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Exploring the emergence of a biojet fuel supply chain in Brazil: An agent-based modeling approach

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Abstract

The aviation industry accounts for more than 2% of global CO_2 emissions. Biojet fuel is expected to make an essential contribution to the decarbonization of the aviation sector. Brazil is seen as a key player in developing sustainable aviation biofuels owing to its long-standing experience with biofuels. Nevertheless, a clear understanding of what policies may be conducive to the emergence of a biojet fuel supply chain is lacking. We extended a spatially explicit agent-based model to explore the emergence of a biojet fuel supply chain from the existing sugarcane–ethanol supply chain. The model accounts for new policies (feed-in tariff and capital investment subsidy) and new considerations into the decision making about production and investment in processing capacity. We found that in a tax-free gasoline regime, a feed-in tariff above 3 R$/L stimulates the production of biojet fuel. At higher levels of gasoline taxation (i.e., 2.46 R$/L), however, any feed-in tariff is insufficient to ensure the production of biojet fuel. Thus, at these levels of gasoline taxation, it is needed to introduce regulations on the production of biojet fuel to ensure its production. Given the current debate about the future direction of the biofuel policy in Brazil, we recommend further research into the effect of market mechanisms based on greenhouse gas emissions on the emergence of a Brazilian biojet fuel supply chain.

KEYWORDS
agent-based modeling, biofuel policies, biojet fuel, Brazil, policy analysis, supply chain

1 | INTRODUCTION

The aviation industry accounts for more than 2% of global CO_2 emissions (Cremonez et al., 2015). To reduce the environmental impact of the aviation sector, the Air Transport Action Group (ATAG) has established goals to reach carbon neutral growth from 2020 and reduce net carbon dioxide emissions by 50% (relative to 2005 levels) by 2050 (Group A.T.A., 2012). Unlike for the road transport sector, short-term options to decarbonize the air transport sector are limited. Aviation will rely on liquid fuels with high energy density for decades to come (Group A.T.A., 2012). Biojet fuel is expected to make an essential contribution to the decarbonization of the aviation sector (Mawhood et al., 2016). Nevertheless, production volumes of biojet fuel have been negligible as demand remains low because of high prices (de Jong et al., 2015). The lack of competitiveness of biojet fuel as compared to jet kerosene is one of the main factors hindering the emergence of biojet fuel supply chains.

Brazil is seen as a key player in developing sustainable aviation biofuels owing to its long-standing experience with biofuels (Boeing, FAPESP & UNICAMP, 2013) and its increasing demand for jet fuel. Brazil is the world's sixth largest domestic aviation market (Oxley & Goodger, 2015). Currently, Brazil consumes 6 M ton/year of jet fuels and it is projected that the required jet fuel amounts to over 20 M ton/year in 2050 (Pashaei Kamali, Borges, Osseweijer, & Posada, 2018). The research into the potential of up taking biofuel production in Brazil has mainly focused on availability of feedstocks (Cantarella, Nassar, Cortez, & Baldassin, 2015) and techno-economic and environmental impact assessments (Alves et al., 2017; Moreira, Gurgel, & Seabra, 2014). Although the Brazilian ethanol and biodiesel supply chains are a clear example of the benefits of long-term policies on the development of the bioenergy sector (Alonso-Pippo, Luengo, Alonsoamador Morales Alberteris, García del Pino, & Duvoisin, 2013), not much attention has been hitherto paid to the influence of policies on the emergence of biojet fuel supply chains.

1.1 | Literature review

A recent strand of literature has focused on the effect of policy instruments on the aviation sector's economic and environmental performance. The most studied policy instruments include the EU Emission Trading Scheme (ETS) (Anger, 2010; Scheelhaase, Grimme, & Schaefer, 2010; Vespermann & Wald, 2011), the US federal aviation administration (Winchester, McConnachie, Wollersheim, & Waitz, 2013), and carbon pricing (Sgouridis, Bonnefoy, & Hansman, 2011).

In the analysis of the implications of including the aviation sector in the European emission trading scheme (EU ETS), Anger found that this policy has a negligible effect on the EU economy and leads to reductions in the CO_2 emissions (Anger, 2010), whereas Vespermann and Wald (2011) concluded that the air transport sector is unable to yield significant reductions of emissions under the EU ETS. Scheelhaase et al. (2010) found that including the aviation into the ETS would incentive airports to maximize their output in terms of RTK[1] in 2010 regardless of the emissions caused, and would have a moderate impact on the price increase.

To assess the impacts of the US Federal Aviation Administration (FAA) on the economic and environmental performance, Winchester et al. (2013) used an economy-wide model coupled with a partial equilibrium model of the aviation industry. The authors found that meeting the aviation biofuel target has a small impact on CO_2 emissions and that it is an expensive abatement option relative to alternatives.

Sgouridis et al. (2011) developed the Global Aviation Industry Dynamics (GAID) model to assess the impact of five generic policies (i.e., (a) technological efficiency improvements, (b) operational efficiency improvements, (c) use of alternative fuels, (d) demand shift, and (e) carbon pricing) on the reduction of emissions of the aviation sector. The authors found that improvements in the efficiency of technology, use of biofuels, moderate levels of carbon pricing, and reduction in short- and medium-haul travel are required for the transition of the aviation sector to sustainable mobility.

De Jong used a cost optimization model (RESolve-Biomass) to project the consumption of renewable jet fuel (RJF) in the EU and its environmental performance. The model accounts for the anticipated regulatory context in the EU (i.e., RED-I, RED-II proposal[2], the EU Emission Trading Scheme (EU ETS), and the Global Offsetting and Reduction Scheme for International Aviation (CORSIA)), competition for biomass from other bio-based sectors, and the availability of biomass and conversion technologies. He found that a 1.2 multiplier for RJF, (advanced) biofuel targets, and high prices of fossil jet fuel relative to other fossil fuels drive the introduction of RJF in the EU. Nevertheless, a higher multiplier may lead to lower GHG emission reductions (de Jong, 2018).

These studies have focused on understanding the impact of certain policies on the aviation sector. As they used models that either assume the existence of static equilibria or assume that the dynamics of the system is governed by the predetermined system structure, none of these studies explored the institutional conditions for the emergence of a biojet fuel supply chain.

The contribution of this work is to provide insights into the institutional conditions that might lead to the emergence of a biojet fuel supply chain from the existing Brazilian sugarcane–ethanol supply chain. The analysis focuses on the impact of institutions on actors' decision making about production and consumption of biofuels. Thus, the spatially explicit agent-based model that describes the Brazilian sugarcane–ethanol supply chain (Moncada et al., 2018) was extended to account for the processes and mechanisms that may lead to the emergence of a biojet fuel supply chain. The aim of the model is to answer the following research question: *Under what institutional conditions (i.e., formal policies) may the biojet fuel supply chain emerge in Brazil in the period 2015–2030?*

The remainder of the paper is organized as follows. Section 2 describes the conceptual framework that underpins the development of the agent-based model. Section 3 describes the results obtained which are discussed in section 4.

[1]Revenue tonne kilometers.

[2]The RED-II proposes a multiplier to incentivize the production of biofuels for the aviation and marine sectors. Renewable fuels supplied to these sectors may count 1.2 times their energy contents toward the target.

2 | MATERIALS AND METHODS

This section describes the concepts and modeling considerations required for the potential emergence of a biojet fuel supply chain. We divided this section in four subsections. In the first subsection, we give a brief description of the Brazilian sugarcane–ethanol supply chain and argue why this supply chain can be used as a starting point for the emergence of a biojet fuel supply chain. Then, we describe how the biojet fuel supply chain is conceptualized. In the third subsection, we describe the agent-based model using the ODD protocol[3] (Grimm et al., 2006). Finally, we describe how we modeled the policies that aim to incentivize the investment in and production of biojet fuel.

2.1 | System description

In this study, we use the Brazilian sugarcane–ethanol supply chain as a "seed" to "grow" a biojet fuel supply chain. The main actors in the sugarcane–ethanol supply chain are farmers, mill owners, fuel suppliers, and drivers. This supply chain has been shaped by governmental support (e.g., ProAlcool program) and the introduction of technological innovations, such as flex plants and flex vehicles. Flex technology enables plants to produce flexible ratios of sugar and ethanol from sugarcane (McKay, Sauer, Richardson, & Herre, 2015). With regard to ethanol production, the plants can produce either hydrous ethanol (up to 4.9% v/v of water), or anhydrous ethanol (up to 0.4% v/v of water), or both. Similarly, the introduction of flex vehicles brought flexibility into the demand side of the supply chain. This demand consists of mostly flex vehicles and regular vehicles. Flex vehicles can be powered by E100 (hydrous ethanol), gasohol (a blend of gasoline and anhydrous ethanol, of which the max share of anhydrous ethanol is 27.5% v/v due to technical limitations of regular vehicles; Demczuk & Padula, 2017), or any mix between these two. Unlike flex vehicles, regular vehicles can be only powered by gasohol.

Institutional arrangements and policy instruments influence the behavior of the sugarcane–ethanol supply chain. One of the most important institutional arrangements is CONSECANA-SP. This institutional arrangement reduces the uncertainty in the interaction between farmers and mill owners by determining the price of sugarcane. This price is determined by the amount of total recoverable sugar (TRS) in the sugarcane and the prices of sugar and ethanol on the domestic and foreign markets (Ferraz Dias de Moraes & Zilberman, 2014). On the other hand, policy instruments such as blending mandates (e.g., of anhydrous ethanol in gasohol) and taxes levied on hydrous ethanol, anhydrous ethanol, and gasoline influence the behavior of the supply chain by shaping the patterns of production and consumption of ethanol.

