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Innovation opportunities in the Brazilian sugar-energy sector

Daniella Fartes dos Santos e Silva*, José Vitor Bomtempo, Flávia Chaves Alves

Universidade Federal Do Rio de Janeiro, Av. Pedro Calmon, 550 - Cidade Universitária, Rio de Janeiro, RJ, 21941-901, Brazil

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ABSTRACT

Brazil is the second largest producer of ethanol in the world and it has the most competitive raw material: the sugarcane. Even though this industry has undergone great productivity gains, it still offers promising innovation opportunities. Some of these opportunities include second-generation ethanol, biogas and biochemicals. Seeking to address the main difficulties faced by the Brazilian sugar-energy sector in terms of innovation, the objective of this work is to analyze the innovation opportunities in the Brazilian sugar-energy sector, as well as their main drivers and inhibitors, from the Innovation System Agents (ISA) perspective according to the Sectoral System of Innovation (SSI) approach. Therefore, 17 experts were interviewed, and an analytical framework was developed to analyze the innovation opportunities. It was verified that the difficulties to innovate occur due to inhibitors present along all dimensions of the sectoral system. To solve this, the creation of an ecosystem with players from other sectoral systems was suggested.

1. Introduction

The use of sugarcane in Brazil began during the colonization period, when the focus was only on the production of sugar. Later, in the 1970s, via *Programa Proálcool* (the National Alcohol Program), the government encouraged the fast increasing in ethanol production. This program aimed to reduce dependence on automotive gasoline following the oil shocks in 1973 and 1979. The result was a 20-fold increase in production over a 16-year period (Stattman et al., 2013). Since 2003, flexible-fuel vehicles (FFVs) – vehicles that can use both gasoline and ethanol – have been replacing single fuel (ethanol-only or gasoline-only) cars, and by 2007 the production of ethanol-only vehicles was ended. By 2017, FFVs accounted for 88.6% of vehicle sales in Brazil (ANFAVEA, 2018).

Today Brazil is the second largest producer of ethanol in the world and it has the most competitive raw material. Three main reasons can be cited: firstly, the cost of producing sugarcane ethanol in Brazil is 50–60% lower and 20–30% lower, in comparison with corn and beet, respectively, two important raw materials (Manochio et al., 2017). Secondly, sugarcane provides a higher productivity of ethanol per hectare (6314 l/ha) than corn (2729 l/ha) (Donke et al., 2016). Thirdly, it reduces greenhouse gas emissions by 60%–90%, a more significant reduction compared to corn (40%–55%) (Chum et al., 2014).

The Brazilian sugar-energy sector can be divided into two parts: industrial and agricultural. While it is widely recognized that the agricultural part has enormous potential for improvement and innovation (Nyko et al., 2013), the industrial part is often considered mature (Arruda, 2011; Goldemberg and Guardabassi, 2010; Moraes et al., 2015; Rico et al., 2010), thus inducing the idea of few innovation opportunities in this specific part. However, when analyzing the average value of total reducing sugars (TRS) lost at Brazilian mills, as well as the underutilization of agroindustrial waste, this consideration can be questioned. In 2009, an average of 14.14% of the sugarcane TRS was lost during the industrial process (CGEE, 2009), and this figure has not decreased significantly in recent years (NOVACANA, 2018a), a very relevant proportion when compared to the small losses in other industries. This indicates a potential for optimization that goes beyond mere incremental improvements, by opening up opportunities for innovation in crucial stages of the process, such as extraction and fermentation (Lopes et al., 2016).

Other innovation opportunities in the industrial part are due to the potential for transforming waste, such as bagasse and vinasse, into usable products, such as second-generation (2G) ethanol (IEA, 2017), bioelectricity (Souza et al., 2018), biogas (Milanez et al., 2018), and biobased chemicals (OECD, 2018).

Teece (2007) has postulated that, when innovating in an open economy with rapid innovation, the way the firms sense and shape

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* Corresponding author. Rua Francisco Sá nº 38 apto. 702. Copacabana, Rio de Janeiro, RJ. CEP: 22080-010, Brazil.

E-mail address: daniella.fartes@hotmail.com (D.F. dos Santos e Silva).

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opportunities and threats influences how - and if - the companies will promote these innovations. Thus, the ability to innovate goes beyond technological capacity. Consequently, innovation is the result of successful interaction between different industry dimensions, such as companies, research institutions, development agencies, laws, and regulations. To explain this, the Sectoral System of Innovation (SSI) approach addresses the role of these different dimensions in the innovation process, explaining the fact that the innovation performance of a sector must be analyzed through the interaction of a set of actors rather than only the efforts of a company (Malerba, 2006).

In this context, the following question raises: what are the main difficulties identified by the Brazilian sugar-energy sector in terms of innovation in the industrial part of the sector? Seeking to address this issue, the objective of this work is to analyze the innovation opportunities in the Brazilian sugar-energy sector (industrial part) and their main drivers and inhibitors from the innovation system agents (ISA) perspective.

This article is organized as follows: Introduction, section 2 (literature review from SSI approach), section 3 (the methodology), section 4 (the main factors that drive or inhibit each innovation opportunity, with a scenario of innovation in the sugar-energy sector), and last section (conclusions).

2. Literature review

This section firstly discusses the evolution of the Sectoral Systems of Innovation concept proposed by Malerba (2006), focusing on three dimensions: knowledge and technological domain, actors and networks, and Institutions. Secondly, a description of the Brazilian Sugar-Energy Sector is presented.

