Energy Policy 108 (2017) 70–77

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Perspectives for the Brazilian bioethanol sector: The innovation driver

Sergio Luiz Monteiro Salles-Filho[a,*], Paula Felício Drummond de Castro[a], Adriana Bin[b], Charles Edquist[c], Ana Flávia Portilho Ferro[a], Solange Corder[a]

[a] Department of Science and Technology Policy —DPCT, Institute of Geosciences, University of Campinas, UNICAMP, Brazil
[b] School of Applied Science, University of Campinas – UNICAMP, Sao Paulo, Brazil
[c] CIRCLE, Lund University, Sweden

ARTICLE INFO

Keywords:
Innovation
Bioethanol sector
Brazil
Leadership
Second-generation ethanol
Biofuels

ABSTRACT

This article addresses the future of Brazil's bioethanol sector, focusing on its capabilities to innovate, its efforts toward producing cellulosic ethanol, and on recently implemented policies. Contrary to what has been argued in the literature, Brazil may not be prepared to face the technological and market challenges now emerging in the biofuels domain worldwide. Important productive investments were made by oil, energy, and chemical companies in bioethanol production in Brazil in the first decade of the 2000s; however, that sector has not shown levels of investment in innovation—either for first- or second-generation bioethanol—compatible with the challenges of making bioethanol a global commodity. Even considering recent policies in Brazil toward cellulosic bioethanol, the results achieved have been far from sustainable. This situation is partially due to uncertainties surrounding biofuels worldwide and partially due to contradictory policies toward liquid fuels in Brazil. The Brazilian government has simultaneously promoted both fossil fuels and renewables, thereby creating ambiguity among decision makers. These and other findings were drawn from an in-depth survey on innovation in the bioethanol sector in Brazil conducted in 2014 among 35 productive units affiliated to 58 industrial groups.

1. Introduction

This paper addresses the current situation and future prospects of the bioethanol sector in Brazil; there is a particular focus on innovative efforts and capabilities in that sector. Evidence from a wide survey conducted among companies engaged in sugarcane bioethanol production indicates that investment levels in innovation are incompatible with the productivity and diversification challenges that are needed to maintain the country's global leadership, particularly in second-generation bioethanol. Innovative capability is mostly found in Brazil's public and private research organizations, not its companies. This would not pose a problem if companies adopted and invested in internal management competencies to modernize their facilities and become part of the innovation process. However, concerns arise because bioethanol companies are much more focused on solving short-term bottlenecks than on building internal capabilities to manage innovation.

Until recently, Brazil was considered the indisputable global leader—in terms of both production and technological development—in the bioethanol sector. The country has a tradition of generating sugarcane varieties and mastering the technologies to produce sugarcane, ethanol, and sugar. Lately, besides bioethanol and sugar, that sector has become important in supplying electricity generated from bagasse. Some studies have indicated that Brazil's experience in the sugar-energy sector[1] could make it a model for other countries (Furtado et al., 2011; Goldemberg, 2007).

Brazil is still the world's largest producer of both sugarcane and sugarcane ethanol. During the 2014–15 crop year, approximately 9 million ha of sugarcane produced 634 megatons (Mt) of harvested cane, 35 Mt of sugar, and almost 29 billion L of ethanol (CONAB, 2016). However, since 2006, the world's largest producer of bioethanol (mainly from maize) has been the United States: nearly 57 billion L of ethanol were produced there in 2015, which is almost twice Brazil's production. Together, the United States and Brazil account for 85% of worldwide ethanol production (RFA, 2016). In 2014, the United States surpassed Brazil in terms of exports: 2.9 billion L, which is over 980 million L more than Brazil (Araújo, 2016). These figures reflect the relatively small international market for bioethanol (around 5 billion L).

* Corresponding author.
E-mail address: sallesfi@ige.unicamp.br (S.L.M. Salles-Filho).

[1] This paper mainly focuses on bioethanol. However, in Brazil, the great majority of bioethanol is made in refineries that also produce sugar and electricity. Thus, in this paper, we employ the two terms interchangeably: bioethanol and sugar-energy sector.

http://dx.doi.org/10.1016/j.enpol.2017.05.037
Received 27 June 2016; Received in revised form 15 May 2017; Accepted 18 May 2017
Available online 29 May 2017

According to Pavitt (1984), the market structure of the sugar-energy sector in Brazil can be characterized as both intensive in scale and supplier dominated. It has acquired or adopted technologies from other sectors, particularly from upstream industries. Furthermore, the sector is historically concentrated and organized in sizable economic groups—either national or multinational. In the past 10 years, more countries and companies have been investing in technologies to make ethanol production feasible using feedstock other than sugarcane and maize. Most of those efforts have focused on the industrial production of second-generation ethanol (2GE) or cellulosic bioethanol (Cardona et al., 2010; Dias et al., 2011; Griffin et al., 2016; Larrea, 2013; Macrelli et al., 2012; Milanez et al., 2015).