One of the main factors hindering the production of biojet fuel is its lack of economic competitiveness as compared to fossil jet fuel (de Jong et al., 2015). The gap between the fossil jet fuel price and the biojet fuel price could be reduced by using existing social and physical infrastructure. In this study, we use the social and physical infrastructure defining the sugarcane–ethanol supply chain to breed a biojet fuel supply for two main reasons. First, the existence of a well-established agro-industrial sector dedicated to the production of ethanol (Barbosa Cortez, 2014). Second, biojet fuel can be produced from ethanol through the route alcohol to jet fuel. This route involves four steps (see Figure 1): dehydration of ethanol, oligomerization of ethylene, distillation of wide spectrum hydrocarbon, and hydrogenation of the saturated hydrocarbon. Recently, ASTM approved a biojet fuel produced from isobutanol for commercial use in blends of a maximum level of 30% in kerosene (GreenAir, 2016).

The emergence of a biojet fuel supply chain in the Brazilian context requires the addition of new elements into the existing sugarcane–ethanol supply, such as actors (i.e., airports), technology (alcohol to jet fuel) and institutions, supporting the introduction of biojet fuel (e.g., feed-in tariff and capital investment subsidy). The next section describes how the sugarcane–ethanol supply chain is conceptualized and formalized into a computational model, and how the aforementioned elements are added to this formalization.

2.2 | Conceptual framework

A system diagram of the Brazilian biojet fuel supply chain is presented in Figure 2[4]. The system is analyzed from the hypothetical viewpoint of the Brazilian government. This perspective is characterized by a government that aims to use the existing sugarcane–ethanol supply chain as a substrate for the emergence of a biojet fuel supply chain. The government's policy instruments are a capital investment subsidy and a feed-in tariff. We use these supply-side policies because biojet fuel is in an early phase of introduction to the market, and thus, it is necessary to reduce the risk aversion of potential investors (Agency I.E., 2010). It is assumed that the behavior of the system is shaped by the external factors depicted in Figure 2.

Complex adaptive systems theory is used for the analysis of the phenomenon of the emergence of a Brazilian biojet fuel supply chain from the existing sugarcane–ethanol supply

[3]The Overview, Design concepts, and Details (ODD) protocol is a method used to describe agent-based models. This protocol was developed by Grimm et al. (2006).

[4]The scope of the capital investment subsidy and feed-in tariff is limited to incentivize the production of biojet fuel to satisfy domestic demand, for it is unlikely that national governments will subsidize biojet fuel for international flights.

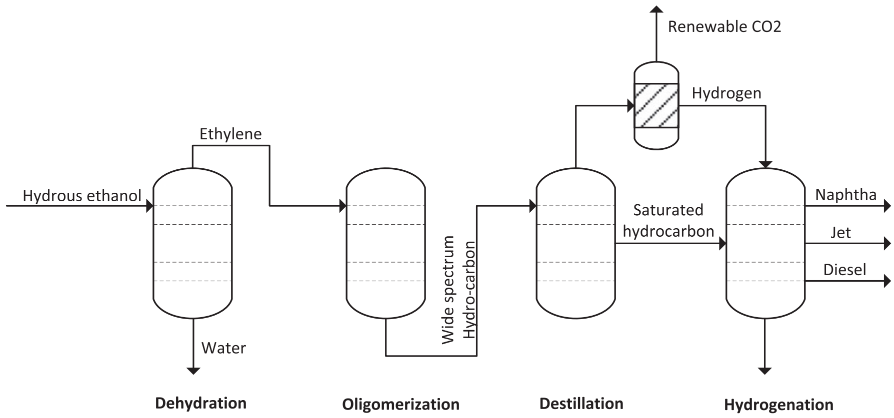

FIGURE 1 Steps of the alcohol to jet process (adapted from Ref. Barbosa Cortez, 2014)

chain. This supply chain is considered as a complex adaptive system. This system consists of heterogeneous actors (farmers, sugar/ethanol producers) who constantly adapt their behavior (e.g., decision making about production and consumption of biofuels) in response to other actors' behavior and to changes in the environment (e.g., changing market prices).

The conceptualization of the system builds on the conceptual framework developed by Moncada, Lukszo, Junginger, Faaij and Weijnen (2017), which has been used in the analysis of the German biodiesel supply chain (Moncada, Junginger, Lukszo, Faaij, & Weijnen, 2017) and the Brazilian sugarcane–ethanol supply chain (Moncada et al., 2018). This framework describes a system by using concepts from complex adaptive systems theory and from the neo-institutional economics school of thought. The main tenet of this framework is that the state of the system at macro level (macro-behavior) emerges as a result of the interaction of three elements at micro level: the physical system, the network of actors, and institutions (see Figure 3).

The physical system specifies the physical objects in the system, such as farms, mills/distilleries, vehicles, and airports. The actors are the entities that make decisions and perform a role in the system. In the biojet fuel supply chain, actors are farmers, mill/distillery owners, vehicle owners, and airport managers. Finally, institutions are the rules that structure social interaction (Brown, 2003). Examples of institutions are as follows: traditions, norms, legislation, policies, and governance structures.

Actors' behavior and the interaction among actors are governed by institutions at different levels. At the level of "games," institutions shape actors' behavior through heuristics and shared strategies that influence decision making. For instance, the selection of production ratios for sugar/ethanol/biojet fuel by mill owners is constrained by technical constraints and driven by profit maximization strategy. The level of institutional arrangements determines the interaction among actors. We use the CONSECANA-SP mechanism to describe the interaction between farmers and mill owners. We assume that the interaction between mill and vehicle owners and between mills and airports is governed by a supply–demand mechanism. Finally, the formal institutional environment refers to the rules of the game. Blending mandates for anhydrous ethanol in gasoline and taxes levied on hydrous and anhydrous ethanol are examples of institutions at this level in the Brazilian sugarcane–ethanol supply chain.

2.3 | Modeling framework

The conceptual framework is formalized into a computational model with the aim of analyzing the influence of the feed-in tariff, capital investment subsidy, and the tax levied on gasoline on the emergence of a biojet fuel supply from the existing sugarcane–ethanol supply chain. The selection of the model was based on the aim of the study. At the core of this aim is the concept of emergence. Emergence is defined as *"the arising of novel and coherent structures, patterns, and properties through the interactions of multiple distributed elements"* (Wilensky & Rand, 2015). Agent-based modeling was chosen as the modeling paradigm as, unlike approaches such as general equilibrium modeling, supply chain optimization, and system dynamics, it enables one to describe a phenomenon in terms of unique and autonomous agents that interact with each other and the environment (Railsback & Grimm, 2011). Moreover, agent-based modeling is arguably the most suitable tool for modeling a complex adaptive system because of its bottom-up approach and easiness of including different formalisms into the model (van Dam, Nikolic, & Lukszo, 2013).

This study builds on a spatially explicit agent-based model of the Brazilian sugarcane–ethanol supply chain (Moncada et al., 2018). This agent-based model uses land projections to explicitly account for expansion of land for sugarcane production in specific locations. These projections are provided by the PCRaster Land Use Change (PLUC) model (Verstegen, Karssenberg, van der Hilst, & Faaij, 2012). The

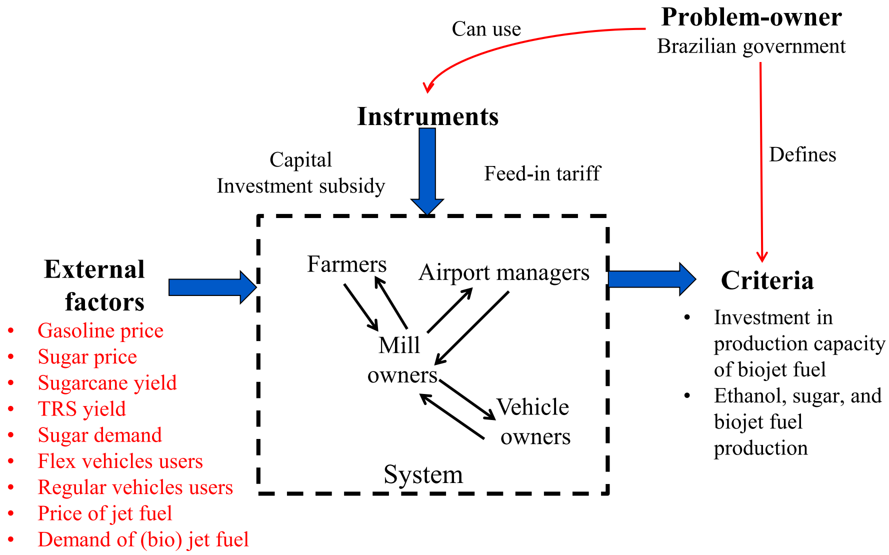

FIGURE 2 System diagram of the Brazilian sugar/ethanol and biojet fuel market

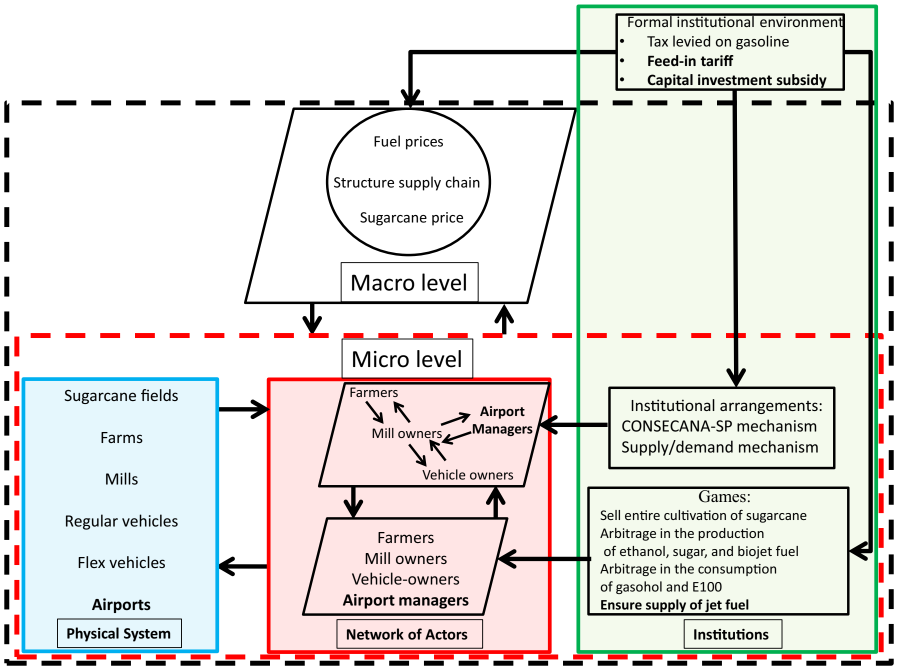

FIGURE 3 Conceptual framework. Elements in bold are the elements added to the Brazilian sugarcane–ethanol supply chain