2.1. Sectoral System of Innovation

Several attempts have been made to measure innovation. For example, investment in R&D and the attainment of patents have been used as innovation metrics. However, this approach considers the firm as the unit of analysis and observes only inputs and outputs, without looking into the innovation process among different players in the sector. In order to better understand the difficulties associated with exploring the innovation opportunities within the Brazilian sugar and ethanol industry, this study takes the Sectoral System of Innovation perspective. In this approach, the innovative performance cannot be analyzed by focusing on the efforts and achievements of companies individually (Malerba and Orsenigo, 1996). Instead, innovation is a result from the interaction of actors of the same or different institutional natures (Malerba, 2006).

First scholars exploring the Innovation Systems (IS) approach considered the analysis at national level, by combining the R&D activities and the role of universities, research institutes, government agencies and policymakers (Freeman, 1987; Lundvall, 1992; Nelson, 1993). In 1992, Lundvall defined IS as a set of discrete components and their relationships. This definition recognized that economic, political and cultural factors influences the organization of IS, by helping in determining the scale, direction and success of innovation activities.

In an attempt to understand the specific characteristics of an industry, Malerba and Orsenigo (1996) introduced the SSI approach. According to Malerba (2006), sector is a set of activities that are unified by some groups of products targeted to a specific or emerging demand and that share some common knowledge base. Thus, according to the SSI approach, innovation is considered as a process that involves systematic interactions for a wide range of actors for generating and exchanging relevant knowledge on innovation.

As defined by Malerba (2006), the SSI approach focuses on three main dimensions:

Knowledge and Technological Domain*:* This dimension is essential to delimit the sector, for any sector can be characterized by a specific knowledge base. It is important to highlight that this boundary is not fixed, so it can change as knowledge expands or shrinks.

Actors and Networks*:* This dimension characterizes the industry, for it brings together all of its agents. These agents can be individuals or organizations. Organizations can be companies or other institutions, such as universities, financial institutions or government agencies. They may also form part of a company (e.g., R&D or production departments). Networks consist of interactions among actors, such as workshops, partnerships, legal agreements, and contracts.

Institutions: Institutions include standards, routines, common habits, established practices, regulations and laws, among others. Interactions between agents are shaped by the institutions.

Actors and networks are a particular dynamic dimension, because it involves multiple relationships occurring simultaneously at different organizational levels, thus being a critical issue in the analysis of singularities in the innovation process. While firms have been considered the key actors in SSI, public institutions and other organizations (for example, research laboratories) have long been identified as playing important roles (Sapsed et al., 2007).

Several researchers have explored the SSI approach in both theoretical (Geels, 2004; Coenen and Lopéz, 2010) and practical (Furtado et al., 2011; Tuncel and Polat, 2016; Wicki and Hansen, 2017) ways. However, few authors have used SSI to identify innovation barriers in specific sectors. This article aims to contribute in filling this gap and adding a new way to explore SSI approach.

2.2. Sectoral System of Innovation — The Brazilian sugar-energy sector

Proálcool was one of the milestones for the development of a relevant Brazilian biofuels market and started the structuring process of the Sugar-Energy System of Innovation (SESI). This program has strongly encouraged the production of ethanol and it is considered responsible for the modernization, expansion and construction of new mills and farms (Dunham et al., 2011).

The introduction of the flexible-fuel vehicle is considered other milestone for the SESI, because it boosts the production of hydrated ethanol. Thus, SESI's innovation activities were mainly directed towards improving the productive system already established by the large sugar mills.

Fig. 1 shows the main SESI agents, as well as production, knowledge and financial flows. Furtado et al. (2011) highlighted the importance of agricultural research within the system. Both research institutions and universities make efforts to increase productivity in the field and generate more productive and resistant sugarcane varieties. However, little is discussed in the literature about the recent efforts within the SESI, to innovate on the industrial side. This reinforces the need to discuss its innovation opportunities.

3. Material and methods

The methodology of this study followed the sequence presented in Fig. 2. First, the innovation opportunities (I.O.) to be studied were selected by considering two criteria: to be related to the traditional process of ethanol production (also called first generation) or to be included in the National Innovation Program PAISS (Support Plan for Industrial Technological Innovation in the Sugar-Energy and

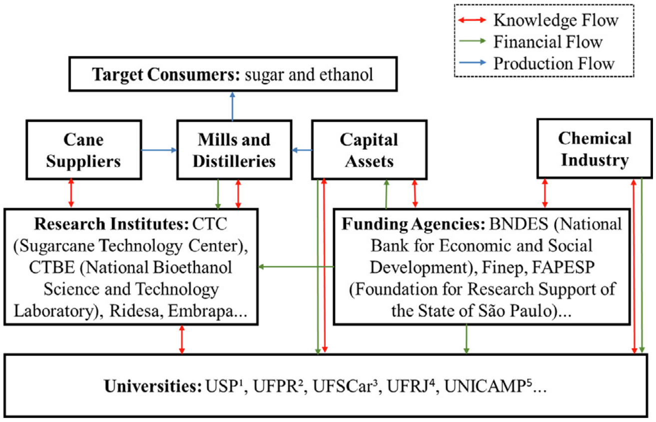

Fig. 1. Sugar-energy system of innovation.
Source: Adapted from Furtado et al. (2011). (COLOR NEEDED)
[1] Universidade de São Paulo
[2] Universidade Federal do Paraná
[3] Universidade Federal de São Carlos
[4] Universidade Federal do Rio de Janeiro
[5] Universidade Estadual de Campinas.

