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Innovation subject to sustainability: the European policy on biofuels and its effects on innovation in the Brazilian bioethanol industry

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Abstract

Biofuels are a suitable complement for fossil energy in the transport sector and bioethanol is the main biofuel traded worldwide. Based on the assumption that innovation can be influenced by regulation, the Brazilian bioethanol industry is facing new requirements from external actors while reaching for international markets. Until 2010, national environmental laws were the main sustainability instrument that the biofuel industry faced. With the introduction of sustainability criteria for biofuels in the European Fuels Quality Directive (FQD) and Renewable Energy Directive (RED) of 2009, bioethanol producers have been pressured to innovate in respect of the requirements of future markets. Here, the aim is to analyse the case of Brazil, given the potential exports of sugarcane-based ethanol from this country to the EU. Brazil provides an interesting overview of how a bioethanol industry innovated while facing sustainability requirements in the past. A comparison between the European requirements and the industry´s status quo is then explored. The EU criteria are likely to have effects on the Brazilian bioethanol industry and incremental improvements in sustainability levels might take place based on the sustainability requirements. In addition, the industry could follow two other paths, namely risk diversification by engaging in multi-output models; and market leakage towards less-regulated markets. At the same time, an environmental overregulation of the biofuel market may make it more difficult for emerging biofuel industries in other countries, especially in Africa, by creating a barrier rather than contributing to its expansion. The results of this analysis show the main challenges to be addressed and the potential positive and negative impacts of the European Union biofuels policy on the Brazilian bioethanol industry.

Keywords

Bioethanol, Innovation, Sustainability, Sugarcane, European Union, Brazil

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INTRODUCTION

Biofuels have been the target of much interest, debate and research. For multiple reasons, it is in the interest of individuals, governments and international organisations to reduce the established dependency on oil-based transport fuels. In this context, and given the restrictions posed by the existing transport sector infrastructure, biofuels are an option for a more sustainable energy carrier, while better options mature.

In recent decades, ethanol fuel has grown from small scale and unregulated production to a major industry, acting now as a significant blend alternative in the global transport fuel pool (UNCTAD 2009).[1] Innovation processes have been key enablers to the scale and market dynamics which exist in bioethanol markets (Walter 2009). Global bioethanol production reached 86.1 billion litres in 2011 (REN21 2012). High oil prices became the main motivation for the expansion of this market, but policy drivers for biofuels also included issues of energy security, climate change as well as rural development (Correlje and Van der Linde 2006; European Commission 2007). The European Renewable Energy Directive (2009/28/EC) provided incentives towards an increased share of biofuels in Europe´s transport sector. The directive was initially proposed in January 2008, shortly before oil prices peaked at USD 146 per barrel. The directive also contained a sustainability scheme applicable to biofuels, mandatory for such fuels to be counted towards the 10 per cent renewable energy target in the transport sector by 2020.

In the context of international competition, industries are required to keep pace with innovation on a constant basis and this is no different for the bioethanol industry. While seeking ways to improve production systems, the bioethanol industry is faced with different sustainability requirements which tend to influence its future innovation paths. Brunnemeyer and Cohen (2003) found evidence that environmental innovation is most likely to occur in industries that are internationally competitive, which suits the present context for bioethanol.

This paper uses the case of the Brazilian sugarcane-based ethanol industry, investigating how its innovation forces behaved in the past while facing national sustainability regulations, and how they are likely to respond to the sustainability criteria introduced by the European Fuels Quality Directive and Renewable Energy Directive from 2009. Brazil is chosen here due to its status as the biggest sugarcane-based ethanol producer worldwide and with significant potentials for exports in the medium and long term. This paper assumes that Brazilian bioethanol may be a relevant contributor to the 10 per cent renewable energy share in the transport sector proposed by the European Directive (Goldemberg and Guardabassi 2009).[2]

Nevertheless, Brazil is likely to keep increasing its ethanol production in the long term, considering its sugarcane expansion in the last decade (MAPA 2009a) and the Brazilian plan for this sector (MAPA and Embrapa 2006), although most of this growth is expected to supply primarily the Brazilian domestic ethanol market, which is still in expansion. In spite of the recent crop shortfalls and reductions in the number of greenfield projects in Brazil, this sector is likely to recover its capacity of investment in the coming years, given the favourable macroeconomic fundamentals of this sector, such as growing international demand, carbon markets, the global need for renewable liquid fuels, and the gradual depletion of oil reserves.

In order to proceed with the analysis of how the European policy for biofuels could affect innovation paths of the Brazilian bioethanol industry, this paper is divided into three broad sections. First, a discussion of concepts on the sources of innovation is presented. Secondly, the historical sources of innovation in the Brazilian bioethanol industry are discussed and classified in two broad categories, namely endogenous and exogenous sources of innovation. The third part of the paper focuses on the signals sent by the European sustainability criteria for biofuels towards future innovation paths of Brazilian ethanol, examining and discussing their potential impacts based on how the industry reacted previously when subject to similar national laws. The methodology was based on an extensive literature review and semi-structured interviews with policy makers and private sector representatives.

SOURCES OF INNOVATION

Innovation is a process that improves the production, diffusion and utilisation of resources within a system. Innovation is not a linear process and generally causes disequilibrium in economies, leading them to higher levels of competition and development (Schumpeter 1934). The emergence of innovative processes is highly dependent on forward and backward linkages between industries, suppliers, consumers and their respective demands for improvement and adaptation (Hirschman 1958; Robertson 2003).

We consider in this paper that innovation paths can be influenced by two main forces: endogenous (produced or growing from within) and exogenous (derived or developed from outside). The first is specific to industry concern, driven by profit-seeking, competitive behaviour. The second is specific to where innovation processes occur in national or international business spaces, where firms are subject to regulation and standards (Tonelli et al. 2010; Lachenmaier and Woessmann 2004). Jaffe and Lerner (2005) state that innovation can be influenced by public policy in two main ways: by raising costs to industries and by changing the rate and path of future innovation. Policy also plays an important role for market deployment of technologies, especially via standardisation (De Souza and Hasenclever 2008).