agent-based model was designed using the pattern-oriented approach (Grimm, 2005). The model was structured based on three patterns: flexibility in the production of sugar/ethanol, flexibility in the consumption of ethanol, and the location of sugarcane availability.

We extend the scope of that model by adding new actors (airports), new policies (feed-in tariff and capital investment subsidy), new technologies (biojet fuel production), and new considerations into the decision making about production and investment in processing capacity. With regard to production, mill owners need to decide how to allocate the sugarcane for the production of sugar, ethanol, and biojet fuel. With regard to investment, mill owners need to assess whether to invest in a conventional flex plant or to invest in a flex plant that includes the production of biojet fuel. Below, we describe in more detail the features added to the model. The description of the agent-based model is based on the ODD protocol proposed by Grimm et al. (2006).

2.3.1 | Purpose

The aim of the model is to study the influence of supply-side policies (i.e., feed-in tariff and capital investment subsidy) on the emergence of a biojet fuel supply chain in Brazil.

2.3.2 | Entities, state variables, and scales

The entities in the model are the actors in the supply chain: farmers, mill owners, car drivers, and airport managers. The farmers' main state variables are as follows: farm area,

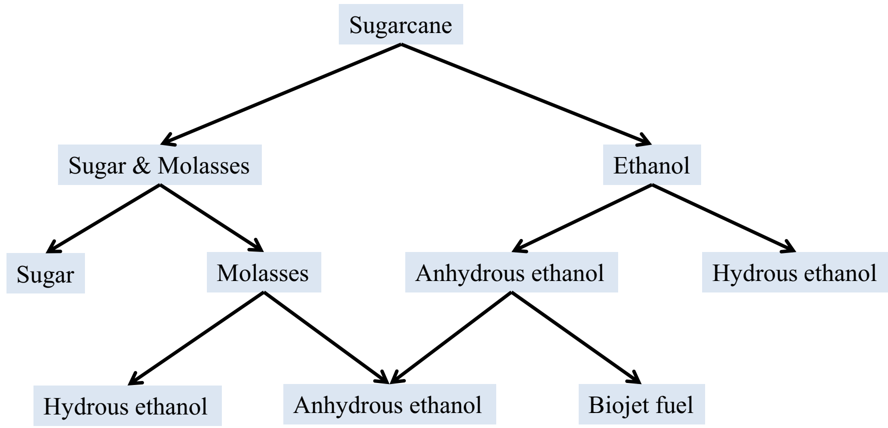

FIGURE 4 Levels of decision as to production of sugar, hydrous, anhydrous ethanol, and biojet fuel by the owners of flex plants. This decision making is based on market signals

sugarcane yield, and total recoverable sugar (TRS) yield. The mill/distillery owners' main state variables are as follows: type (flex plant, sugar plant, ethanol plant, or flex-biojet fuel plant), sugarcane processing capacity, production costs, and production ratio of sugar, ethanol, and biojet fuel. The drivers' main state variables are as follows: vehicle type (flex vehicle, regular vehicle), energy demand, and preferences in the consumption of fuels[5]. The airports' main state variables are as follows: total demand for jet fuel and the blending constraint for biojet fuel. Farmers and mills are modeled spatially explicitly, whereas drivers and airports are not. This is because the (bio)jet fuel, E100, and gasohol prices are considered uniform over space. The global environment consists of the policy instruments (feed-in tariff, capital investment subsidy, and gasoline tax) and the exogenous factors (annual world market prices of sugar and gasoline, number of flex and gasohol vehicles, sugar demand, sugarcane and TSR content yield, and price and demand of jet fuel). The temporal extent of the model is 18 years (2013–2030), and the time step is one year. The model is spatially explicit, covering the whole of Brazil. The input from PLUC to the agent-based model has a resolution of 5 × 5 km.

2.3.3 | Process overview and scheduling

The process consists of a series of events that take place in discrete periods within a year. The process starts during the harvest season, where farmers *harvest sugarcane*, *negotiate* with the mill agents about price and quantity to be traded, and *deliver the sugarcane* to the mill as it was agreed. As the interaction between farmers and mill agents is bound to their spatial location, these transactions are decentralized and take place at different locations.

Mill/distillery owners *store* the sugarcane and maximize profits *by deciding on volumes of sugar, hydrous ethanol, anhydrous ethanol, and biojet fuel to be produced* (Figure 4). In each time period, mill/distillery owners *produce* sugar, ethanol, and/or biojet fuel and *enquiry about prices and quantities* of sugar and ethanol *to the sugar and fuel markets*. Drivers *choose between E100 and gasohol* based on relative prices. Airports *choose between biojet fuel and fossil fuel* based on market prices[6]. According to the market outlook, mill agents *decide about the expansion of the sugarcane processing capacity* to produce either sugar/ethanol or sugar/ethanol/biojet fuel. The new sugarcane processing capacity starts operation at the third year of construction. An overview of the model narrative and a description of some of the most important processes are presented in Supporting Information Appendix S1.

2.3.4 | Design concepts

The basic concepts underpinning the design of the agent-based model are presented below. The reader is referred to Moncada et al. (2018) for a more comprehensive description of the concepts that guide the design of the agent-based model.

Basic principle: The basic principle applied in the model is the rational choice theory. This theory is used to describe the decision making on production of sugar, ethanol, and biojet fuel.

Emergence: Emergent system dynamics includes gasohol and E100 prices, total production of sugar, ethanol, and biojet

[5]The criterion for choosing ethanol (E100) as opposed to gasoline is the ratio of ethanol price to gasoline price. According to economic theory, this ratio should be less or equal to 0.7 as on average E100 is considered to deliver 70% of the mileage of gasoline for the same volume of fuel. In this study, however, we introduce heterogeneity in the value of this ratio to account for that some drivers have a preference for the consumption of ethanol even when this fuel is not the optimal choice.

[6]In reality, the individual airline companies are the ones that decide whether to use jet fuel or biojet fuel. Nevertheless, we aggregated the demand of these airlines at the airport level for modeling purposes.

fuel, total demand for biojet fuel and jet fuel, and the expansion of the processing capacity of sugarcane.

Adaptation: Flex mill owners and the drivers of flex vehicles are the entities that exhibit adaptive behavior in the model. The strategic behavior of drivers of flex vehicles and owners of flex mills is described in detail in Moncada et al. (2018). Owners of flex mills that also produce biojet fuel adapt their production ratios of ethanol/sugar/biojet fuel based on market signals (see Figure 4). This behavior is driven by a profit maximization strategy. Thus, high prices of sugar (or ethanol or biojet fuel) lead to an increase in the production of sugar (or ethanol or biojet fuel).

The decision of the flex mills about the volumes of sugar, ethanol, and biojet fuel to be produced is modeled as an optimization problem as presented below:

$$\max_{x_s,\, x_h,\, x_{hm},\, x_{bj}} f = \sum_{i=1}^{4} \pi_i \tag{1}$$

subject to[7]:

$$x_{s_{min}} \leq x_s \leq 0.65 \tag{2}$$

$$0.2 \leq x_h \leq x_{h_{max}} \tag{3}$$

$$0.2 \leq x_{hm} \leq x_{h_{max}} \tag{4}$$

$$0.1 \leq x_{bj} \leq 0.8 \tag{5}$$

where π_i is the profit derived from product i (sugar, hydrous, anhydrous, and biojet fuel), x_s is the ratio of sugar production to sugarcane processed (the rest is used for ethanol production), x_h is the ratio of hydrous production to total ethanol production from sugarcane (the rest is used to produce anhydrous ethanol and biojet fuel), x_{hm} is the ratio of hydrous production to total ethanol production from molasses, x_{bj} is the ratio of biojet fuel production to total anhydrous ethanol production, $x_{s_{min}}$ is the minimum in the ratio of sugar production to sugarcane processed, and $x_{h_{max}}$ is the maximum in the ratio of hydrous production to total ethanol production. Values for $x_{s_{min}}$ and $x_{h_{max}}$ differ among mills. To account for the influence of the gasoline tax on the decision making about the volumes of hydrous and anhydrous ethanol to be produced, it was assumed that $x_{h_{max}}$ is equal to one when gasoline tax is 2.46 R$/L and that $x_{h_{max}}$ is equal to zero when the gasoline tax is 0 R$/L. This assumption follows from the demand response. That is, a high gasoline tax will result in a major consumption of hydrous ethanol and thus will lead to an increase in the price of hydrous ethanol, which in turn will lead mill owners to increase the production of hydrous ethanol. A similar mechanism also applies to the effect of reducing the gasoline tax on the production of anhydrous ethanol.