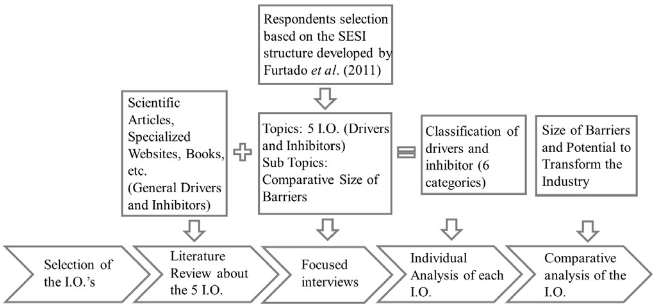

Fig. 2. Methodological flow.

Sugar-Chemistry Sectors). First generation opportunities can be divided into two groups: the actual process of transforming sugar into ethanol and alternatives for the utilization of its residues, bagasse, straw and vinasse. Therefore, five innovation opportunities were selected: energy cogeneration using sugarcane bagasse and straw, generation of vinasse biogas, improvements in the first-generation process, production of second-generation ethanol, and biochemicals (new products). A study developed by the Brazilian Center for Management and Strategic Studies (CGEE, 2012) corroborates the existence of this set of opportunities. The innovation opportunity related to bagasse gasification (present in PAISS) was excluded from the analysis because no company applied for the program in this category. Fig. 3 shows the five opportunities chosen for the analysis.

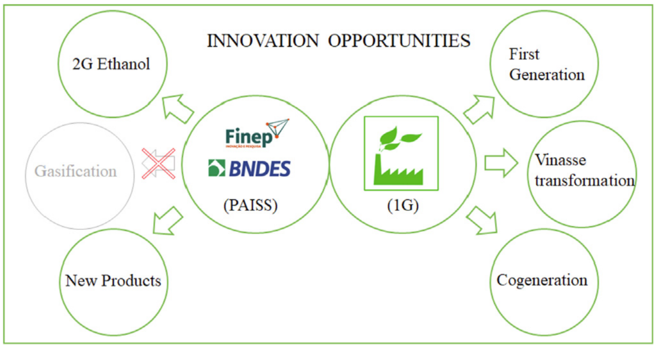

Fig. 3. Selected innovation opportunities in sugar-energy sector.

Second, a literature review on each innovation opportunity was conducted to study its general context. Then, 17 interviews with SESI experts from research (7), industry (7) and policy (3) areas related to the Brazilian sugar-energy sector were conducted. The methodology was based on semi-structured interviews (Jick, 1979), which aimed to identify and discuss innovation opportunities from the ISA point of view. Semi-structured interview is a type of interview with predefined topics (and possibly subtopics), but without a fixed structure. The main advantage of this methodology is that the interviewee can freely express his/her opinions, which leads to a large amount of valuable information. For this study, the topics were exactly each of the five innovation opportunities aiming at identifying and discussing drivers and inhibitors for each of them. The sub-focus concerned a comparison of barrier size for each opportunity according to the interviewee's perception. Individual statements were verified by asking similar questions to multiple informants, by checking statements with quantitative data and archival sources, including corporate presentations and production data. The interviews lasted an hour on average (from 35 m to 2 h 22 m). They were applied from July 2014 to January 2015. All material obtained from the interviews was recorded.

The selection of respondents was based mainly on the SESI structure developed by Furtado et al. (2011). In relation to the policy group, professionals from Brazilian institutions that support innovation, such as BNDES (National Development Bank), in positions of innovation management in biofuels and agribusiness, were interviewed. Specialists from research groups were mainly sought in public universities, such as UFRJ (Federal University of Rio de Janeiro), UNIFEI (Federal University of Itajubá) e USP (University of São Paulo), and major research centers, such as the National Laboratory of Science and Technology of Bioethanol (CTBE), in positions of research leaders. Professionals from sugarcane companies and main suppliers were selected to represent the industry specialists. All respondents held positions related to innovation in the ethanol industry, such as innovation manager, R&D manager and R&D coordinator.

To avoid "bias" and allow interviewees to have full freedom to express their opinions on innovation opportunities (especially among industrial respondents), the names of the interviewees, as well as the companies in which they work, were not disclosed. However, the largest Brazilian ethanol producers, the largest supplier of equipment, and a second-generation ethanol producer were consulted.

After the literature review and interviews, a triangulation with deductive data (literature) and inductive data (interviews) was made. The result is the identification of the key drivers and inhibitors for each opportunity under the classification of 6 categories related to the dimensions of the SSI, as shown in Fig. 4. The categories are:

- **Cost:** In this category, the factor (driver or inhibitor) is associated with increase/decrease in costs for the company. It is related to SSI as a whole, because all three dimensions can influence the cost of a driver or inhibitor. For example, the impact of taxes represents costs associated with **institutions**, the technological level of an invention is associated with **knowledge**, and the bargaining power of suppliers is related to **actors and networks**;
- **Technology:** In this category, the factor (driver or inhibitor) is related to technological opportunities/challenges, i.e., if it requires minimal or extensive research on the topic. It is mainly related to **technological domain**;