Innovation is not only confined to the technological aspects of an industry. Additional dimensions of industrial lobbying, learning curves, advances in governance and risk management all play a role in innovation.[3] Innovation processes are multidimensional, being comprised of production systems and methods, scientific and engineering knowledge, organisation, infrastructures and social patterns of technology use (Smith 2008).

Economic theory provides a possible viewpoint on mechanisms that promote innovation from an international trade perspective (Krugman and Obstfeld 2008; Lachenmeier and Woessmann 2004). Considering tradable commodities such as biofuels, there is often the issue of trade restrictions which reduce the space for industries to operate internationally. As numerous countries make active usage of import tariffs, countries willing to export to markets protected via entry duties must overcome this financial burden to remain competitive.

Although ways of overcoming import tariffs vary significantly, innovation presents itself as one of the more interesting alternatives, as, while costly, it is one of the few options which effectively create value, reducing negative trade-offs such as trade diversion.[4] By innovating, firms can deliver more efficient production and add more value to commodities, resulting in lower costs. According to this argument, tariffs can thus constitute a pressure factor for innovation in export-orientated industries, since they increase the requirements for access to a certain market. Regulations can be seen as analogous to tariffs, in the sense of representing an economic obstacle for market access.

Sustainability strategies in the private sector are not based on altruism, but firmly on down-to-earth marketing decisions to meet specific consumer preferences. According to KPMG (2008) companies see their sustainability strategies as profit-orientated, from which is to be understood that firms seek profit in their operations. The same study states that sustainability is seen by companies as a primary driver of innovation, rather than a cost burden.

When external sustainability regulation signals to an industry that it needs to adapt in order for a market to be fully realised, the first consideration is the impact on costs. Sustainability regulation could limit the scope of market possibilities (e.g. reduce the stocks of eligible land for crop expansion and exclude fossil-intensive technologies), thus meaning an inflation of costs, making existing firms less competitive and new firms unable to emerge in new potential ethanol-producing countries. While societal welfare is pursued by the introduction of sustainability rules, the industry will most likely not be able to maximise profit to the same levels as before, given that part of the revenues will have to be re-invested in order to adapt to the new rules.[5]

During the development of the European Renewable Energy Directive (2009/28/EC), representatives from the Brazilian ethanol industry were quick to approach the European Commission inquiring whether the proposed sustainability criteria would represent a form of red-tape barrier to access to the European Market. The European Commission responded that the sustainability criteria were to apply to both European and non-European producers, with no differentiation whatsoever in the level of requirements. It is still an open discussion as to whether the certification system to be used to verify the adoption of the sustainability criteria for biofuels will represent an equal burden among different ethanol producers in various parts of the globe.[6] However, these discussions are still controversial, because many political and commercial interests are involved in this issue, for example the strong rural lobby from some biofuel local producers in the EU, which are concerned about the potential competition between domestic biofuel production and the Brazilian sugarcane-based ethanol.

This discussion is important because over time the best performers who will lead the international market for bioethanol are likely to be those who excel in innovation rather than those who are best shielded by protectionist policies. Perhaps this calls for a brief discussion of two relevant concepts often present in successful industries:

- Receptive Capacity: a concept formulated by Robertson et al. (2004) which can be applied to the biofuels industry. Perhaps the most interesting variation of this concept in the biofuel industry nowadays is the question: “Will the first generation champions also be the second generation forerunners?” This is dependent on how well the established industry absorbs and perfects the various inputs of innovation that it receives. Natural soil and climate conditions suitable for an efficient biomass production would also affect this competition and tropical countries may still have an advantage over temperate latitudes.
- Forward and Backward linkages: Even though these are relatively old concepts formulated by Hirschman in 1958, the idea of linkages seems to be, from an industrial dynamics perspective, very appropriate to analyse which industries thrive and which become stagnant. Linkages could arise on an intermediate level, in the case of the bioethanol industry moving towards improving the inflow and assimilation from suppliers of agricultural feedstock and applied research (backward linkages) and by coordinating efforts with the automobile industry (forward linkages).

The bioethanol industry behaves in line with Hirschman´s linkage concept. Moreover, the effectiveness of such links when innovation arises remains the key issue for determining which technologies will become market-spread and those which will not.

The initial perception that sustainability regulation tends to elevate costs should not be generalised. Innovation can unlock efficiency gains that compensate for the regulatory burden. Also, the cost of regulation can be overstated before implementation takes place. For example, Warhurst (2005) cites initial estimations of the national costs for improved vehicle emission standards in the UK, pointing to a cost of GBP 16.1-22.8 billion for 1990-2001. In contrast to the early estimations, the UK-based consultancy AEA estimated the costs of the same regulation to be roughly GBP 3 billion over the same period, in an ex post analysis. Therefore, the innovation effects on costs must be analysed case by case.