[7]The boundary conditions were determined based on technical constraints (e.g., the maximum production ratio of sugar to ethanol), model calibration (e.g., the minimum production ratio of sugar to ethanol and maximum production ratio of hydrous ethanol to anhydrous ethanol (Moncada et al., 2018), and assumptions (e.g., the production ratios of biojet fuel to anhydrous ethanol).

Objectives: Flex mill owners are profit-maximizing agents. They aim to maximize their profits by shifting the production ratio of sugar to ethanol and by shifting the production ratio of ethanol between hydrous ethanol, anhydrous ethanol, and biojet fuel. The production ratio of sugar to ethanol has to be between 35% and 65% because of a technical constraint (de Gorter, Drabik, & Just, 2015). Drivers of flex vehicles aim to meet their energy demand by choosing between gasohol and E100. Farmers aim to sell their entire sugarcane cultivation to the owners of flex/distillery plants at the price determined by the CONSECANA-SP mechanism.

Learning/prediction: Mills forecast prices and demand for sugar, ethanol (hydrous and anhydrous), and biojet fuel. The forecasting is used to inform the decision making as to whether to invest in a new flex plant, to invest in a new flex plant with co-production of biojet fuel, or to not invest at all.

Sensing: Farmers, owners of mills, drivers, and airport managers are assumed to know market prices (without uncertainty).

Interaction: The interaction between mills and drivers is mediated via the fuel market. This mechanism is described in detail in Moncada et al. (2018). Farmers directly interact with owners of mills/distilleries in their neighborhood through the negotiation about a contract for the supply of sugarcane. The main issue in the contract is the sugarcane price. This interaction is modeled through the CONSECANA-SP mechanism. Mills interact indirectly with neighboring mills by competing for contracts with farmers in their common sourcing region in the sugarcane market.

In the CONSECANA-SP mechanism, the pricing of sugarcane is based on two variables: the amount of total recoverable sugar (TRS) and the price of TRS. The TRS price is linked to the average market selling prices of three different products (sugar, hydrous, and anhydrous ethanol), over the period of one harvest season. The CONSECANA-SP model then assumes that sugarcane accounts for 59.5% of the production costs of sugar and accounts for 62.1% of ethanol production (Ferraz Dias de Moraes & Zilberman, 2014). In this study, we introduce a modification to the current CONSECANA-SP mechanism to account for the production of biojet fuel from sugarcane–ethanol. To simplify the analysis, this modification of the CONSECANA-SP mechanism neglects the contribution of naphtha and diesel in the determination of the sugarcane price. Accordingly, remuneration to suppliers is done according to these percentages.

$$P^{\mathrm{TRS}}_{\mathrm{Sugar}} = P^{\mathrm{average}}_{\mathrm{Sugar}} \cdot 0.595 \cdot \left(\frac{1}{\mathrm{sc}_{\mathrm{sugar}}}\right) \tag{6}$$

$$P^{\mathrm{TRS}}_{\mathrm{Hydrous}} = P^{\mathrm{average}}_{\mathrm{Hydrous}} \cdot 0.621 \cdot \left(\frac{1}{\mathrm{sc}_{\mathrm{hydrous}}}\right) \tag{7}$$

$$P^{\mathrm{TRS}}_{\mathrm{Anhydrous}} = P^{\mathrm{average}}_{\mathrm{Anhydrous}} \cdot 0.621 \cdot \left(\frac{1}{\mathrm{sc}_{\mathrm{anhydrous}}}\right) \tag{8}$$

$$P^{\mathrm{TRS}}_{\mathrm{Biojet\ fuel}} = P^{\mathrm{average}}_{\mathrm{BJ-Anhydrous}} \cdot 0.621 \cdot \left(\frac{1}{\mathrm{sc}_{\mathrm{anhydrous}}}\right) \tag{9}$$

$$P^{\mathrm{averrage}}_{\mathrm{BJ-Anhydrous}} = P^{\mathrm{average}}_{\mathrm{Biojet\ fuel}} \cdot y_{\mathrm{BJ-Anhydrous}} \tag{10}$$

where:

$P^{\mathrm{TRS}}_{\mathrm{Sugar}}$, $P^{\mathrm{TRS}}_{\mathrm{Hydrous}}$, $P^{\mathrm{TRS}}_{\mathrm{Anhydrous}}$, and $P^{\mathrm{TRS}}_{\mathrm{Biojet\ fuel}}$ are the TRS prices for sugar, hydrous ethanol, anhydrous ethanol, and biojet fuel, respectively, in Reais per kilogram of TRS.$P^{\mathrm{average}}_{\mathrm{Sugar}}$,$P^{\mathrm{average}}_{\mathrm{Hydrous}}$, $P^{\mathrm{average}}_{\mathrm{Anhydrous}}$, and $P^{\mathrm{average}}_{\mathrm{Biojet\ fuel}}$ are the average market selling prices for sugar, hydrous ethanol, anhydrous ethanol, and biojet fuel in Reais per kilogram of sugar, Reais per liter of ethanol, and Reais per liter of biojet fuel, respectively. $\mathrm{sc}_{\mathrm{sugar}}$, $\mathrm{sc}_{\mathrm{hydrous}}$, and $\mathrm{sc}_{\mathrm{anhydrous}}$ are the stoichiometric coefficient for sugar, hydrous ethanol, and anhydrous ethanol, respectively. $y_{\mathrm{BJ-Anhydrous}}$ is the yield of biojet fuel from anhydrous ethanol.

The TRS price for a processing plant *i* is based on weighing the product TRS price with the volumes of each product:

$$P^{\mathrm{TRS}}_{i} = P^{\mathrm{TRS}}_{\mathrm{Sugar}} \cdot \left(\frac{\mathrm{Pr}_{\mathrm{sugar}}}{\mathrm{Pr}_{\mathrm{total}}}\right) + P^{\mathrm{TRS}}_{\mathrm{Hydrous}} \cdot \left(\frac{\mathrm{Pr}_{\mathrm{hydrous}}}{\mathrm{Pr}_{\mathrm{total}}}\right) + P^{\mathrm{TRS}}_{\mathrm{Anhydrous}} \cdot \left(\frac{\mathrm{Pr}_{\mathrm{anhydrous}}}{\mathrm{Pr}_{\mathrm{total}}}\right) + P^{\mathrm{TRS}}_{\mathrm{Biojet\ fuel}} \cdot \left(\frac{\mathrm{Pr}_{\mathrm{biojet\ fuel}}}{\mathrm{Pr}_{\mathrm{total}}}\right) \tag{11}$$

$$\mathrm{Pr}_{\mathrm{total}} = \mathrm{Pr}_{\mathrm{sugar}} + \mathrm{Pr}_{\mathrm{hydrous}} + \mathrm{Pr}_{\mathrm{anhydrous}} + \mathrm{Pr}_{\mathrm{biojet\ fuel}} \tag{12}$$

where:

P^{TRS}_{i} is the TRS price of the plant *i* in Reais per kg of TRS. $\mathrm{Pr}_{\mathrm{sugar}}$, $\mathrm{Pr}_{\mathrm{hydrous}}$, $\mathrm{Pr}_{\mathrm{anhydrous}}$, and $\mathrm{Pr}_{\mathrm{biojet\ fuel}}$ are the total production of sugar, hydrous ethanol, anhydrous ethanol, and biojet fuel of the plant *i*, respectively, in kilograms of TRS.

Stochasticity: The model is initialized stochastically. Drivers' preferences of the relative fuel prices and mills' yields for sugar, hydrous ethanol, anhydrous ethanol, and biojet fuel are randomly assigned among the agents.

Collectives: The model neglects the formation of aggregations among individuals.

Observation: Expansion of the ethanol/sugar/biojet fuel production capacity, production of sugar, ethanol, and biojet fuel are the main key performance indicators.

Initialization: A total of 418 mill agents, 3,715 farmer agents, 2,500 driver agents, and 40 airport managers are initialized for the year 2013. The location of mills and their type (sugar plant, ethanol plant, or flex plant) are based on real spatial data for the year 2013 (Picoli, 2013). Tables 1 and 2 present the parameters that describe the state of the agents at the start of the simulation.

Input data: The behavior of the model is driven by nine exogenous parameters: gasoline and sugar prices, number of flex and regular vehicles, productivity of both sugarcane and the TRS content, sugar demand, jet fuel price, and jet fuel demand. The productivity of both sugarcane and the TRS content is assumed to be constant during the period 2013–2030. The values for sugarcane yield and TRS content yield are 75 t/ha and 140 kg TRS/t, respectively. These values were set out based on historical developments (UNICA, 2017). Projections for the other parameters up to 2030 were retrieved from the literature (see Table 3).

The decision making about investment in processing capacity is based on the estimation of the net present value. The values of the parameters used in the net present value calculation are reported in Supporting Information Appendix S2. It is assumed that mill owners have a different perception of risk in their investment decision. This difference in the perception of the risk was captured by using different values for the discount rate.

Critical assumptions that underpin the model structure are as follows:

- The demand for (bio) jet fuel is perfectly inelastic.
- Biojet fuel is only used in the jet fuel domestic market.
- There is no differentiation in the granting of feed-in tariffs.
- The supply curve of jet fuel is perfectly elastic.
- If there is price parity between biojet fuel and jet fuel, airports opt to first consume biojet fuel. Nevertheless, the demand of biojet fuel is restricted to the maximum blending constraint.