Studies have shown that if 50% of the bagasse produced could be converted into ethanol, it would represent improved production of 60% more liters per hectare (Soccol et al., 2010).[2] This attractive possibility has put 2GE to the forefront in the global agenda toward advanced biofuels. Nonetheless, cost and technological feasibility remain major barriers to such commercial production (Araújo, 2016; Carriquiry et al., 2011; Griffin et al., 2016).

The national projection for cellulosic ethanol production in Brazil for 2024 is up to 429 million L (around 1% of the country's expected total ethanol production) (Brazil, 2015). This information derives from Brazil's “Ten-Year Plan for Energy Expansion–2024,” a document that aims to guide actions and decisions with respect to energy supply. By comparison, the United States in 2015 produced 400 million L of cellulosic ethanol—about 80% of the installed national capacity (UNCTAD, 2016).

Brazil has implemented explicit policies toward promoting 2GE, such as the National Development Bank (BNDES) Plan to Support Innovation in the Sugar-Energy and Sugar-Chemistry Sectors: the PAISS program (Milanez et al., 2015). Another important program, which is focused on research not production, is the Bioenergy Program of the São Paulo Research Foundation (BIOEN). Altogether, these programs have already invested around US$100 million from 2008 to 2015.

Investments in 2GE have increased in many countries, particularly in the United States (Griffin et al., 2016). Worldwide in 2015, there were more than 30 commercial-scale cellulosic ethanol projects, 12 of which were in the United States and two in Brazil. However, it is not clear how countries will advance their biofuel policies. There have been vicissitudes in Europe, China, and India (Harvey and Bharucha, 2016). According to Harvey and Bharucha (2016, p. 86), “In the heyday of biofuel optimism, there was a vision of a new global South-North geopolitical pact for terrestrial transport, with a prospect of ‘18 Brazils’ across the sub-tropical world providing a substantial energy contribution.… Less than a decade later, that vision has dimmed, without any significant alternative to the dominance of conventional fuels in transport.”

From a research and development (R & D) perspective, there have unquestionably been advances in the main scientific and technological fields related to biofuels and bioethanol (conventional and advanced); however, from a production perspective, this is not so evident. The engagement of bioethanol companies in R & D and innovation is much less studied and understood than the engagement of research centers and universities in knowledge generation. Particularly in Brazil, no studies have examined how companies in this sector are innovating.

The present study is based on a survey conducted in 2014 of companies that accounted for about one-third of all Brazil's bioethanol production. That survey gathered data and opinions about the extent to which companies are undertaking innovation and how new technologies and areas of knowledge have been incorporated in their strategies. This paper is structured as follows: main trends in the literature focusing on characteristics of the sugar-ethanol innovation system (Section 2); methodology (Section 3); results and discussion (Section 4); and conclusions and policy implications (Section 5).

2. Literature review

The first-generation ethanol sector in Brazil has been considered successful owing to many factors: natural comparative advantages; significant technological advances; and huge production increases over the past 40 years associated with reducing production costs (Furtado et al., 2011; Goldemberg et al., 2004; Goldemberg, 2013; Leite et al., 2009). Brazil's ethanol production is firmly established and, in principle, ethanol was supposed to be competitive with gasoline in terms of price (Leite and Leal, 2007).

A number of studies have highlighted Brazil's advantages in bioethanol production, stressing its status as first comer (Farrell et al., 2006; Furtado et al., 2011; Hira and de Oliveira, 2009; Macrelli et al., 2012). Some authors have underscored Brazil's unusual capacity to expand sugarcane production without affecting food supply (Bordonal et al., 2015; Cortez et al., 2002; Cortez, 2010; Hall et al., 2011; Harvey and Bharucha, 2016; Leite et al., 2009; Martinelli and Filoso, 2008; Trindade, 2009).

Leite et al. (2009) examined the possibility of Brazil supplying ethanol to replace 5% of the global demand for gasoline by 2025. Besides necessitating more land (namely available pastures), increasing sugarcane productivity would also be required. As will become evident in the present paper, average productivity in Brazil is far from what it could be.

Furtado et al. (2011) emphasized that the sectoral innovation system in Brazil is fairly advanced (Malerba, 2002, 2003; Malerba and Mani, 2009). The system is built around Brazil's sugarcane industry, which includes sugar and ethanol mills, industrial suppliers, public and private research organizations, and governmental agencies.

From the time of the PROALCOOL[3] initiative until recent policies and programs implemented by the federal government (e.g., National Plan for Agroenergy 2006–2011 and Plan for Supporting Innovation in the Sugar-Energy and Sugar-Chemistry Sectors), several related initiatives were undertaken in Brazil; they promoted investment and created internal capabilities in research. Campos et al. (2015) identified almost 140 active research groups working only within universities and at least 30 more groups in public and private research centers.

As well reported in the literature (Cortez, 2016), research laboratories (mostly public, but also some private, not-for-profit) have been responsible for important improvements in bioethanol production, both agriculturally and industrially. For example, sugarcane productivity (as a result of genetic breeding conducted in Brazilian research centers) has doubled since the end of the 1960s; over the same period, ethanol productivity showed a threefold increase. Likewise, technological solutions for waste disposal (particularly for *vinasse*) and efficiency in energy consumption also derived from Brazilian research laboratories.[4]

According to Furtado et al. (2011), the government has played a central role in instigating R & D activities in the bioethanol sector: “The sugarcane agroindustry innovation system is responsible for reassuming leadership of the public sector, in both financing and coordination to guarantee achievement of the targets for medium- and long-term growth of production” (p. 166).