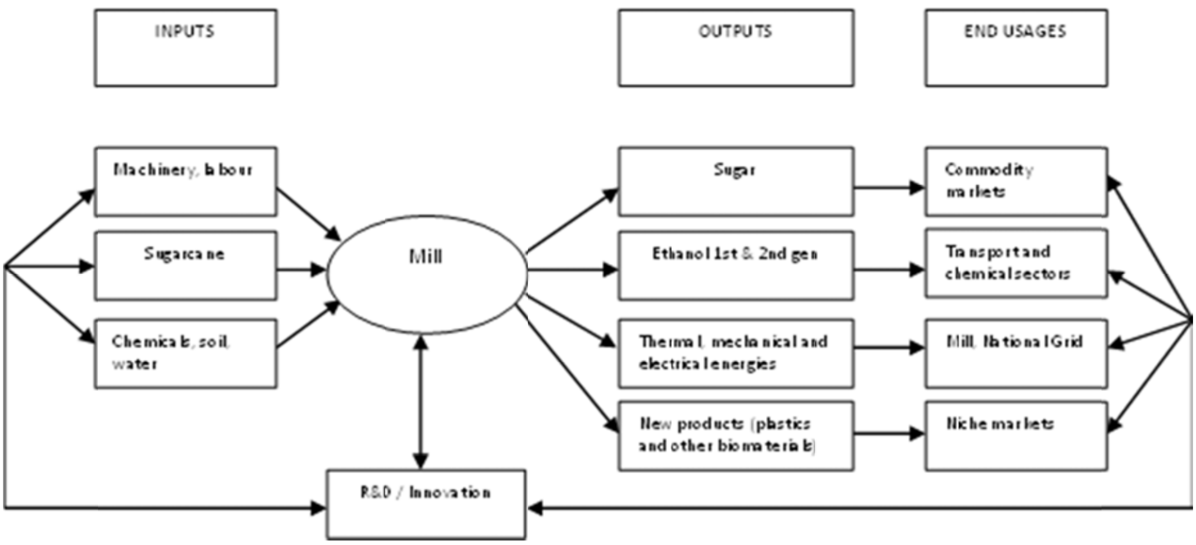
THE BRAZILIAN BIOETHANOL INDUSTRY AND ITS INNOVATION MECHANISMS

The Boston Consulting Group´s global innovation index ranks Brazil as only the twentieth most innovative country in the world (BCG 2009). Adding to this, natural-resource based industries are usually classified as low-tech according to the OECD´s criteria for reinvestment in Research and Development (R&D) (Laestadius 2000). Challenging this perception, the Brazilian ethanol industry is highly innovative and has evolved throughout more than 35 years (Barzelay 1986; Goldemberg et al. 2004). In fact, Brazil has been producing and consuming ethanol in vehicles since the 1930s, but just after 1975 ethanol became a relevant source of energy in the Brazilian energy mix, with the launch of a federal programme called Proalcool. As will be shown in this section, the industry demonstrated great receptive capacity and multiple linkages with other sectors of the Brazilian economy, and these are perhaps the main reasons behind its success (Furtado et al. 2011). This section identifies and analyses the main endogenous and exogenous sources of innovation faced by the Brazilian ethanol industry in the past, highlighting its main mechanisms.

The ethanol industry can be considered as the key dimension in the production, distribution and consumption of biofuels. In the transport sector, two main forms of ethanol usage prevail: as a low blend with gasoline and as a high blend, separate fuel option (Pacini and Silveira 2010a and 2010b). The industry is growing increasingly international. It is now not only confined within a country (as it has been for almost three decades in Brazil) but has a cross-border, international character. As an interconnected system, it is hardly possible to dissociate the industrial part (mills) from feedstock plantations and demand structure (vehicle fleets). Besides, companies that own the mills in general also manage feedstock production, having land ownership or renting lands, although independent farmers are very important in the Brazilian sugarcane production chain too, including thousands of small farmers. Therefore, from efficiency and sustainability perspectives the performances and linkages among plantations, industry and fleet are of primary concern. The integration of these variables is a fundamental benchmark for bioethanol production in order to obtain a better energy and greenhouse gases balances than fossil fuels.

In addition to the connection between plantation and mills, the bioethanol chain includes the demand structure represented by the fleet. Major changes in the industry were caused not by agro-industrial processes, but by innovation on the demand side such as the introduction of flex-fuel technologies. Ethanol has been used in two main forms in Brazil: as a blend of anhydrous ethanol (99.3 per cent ethanol minimum) into gasoline (E18-E25);[7] and in its pure form i.e. E100, in this case hydrous ethanol (92.6 - 94.7 per cent ethanol and remaining water residues). Prior to 2003 fleets were mono-fuel, with cars using either ethanol or gasoline. After 2003, the flex-fuel technology effectively made these two fuels interchangeable, allowing new vehicles to run on any blend of gasoline and ethanol. This interchangeability alleviated demand-side bottlenecks, allowing a renaissance in agro-industrial processes tied to bioethanol production. Therefore, firms autonomously engage in innovation by improving technology, and this involves research processes (Figure 1).

Figure 1: A conceptual model of the Brazilian bioethanol industry.



Source: Developed by the authors, based on Andersen (2009) and BNDES (2008).

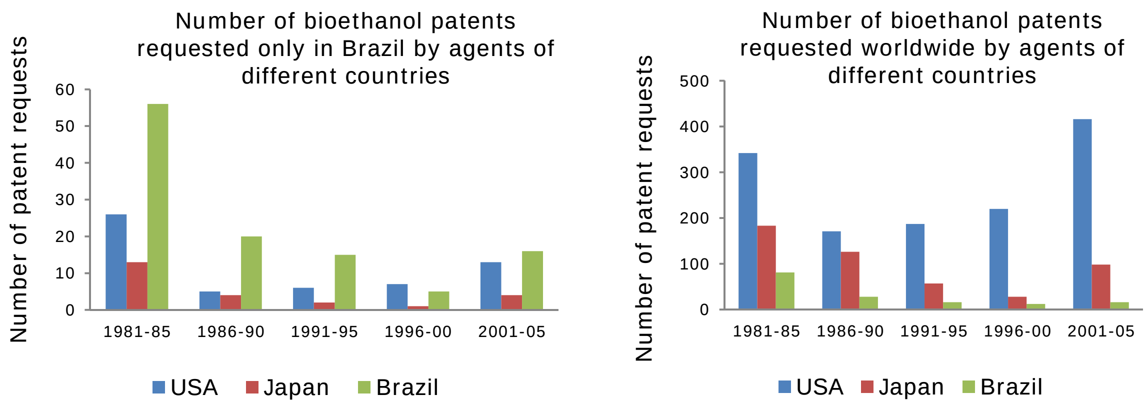
Given the existence of functional and established industrial processes for bioethanol, why is innovation needed and when does it happen? An insight into these questions can be found in the conceptual framework from Swedish economist Erik Dahmén, who described sources of structural tension which drive technological innovation and market possibilities (Andersen 2009):

- Introduction of new methods of production and marketing;
- Appearance of new markets and marketable products and services;
- Opening of new markets;
- Exploitation of new sources of raw material and energy;
- Scrapping of old methods of producing and marketing products and services;
- Decline and fall of old markets;
- Closing of old sources of raw material and energy.