2.4 | Modeling of the policies incentivizing production, consumption, and investment in biojet fuel

In this study, we use two supply-side policies: the feed-in tariff and the capital investment subsidy. A feed-in tariff is a policy instrument used to accelerate investments in renewable energy sources. This policy instrument offers long-term purchase agreements for the sale of renewable

TABLE 1 Farmers, vehicle users, and airport state variables and independent variables

Parameter	Value	Brief description	Units
Farmers			
Initial-number-farmers	3,715	initial number of farmers	—
Farm-a	2,500	farm area	ha
Yield-SC	75	yield of sugarcane per hectare	t/ha
Yield-TRS	140	yield of total recoverable sugar per ton of sugarcane	kg/t
Drivers			
Type		gasohol; flex	—
Demand	47,244	energy demand per vehicle	MJ/year
Preference-relative-price[a]	*N* (**0.9**, 0.1)	value in the relative price that determines the consumption pattern of the driver *i*. Values of the relative price higher than the individual relative price lead to consumption of gasohol by the driver	—
Airports			
Total-demand-jet-fuel	N.A	total demand of jet fuel. This demand can be either satisfied with jet fuel or partially satisfied with renewable jet fuel. This parameter depends on the projections for domestic demand of jet fuel in Brazil	Ml/year
Blending constraint[b]	30	Blending constraint of biojet fuel	%
Independent variables			
Blend-mandate[c]	23	blend mandate	%
Tax-gasoline[c]	1.23	tax levied on gasoline	R$/L
Tax-hydrous[c]	0.30	tax levied on hydrous ethanol	R$/L
Tax-anhydrous[c]	0.05	tax levied on anhydrous ethanol	R$/L
Feed-in-tariff	[3–6]	feed-in tariff for biojet fuel production	R$/L
Capital-investment-subsidy	[0–20]	governmental financial aid that covers a share of the total depreciable capital required to build a biojet fuel plant	%

[a]The values in bold were obtained from the model calibration (see Moncada et al., 2018). [b]The blending constraint of 30% is only valid for the biojet fuel produced from ethanol. [c]These values were retrieved from de Gorter, Drabik, Kliauga, & Timilsina (2013).

energy. The payment levels can be differentiated by the type of technology, resources, and location so as to better reflect production costs. In this study, we use the fixed feed-in tariff, which can be considered independent of the market price and we neglect any differentiation in the payment levels.

Let us consider the supply of jet fuel and biojet fuel as shown in Figure 5. If the payment level of the feed-in tariff is *Pfeed-in tariff*, then the maximum supply to the fuel market is *Qfeed-in tariff*. The government offers a payment equivalent to *Pfeed-in tariff* to the producers that bid biojet fuel until *Qbiojet fuel* = Qfeed-*in tariff*. Nevertheless, it is assumed that the government bids *Qfeed-in tariff* to the jet fuel market at the same price of the fossil jet fuel *Pfeed-in tariff*.

Capital investment subsidy is a supply-side policy used to incentivize investment in production facilities. This policy instrument aims to reduce the risk aversion of investors by covering a percentage of the total fixed capital investment. In this study, we use capital investment subsidy as an instrument to only incentivize the production of biojet fuel. Thus, we add a cap in the production ratio of hydrous ethanol and a floor in the production ratio of biojet fuel to the plants that benefit from the capital investment subsidy. We assume a cap in the production ratio of hydrous ethanol of 0.5 (i.e., $x_{\text{hydrous}}^{\text{cap}} = 0.5$ and a floor in the production of ratio of biojet fuel of 0.5 (i.e., $x_{\text{biojet}}^{\text{floor}} = 0.5$.

3 | RESULTS

In this section, we describe the influence of the capital investment subsidy, the feed-in tariff, and the gasoline tax on two relevant aspects: the investment in sugarcane processing capacity[8] and the production of hydrous ethanol, anhydrous ethanol, and biojet fuel. We also present the influence of the feed-in tariff and capital investment subsidy on the subsidy costs. The results for investment in processing capacity and production of biofuels are presented in a matrix of 12 panels defined by the capital investment subsidy and the feed-in tariff. The results for the subsidy costs are presented in a matrix

[8]This sugarcane processing capacity includes the production of sugar, ethanol, and biojet fuel.

TABLE 2 Mill state variables

Parameter	Value	Brief description	Units
Mills			
Number-sugar-mill-plants	10	number of the sugar plants	—
Number-ethanol-mill-plants	83	number of ethanol plants	—
Initial-number-flex-mill-plants	325	number of the mill plants	—
Proc-capacity[a]	[1, 5]	processing capacity of sugarcane	Mt SC
Yield-sugar-SC[b]	U (119, 146)	yield of sugar per ton of sugarcane	kg/t
Yield-hydrous-SC[b]	U (83, 92)	yield of hydrous ethanol per ton of sugarcane	L/t
Yield-anhydrous-SC[b]	U(79, 88)	yield of anhydrous ethanol per ton of sugarcane	L/t
Yield-biojet-fuel-SC[c]	U (35,42)	yield of biojet fuel per ton of sugarcane	L/t
Yield-ethanol-molasses	U (8, 10)	yield of ethanol from molasses per ton of sugarcane	L/t
Sugar-proc-cost	U(41, 51)	processing cost of sugar per ton of sugarcane	R$/t
Hydrous-proc-cost	U (14, 17)	processing cost of hydrous ethanol per ton of sugarcane	R$/t
Anhydrous-proc-cost	U (25, 31)	processing cost of anhydrous ethanol per ton of sugarcane	R$/t
RJF-proc-cost	U (18, 23)	processing cost of biojet fuel per ton of sugarcane	R$/t
Prod-ratio-sugar[c]	U (**0.5**, 0.6)	proportion of sugarcane that is used to produce sugar	—
Prod-ratio-hydrous[c]	U (0.2, **0.5**)	proportion of sugarcane that is used to produce hydrous ethanol	—
Prod-ratio-biojet-fuel	U (0.2–0.8)	proportion of sugarcane that is used to produce biojet fuel	—
Prod-ratio-hydrous-molasses	U (0.2, 0.5)	proportion of ethanol produced from molasses that is used to produce hydrous ethanol	—

The values in bold were obtained from the model calibration (Moncada et al., 2018).
[a]The distribution of the production capacity was based on Valdes (2011). [b]It is assumed that the differences in the yields are due to differences in industrial efficiencies between mills and distilleries. [c]Retrieved from Santos, Mussatto, Osseweijer, van derWielen & Posada (2018).

of four panels defined by the capital investment subsidy and the feed-in tariff. The gasoline tax or the type of biofuels is presented by different colors in each panel. The results presented below correspond to a tax levied on hydrous and anhydrous ethanol of 0.3 R$/L and 0.05 R$/L, respectively.

Figure 6 shows the evolution of sugarcane processing capacity. There is a threshold in the investment in processing capacity: No investment, and thus no production of biojet fuel, takes place at a feed-in tariff of 3 R$/L. If the feed-in tariff is increased above 3 R$/L, there is an increase in investment in processing capacity. Nevertheless, the expansion of the processing capacity is almost brought to a halt in the year 2020 if the feed-in tariff is 4 R$/L. As an illustration, when comparing the scenarios with a capital investment subsidy of 20%, a feed-in tariff of 4 R$/L, and a gasoline tax of 0, 1.23, and 2.46 R$/L, the sugarcane processing capacity is 165, 93, 0 million tons in 2020, whereas it is 208, 93, and 0 million tons in 2030, respectively. If the feed-in tariff is 6 R$/L and the tax levied on gasoline is equal or less than 1.23 R$/L, the expansion in processing capacity also evolves nonlinearly. For instance, in the period 2020–2025, for a feed-in tariff of 6 R$/L and a capital investment of 20%, the investment in processing capacity grows 16.9% and 14.5% if the gasoline tax is 0 R$/L and 1.23 R$/L, respectively. This threshold is due to that values of the feed-in tariff below 4 R$/L are unable to outweigh the biojet fuel production costs.

The effect of the gasoline tax on the investment in sugarcane processing capacity hinges on the feed-in tariff. As the feed-in tariff increases, the effect of the gasoline tax on the investment in processing capacity increases too. For instance, when comparing the scenarios with a gasoline tax of 0 R$/L, a capital investment subsidy of 20%, a feed-in tariff of 6 and 5 R$/L, the processing capacity is 1,100 instead of 1,000 in 2025. Tax-free gasoline leads to increased investment in processing capacity. A reduction in the gasoline tax, at a high feed-in tariff, results in an increased investment in production capacity because in this tax regime, the demand for anhydrous ethanol increases. This increase in the demand for anhydrous ethanol leads to an increase in its price. The combination of high prices for anhydrous ethanol and high prices for biojet fuel (i.e., feed-in tariff) provides the right signals to investors. On the other hand, the effect of the capital investment on the investment in processing capacity is marginal.