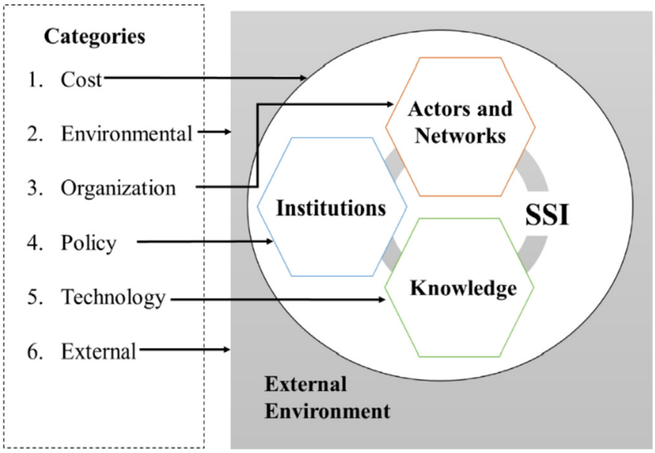

Fig. 4. Association between categories and SSI dimensions.

- **Environmental:** In this category, the factor (driver or inhibitor) is related to environmental issues. It is related to both SSI and external environment;
- **Organization:** In this category, the factor (driver or inhibitor) is related to the organizational/managerial characteristics of the companies. It is mainly related to **actors and networks**, because it is related to the organizational structures of SSI companies;
- **Policy:** In this category, the factor (driver or inhibitor) is related to actions within the policy sphere. It is mainly related to **institutions**;
- **External:** In this category, the factor (driver or inhibitor) is associated with external characteristics, i.e., it cannot be controlled by the industry, and it is not part of any of the above categories. It is related to the environment outside the SSI.

Finally, an analytical framework was developed to analyze innovation opportunities concerning two aspects: barriers to explore the innovation opportunity, and innovation opportunity and its potential to transform the industry. Barriers to innovate were classified as low, medium or high, based on discussions about the inhibitors for each innovation with the interviewees and triangulation with the information from the literature review. Policy and External inhibitors tend to raise these barriers, since SESI agents have few mechanisms to change them, which means that they tend to be **high**. Organizational and Technological inhibitors also tend to raise barriers, but the SESI agents are better positioned to promote actions to overcome them. Scientific advances made by research centers and universities, workshops and congresses that seek to bring together industry and research are examples of mechanisms that can reduce technological and organizational barriers. Thus, Organizational and Technological inhibitors tend to be **medium** barriers. Cost inhibitors vary according to their origin. They were classified mainly based on the responses. As the innovation opportunities investigated are related to more environmentally-friendly processes, no environmental inhibitors were identified.

The potential to transform the industry mainly involves the emergence of new actors, knowledge and institutions in the SESI, meaning the extent of change in the SESI. For example, process innovation tends to change the industry only in the upstream part of the value chain, involving new technologies, new suppliers, and professionals with new specializations, among others. On the other hand, product innovation can promote greater transformations in the sector by involving also the downstream part of the chain - new consumers, new forms of distribution, new marketing strategies and new competitors. Innovations can also change the institution environment, as it may require new institutions, as new technical standards for a new product.

4. Results and discussion

This section discusses the above-mentioned innovation opportunities in the following order: cogeneration and sale of sugarcane bagasse bioelectricity, second-generation ethanol, vinasse biogas production, first-generation process improvements, and new products. The analysis is focused on discussing the main factors responsible for boosting or inhibiting each opportunity.

4.1. Cogeneration and sale of bioelectricity

The sugarcane industry has developed energy self-sufficiency. The availability of a large amount of sugarcane bagasse, a residue which is difficult to store, favored the development of the bagasse burning process to support the plant. Increasing the energy efficiency of this process has led to the opportunity to sell electricity to the grid (Souza et al., 2018).

There are several advantages related to the sale of sugarcane bioelectricity. Besides being a renewable form of energy, it is also a distributed source, since it is produced close to consumers by a large number of mills (Nyko et al., 2010). In addition, electricity is generated near the main consumption center in the country, the southeast region, especially the State of São Paulo.

Another advantage is that most of bagasse is generated in Brazil during the low rainfall period and low hydroelectric generation. This complementarity can be used to balance the oscillations of the country's energy supply, 64% of which is produced by hydropower (MME, 2016).

The energy potential of sugarcane waste is enormous. Nyko et al. (2010) estimated that 75% of the bagasse and 70% of the straw produced by the Brazilian sugarcane industry in one year could generate 30,000 MW, which is more than twice the annual Itaipu hydroelectric power output, the second largest hydroelectric power plant in the world.

Despite the conditions that favor sugarcane bagasse and straw cogeneration, a small number of mills make use of this potential source of revenue. In Brazil, according to NOVACANA (2017), less than half of the plants sell energy. This is due to the challenges associated with exploiting this opportunity, such as modernization of the facilities, investment in grid connection system and competition at energy auctions with wind power plants. Also, alternative competing uses of bagasse could arise, considering that it can also be employed for second-generation ethanol production (this topic will be further analyzed).

Table 1 lists the main drivers for selling bioelectricity. These include **cost** and **environmental** factors, because the raw material used is a renewable low-value residue, and **external** factors, i.e., drivers from outside the SSI domain that create incentives in favor of this innovation opportunity, such as increased energy demand in Brazil and the intermittence of supply from hydroelectric systems.