According to Spiro (2009), the economic contribution of research and development at the industry level can take place in different forms. These include R&D processes leading technology to: become embedded in machines (Malcolmson 1975); take over certain tasks (Zeira 2007); improve existing products (Grossman and Helpman 1991); improve efficiency (Sollow 1956; Romer, 1990); and even generate new industries (Aghion and Howitt 1992).

In many sectors patent requests are related to innovation performances. However, this correlation does not happen in the Brazilian bioethanol industry. Patent data points to the United States, the European Union and Asia as having more patent applications than Brazil (Figure 2), although Brazil presents the best performance in ethanol production. The US and Japan led in the number of patent requests, despite the fact that Brazil had the largest ethanol production in the world until 2005, currently just behind the US and working without a subsidy policy. Hence, the smaller number of ethanol patents deposited by Brazilian industries worldwide most likely reflects Brazil´s lack of tradition in patenting, not a deficit in innovation.

Figure 2: Number of bioethanol patents requested in Brazil and as a total in the world, by country of requesting agent.



Source data: Brazilian Federal Patent Database, Cleantech Group (2008) and Mayerhoff (2006) and European Patent Office (EPO).

R&D investment was almost twice as high in the USA as in Brazil (Harari 2008). Against the odds, Brazilian ethanol has become the only renewable source of transport energy that is competitive with petrol so far (Hira and Oliveira 2009). At the same time, the strong protectionism of the European Common Agricultural Policy has not been particularly beneficial towards the European bioethanol industry, as it clearly failed to evolve into a market-based and subsidy-free competitive force in international markets (Wiesenthal et al. 2008; Costa 2007).

Innovation can also be fostered by market conjunctures. The nominal peak in oil prices in mid 2008 raised international interest in the Brazilian bioethanol experience and as a consequence the industry strived to increase output and many governments enacted blending mandates (UNCTAD 2009). As oil-based fuels became expensive, potential markets for biofuels naturally expanded.[8] Therefore, in order to analyse the innovation pressure on the bioethanol industry, the following section presents a conceptual discussion about its two main forms i.e. endogenous and exogenous, as already mentioned. This classification is important for understanding the different causes and effects involved in each part of the whole innovation process.

Endogenous innovation

Endogenous pressures for innovation can be understood as those pressures driven by the natural competitive character of firms, which continuously seek to improve cost-performance by developing more efficient machinery, fermentation processes, labour skills and co-generation output. Endogenous innovation determines the competitive edge of a firm, which is itself a determinant of its profitability (Lima 2002).

Innovation has played a central role in the history of ethanol industry (Walter 2009). At the same time, investments in research and development alone did not correlate to industrial success. The Brazilian bioethanol industry has only invested in R&D half of what has been allocated to such a purpose in the industry equivalent in the United States (Harari 2008). However, various reference indexes over time – energy balances, carbon emissions, market prices – favour the Brazilian ethanol experience instead, as recognised even by biofuel critics (Pimentel 2003). This reinforces the idea that successful innovation is not a reflection of the proportion of resources devoted to R&D, but rather how the resources are used (Andersen 2009: 3).

The main bioethanol producers i.e. the USA and Brazil have two fundamental differences regarding their ethanol industries. Firstly, the feedstock used in the North American production process is mainly maize (corn), while in the Brazilian case, sugarcane is mostly used. Secondly, the average geographic conditions such as solar incidence, water availability and average temperatures are more favourable in a larger proportion of the Brazilian territory, when compared to the USA. Although Brazil has an efficient sugarcane industry, other agricultural industries in the USA, such as wheat, soybeans and corn, show an efficient model and aggressive participation in the world market. Therefore, the differences between Brazilian and American ethanol industries can be partially explained by geographical conditions and their respective feedstock choices.