Notwithstanding some remarkable technological improvements achieved in the past 50 years for first-generation bioethanol, in the present article we argue that this successful story does not represent

[2] Studies have shown that in coming years, the ethanol yield per hectare of sugarcane—presently 6000L/ha—could amount to 10,000L/ha if 50% of the produced bagasse were converted to ethanol (Soccol et al., 2010).

[3] PROALCOOL stands for National Program for Ethanol Production, and it was implemented in 1975. For a historical perspective of this program, see Cortez (2016).

[4] For a comprehensive description of the contributions of research to the sugar-energy sector in Brazil, see Cortez (2016).

any guarantee for Brazil to reach worldwide leadership in biofuels.

Sousa et al. (2016a, 2016b) compared bioethanol innovation and technological systems in Brazil and the United States. They concluded that Brazil still has advantages over the United States in terms of availability of feedstock (straw and stalks other than sugarcane) and land (no serious restrictions over food supply and changes in land use). Many authors have stressed the advantages of positive interaction within the sugar-energy sector in Brazil: economic exploitation of sugar, bioethanol (whether from sugar or celluloses), and electricity would give the country unique comparative advantages (CGEE, 2012; Milanez et al., 2015). Indeed, Milanez et al. (2015) emphasize that first and second generation may be complementary, depending on the relative prices of bioethanol, gasoline, sugar, and electricity. According to those authors, this would offer a unique advantage for Brazil worldwide.

Production and demand for bioethanol as liquid fuel have in fact increased in Brazil over the past 13 years. A critical stimulus for this trend was the introduction of flex-fuel engines in the early 2000s. When investigating this phenomenon, Souza and Pompermayer (2015) identified a close relationship between the increase in internal consumption of bioethanol and the introduction of flex-fuel light cars in the Brazilian market in 2003. In 2006, the sales of flex-fuel vehicles surpassed those of single-fuel vehicles, and the former became predominant in Brazil. By early 2010, flex-fuel vehicles accounted for 90% of total light vehicle sales. Since then, the proportion of flex-fuel vehicle sales has been consistently above 85% of total light vehicle sales in Brazil (ANFAVEA, 2016).[5]

The growth of the flex-fuel market has had an economic consequence for consumers. There are many reasons for consumers choosing gasoline rather than ethanol as a fuel, such as sustainability, local production, and employment generation. However, a highly sensitive factor is the relative prices of the two fuels. It is widely known that gasoline and ethanol cannot be perfectly substituted for each other, particularly because of differences in their energy content. Roughly speaking, 0.7 L of gasoline is equivalent to 1 L of ethanol. Thus, to be competitive for consumers, the price of ethanol should be under 70% that of gasoline.

In this situation, Brazil's internal policies regarding liquid fuel production and consumption (including price-control policies) are critical in determining bioethanol demand and—by extension—the pace of market growth. As pointed out by many authors (Araújo, 2016; Milanez et al., 2015; UNICA, 2014), the Brazilian government has applied a policy of controlling inflation based on the regulation of gasoline and other oil derivative prices. This policy, which was effective from 2011 to 2015, strongly influenced the rationale of economic agents because cheap gasoline became a reference pricing. Fig. 1, based on Souza and Pompermayer (2015), shows the relationship between gasoline and ethanol prices compared with the consumption of hydroethanol in Brazil for 2006–15.

A major impact of that policy was reduction in demand for ethanol between 2011 and 2015. According to Milanez et al. (2015), that period showed a strong decrease in investment in the ethanol sector—both for opening new plants (greenfield mills) and expanding existing ones. Part of this phenomenon is clearly due to the price policy noted above. As evident in Fig. 1, the consumption of bioethanol as liquid fuel presents a quasi-symmetric curve compared with the relative proportion of ethanol and gasoline prices over that period. The more that proportion rises above 70%, the less consumers will feel inclined to fill their tanks with bioethanol—and vice versa.

To complete the picture, that situation arose at a time when Brazil was heavily dedicated to exploring oil and gas in pre-salt fields. Since 2005, through the state-controlled company Petrobras, the Brazilian government has defined pre-salt fields—and the whole oil and gas productive chain—as a high priority for the country's economic and social development.

The policy for exploring pre-salt fields and that of controlling gasoline prices resulted in contradictory signals about the government's intentions toward renewables. As pointed out by Harvey and Bharucha (2016), "In Brazil, within the context of low global oil prices, a pro-poverty pro-oil politics of recent years has contributed to the negative environment for further biofuel innovation and development" (Harvey and Bharucha, 2016: p. 87).