A tax-free gasoline regime favors the production of anhydrous ethanol over hydrous ethanol and biojet fuel (see Figure 7). This pattern in the production of anhydrous ethanol is due to the assumption that owners of flex plants will only produce anhydrous ethanol if the gasoline tax decreases

TABLE 3 Definition of the exogenous parameters

Year	Sugar demand[a] [Mt]	Nominal sugar price[b] [US$/kg]	Nominal crude oil price[c] [US$/bbl]	Number of flex vehicles[d] [millions]	Number of regular vehicles[d,e] [millions]	Price of jet fuel[f] [R$/L]	Domestic demand of jet fuel[g] [Ml]
2013	34.85	0.39	104.08	23	15	2.20	2,550.15
2014	35.92	0.37	96.20	26	14	2.03	2,750.41
2015	36.94	0.30	50.80	28	13	1.07	2,945.36
2016	37.88	0.40	42.80	30	13	0.90	3,072.70
2017	38.76	0.40	55.00	32	13	1.16	3,200.04
2018	39.58	0.40	60.00	35	13	1.27	3,308.38
2019	40.33	0.40	61.50	37	13	1.30	3,400.36
2020	41.01	0.40	62.90	40	13	1.33	3,471.43
2021	41.63	0.39	64.50	43	13	1.36	3,545.86
2022	42.19	0.39	66.00	46	13	1.39	3,604.68
2023	42.67	0.39	67.60	49	14	1.43	3,657.75
2024	43.09	0.39	69.30	53	14	1.46	3,707.72
2025	43.45	0.39	71.00	56	14	1.50	3,757.24
2026	43.74	0.39	72.80	59	14	1.54	3,808.96
2027	43.97	0.39	74.60	62	15	1.58	3,865.54
2028	44.13	0.38	76.40	66	16	1.61	3,929.62
2029	44.22	0.38	78.20	69	17	1.65	4,003.86
2030	44.25	0.38	80.00	73	17	1.69	4,091.43

[a]The demand of sugar was calculated based on results reported by the MAGNET model (Jonker et al., 2016). [b]Retrieved from Ref. (Santos et al., 2018). The ratio of domestic price of sugar to the international price is 1:1.2 (Haley, 2013). [c]The ratio of crude oil price to gasoline price is 1:1.2 (Zana, 2013). [d]Retrieved from Ref. (Baran & Legey, 2013; Belincanta, Alchorne, & Teixeira da Silva, 2016). [e]Regular vehicles only can use gasohol (blend of gasoline and anhydrous ethanol. The maximum blend of anhydrous ethanol in gasohol is 27.5% v/v). [f]The ratio of crude oil price to jet fuel is 1:0.08 based on Ref. (Mundi, 2018). [g]It is assumed that the domestic demand amounts to 30% of the total demand of jet fuel. The projections of the total demand for jet fuel were retrieved from Ref. (Barbosa Cortez, 2014).

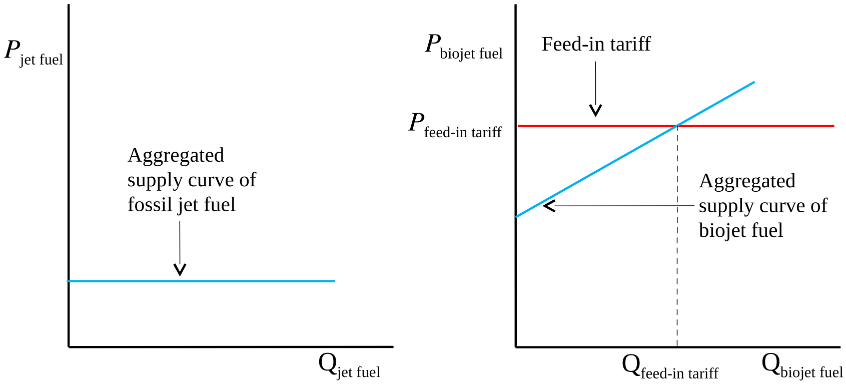

FIGURE 5 Hypothetical supply curves of jet fuel and biojet fuel

to 0 R$/L. An increase in the feed-in tariff (above 3 R$/L)

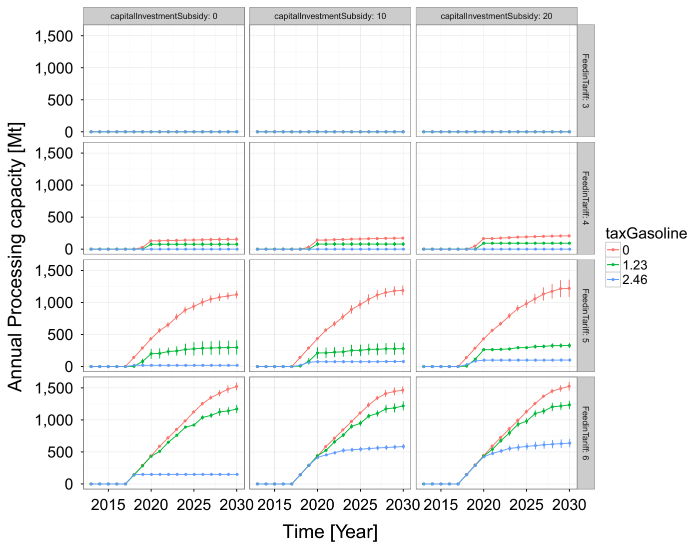

FIGURE 6 Sugarcane processing capacity of mills that include the production of biojet fuel for different combinations of the capital investment subsidy, feed-in tariff, and tax levied on gasoline. Capital investment subsidy as a percentage of the total depreciable capital for investment in a biojet fuel plant. Feed-in tariff and gasoline tax in R$/L. Blend mandate = 23%v/v, hydrous tax = 0.3 R$/L, and anhydrous tax = 0.05 R$/L

leads to an increase in the production of hydrous ethanol and biojet fuel. When comparing the scenarios with a capital investment of 10% and feed-in tariff 5 and 4 R$/L, the biojet fuel production is 2,700 instead of 1,000 Ml and the production of hydrous ethanol is 10,000 Ml instead of 6,000 Ml in 2025. Also, the effect of the capital investment subsidy on the production of biofuels depends on the feed-in tariff. At values of the feed-in tariff above 4 R$/L, an increase in the capital investment subsidy leads to an increase in the production of hydrous ethanol and to a decrease in the production of both biojet fuel and anhydrous ethanol. For instance, when comparing the scenarios with a feed-in tariff of 5 R$/L and capital investment of 0 and 10%, the production of hydrous ethanol is 4,000 instead of 8,000 Ml, the production of biojet is 1800 instead of 1700 Ml, and the production of anhydrous ethanol is 25,000 instead of 21,000 Ml in 2020. This increase in the production of hydrous ethanol is due to the constraints in the production of hydrous ethanol and biojet fuel imposed on the plants that benefit from the capital investment subsidy.

The mandate of producing a certain minimum of biojet fuel led to an optimal distribution of the production ratios that favor the production of hydrous ethanol. A further increase in the capital investment subsidy did not change the production patterns of hydrous and anhydrous ethanol and biojet fuel. This is due to that the constraints in the production of hydrous ethanol and biojet fuel are assumed to be independent of the level of the capital investment subsidy. That is, the obligations imposed to the plants that received a subsidy of 10% are equal to the obligations imposed to the plants that received a subsidy of 20%.

As shown in Figure 8, there is an oscillating behavior in the production of hydrous and anhydrous ethanol if the tax levied on gasoline is 1.23 R$/L. This behavior is the result of both the fuel choice of owners of flex vehicles that shifts between two states (i.e., consumption of either gasohol or hydrous ethanol) and the myopic behavior of the owners of the mills as to production of ethanol. This gasoline tax regime favors the production of anhydrous ethanol rather than hydrous ethanol. There is production of biojet fuel only if the feed-in

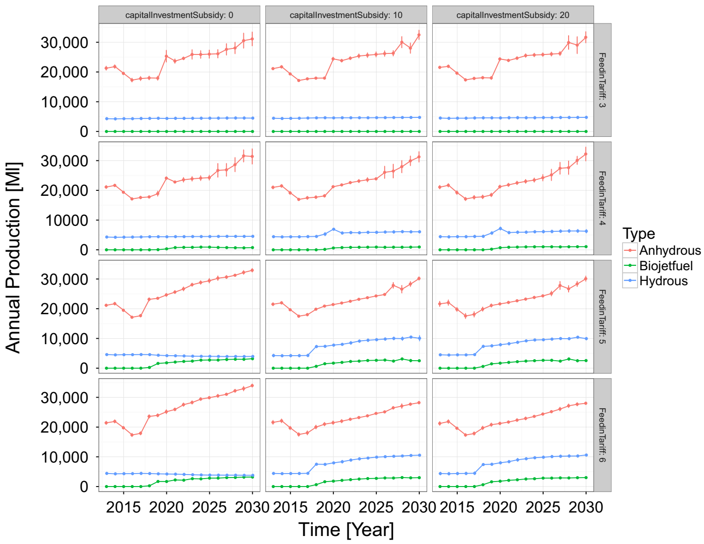

FIGURE 7 Production of hydrous ethanol, anhydrous ethanol, and biojet fuel for different combinations of the capital investment subsidy and feed-in tariff. Capital investment subsidy as a percentage of the total depreciable capital for investment in a biojet fuel plant. Feed-in tariff in R$/L. Gasoline tax = 0 R$/L, blend mandate = 23%v/v, hydrous tax = 0.3 R$/L, and anhydrous tax = 0.05 R$/L

tariff is equal to or greater than 4 R$/L. The year of initial production of biojet fuel depends on the feed-in tariff. The supply chain starts producing biojet fuel in 2018 and 2020 if the feed-in tariff is 4 and 6 R$/L, respectively. There is an oscillating behavior in the production of biojet fuel if the feed-in tariff is greater than or equal to 5 R$/L. At a feed-in tariff of 5 R$/L, the production of biojet fuel oscillates between 800 and 2000 millions of liters, whereas at a feed-in tariff of 6 R$/L, the production of biojet fuel oscillates between 2000 and 3,000 millions of liters. This oscillating behavior is also caused by the interaction of decision making between owners of flex vehicles and owners of mills about consumption of fuels and production of ethanol, respectively. In reality, this fast oscillation is unlikely to happen because actors adapt their behavior gradually. Nevertheless, the impact of this deviation of reality on the conclusions is negligible because this study focuses its analysis on extreme values in the gasoline tax (i.e., 0 and 2.46 R$/L). At these values of the gasoline tax, decisions about the production and consumption of ethanol converge to one state (Figure 7 and Figure 9).