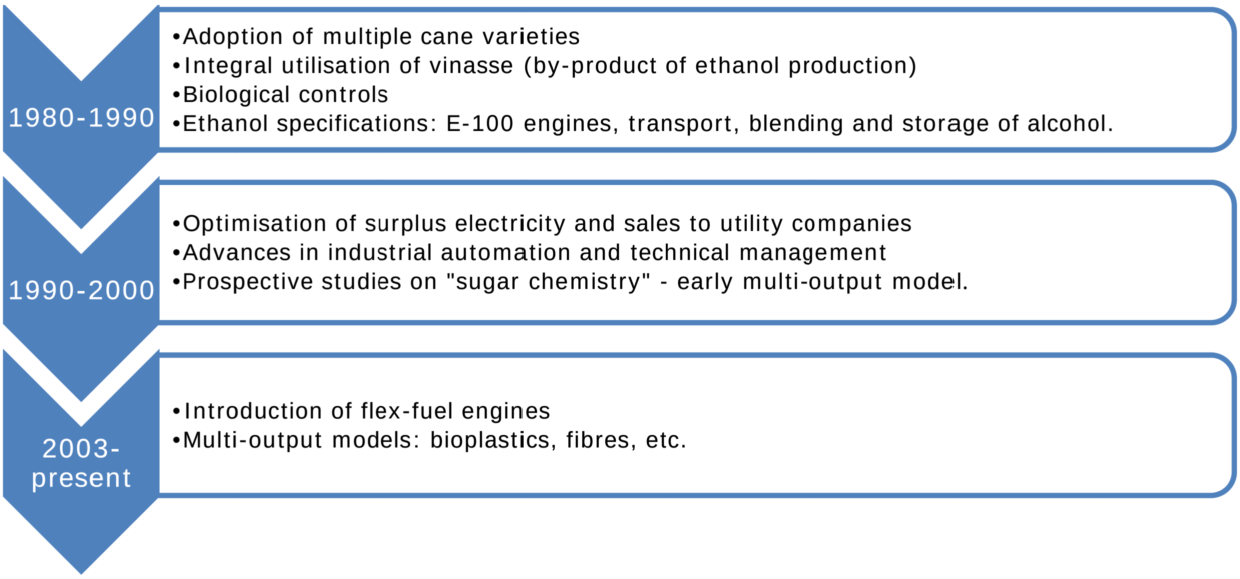
Ricardian comparative advantages would advocate that the higher solar incidence, water resources and low-cost labour would give a fundamental advantage to Brazilian ethanol production and potentially to many other tropical countries as well. However, this is not enough to explain the Brazilian case, since not all sugarcane producing countries (e.g. Mozambique, Cuba, Tanzania, South Asian countries) in the tropical region, with low labour costs and large agricultural potential, have managed to build-up a highly productive and innovative bioethanol production in the same way that Brazil has to date. In addition, for highly-mechanised first generation and especially second generation biofuels, which are in principle more capital intensive, the European industry would appear more competitive.

Therefore, Brazilian success in the ethanol industry is not only a consequence of its geographical advantages in agricultural production, but also the pioneering activities of innovation and investments carried out during past decades by both public and private sectors. Important institutions contributed to this progress, such as: Sugarcane Technology Centre (CTC); Interuniversity Network for the Development of Sugarcane Sector (Ridesa); and the former Sugar and Alcohol Institute (IAA), through its sugarcane research programme called Planalsucar. Moreover Brazil has not only innovated in its ethanol industry, but is also becoming a technology exporter in this sector.[9]

The sugar market was historically the main raison d'être of sugarcane activity in Brazil. A long-time international commodity, Brazilian sugar, however, was exposed to foreign competition and experienced innovation pressures accordingly. The integration between the sugar and ethanol markets is an advantage for its sugarcane industry for it increases the yields in the combined sugarcane mills, for example using the molasses remaining from the sugar factory in the ethanol distilleries, amongst other technical aspects. It can be seen that its successful ethanol programme benefited indirectly from the sugar-led investments of previous decades. Currently, Brazil is a leading country in the international sugar market, with more than 50 per cent of world sugar exports in the free-of-quotas market share (ISO 2010).

In addition to these arguments, Krugman's and Obstfeld's (2008) views on international economics, especially trade barriers, state that creating incentives for innovation can only be partially used to explain the past innovation pressures in the Brazilian ethanol industry. The international ethanol trade started to put pressure on the industry much later than the sugar market. This effect started in about 2003, paving the way for the commoditisation of bioethanol as the US and the EU began importing it. However, as can be seen in Figure 3, innovation in the sugarcane industry has increased steadily in Brazil, achieving substantial cost-performance long before the introduction of flex-fuel technology (Fingerut 2004; Van den Wall Bake et al. 2008). Thus, the innovation processes acting on the biofuels industry prior to 2003 were most likely driven by internal policy and native industrial dynamics.

Figure 3: Endogenous innovation timeline in the Brazilian ethanol industry.



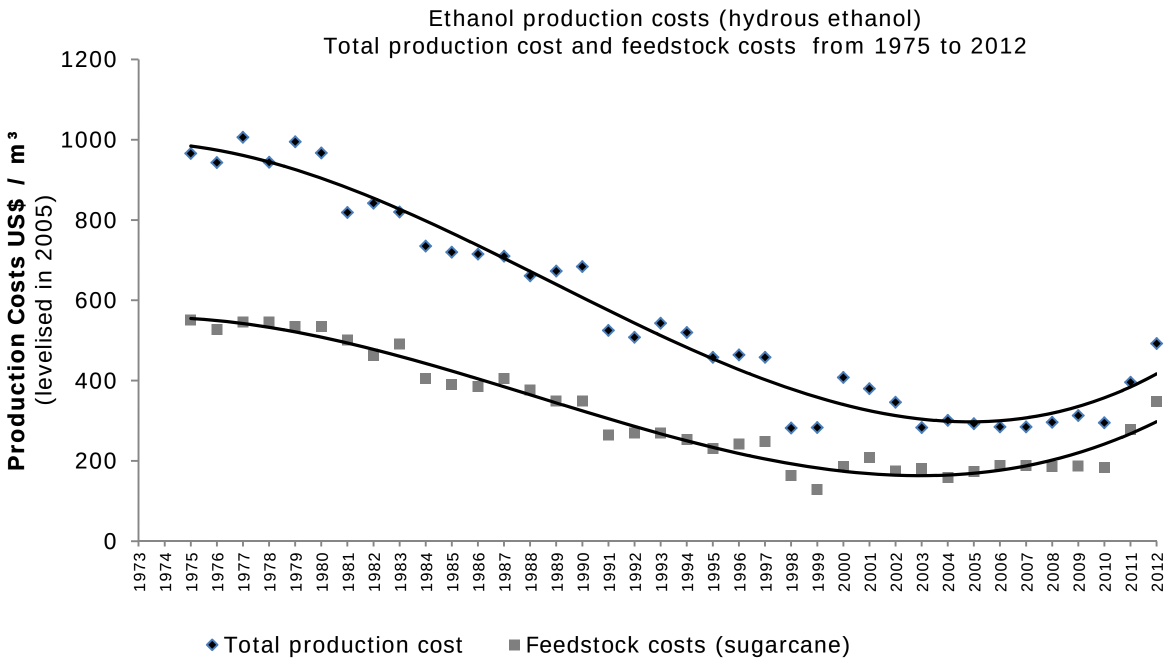
Source: adapted from Macedo (2007)

The Brazilian ethanol industry has translated innovation into yield. For instance, from the beginning of the Proalcool Programme (i.e. 1975) to the last crop seasons, the agricultural yields of sugarcane production increased from 47 t/ha to 78 t/ha (without using full irrigation systems), and in terms of TRS (total reducing sugar) from 105 kg/t to almost 150 kg/t (MAPA, 2009a). In the same period, sucrose-to-ethanol conversion increased by 14 per cent and the productivity of industrial fermentation achieved a 130 per cent improvement (Macedo 2007).