As noted above, the bioethanol sector in Brazil has achieved important developments in all main components of the production chain. This has been widely reported in the literature (Campos et al., 2015; CGEE, 2012; Cortez, 2010; Cortez, 2016; Furtado et al., 2011; Goldemberg et al., 2004; Goldemberg, 2013). Despite the country's long tradition of generating new sugarcane cultivars and developing agronomic techniques for sugarcane production, harvesting, and processing, important technological bottlenecks remain at the top of company agendas, as shown by Milanez et al. (2015) and Salles-Filho et al. (2016).

Regarding 2GE technologies, studies based on bibliometric analyses of scientific publications and patents (Dal Poz and Silveira, 2015; João et al., 2012; Souza, 2013; Souza et al., 2015) have shown very low levels of participation by Brazilian researchers and organizations. Examining publications in the Web of Science and patents drawn from PatBase, Souza (2013: p. 179) concluded that the "state of art of second generation comes exclusively from American authors" and that Brazilian participation was marginal in core technologies related to lignocellulosic ethanol. After comparing the main biofuel R & D programs of the United States and Brazil (Biomass Program of the Department of Energy and PAISS program of BNDES, respectively), one study found that the US program had over 10-fold greater financial resources than its Brazilian counterpart (Pereira et al., 2015).

Even with first-generation bioethanol—and despite achievements in terms of productivity and efficiency—the adoption of new technologies by Brazilian companies is highly heterogeneous and has kept productivity averages at low levels. As Campos et al. (2015) have demonstrated, Brazil's bioethanol innovation system has come to something of an impasse: many of the findings obtained by research organizations fail to be adopted by companies—both in agriculture and industry.

Brazil has developed an important domestic market for bioethanol; this reflects the positive impact of previous investments in this sector—in both productive and technological capacities. With the benefit of hindsight, there is consensus that this course has been successful; initially, however, there is uncertainty over which emerging trajectories will prove to be so. Traditional and established advantages with first-generation production do not provide sufficient basis for supporting new development possibilities for biofuels, particularly with second-generation production.

In the following sections, we present the methodology and results of a representative survey focused on innovative practices in Brazilian bioethanol companies.

3. Methodology

The results presented in this paper were obtained from the NAGISE program,[6] which is a pioneer, systematically and methodologically structured initiative for developing innovation and innovation management in Brazil's sugar-energy sector. The program was conducted in 2014 through three main activities. The first was a 96-h training course, with 24 class sessions on innovation management directed at

[5] As a consequence, in the period 2003–09, the production of bioethanol in Brazil almost doubled (Milanez et al., 2015).

[6] NAGISE stands for Center for Innovation Management in the Sugar-Energy Sector. It is a multidisciplinary group located in the School of Applied Sciences of the University of Campinas (UNICAMP).

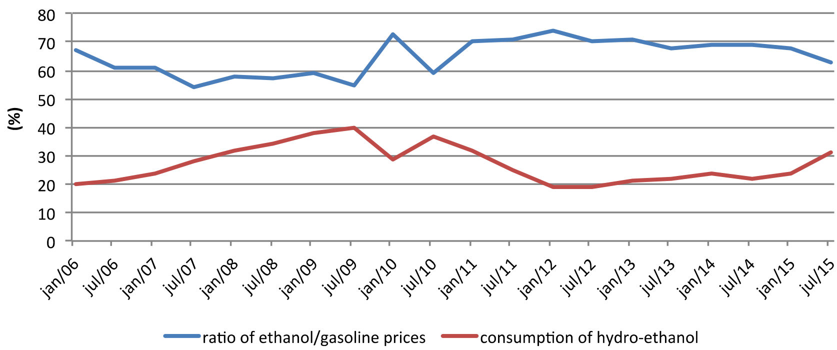


Fig. 1. Evolution of the ratio of ethanol/gasoline prices and market share of hydro-ethanol in Brazil.

professionals in the sugar-energy sector. Approximately 80 participants attended the course. They were from 35 industrial units from different segments in the sugar-energy chain, representing 27 companies linked to 58 national and multinational economic groups through capital participation.

The second activity was a survey applied to course participants. It covered the following issues: part 1, profile of participating companies (including capital participation, main business, geographic location, employees, productivity, and main markets); part 2, innovative efforts and their outputs and outcomes (including new products and services, R & D and other innovative activities, innovation drivers, organizational and marketing innovation, cooperation for innovation, intellectual property rights, and innovation funding); and part 3, innovation management (including innovation management capabilities, innovation management practices, and barriers for innovation management). Part 2 was mainly based on questions from the Brazilian Innovation Survey, PINTEC.[7] Part 3, dealing with innovation management indicators, was based on the findings of Dodgson et al. (2008), Hidalgo and Albors (2008), Phaal et al. (2006), and Tidd et al. (2008).

Professionals from the same industrial unit answered the survey together using a Web-based platform, in which every company had its own secure domain. Each company had a mentor from NAGISE, who helped participants in properly completing the survey, using face-to-face and remote interactions. The 35 industrial units surveyed represented one-third of Brazil's bioethanol production; the 58 economic groups to which they were attached represented two-thirds of national production. It is notable that all three Brazilian companies making investments in cellulosic ethanol took part in the NAGISE program: Raizen (around 40 million L/year), GranBio (about 80 million L/year), and CTC (experimental scale).