However, several challenges are associated with exploiting this opportunity (Table 1). Two of the greatest challenges are the high capital and operational costs needed to increase the process efficiency and the uncertainty in relying on spot market prices. This is because energy auctions have a specific form of contracting via Renewable Energy Auctions, where sometimes the price of kWh produced from sugarcane is lower than that associated with other sources, such as wind (MME, 2016). Although there is an institutional structure that promotes a regulated market for selling bagasse electricity, the competition generated by the auction format inhibits the interest of the industry.

Table 1
Key drivers and inhibitors for cogeneration.

Drivers	Category	Inhibitors	Category
Biomass availability (bagasse and straw).	Cost	Investments in more efficient equipment.	Cost
Increased energy demand in Brazil	External	Investment in network connection	Cost
Irregularity of the hydroelectric system	External	Controlled prices that compete with wind energy	Policy
Complementarity of seasonality (bioelectricity and hydroelectric power)	External	Competition with second-generation ethanol.	Organization
Renewable feedstock	Environmental		
Substitute for fossil power station	External		
Distributed generation and close to consumption centers	External		
Industry revenue increase	Cost		

Note that, in addition to the high investments to be made both internally (increasing process energy efficiency) and externally (grid connection), there are also **policy** related inhibiting factors with problems hard to be solved, because they involve **actors** and **institutions** outside the SSI, such as the structure of energy auctions and the lower price offered by wind farms.

Another important aspect to highlight is the possible competition for bagasse to produce 2G ethanol. However, research specialists pointed out the energy potential of lignin (a by-product of 2G ethanol production) as a bagasse substitute for the generation of bioelectricity, which has a calorific potential three times greater than bagasse.

In short, the decisive action required to increase the exploitation of the opportunities for selling bioelectricity involves reducing the investment risks, which are mainly related to the structure of the energy auctions, a challenge located at the **institutions** level, which is difficult to overcome solely by efforts made by companies within the sector, since it involves a dimension that influences several sectors besides the SESI.

4.2. Second-generation ethanol

The great demand for new sources of clean energy is among the main factors driving the use of cellulosic residue as raw material. With regard to the ethanol industry, sugarcane bagasse and straw are the main lignocellulosic materials available for second-generation ethanol.

The 2G ethanol technology consists of extracting and processing fermentable sugars from lignocellulosic material. This requires preliminary steps before the fermentation, particularly pre-treatment to breakdown and remove the lignin and enzymatic hydrolysis to transform the cellulose and hemicellulose molecules into fermentable sugars.

The most relevant advantages of 2G ethanol are the possibility to improve production by 50–60% without increasing the planted area; the high amount of biomass available (around 270–280 kg of bagasse and 140 kg of straw per ton of sugarcane) (Canilha et al., 2012); the availability of bagasse at the industrial facility, since it is generated at the mill; and the availability of equipment and utilities, especially during the off-season (IEA, 2017).

Table 2 summarizes the main inhibitors and key drivers for 2G ethanol. It is important to note the **policy** driving factor, i.e., at the **institutions** level, related to the creation of PAISS, an initiative that allocated efforts specifically related to innovation in the sugarcane industry.

Despite the advantages of 2G ethanol, there are challenges related to its implementation, particularly technical issues due to the need for further steps in the process. This leads to a need to increase the input from the **knowledge and technological domain**, both in relation to the use of new raw materials and the development of new processes. These difficulties are highlighted by the fact that none of the six commercial plants around the world that started operation between 2013 and 2016 have yet reached the projected production (NOVACANA, 2018b).

There are also challenges related to **policy**, for example, the absence of a demand policy for 2G ethanol, i.e., the **institutions** feature is lacking. This demand policy could enable learning process and, consequently, a reduction in production costs. Finally, there are also **organizational** challenges, mainly related to dealing with new **actors**, new suppliers and more specialized professionals.

In summary, the production of 2G ethanol seems to be associated with technical, policy and organizational challenges. However, the efforts made within the three dimensions of SI act to reduce these barriers. In the **knowledge** dimension lie the efforts of large specialized laboratories, such as CTBE and CTC (Sugarcane Technology Center), and advances made by universities in this new technology. In the **actors and networks** dimension, the presence of large companies interested in 2G ethanol production, such as enzymes producers, technology licensors and energy companies, helps in establishing the partnerships needed for the development

Table 2
Key drivers and inhibitors for 2G ethanol.

Drivers	Category	Inhibitors	Category
Increased world demand for biofuels	External	Pre-treatment challenges	Technology
Renewable feedstock	Environmental	Hydrolysis challenges	Technology
Biomass availability (bagasse and straw).	Cost	Fermentation (C5 and C6) challenges	Technology
Ethanol production increase	Cost	Straw logistics and transport	Technology
No competition with food	External	Solids processing challenges	Cost
Emission reduction	Environmental	Lack of incentives	Policy
Bagasse as part of the purchased feedstock	Cost	Absence of biomass market pricing	Organization
Availability of equipment and utilities (Off-season)	Cost	Integration Level (1G+2G)	Organization
Same product	Organization	Need of new agents and creation of new networks in the upstream process (enzymes suppliers, new equipment suppliers, yeast suppliers, etc.)	Organization
External markets as a potential buyer	Organization	Lack of biotechnology specialized professionals	Organization
Creation of the PAISS	Policy		

of this technology. In the **institutions** dimension, there are the PAISS I and PAISS *Agrícola* (Second version of PAISS focusing on agricultural innovations), which acted to stimulate the commercial production of 2G ethanol. Finally, 2G ethanol production faces significant barriers, but the efforts made at all the dimensions of SSI are slowly overcoming them.