As Figure 3 also shows, researchers began to investigate new possible uses for sugar and ethanol, which become known as sugar and ethanol chemistry, an attractive concept for early biorefineries (Andersen 2008: 27). A large range of chemical products made from both sugar and ethanol was intensively researched. This sugar and ethanol chemistry has been studied since the 1980s and more intensively after the end of the Proalcool Programme, in 1990. However, the relatively low oil prices in the 1990s damaged the economical viability of this new market, but an important consequence of this early investigations into alternative usages for sugarcane is that when ethanol reached the world stage after 2003, technological capabilities and research lines were at least partially developed, allowing firms to carry on old concepts in a new market context providing price-premiums for renewable plastics (Braskem 2009). Sugar-based biodegradable and non-biodegradable plastics have been proven feasible by using the surplus of sugar production (Velho and Velho 2006); similarly, ethanol can be chemically processed into ethylene, which can then be converted to, for example, poly-ethylene, the most widely used plastic (Piringer and Baner 2008).

As a result of constant innovation in the sugarcane industry, the cost of ethanol production has fallen over recent decades, as illustrated in Figure 4. This decrease is significantly contributing to the re-emergence of the chemical industry of ethanol, under a sugarcane biorefinery concept. Hence, the Brazilian ethanol industry achieved its success via both improvements in traditional production processes and also due to novel ways of adding value to production. Figure 4 also shows that the feedstock costs, i.e. sugarcane, represent between 45 per cent and 65 per cent of the total ethanol production cost. Thus innovation at the agricultural level also has a significant impact on the total ethanol production cost. The calculated coefficients of determination (R2) for both curves (total production costs R2 = 0.9662; and feedstock costs R2 = 0.9647) significantly fitted the data, showing that the regression curves reasonably explain the observed variations. The variation of these levelised costs in Brazilian Real and previous national currencies might have an even greater correlation, because of the high exchange-rate variation with the US dollar throughout this period. For the crop-season 2011/2012 an increase in the total production costs of ethanol was expected, mainly due to the recent increase in the agricultural costs of sugarcane, which were impacted by unfavourable weather and low investments in crop renewal, including in fertilisers, in recent years (Jank 2011).

Figure 4: Ethanol production costs: Total production cost and feedstock costs (1975-2012) for hydrous ethanol (E100).



Source: Prepared by the authors. Data sources: Van den Wall Bake et al. (2008) and information provided by ESALQ/PECEGE at the University of São Paulo.

With regard to the automobile fleet, the introduction of flex-fuel technology in 2003 effectively created a new market for the then declining Brazilian ethanol industry. This technology allowed ethanol to be supplied to a market that was once captive to gasoline-driven vehicles, as most of the new vehicles produced in Brazil became equipped as factory standard with flex-fuel technology (Hira and Oliveira 2009). Technical improvements in the fleet were also present before flex-fuel vehicles became widespread, such as the development of corrosion-resistant engines in the late 1970s and early 1980s (Sperling 1987; Cortez 2010; Goldemberg 2004). In addition, government regulation adapted the tax system for these new vehicles by slightly reducing the tax on imported products (IPI) in order to keep their selling prices competitive with the traditional gasoline technology for the consumers. Therefore the flex fuel vehicles acted as both endogenous and exogenous factors of innovation.

Another important innovation applied in the sugarcane industry was the production of energy in combined heat and power systems (CHP or cogeneration), using the bagasse, a solid by-product from industrial process (Strapasson 2008). The re-utilisation of the distillery wastewaters (vinasses) and the filter cake as fertilisers as well as the higher share of mechanical harvesting meant major improvements in the system too.

The integration of all these technologies and sources of innovation has been a key-issue for the competitiveness of the sugarcane sector. However all of this occurred in a country which lacks a patenting tradition, at least as measured by conventional benchmarks, as already presented. It is known that patent statistics do not clearly represent how innovative industries are, due to the fact that not all patents produce the same impact on markets (Watanabe et al. 2001). They can at best be seen as a measure of business interest in the future of specific technologies, possibly hinting at future innovation paths. Contrary to the trend pictured in patent deposit statistics, Brazilian sugarcane-based ethanol became a symbol of a value-added product and highly dynamic endogenous innovation. Thus, patenting tradition differs in the industrial sector, since some industries innovate without registering patents (Cassiolato et al. 2009).

Moreover, there are many environmental benefits in the sugarcane industry compared to fossil fuels (Strapasson and Job 2007), but much of the environmental performance of the sugarcane ethanol industry derives from domestic regulatory requirements, i.e. an exogenous factor, as discussed in the next section.

Exogenous innovation

In addition to the endogenous competitive forces which led to strong technological progress from the late 1970s, external pressures were paramount for transforming the industry. Exogenous innovation pressures originate in regulation from national and supranational authorities, but also from the requirements of market agents. They usually take the form of regulation or standards seeking to guarantee minimum quality levels or minimise negative externalities of various sorts. Broad legislation has covered the sugarcane industry in Brazil throughout the period of the Sugar and Alcohol Institute (IAA, a federal body which regulated the sugarcane sector between 1933 and 1990) and then less intensively after its liberalisation in the 1990 onwards (MAPA 2009b). Currently the Brazil's Government aims to enhance the regulation system in order to guarantee the domestic ethanol supply and to reduce high price volatility through the year.