The third main NAGISE activity was technical support for participating companies in developing strategic plans for innovation and innovation management; the focus was on their priorities for future investments regarding scientific and technological, marketing and organizational, and institutional and regulatory challenges. The prioritization process took into account seven main criteria: (1) increase in productivity levels; (2) reducing operational costs; (3) generating new business models; (4) generating social-environmental benefits; (5) technical feasibility; (6) time frame for maturity; and (7) aggregated importance for the sector (sectoral perspective). Strategic plans were also elaborated using the Web-based platform and employing mentor support.

We analyzed data collected from the above survey and also from the companies' strategic plans regarding their priorities for future investments using descriptive statistics. We also made comparisons with innovation and sectoral indicators for Brazil. In the following section, the absence of international comparison is due to Brazil's biofuel sugarcane-based sector being a unique case in the world.

4. Results and discussion

The data collected from the survey and strategic plans during the NAGISE program are organized in four parts: company profiles; technological and non-technological innovation; innovation management; and summary of main findings (including priorities set by companies for future investments).

4.1. Company profiles

The NAGISE program participants included representatives of 14 independent companies. The remainder were from groups whose headquarters were located in Europe (three), the United States (one), and—the majority—in Brazil (nine). One-quarter were from companies with foreign capital and controlled by groups from the United States, Europe, and Asia. Three groups or companies were joint ventures between Brazilian and foreign companies or groups. An extended analysis of these data can be found in Salles-Filho et al. (2016).

The great majority of companies (23 of 27) operated in sugar, bioethanol, or bioelectricity. This activity reflects the main products in terms of total sales for 2011–12 for 18 of the companies. Only four of the groups or companies declared ethanol to be the most and sugar to be the second-most important product; only one of the companies was 100% dedicated to ethanol production. Four companies also operated in other business areas: two in biotechnology and two in engineering consultancy.

The location of the participating companies reflected the geographic distribution of the sugar-energy sector in Brazil: 22 companies were located in the Southeast region (with strong prevalence in the state of São Paulo); two were in the Central-West region; and three were in the Northeast region. According to UNICA (2013), the Southeast and Central-West regions were responsible for 91% of sugar production and 93% of ethanol production; the state of São Paulo alone accounted for 63% of Brazil's sugar production and 51% of its ethanol production.

The participants represented large corporations with 1000–5000 employees. Five companies or groups had over 10,000 employees; the biotechnology and service companies had up to 320 employees. The levels of highly qualified employees were as follows: for every 23 employees, there was one with higher education; for every 10,000 employees, there were not more than 10 people with a master's degree or four with a PhD.

The majority of participating companies (71%) reported average agricultural productivity that was slightly higher than the Brazilian average, which is less than 70 t/ha according to CONAB (2016). However, some fields in the state of São Paulo had average agricultural productivity of about 100 t/ha, which was much higher than the national average. In terms of ethanol, half of the participating

[7] PINTEC is a survey conducted every 3 years among Brazilian industrial companies by the National Institute of Geography and Statistics (IBGE). It is strongly based on the OECD's Oslo Manual (OECD, 2005).

Table 1
Innovation and degree of novelty.

Degree of novelty	Productive units that declared			
	Exclusively product innovation	Exclusively process innovation	Both product and process innovations	No innovation
new to company	1	7	15	–
new to Brazilian market	0	3	8	–
new to the world market	0	0	2	–
not defined	–	2	5	
Total	1	12	30[a]	7

[a] The actual number of productive units that declared both product and process innovations was 15. The number 30 refers to these 15 productive units assigning degree of novelty of their efforts in both product and process innovations.

companies declared productivity of approximately 4 m^3 ethanol/ha; that is about 33% less than the figure reported for the 2011–12 agricultural year in São Paulo (CONAB, 2016). This finding is probably due to the specificities of the industrial units to which the participants belonged.

Finally, the participating companies were much more oriented to the domestic market, which accounted for 76% of their business. Europe and Asia (8% each) were the main destinations in the international market.

4.2. Technological and non-technological innovation

The majority of the 35 productive units in the NAGISE program implemented new products or processes in the 2011–12 crop year. The Brazilian Innovation Survey (IBGE, 2013) reported proportions of 36% and 56%, respectively, for innovation in industry and innovation in large corporations during the same period for all industrial sectors. Even taking into account that NAGISE participants are large companies, there is still a conspicuous difference between innovation in the country as a whole and that in our sample. A possible reason for that is an “innovation bias” among companies that participate in the NAGISE program: all of them already had corporative activities dedicated to innovation before the program began.

As indicated in Table 1, 12 (43%) of the productive units that declared some kind of innovation in 2011–12 were dedicated exclusively to process innovation; just one was exclusively involved in product innovation, while the other 15 (54%) were involved in both. This situation differs from the general situation in Brazil: 53% of the industry has declared that its innovative efforts are devoted exclusively to process innovation, 9% exclusively to product innovation, and 39% to both. Two complementary reasons can account for these differences: (1) the aforementioned bias of the NAGISE sample; and (2) this sector is based on commodities (sugar, ethanol), and innovation with commodities is normally lower than with other products.