4.3. Vinasse biogas production

Vinasse is one of the main byproducts of ethanol production. It is generated at the distillation stage in large quantities, around 10–15L per liter of ethanol. It presents a serious pollution risk due to its high organic load (Milanez et al., 2018). Regarding the options proposed for using vinasse, fertigation has by far the broadest application. This involves the irrigation of crops through the infiltration of soil with raw vinasse. In relation to unprocessed vinasse, it irrigates and fertilizes the crops, lowering the cost associated with chemical fertilizers.

Although these advantages are significant, studies have shown that the application of vinasse to the soil can adversely affect the environment, such as soil salinization, metal leaching, changes in soil quality due to nutrient imbalance, increased phytotoxicity and unpleasant odor (Milanez et al., 2018; Christofoletti et al., 2013).

Biogas production in an anaerobic digestion process, which promotes biodegradation of the organic part of vinasse, offers an alternative to fertigation. The biodigested vinasse, despite the reduction of the organic content, retains its fertilizing potential and can be used in sugarcane cultivation (Christofoletti et al., 2013). Several opportunities are associated with biogas within ethanol mills, such as boiler fuel to generate steam and drive the grinders, as fuel for sugarcane transportation and electric generator turbines (Szymanski et al., 2010).

Furthermore, biogas can be used as substitute natural gas in light and heavy engines or to generate electricity. Milanez et al. (2018) calculated that vinasse produced by the Brazilian ethanol industry in 2017 could produce 3.8 billion Nm^3 of biogas.

Given this potential, experts highlighted the main drivers and inhibitors associated with the transformation of vinasse into biogas, as detailed in Table 3.

Concerning the key drivers, the possibility of replacing diesel in the heavy engine fleet is one of the main advantages of producing vinasse biogas. Research on the use of unconventional gas in heavy-duty engines helps to boost this opportunity. This contributes to increasing the **knowledge and technological domain** related to biogas opportunities.

However, the main inhibiting factor is **policy (institutions)**. More than half of respondents emphasized that while the law is not specific about the risks associated with fertigation, this simple and inexpensive disposal of vinasse will be preferable to producing biogas.

4.4. Opportunities in the first-generation process – process innovations

Discussion regarding the innovation potential in the traditional process of ethanol production, i.e., first-generation, is controversial. One side argues that the exhaustion of sugar-energy technology is based on industry maturity, especially with regard to the industrial processing of sugarcane (Arruda, 2011; Goldemberg and Guardabassi, 2010; Moraes et al., 2015; Nyko et al., 2010). On the other side, researchers defend that the innovation potential is based on new technologies, mainly process innovations, which increase not only the amount of sugar converted but also lower water, energy and labor costs (CGEE, 2009; Lopes et al., 2016; Monteiro et al., 2018). An aggravating factor in this discussion is the technological heterogeneity of ethanol plants in Brazil.

The main losses of sugar are concentrated on key stages of the process, such as washing, extraction, fermentation and distillation. This loss is quite significant, indicating that there are opportunities for process improvements.

This study identifies many innovation opportunities in the first-generation process. The most promising opportunities include: sugarcane cleaning, modifying the extraction process from milling to diffuser, fermentation with selected yeast strains, pervaporation through membranes and use of molecular sieves.

Table 4 below summarizes the results related to first-generation process opportunities. They show that both drivers and inhibiting factors presented by the experts are related to **cost**. This result reflects the dilemma that firms face on deciding whether the investments required to modernize the plant worth the small increases in productivity, considering that many of these technologies have not yet been tested on an industrial scale in this industry.

The search for industry-wide modernization faces significant challenges, for the industry is quite heterogeneous. A plausible view that emerged in the interviews was that few groups in this sector would be able to move towards a more efficient and modern process.

Although in the past the SESI structure has increased the efficiency of many industrial plants via *Proálcool*, as the industry has matured, it no longer facilitates the process innovation to the same degree. To the contrary, few SI agents, such as leader companies and equipment suppliers, currently play this role.

4.5. Biochemicals – product innovation

The development of biomass chemicals is directly related to the progress of the biobased industry. Bomtempo and Alves (2014) presented some of the main drivers for its emergence, such as the significant advancements in industrial biotechnology and the environmental restrictions on fossil raw materials.

According to Bozell and Petersen (2010), the development of

Table 3
Key Drivers and Inhibitors for biogas.

Drivers	Category	Inhibitors	Category
Increased energy demand	External	High investment	Cost
Increased demand for biofuels	External	Long retention time	Technology
Renewable feedstock	Environmental	Production of corrosive gases	Cost
Organic content reduction	Environmental	Production of gas with unpleasant odor	Cost
Biodigested vinasse retains its fertilizing potential	Cost	Lack of legislation for fertigation	Policy
Electricity and steam generation	Cost	High volume	Cost
Biomethane production	Cost		
Similar products to those already produced by mills (electricity and fuel)	Organization		
Scientific research of unconventional gas in heavy-duty engines	External		

Table 4
Key drivers and inhibitors for 1G process.