Exogenous innovation does not necessarily increase profitability, but seeks to guarantee acceptance in a regulated market (Jaffe and Lerner 2005). In this sense, the Brazilian ethanol industry has been subject to various exogenous innovation pressures in the past, mostly in the form of national legislation. These sought to mitigate the potentially negative environmental and social impacts of biofuels production. A summary of the exogenous pressures which have led to systemic innovation in the Brazilian ethanol industry is presented in this section.

Sugarcane harvest

Unlike bioethanol feedstocks from colder countries, sugarcane has extensive and sharp foliage covering the sucrose-rich canes and crop fires are used to remove the excess foliage of sugarcane prior to harvesting. This was a common and useful practice for many years before mechanisation became viable. Artificial fires facilitate the manual harvest of sugarcane, but at the same time emit a large amount of carbon dioxide and pollutants into the atmosphere (Strapasson and Job, 2007). This phenomenon has sparked a strong debate in Brazil (SPPT 2005; Uriarte et al. 2009). Evidence correlates the practice of crop fires to the large incidence of respiratory disease in nearby communities (Cançado 2007).

Faced with societal pressures to regulate the practice of crop fires, the state of Sao Paulo, responsible for about 60 per cent of the Brazilian sugarcane production, imposed norms in 2002 on how crop fires should be used, as well as a deadline for their phase-out.[10] The industry responded with an increased share of mechanical harvesting, which is efficient for low declivity terrains and does not require the usage of fire. The increase in mechanisation processes also reduced the number of accidents in comparison to manual harvesting (Scopinho et al. 1999). There is an additional advantage to mechanical harvesting regarding the lifecycle emissions of sugarcane, as avoiding exfoliation via fire helps further reduce carbon emissions in the ethanol fuel cycle. Other Brazilian states are trying to adopt this practice. Additionally, in 2009 the federal government submitted the Federal Law Project n. 6.077 to the Brazilian Parliament's approval, regulating sugarcane burning at the national level, but this project is still under analysis in Parliament.

Mechanisation cannot be seen as a simple consequence of exogenous governmental pressures to phase out crop fires. The cost of harvesting sugarcane with machines is lower than doing so using manual labour, where soil declination allows (Van den Wall Bake et al. 2008: 651). Barriers to accessing this harvesting modality consist mostly of large investments in machinery, but once carried out, operational costs tend to be lower than manual harvesting.[11] On the other hand social public policies must be implemented to integrate the displaced workers into other agricultural and industrial activities. In addition, areas with more than 12 per cent of declivity are still not suitable for mechanisation and this is the case for many traditional areas in Brazil, especially in most of the northeast states (e.g. the states of Pernambuco, Paraíba and Alagoas) and parts of the central and southern states (e.g. the state of Minas Gerais), where sugarcane has been produced for centuries. In addition, depending on the sugarcane variety and type of mechanical harvester, sugarcane can have a yield reduction in the subsequent crop season (proportionally slightly worse than in the manual harvest), mainly due to damage to the plant root system caused by the vibrations of the harvester's cutting blades. Therefore, technology innovation is still required to overcome this challenge.

Water resources

Brazilian environmental law foresees conservation areas in which no agricultural activity can take place. Brazilian Federal Law n. 7.803 from 1989 states that no crops should be cultivated within 30 meters of the riverbank. In addition, Brazilian Law 12651/2012, which recently revoked Law 7.803/1965 (former forestry code law), prohibits cultivation near wetlands, sand-dune barriers, and water springs. Important amendments to Brazil's environmental legislation were extensively discussed at the Brazilian Parliament with the purpose of establishing a new Forestry Code Law (Araújo and Strapasson 2009), which then resulted in the Brazilian Law 12651/2012.

There are concerns about whether this legal framework is enforced at all. This is partly due to the economic power of the agricultural sector, the high costs and bureaucracy attendant on environmental legislation, and partly because of fragile enforcement mechanisms reliant on understaffed institutions such as the state attorney´s office, the forestry police and the Brazilian Institute of Environment and Renewable Natural Resources – IBAMA (Martinelli and Filoso 2008). Still, the sugarcane sector, for instance in the state of Sao Paulo, significantly contributes to native forest recovery, especially in the riparian vegetation zones, under the Agro-Environmental Protocol agreed with the Secretariat of the Environment in this Brazilian state (SMA 2011).

Labour protection norm NR31 and the National Sugarcane Labour Agreement

Sugarcane harvesting is considered to be a harsh activity for those involved in field operations (Martinelli and Filoso 2008: 893). With regard to labour conditions, there is a wide body of legislation in Brazil, which involves high penalties, surveillance and standards. One important piece of legislation is Brazilian Norm NR 31, adopted in 2005, which lists a variety of obligations to protect workers engaged in sugarcane activity, including protective gear, working hours, health and insurance cover, which are often not available in other agricultural activities (MTE 2011).

The problem of enforcement is again present regarding labour protection norms (Martinelli and Filoso 2008: 893). Although widely adopted in the state of São Paulo, it would be challenging for all sugarcane areas in the country to follow special labour protection norms like NR 31, which is frequently questioned by farmers and industrials on the basis of being difficult and costly to put into practice, especially in rural areas. The Brazilian sugarcane industry associations indirectly recognise the problem, stressing their commitment to improving labour standards within the agro-industry (Desplechin 2010).