As might be expected from the sector profile, product innovations were mostly developed by the companies themselves; they may be characterized as efforts toward modernization and technological updating, especially in the agricultural segment. Common examples of product innovations cited by the companies were sugarcane cultivars, sugar of different standards, electricity from bagasse, and by-products for human and animal food supplements. Very few cases of fermentation and distillation processes were described; they largely reflected incremental development. Process innovations mainly took the form of incremental development; they were particularly evident in such agronomic practices as soil preparation and cultivation, pest and disease control, harvesting equipment, recuperation of straw and stover, and techniques to improve electricity generation from bagasse burning.

Regarding 2GE, major investments in innovation in Brazil are being made by Raizen, GranBio, and CTC; different types of technology are being developed. However, it should be noted that the technological core of 2GE (enzymatic hydrolysis) is imported in all cases. As demonstrated by Souza et al. (2015), research in Brazil is strongly directed toward fermentation processes; it is poorly focused on hydrolysis.

Taking the whole set of innovations declared by the productive units engaged in the NAGISE program—and employing the classification of degree of novelty of the Organization for Economic Cooperation and Development—60% of new products and 93% of new processes introduced by the companies were novel just at the firm level. This means that the main course of corporative innovation is characterized by acquiring technologies already available on the market or developed by suppliers upstream of the production chain. There were just two cases of completely original innovations: both were characterized as product adaptations to meet particular geographic conditions (Table 1).

Fig. 2 illustrates the main drivers pushing innovation in the companies surveyed. The most important were those related to regulatory, environmental, and social issues. That was true for the most common applications: harvesting (replacing manual harvesting by machines); water reuse; waste treatment (vinasse); and cogeneration of electricity and heat. Maintaining market share was also important. The less important drivers were those related to opening new markets and portfolio diversification.

By way of comparison, data from the national innovation survey PINTEC (IBGE, 2013) indicate that environmental and regulatory drivers were among the most relevant drivers of innovation in Brazil. This emphasizes the critical role of regulatory drivers in promoting innovation in the country's bioethanol industry.

With respect to in-house R & D, about half of the companies participating in the NAGISE program had internal systematic activities, involving 122 full-time professionals with higher education degrees. However, very few researchers had a master's (10 people) or PhD degree (four people).

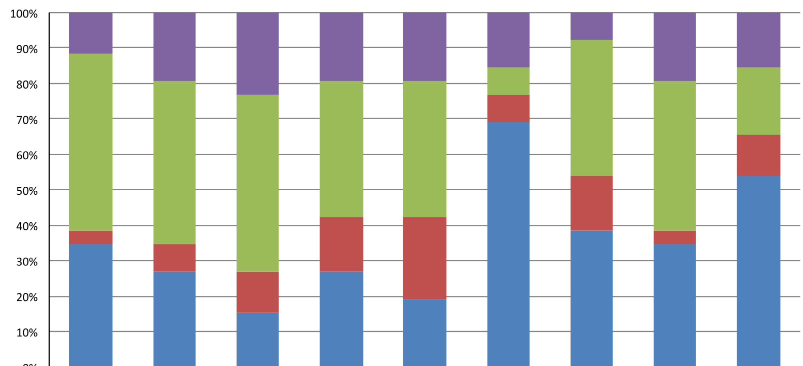
Over a 15-year period (2000–14), 25 patents were filed in Brazil, just three of which were covered by the Patent Cooperation Treaty; 26 cultivars were registered in Brazil by companies participating in the NAGISE program. However, almost all the patents and cultivars were registered by a single company—a biotechnology firm that develops technologies for an association of bioethanol companies.[8]

An important portion of the innovative activities among companies related to non-technological innovation (managerial, organizational, and commercial innovations). Almost all the productive units reported some activity in this domain. Fig. 3 shows how the companies pursued non-technological innovation.

4.3. Innovation management

Internal capabilities dedicated to management of innovation help clarify companies' efforts toward innovation. Fig. 4 indicates that just three productive units had their own full-time staff dealing with innovation management activities; 10 units had part-time personnel

[8] For details about intellectual property in this sector, see Salles-Filho et al. (2016).



	Regulatory compliance	Controlling health and safety aspects	Reduction of environmental impacts	Reduction of production costs	Increase capacity production	Opening new markets	Expansion of market share	Market share maintenance	Portfolio diversification
High relevance	3	5	6	5	5	4	2	5	4
Medium relevance	13	12	13	10	10	2	10	11	5
Low relevance	1	2	3	4	6	2	4	1	3
Not relevant	9	7	4	7	5	18	10	9	14

Fig. 2. Main drivers of technological innovations undertaken by productive units (n = 35).