Figure 9 presents the evolution of the production of biojet fuel, hydrous, and anhydrous ethanol when the tax levied on gasoline is 2.46 R$/L. These conditions favor the production of hydrous ethanol rather than anhydrous ethanol. Unlike the previous case when the gasoline tax is 1.23 R$/L, biojet fuel is only produced at a feed-in tariff equal to or greater than 5 R$/L and a capital investment subsidy equal or greater than 10%. For instance, when comparing scenarios with a gasoline tax of 2.46 R$/L, a capital investment subsidy of 20% and a feed-in tariff of 6 and 5 R$/L, the production of biojet fuel is 1600 instead of 230 Ml in 2025. With regard to the production of hydrous and anhydrous ethanol, at a capital investment of 20% and a feed-in tariff of 6 R$/L, the production of hydrous ethanol stays approximately constant at a value of 30,000 million liters as of 2020, whereas the production of anhydrous ethanol grows approximately 8% per year in the period 2025–2030. This behavior in biofuels production is due to the constraints in the production of hydrous ethanol and biojet fuel imposed on the plants that benefit from the capital investment subsidy. In this case, the cap imposed in the production of hydrous ethanol favors the production of anhydrous ethanol and biojet fuel. The large standard deviations in the production of hydrous and anhydrous ethanol in 2024, 2025, and 2026 show that, although the surge in the production of hydrous ethanol is always present, its exact timing differs between these 3 years over the model runs.

Figure 10 presents the trade-offs between the production of hydrous ethanol and biojet fuel in the year 2030. Patterns in biojet fuel production in 2030 hinge on the interaction of gasoline tax, capital investment subsidy, and the feed-in tariff. In a tax-free gasoline regime, an increase in the feed-in tariff results in an increase in the production of biojet fuel. The effect of the capital investment subsidy on the production of biojet fuel is characterized by a threshold. Excepting for the regime of free-tax gasoline in combination with high feed-in tariffs, the production of biojet fuel increases when the capital investment subsidy is higher than zero. Nevertheless, a further increase in the capital investment subsidy does not further incentivize the production of biojet fuel. This is due to the assumption that the constraints in the production of hydrous ethanol and the mandates in the production of biojet fuel are independent of the level of the capital investment subsidy. In this regime (i.e. free gasoline tax in combination with a capital investment subsidy higher than zero), an increase in the feed-in tariff favors the production of both hydrous ethanol and biojet fuel.

At a tax level of gasoline of 1.23 R$/L, the production of biojet fuel in 2030 increases with an increase in the feed-in tariff. At this level of the gasoline tax, no trade-offs exist between production of hydrous ethanol and biojet fuel: An increase in the feed-in tariff leads to higher production of biojet fuel without compromising the production of hydrous

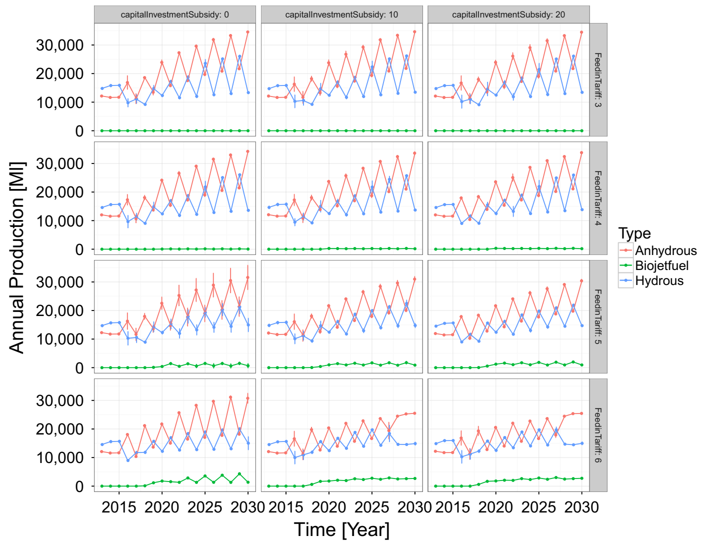

FIGURE 8 Production of hydrous ethanol, anhydrous ethanol, and biojet fuel for different combinations of the capital investment subsidy and feed-in tariff. Capital investment subsidy as a percentage of the total depreciable capital for investment in a biojet fuel plant. Feed-in tariff in R$/L. Gasoline tax = 1.23 R$/L, blend mandate = 23%v/v, hydrous tax = 0.3 R$/L, and anhydrous tax = 0.05 R$/L

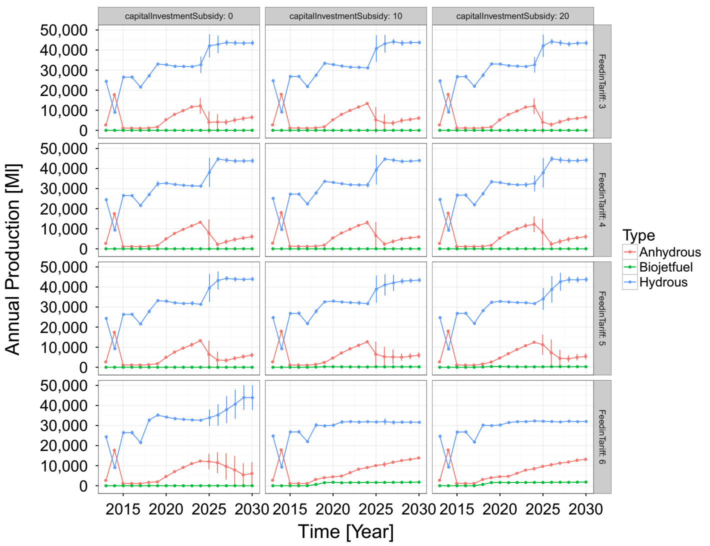

FIGURE 9 Production of hydrous ethanol, anhydrous ethanol, and biojet fuel for different combinations of the capital investment subsidy and feed-in tariff. Capital investment subsidy as a percentage of the total depreciable capital for investment in a biojet fuel plant. Feed-in tariff in R$/L. Gasoline tax = 2.46 R$/L, blend mandate = 23%v/v, hydrous tax = 0.3 R$/L, and anhydrous tax = 0.05 R$/L

ethanol. The effect of the capital investment subsidy on the production of biojet fuel is similar to the one described for the tax-free gasoline regime.

At a tax level of gasoline of 2.46 R$/L, the production of biojet fuel in 2030 increases with an increase in the feed-in tariff if the capital investment subsidy is greater than or equal to 10%. At this level of taxation on gasoline, the effect of the capital investment subsidy on the production of biojet fuel is characterized by a threshold. In this regime, the production of biojet fuel only increases when the capital investment subsidy is higher than zero. This regime is also characterized by a trade-off between the production of hydrous ethanol and biojet fuel. At a capital investment greater than 0%, feed-in tariffs below 6 R$/L lead to largely the production of hydrous ethanol, whereas a feed-in tariff of 6 R$/L leads to an increase in the production of biojet fuel and to a decrease in the production of hydrous ethanol.

All in all, for a feed-in tariff above 4 R$/L, the gasoline tax exhibits an inversely correlated effect on the production of biojet fuel. That is, the higher the gasoline tax, the lower the biojet fuel production. This is due to that a high gasoline tax results in an increase in the demand and thus in an increase in the price of hydrous ethanol. These conditions favor the production of hydrous ethanol. Nevertheless, provided that there are mechanisms that ensue the production of biojet fuel as in this case the capital investment subsidy, the production of biojet fuel (1800 Ml) in 2030 at a gasoline tax rate of 2.46 R$/L is sufficient to satisfy the domestic demand of jet fuel (4,000 Ml) in 2030 because of the blend wall, defined as blending biojet fuel into jet fuel at 30%.

The cost of subsidizing the emergence of a biojet fuel supply chain under different combination of the capital investment subsidy and feed-in tariffs at a gasoline tax rate of 2.46 R$/L is presented in Figure 11. The most significant contribution in costs to spur biojet fuel production comes from a feed-in tariff of 6 R$/L with a cost of approximately 9,000 MR$ per year as of 2020. The contribution of the capital investment subsidy is notably in 2016 with a value of

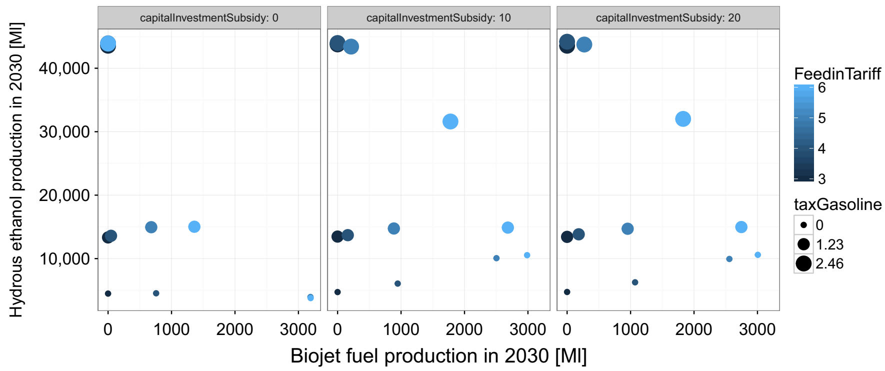

FIGURE 10 Production of hydrous ethanol and biojet fuel in 2030 for different combination of capital investment subsidy, feed-in tariff, and gasoline tax. Capital investment subsidy as a percentage of the total depreciable capital for investment in a biojet fuel plant. Feed-in tariff and gasoline tax in R$/L. Blend mandate = 23%v/v, hydrous tax = 0.3 R$/L, and anhydrous tax = 0.05 R$/L

approximately 1,500 MR$. The general subsidy cost pattern is characterized by the early introduction of the capital investment subsidy followed by a cost regime dominated by the feed-in tariff.

