turbines and aircrafts are already highly efficient [3] and 80% of the emissions come from long-haul flights (which cannot be replaced by alternative transport options) [2], the bulk of the transition will come from the adoption of low-carbon jet fuel derived from biomass.

Conventional jet fuels, usually commercialized under A/A-1 (civil) and JP-8 (military) grades, are produced from crude oil, although ASTM International and other standards organizations also specify the synthesis of alternative jet fuels. Four of the five currently approved routes produce alternative jet fuel exclusively composed of paraffinic hydrocarbons (linear, branched, and cyclic), denominated Synthesized Paraffinic Kerosene (SPK). For use in turbines, SPK must be blended with fossil jet fuel in proportions ranging from 10% to 50%, depending on the conversion route used to obtain it [4]. A single pathway for the production of alternative jet fuels comprising both paraffinic and aromatic compounds, denominated Synthesized Paraffinic Kerosene plus Aromatics (SKA), is also permitted by the organization. Although the mixing of SKA with conventional jet fuel up to 50% is mandatory, such routes tend to focus its application at a longer time horizon. Since this type of jet fuel presents a more similar composition to its fossil counterpart, it could theoretically dismiss blend requirements. In short, the five conversion routes approved by ASTM International (as of September 2017) are: Hydroprocessed Esters and Fatty Acids (HEFA-SPK), which processes vegetable oils and animal fats into hydrocarbons; Fischer-Tropsch Synthesis (both FT-SPK and FT-SKA), in which different feedstocks undergo gasification and further catalytic synthesis to a wide range of hydrocarbons; Alcohol to Jet (ATJ-SPK), which converts isobutanol (and, potentially, other alcohols) into hydrocarbons; and Synthesized Isoparaffins (SIP-SPK), which produces jet fuel-like molecules through fermentation of carbohydrates [4]. Feedstocks for alternative jet fuels include either fossil resources, such as coal, natural gas, and shale oil, or biomass, in the form of lignocellulosic material, lipids, alcohols, and simple carbohydrates. For the remainder of this study, only alternative jet fuels obtained from biobased feedstocks are considered, henceforth referred to as renewable jet fuel (RJF).

The employment of RJF in civil aviation appears to be the best short-term solution for the mitigation of aircraft emissions. Use of RJF in commercial flights is already a reality, mostly after 2008 [5], although still on a modest scale. Recent examples include a series of 80 flights by KLM in Embraer E190 aircrafts from Oslo to Amsterdam employing *Camelina sativa*-based RJF produced by Neste through HEFA processing [6]. Unlike other biofuels, namely biodiesel and bioethanol, worldwide RJF utilization currently lacks incentive mechanisms [7], which are vital for the deployment of industrial units [8].

At present, Brazil is short of a clearly defined national policy to promote the use of RJF, despite recent movements concerning this possibility [9]. Brazil will be obliged to join the CORSIA instrument from 2027 onwards. Within its scope, it is estimated that around 1.5 million tonnes of CO_2 emissions will have to be avoided by 2030 to promote carbon-neutral expansion of international flights originating in the country alone. Besides, as a signatory of the Paris Agreement (COP-21), Brazil established an aggressive Nationally Determined Contribution (NDC) towards cutting GHG emissions. In the aviation sector, the carbon-neutral growth of the entire sector in the country starting in 2020 will require aviation to mitigate between 8.3 and 12.4 million tonnes of CO_2 emissions in 2030 [10]. Other nations, such as China, have also ratified challenging goals to reduce the carbon intensity of civil aviation up to 65% and peak emissions by 2030 [11]. Besides, the European Union has set shorter-term goals aiming at the displacement of 4% of fossil fuel consumption in 2020 – roughly equivalent to 2 million tonnes of RJF [12].

In order to tackle such ambitious goals, Brazil shows a prolific panorama in terms of renewable energy production and biomass cultivation. One crop is specially cultivated for energy purposes: sugarcane, mostly converted into ethanol, sugar, and electricity. Ethanol distilleries can act as host plants for a series of integrated processes for biobased products, ranging from biodiesel [13] to bio-propylene [14], succinic acid [15], microalgal biomass [16], and advanced biofuels [17–19], among which RJF production is comprised. Sugarcane mills can supply electricity, process steam, and raw materials to integrated industrial conversion units, thus consisting in a good example of a true biorefinery concept. The main objective of establishing integrated biorefineries is to profit from process integration advantages to leverage one promising, incipient technological route with inputs of materials, energy, and other utilities coming from a consolidated, more robust plant. This is the case when using outputs from a sugarcane mill to supply an RJF production plant so that the latter can achieve better operational stability and economic performance, as well as lower environmental impacts. Although such biorefinery alternatives are not currently common in the country, their potential for RJF production should be evaluated so as to provide accurate and quantitative information to decision-making processes.

For the estimation of the potential of adding RJF production to the sugar-energy sector, techno-economic and environmental analyses of technological alternatives must be carried out. The work presented herein was developed by the Brazilian Bioethanol Science and Technology Laboratory (CTBE), in partnership with Embraer S.A. and The Boeing Company, concerning the possibility and feasibility of RJF (within SPK specification limits) production in the Brazilian context from different feedstocks in integrated biorefineries with ethanol distilleries. The Virtual Sugarcane Biorefinery (VSB), an innovative framework developed by CTBE [20], was employed in the sustainability assessment of different biorefinery alternatives. This study considered the establishment of completely self-sufficient biorefineries, i.e. which only take different types of biomass (sugarcane stalks and straw, eucalyptus, and vegetable oils) as main inputs and do not rely on external energy supply (e.g. electricity, natural gas, or other energy sources) for operation. Three production routes were analyzed, following their relevance in a worldwide context and their potential of large-scale deployment in Brazil: HEFA, FT, and ATJ [21]. In the designed scenarios, HEFA routes processed palm, macauba, or soybean oils, while FT conversion was based on gasification of either sugarcane lignocellulosic fractions or eucalyptus, and ATJ converted isobutanol or ethanol into RJF. All work was developed with data from both scientific and open literature, and with CTBE's know-how on Brazilian sugarcane biorefineries. The annual jet fuel output of each integrated biorefinery scenario is compared to a pre-determined jet fuel substitution target. In this work, RJF production was aimed at 5% of the conventional jet fuel consumption in Brazil in 2014[1] of 7.5 billion L [22], corresponding to the production of 375 million L of RJF/year.

When assessing techno-economic and environmental impacts of RJF production, authors often consider standalone plants, regardless of the feedstock: lipids (microalgae, *Pongamia pinnata*, *Jatropha curcas*, *Camelina sativa*, *Brassica carinata*, used cooking oil, and conventional vegetable oils) [23–30]; lignocellulosic material (LCM), such as poplar and sugarcane bagasse [31–34]; and alcohols [35]. The potential of RJF production in Brazil has been previously overviewed, also as independent plants [21,36]. The integration with sugarcane mills itself is an innovative configuration which mitigates risks inherent to RJF technologies. RJF production in integration with sugarcane mills has already been assessed for the ATJ technology in South Africa [35] and for both ATJ and SIP routes in Brazil [37]. Moreover, De Jong et al. [24] confirmed the advantages of integration between RJF production and (unspecified) incubator facilities to the reduction of minimum jet

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[1] The following year saw a slight reduction of 1.5% in conventional jet fuel consumption, thus indicating the current stability of the Brazilian internal market.