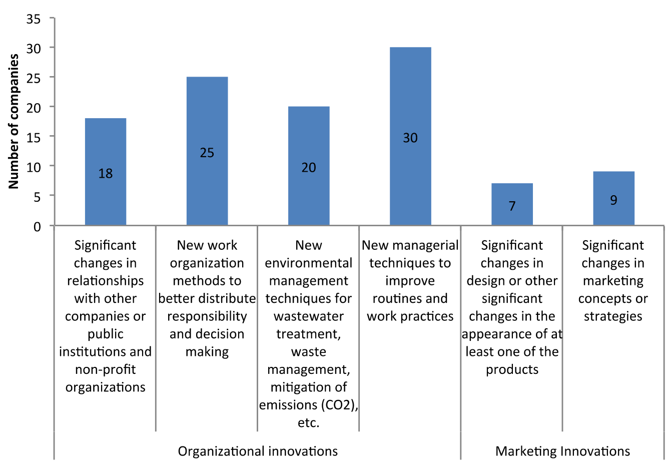


Fig. 3. Organizational and marketing innovations undertaken by productive units (n = 30).

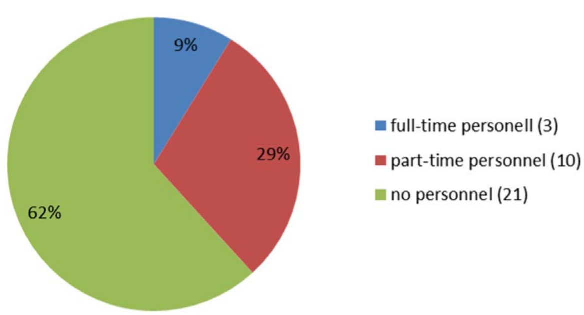


Fig. 4. Personnel dedicated to innovation management among productive units (n = 34).

dedicated to such activities. Although small (up to five people), these fully dedicated areas were based on professionals formally trained in innovation management. In units with part-time dedicated staff, innovation management activities were decentralized in several areas or departments. In all, 21 units (one did not respond) stated they did not have any personnel (their own or outsourced) dedicated to innovation management. Just three productive units declared that they had an innovation management plan for guiding innovative activities.

The above findings are not necessarily bad or good. There are no comparable data from other sectors in Brazil. However, several innovative challenges have emerged worldwide in biofuels. Given the strategic importance of bioethanol in Brazil, the minimalist approach to innovation management detailed above deserves great consideration, particularly from a policy perspective.

Complementary data should be noted. Among the participating companies, just three had at least once submitted proposals for R & D funding agencies over the previous 3 years. Regarding fiscal incentives for R & D and innovation, just two companies had once applied for federal programs in the country.

4.4. Summary of main findings

To summarize our findings, companies are particularly interested in adapting production to regulatory constraints. Companies also look for incremental innovations in the agricultural sector: specifically, new cultivars to improve sugarcane productivity. It is interesting here that Brazil possesses a long tradition of genetic breeding programs, as indicated in various studies (Brasileiro et al., 2014; Campos et al., 2015; Furtado et al., 2011; Landell et al., 2014). Considering only higher education institutions, Campos et al. (2015) identified around 140 research groups in bioethanol; 30% of them were dedicated to sugarcane breeding. According to Campos et al. (2015), Brazil has at least four large-scale, comprehensive sugarcane breeding programs: two in public and two in private organizations.

We believe that the supply of sugarcane cultivars cannot really be considered a bottleneck in Brazil. On average, productivity levels vary over 35% within the same region (such as the state of São Paulo) with similar conditions of soil, topography, and climate; thus, important technological asymmetries certainly exist among producers. These differences are partly due to the adoption of sugarcane varieties. The NAGISE program participants agreed that increasing productivity levels in the state of Sao Paulo from 70 t/ha to 100 t/ha would be perfectly possible—both technically and economically.

Several new issues have been frequently addressed in sugarcane genetic breeding. Landell et al. (2014) listed some of them for both first- and second-generation ethanol: germplasm characterization; regional adaptation; drought tolerance; molecular markers and marker-assisted selection; and identifying novel genes for genetic transformation. Notwithstanding these scientific and technological challenges, Brazil has a great many commercial varieties of sugarcane that could be adopted by producers, thereby contributing to the country's productivity.

There is something of a discrepancy between the domestic situation of Brazil's sugar-energy sector and the global movement toward renewables and clean energy. With few exceptions, innovation within companies does not address the two main challenges for this sector: going beyond the domestic market and developing bioethanol as a global commodity; and making 2GE a technical and commercial reality.

On the contrary, the large majority of companies are still dealing with chronic problems related to productivity and profitability in the domestic market.

Movements in the capital structure of companies were observed during the first decade of the 2000s, when large groups of oil, energy, and chemical companies took over local sugar-energy mills or built important joint ventures. However, Brazil's sugar-energy sector is still focused on incremental innovations for first-generation bioethanol. Further, the concerns revealed by the NAGISE program participants indicated traditional technical bottlenecks, such as sugarcane productivity, logistics, and mechanization, where solutions are mostly—or potentially—available.