4 | DISCUSSION

The results suggest that the emergence of a Brazilian biojet fuel supply chain, from the existing sugarcane–ethanol supply chain, is largely driven by a tax-free gasoline regime and a feed-in tariff greater than 3 R$/L (see Figures 6 and 10), provided that the policy landscape for both road transport and aviation sector remains stable, that the demand for (bio) jet fuel is perfectly inelastic, that there is no differentiation between the type of technologies, resources, and location in the granting of feed-in tariffs, and that the effect of import and export tariffs on the market is negligible. We also found that the effect of the capital investment subsidy on sugarcane processing capacity is negligible. These findings are in line with the reported by Del Rio & Bleda who point out the advantages of feed-in tariff to lower risks in renewable energy investment (del Río & Bleda, 2012).

The results also suggest that the production patterns of biojet fuel are heavily influenced by the gasoline tax (see Figures 7–9). A tax-free gasoline regime favors the production of biojet fuel even when the capital investment subsidy is zero, that is, even in situations where the constraint for hydrous production and the mandate for biojet fuel production imposed on the plants that receive the capital investment subsidy were absent. Unlike the tax-free gasoline regime, an increase in the level of taxation of gasoline requires mandates for the production of biojet fuel to ensure its production. Whilst changes in the values assumed for the cap and floor in the production ratio of hydrous ethanol and biojet fuel, respectively, will bring about different absolute production quantities for the three fuels, the production patterns of biojet fuel will remain qualitatively similar.

We found that there is a trade-off between the production of hydrous ethanol and biojet fuel in 2030 at high levels of taxation of gasoline (see Figure 10). This insight may be relevant for a Brazilian government that strives for the decarbonization of both the road transport sector and the aviation sector. If the sugarcane–ethanol supply chain is used to support the emergence of a biojet fuel supply chain, our results suggest that increasing the level of gasoline taxation, introducing regulations in the production of biojet fuel through mechanisms as the capital investment subsidy, and a feed-in tariff of 6 R$/L increase the production of hydrous ethanol without compromising the production of biojet fuel. In fact, the biojet fuel produced at a gasoline tax rate of 2.46 R$/L, a capital investment subsidy of 10%, and a feed-in tariff of 6 R$/L is sufficient to satisfy 30% of the domestic demand (blend wall). Our results also suggest that the feed-in tariff has the most significant contribution in the costs to spur biojet fuel production (see Figure 11).

Biojet fuel is considered a cornerstone in the strategy to achieve the GHG emissions reduction targets[9] of the aviation sector. Spurring the production and consumption of biofuels requires specific policies at the national level and international level. At the national level, we showed in this study what policy instruments are necessary to enable the emergence of a biojet fuel supply chain from the existing sugarcane–ethanol supply chain. At the international level, government, industry, and civil society representatives reached an agreement on a global market-based measure (GMBM) to reduce aviation carbon emissions through offsetting. Nevertheless, it is unclear whether this market mechanism will drive the development of biojet fuel supply chains. The model developed in this study could be coupled with models developed to describe other biomass and biofuels markets in different geographies via a multimodel ecology framework[10] (Bollinger, Nikolić, Davis, & Dijkema, 2015). Therefore, we can account for the inherently international nature of the aviation sector and provide insights as to the effect of market mechanisms on the deployment of biojet fuel supply chains.

[9]The Air Transport Action Group (ATAG) has established goals to reach carbon neutral growth from 2020 and reduce net carbon dioxide emissions by 50% (relative to 2005 levels) by 2050.

[10]Multimodel ecology is defined as "an interacting group of models coevolving with one another in a dynamic sociotechnical environment" (Bollinger et al., 2015).

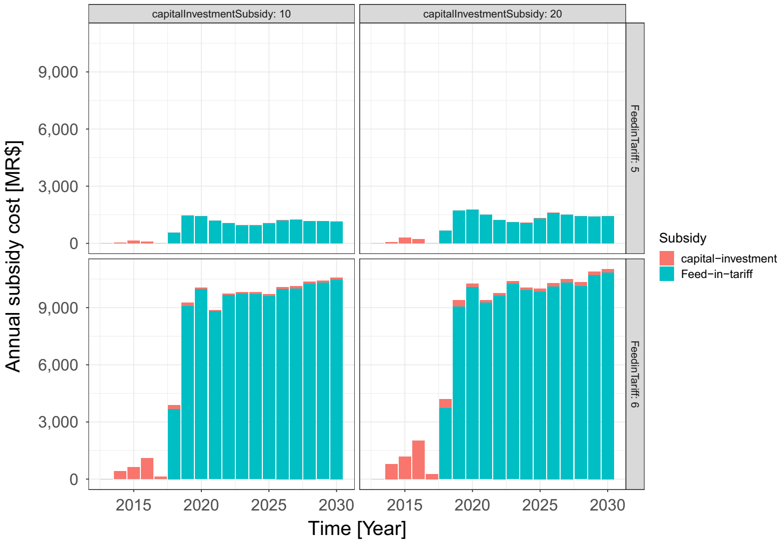

FIGURE 11 Evolution of the subsidy cost to spur the emergence of a biojet fuel supply chain at a gasoline tax rate of 2.46R$/L. Capital investment subsidy as a percentage of the total depreciable capital for investment in a biojet fuel plant. Feed-in tariff and gasoline tax in R$/L

Our study applies a number of key enhancements to the exploration of the emergence of a biojet fuel supply chain. First, to the best of our knowledge, this is the first study that provides insights into how different policy instruments may steer the emergence of a biojet fuel supply chain. Previous analyses are qualitative and thus only offer a description of the phenomenon of emergence, not a quantification (Nair & Paulose, 2014). Second, this is the first work that shows how the sugarcane–ethanol supply chain can be used as a platform for the emergence of a biojet fuel supply chain.

Our study also applies a number of key enhancements to the agent-based modeling of the Brazilian ethanol supply chain (Moncada et al. (2018). First, it modifies the CONSECANA-SP mechanism to account for the production of biojet fuel. Second, it adds the option of investing in biojet fuel production. Finally, it incorporates the feed-in tariff and the capital investment subsidy into the analysis.

From the methodological viewpoint, we have shown how a modeler can use the conceptual framework developed by Moncada, Lukszo et al. (2017) and the ODD protocol to build an agent-based model to explore the emergence of a biojet fuel supply chain. The advantage of using the conceptual framework is that offers a systematic method to identify social processes, theories and structures that underlie the model's design. That is, the conceptual framework identifies the elements that one needs to consider for the modeling of a biofuel supply chain, such as actors' decision making and interaction, social structures, and the effect of policies on actors' behavior. This is considered useful in the light that current biomass/biofuels markets models neglect the effect of social processes, differences between individual actors, and social structures on the evolution of the system. As we have shown in this study, these processes play an important role in the emergence of a biojet fuel supply chain.

This approach, however, does have some limitations. First, we limit our analysis to the use of supply-side policies granted by the Brazilian government. We neglect the introduction of any market mechanism[11] to stimulate the production of biojet fuel driven by the goal to improve the greenhouse gas emissions performance. These market mechanisms may become relevant to the decarbonization of the aviation industry as this sector is inherently international. Second, given the scope of this study, we neglect the interaction of the production of biojet fuel by the alcohol-to-jet fuel pathway with other potential production routes (e.g., hydroprocessed esters and fatty acids (HEFA), direct fermentation sugars to hydrocarbons (DFJ), biomass gasification, and Fischer–Tropsch syngas to jet (GFT)). Indeed, the emergence of biojet fuel supply chains is largely the result of both the collaboration among the stakeholders in the supply chain and the competition for resources with actors who use different technologies or with actors in other sectors. Third, we neglect the contribution of co-products in biojet fuel production (i.e., diesel and naphtha) in the determination of sugarcane price through the CONSECANA-SP mechanism. Discussions among farmers, sugar/ethanol producers, and potential biojet fuel producers, on how to account for the influence of biojet fuel production and co-products in the pricing of sugarcane, may hinder or speed up the development of the biojet fuel supply chain in Brazil. Fourth, we neglect the effect of the electricity market (i.e., electricity prices) on the producers' decision making as to production of sugar, ethanol, and biojet fuel. Finally, we neglect the competition for ethanol between the road transport sector and emergent independent biojet fuel producers[12], which may have an impact

[11] A market mechanism refers to the process whereby the market solves resource allocation problems.

[12] Independent biojet fuel producers are the actors that only produce biojet fuel.

on ethanol prices and ethanol production and consumption patterns.

Yet, this study provides new insights into the emergence of a Brazilian biojet fuel supply chain under different policy landscapes. A further step would be to incorporate the ongoing discussion about the biofuel policy in Brazil into the analysis, namely the creation of a market mechanism that aims for the reduction of greenhouse gas emissions by rewarding the production of cleaner biofuels.

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