Drivers	Category	Inhibitors	Category
Income gains with increased productivity (ethanol, sugar and energy)	Cost	Capital investment	Cost
Reduced spending on labor-work (process automation)	Cost	Investment in services (mostly for process automation)	Cost
Reduction in maintenance costs (new equipment and new materials)	Cost		

biochemicals is one of the pillars for the success of a biorefinery. The authors argue that it depends on two strategic goals: energetic and economic. The first one focuses on the replacement of large volumes of oil for transport with biofuels, such as ethanol and biodiesel, which are associated with low prices and high volumes. However, investment in operations focused exclusively on the production of biofuels can present a significant barrier to the achievement of economic goals. Production of biomass chemicals, which would be associated with low volumes and high prices, would come as an incentive and a solution for both goals, economic and energetic.

The potential of the biobased industry is huge (OECD, 2018). Not only can fossil-based chemicals be replaced, but also novel chemical molecules can extend the markets, incorporating new processes, products and players. Clearly, this transformation is associated with major challenges, and the large variety of chemicals that can be produced is one of them. Table 5 shows the main factors that boost and inhibit this opportunity.

Despite the considerable **technological** challenges, Table 5 shows that many inhibiting factors are **organizational**. Challenges are present in the selection of drop-in products (products identical to those produced from fossil feedstock) and not drop-in products. In the first case, there is competition with fossil-based products, which goes far beyond competition in terms of price, still being related to issues associated with the lack of experience in new markets - supplier relationships, experience with regulations, quality parameters, market awareness and complementary assets, among others.

In the second case, creating new markets represents a huge challenge, taking both the advantages (e.g., entering without competition and being the first to gain experience) and the disadvantages (e.g., taking the risks alone and allowing future competitors to learn from their experience) of being a first-mover. Another organizational issue is the managerial difficulty of dealing with different types of products like commodities and specialty chemicals.

In contrast to these challenges, a driving factor that could help in facing such difficulties is the interest of companies from other sectors (particularly the chemical industry), to create partnerships in order to take advantage of these innovation opportunities, that is, interest from new agents entering the sugarcane SI and transforming it to promote such innovations. This exchange of skills through partnerships would be one way to boost the development of the Brazilian biobased industry, with the participation of actors from the sugar-energy sector.

5. Disassembling the innovation opportunities in the Brazilian sugarcane industry

Table 6 summarizes the five opportunities analyzed in terms of barriers to innovation and the potential to transform the industry.

When analyzing the barriers to each opportunity, it is possible to observe that 2G ethanol and cogeneration have medium barriers. Despite 2G ethanol still has many technological challenges to be faced, the mobilization of several SSI agents (at the level of Knowledge, Actors & Networks, and Institutions) in developing this innovation reduces the challenges. Concerning cogeneration, although there is a barrier related to Institutions, which in general is considered high, interviewees considered it medium. The problem here is not the absence of an Institution, but its form, which generates competition with other renewable energy. The existence of a regulated market for the sale of bioelectricity, besides the spot market, reduces this barrier.

First-generation ethanol opportunities seem to present lower barriers, especially due to the expertise accumulated by producers and major suppliers. Therefore, the challenges are centered on managing the risks of new investments. Biogas and new products showed the highest barriers because they require profound changes throughout the SSI. The main biogas barrier is the lack of stricter legislation for fertigation, and the main barrier to chemicals is the numerous organizational challenges in managing new products and entering, or even creating, new markets.

This analysis shows that the industry tends to keep the same products, focusing on energy and ethanol, products that are familiar to the industry in relation to production and commercialization. This reflects an industry where innovation occurs incrementally, and often the production companies are not the source of innovation, outsourcing this task to equipment suppliers and laboratories. According to Pavitt (1984) classical typology, this industry shows supplier-dominated behavior; in other words, it has limitations in terms of competence to develop technologies internally.

The potential to transform the sector is related to change in the 3 dimensions of sugarcane SI: Knowledge, Actors & Networks, and Institutions. Since they do not involve many new actors and new knowledge, cogeneration and innovations in the first-generation

Table 5
Key drivers and inhibitors for new products.

Drivers	Category	Inhibitors	Category
Biomass availability (bagasse and straw)	Cost	Development of conversion technologies	Technology
Renewable feedstock	Environmental	Competition with fossil products (drop-in)	Organization
Potential to replace fossil chemicals	Environmental	Development of new markets (not drop-in)	Organization
Way to achieve strategic economic goals	Organization	Product portfolio and definition of market niches	Organization
Possibility to reach niche markets with renewable chemicals	Organization	Management of differentiated products (biofuels x chemical)	Organization
Interest from chemical companies	External	Biomass competition	Organization
		Need for large plants to enable the new products	Cost
		Lack of incentives	Policy
		Need for partnerships	Organization

Table 6
Summary of the five innovation opportunities.

Opportunities	Main Inhibitors	Barriers	Potential to transform the industry	
2G Ethanol	Tech; Organiz.;	Medium	Medium	Changes upstream
Cogeneration	Policy; Organiz.;	Medium	Low	Small changes downstream
1G Process	Cost	Low	Low	Small changes along the value chain
Biogas	Policy Tech; Cost	High	Medium /High	Medium if it is for power generation - Changes upstream High if for biofuel production - Changes the entire chain
New Products	Tech; Policy; Organiz.;	High	High	Major changes along the entire value chain

process do not show high potential to make significant changes in the industry. Concerning the cogeneration, there is a change in **institutions**, since the sugar-energy sector incorporates the guidelines of public energy auctions in SI, but this change has taken place without major business barriers. The main difficulties seem to be the competition in price with other renewable energy sources.