5. Conclusions and policy implications

Companies participating in the NAGISE program (composed of all the largest sugar-energy companies in Brazil, representing more than 30% of total bioethanol produced in the country) showed modest interest in innovation. With some exceptions, they did not indicate innovation efforts beyond the Brazilian domestic market. They were not making consistent paths efforts toward producing 2GE. This finding is generally unsurprising: in traditional sectors worldwide, most companies focus on ongoing technological, commercial, organizational, and institutional bottlenecks. What is surprising is the relatively slow movement of companies, including large multinational groups, in facing new technological challenges in the biofuels domain.

From a sectoral viewpoint (Fernandes and Lima, 2012), the majority of companies making bioethanol also produce sugar (and electricity); thus, their decisions on investment are strongly influenced by the relative prices of sugar and ethanol and, more recently, of electricity. The feedstock is the same—sugarcane; therefore, choosing to manufacture one or the other product is a rational short-term decision. In addition, as noted above, the relative price of gasoline is a critical factor in decision making in this sector. Since the biggest market for bioethanol is fuel for light cars, it is always competing with other fuels, whether renewables or non-renewables.

As well as these sectoral determinants, other restrictions, such as interest rates and contradictory policies toward fossil fuels and renewables, need to be considered toward understanding the paths of innovation in Brazil's sugar-energy sector. On one hand, macroeconomic variables centered on supporting high interest rates reduce opportunities for investment. On the other hand, regardless of persistent official rhetoric about renewables, policies concerning liquid fuels in Brazil have prioritized gasoline, threatening the competitiveness of ethanol (UNICA, 2014). Under these circumstances, the data obtained from the NAGISE program participants are fairly coherent: firms do not take steps toward increasing their technological capacity in this sector. Accordingly, the core technologies for 2GE have not been developed in Brazil. Instead, they have come from the United States and Europe (Griffin et al., 2016; Silveira et al., 2016; Sousa et al., 2016a, 2016b).

The future scenarios for biofuels are rather unclear. Different countries have proposed different policy paths (Milanez et al., 2015). Bioethanol has to compete with other renewables, such as biodiesel, electric engines, and other transportation modes. One new factor on the global scene is the Paris Agreement, which promotes a progressive reduction in CO_2 emissions (FCCC, 2015). Although the effects of the Paris Agreement on policies and markets cannot be predicted, the agreement would appear to be of high importance in any prospective appraisal of biofuels. Biofuels, particularly bioethanol, present a possibility for countries to achieve their Nationally Determined Contributions and so swiftly decrease CO_2 emissions. However, as pointed out by Harvey and Bharucha (2016), nothing can be assured about the future of biofuels in a country's policies. The national context can either accelerate or impede the trend toward using cellulosic bioethanol; that trend will depend strongly on technological development and diffusion, national policies for renewables, and economic advantages over other renewables.

In this paper, we have examined the odd situation of the sugar-energy sector in Brazil: it is simultaneously competitive and conservative with regard to innovation. Its competitiveness is based on both comparative and competitive advantages, the latter being strongly underpinned by agronomic research and sugarcane genetic breeding. Despite the respectable research structure for sugarcane, sugar, and bioethanol, innovative efforts by companies are modest and so are their internal structures and capabilities to innovate. It is unclear to what extent this sector will be able to make the transition from first- to second-generation bioethanol production.

Initiatives to develop technologies and build industrial facilities to produce 2GE are strongly based on public policies. The PAISS program, coordinated by BNDES and the Brazilian Innovation Agency (FINEP), has since 2011 supported direct investment in one pre-commercial and two commercial plants in the country. The BIOEN program, coordinated by the São Paulo Research Foundation (FAPESP, 2016), has financed several research groups in the state of São Paulo, promoting multidisciplinary scientific and technological developments. Commercial investment is in progress, though it is not yet stable.

The expansion of Brazil's bioethanol sector is strongly dependent on expanding exports. The domestic market for bioethanol still has room for expansion (mainly in transportation but also as feedstock for chemicals and petrochemicals); however, it is clearly insufficient to change the pace of investment in innovation, whether first or second generation.

Any efforts to develop commercial 2GE in Brazil have to be supported by explicit policies to make bioethanol a global commodity. This conclusion also appears to apply to first-generation bioethanol. The levels of investment in innovation—even in simple modernization—can increase only if companies feel such investment to be critical. That situation would require competitive pressure. With the present market structure of Brazil's sugar-energy sector, there are no serious short-term internal or external threats, creating little pressure for innovation. Companies will react if they foresee global market opportunities or if they feel threatened by a changing scenario for 2GE and new market entrants. That is why companies have made minimal innovative efforts: they do not need to go beyond such efforts.

The future of the sugar-energy sector, particularly bioethanol, in Brazil will depend on a convergent (not divergent, as is currently the case) policy mix. Such a policy mix should include instruments to develop global markets and clear, encouraging regulatory mandates for renewables. Programs based only on financial support for innovation will be ineffective if they stand alone in a scenario in which most companies are not really interested in changing their trajectories. Innovation in first- and second-generation bioethanol will strongly depend on this.

Acknowledgements

The NAGISE program was supported by the Brazilian Innovation Agency (FINEP), under Agreement 01.12.0267.00. The authors would like to thank the companies whose participants made this research possible.

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