For 2G ethanol, the transformative power is considered medium because, despite being the same product, the value chain will involve several new actors and knowledge, such as enzymes, genetically modified yeasts, new agricultural processes and greater proximity to research labs and universities.

In the case of biogas, the degree of transformation can vary according to its use. If the goal is to generate electricity, the transformation is medium because this involves a high level of expertise already gained through the sale of bioelectricity (such as the energy auctions - **institutions**), but, if the goal is the production of biomethane, the need to create an entire supply chain arises, transforming the current sugarcane industry.

Regarding these innovation opportunities, production of chemicals is undoubtedly the most likely to transform the SSI, and this transformation would occur in all dimensions of SSI. Thus, new **actors and networks** would be required both downstream and upstream along the value chain, particularly chemical companies, as consumers and complementors. The **technological domain** would be expanded to be able to generate these products, which differ significantly from those traditionally produced. There would also be changes at **institutions** level, such as regulations for new products and laws encouraging biobased products.

Finally, upon analyzing the opportunities in general, this work shows that the main inhibiting factors are related to: Technology, Organization, and Policy. According to Fig. 3, the presence of technological factors is directly involved with the dimension **knowledge and technology domain**, where knowledge needs to be accessed, appropriated and accumulated, to overcome technological barriers. The organizational factors are mainly related to the management of new products and networking with new agents, that is, they are related to the **actors and networks** dimension. Lastly, the policy factors are related directly to the **institutions** dimension. In other words, in addition to the tendency of the sector to remain confined to its traditional products (ethanol and energy), the SESI also presents inhibiting factors directly related to the 3 SSI dimensions. This explains, at least partially, the rigidity of the sector in terms of innovation.

It is interesting to highlight that most interviewees showed an interest in more radical innovations and affirmed that they keep up to date on such opportunities. This works as a driver to reduce such stiffness. Even if this interest is not directly reflected in measures to promote innovation, it suggests that the sector would be receptive to initiatives coming from external players such as the chemical industry. An external agent, in partnership with SESI, could be better positioned to promote innovations.

Thus, two alternatives, possibly in combination, arise to boost innovation in the sector. The first one is to focus on the specific inhibitors that stiffen the SSI environment, thus facilitating innovation from the sector itself. The second one is to bring the SESI closer to other sectors that have lower barriers to promote the innovation in partnership.

The second alternative aims to stimulate an ‘ecosystem’ with different industries to explore the opportunities together. Experiences and skills brought by external agents serve both to aggregate new ways to overcome the barriers and to share the risks of innovation. Specific barriers, such as the development of technologies for producing biobased chemicals, may have solutions already established in other industries.

6. Conclusions

This article explores the SSI approach to identify and classify innovation barriers and drivers in a traditional sector of the Brazilian economy. It aims at analyzing five innovation opportunities in the Brazilian sugarcane industry and adding a new way to explore SSI approach.

As an applied contribution for understanding the sugar-energy sector, this analysis identifies that the inhibitors are distributed throughout the three dimensions of SSI, creating a rigid environment for innovation. It also shows that the sector has a supplier-dominated behavior and it tends to keep the same type of products, focusing on energy and ethanol. Therefore, the difficulties associated with the innovation opportunities are often too high to be exploited by the SESI in its present configuration.

However, given the sector's willingness to innovate with other sectors, the possibility of creating an innovation ecosystem, where actors from other sectors could bring their skills, in order to help overcoming the challenges, comes to light. Thus, this article suggests the search for solutions through partnering with organizations from other industries, to overcome such barriers. Companies closer to final consumers, such as biofuel producers and distributors and chemical companies, can be the key elements to leverage innovation (for example, production of biobased chemicals, biogas and 2G ethanol).

It is reasonable to assume that other traditional agribusiness sectors may also have promising innovation opportunities - as well as similar difficulties in innovating. This study sheds some light on how to identify and analyze innovation opportunities in these sectors. A suggestion to identify this innovative potential in agribusiness sectors is to evaluate the availability of renewable cellulosic biomass and its residues. The cellulosic raw material has been seen (OECD, 2018; IEA, 2017) as a promising source of substitution to petroleum for the production of fuels and chemicals.

Another alternative to identify innovation opportunities is to evaluate the current process efficiency, such as consumption of utilities and potential for energy cogeneration. Similar to the Brazilian sugar-energy sector, other sectors may not explore some opportunities, because they face difficulties to deviate from their "technological path," a feature present in supplier-dominated sectors (Pavitt, 1984).

Therefore, in addition to the specific contributions to the Brazilian sugar-energy sector, this work opens the possibility of questioning the innovative potential of several traditionally mature sectors, especially those based on renewable and low-cost biomass.

This study is mainly based on 17 interviews with industry experts from research (7), industry (7) and policy (3) areas related to the Brazilian sugar-energy sector. Although the methodology of semi-structured interviews and non-disclosure of respondents' names is employed to avoid bias, restriction to the sample interviewed is a limitation.

Therefore, for future work, expanding the sample of respondents in SESI and including other SSIs that could explore these opportunities in an innovation ecosystem perspective are suggested. Thus, other sectors' perception, possibly more willing to accept innovation risks, may bring different conclusions about barriers to innovation.

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None.

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