Additionally, in 2009, the National Sugarcane Labour Agreement was signed, as a term of social commitment between representatives from the sugarcane industries (e.g. UNICA and Forum Nacional Sucroenergético) and agricultural labour organisations (e.g. CONTAG and FERAESP). The negotiation process for this agreement was mediated directly by the Office of the Presidency of the Republic together with the Ministry of Labour and Employment (MTE) and the Ministry of Agriculture, Livestock and Food Supply (MAPA). This agreement is voluntary with the aim of enhancing best labour practices in the sugarcane sector, focused on agricultural activities, especially because the mechanical harvest is not fully expanded in all sugarcane fields.

It is important to emphasise that, despite the fact that manual harvesting is arduous work, of the approximately 1.3 million people formally working in the sugar cane sector in Brazil around 500,000 people work as sugarcane cutters (Sousa and Macedo, 2009). Hence the conversion from manual to mechanical harvesting must be gradual in order to allow the incorporation of these workers into other activities; some of these employees could work at the sugar and ethanol industries, for example. The current challenge is to stimulate best labour practices while also promoting mechanical harvesting. Therefore, the social agreement was a pioneering initiative in terms of collective labour negotiation at a national level and could be used as a reference for other sugarcane producing countries worldwide. This modernisation process is a market trend and even with mechanical harvest, ethanol still generates more jobs than gasoline per unit of energy delivered (Sousa and Macedo, 2009).

Legal reserve for native vegetation and the Sugarcane Agroecological Zoning

Environmental regulation also presents exogenous innovation effects in the sugarcane sector. For example, restrictions in land use were implemented via environmental legislation in Brazil. Federal Law n. 12651/2012 foresees 20 per cent natural reserve for native species in agricultural properties for the main sugarcane production regions. These reserves can be even higher in other Brazilian regions, up to 80 per cent. Mandatory reserves per farm at such levels are not seen in Europe for instance.

Although sugarcane is cultivated on less than 1 per cent (8.3 million ha) of the Brazilian territory (851 million ha), and only 0.6 per cent considering the amount used for ethanol production, the potential impacts of its large scale expansion has been discussed by the Brazilian Government and the international community, taking into account the high biofuels market potential worldwide. Therefore, in 2009 the Sugarcane Agroecological Zoning scheme was published as an additional environmental requirement for the sustainable sugarcane expansion. The work was carried out by a technical working group[12] coordinated by the Ministry of Agriculture, Livestock and Food Supply (MAPA) and the results were published by the Brazilian Government as a legal framework[13] and also through Embrapa Soils (Embrapa 2010; Manzatto et al. 2009). This case could be used as an innovation reference for the sustainable expansion of biofuels worldwide, as proposed by Strapasson et al. (2012).

Agroecological Zoning sought to promote sustainable land-use in a symbiotic relationship between food production and the environment, by respecting legal boundaries. With this mapping tool, sugarcane expansion will most likely occur on those pasture lands, of which Brazil has more than 170 million ha, with a significant proportion of low efficiency livestock production. In order to avoid negative impacts on land use change, sugarcane agroecological zoning has excluded the following areas for the expansion of this crop: all the Amazon Region, Pantanal (swampland biome) and the high Paraguay-river Basin; any native vegetation, including Cerrado (a Savannah-like biome) and the Atlantic forest; any indigenous reserves; areas with a high conservation value (UN-consistent); areas lacking favourable conditions on soil and climate; areas with more than a 12 per cent slope, in order to promote mechanical harvesting; and areas that demand full irrigation to produce sugarcane.

The zoning has ruled out 91 per cent of the Brazilian territory for sugarcane development. Nevertheless the available areas for its expansion are 63 million ha, ten times more than the current sugarcane area planted for ethanol production. Thus, Brazil is already committed to avoiding building new sugarcane mills in environmentally sensitive areas. Transport costs dictate that sugarcane must be cultivated at a maximum distance of 40km from processing mills, preventing expansion of sugarcane plantations into non-indicated areas, according to agroecological zoning. The legal framework has also made any source of financing conditional upon this zoning. In practical terms, there is no funding for projects that do not meet this legal framework, from any bank, such as BNDES and Banco do Brasil. This measure is key public policy for promoting a responsible expansion of sugarcane in Brazil in line with climate change commitments (Araújo and Strapasson 2009) and reducing the risk of potential negative land use change effects from biofuels expansion (Strapasson et al. 2012). As a result, according to the SAP-Cana[14] database, since the publication of this zoning in 2009, all new industrial projects have been installed according to the agroecological zoning requirements to date i.e. only in municipalities authorised by the zoning legal framework.

In addition to this agroecological zoning there is another official zoning in Brazil called Ecological-Economic Zoning, which disciplines land use as a whole, in a more general context than agroecological zoning, through the identification of areas for agriculture, environmental conservation and others. Ecological-Economic Zoning is supported by a federal legal framework but its description must be established and approved by each state parliament. This type of zoning has been already implemented for the Amazon region for example (Strapasson et al. 2012).

THE SIGNALS SENT BY EUROPEAN DIRECTIVE 2009/28/EC TO THE BRAZILIAN ETHANOL INDUSTRY

In the European Union, biofuels started to be significantly traded only in the early 2000s (REN21 2012). In the European Renewable Energy Directive (2009/28/EC), sustainability requirements are proposed, creating a long-term market for biofuels coupled with regulations. This provides an exogenous signal to the biofuel industry that innovation is needed to meet the requirements of the newly opened markets.

In the past, national laws were the major external regulating mechanism in the industry. With the introduction of sustainability criteria, an external actor (the European Union) has directly reached the industry, in new cross-border interplay. Since the early development of the European directive Brazil has demonstrated clear interest in EU policies on biofuels, embodied by the sugarcane industry association's (UNICA) decision to open an office in Brussels in early 2008.[15]

Global problems such as carbon dioxide emissions from the sugarcane burning for harvesting were not considered as a priority in past Brazilian environmental regulations linked to the bioethanol sector.[16] Increasing environmental concerns worldwide in the 1990s, especially after the Rio-92 Earth Summit, pointed out new issues should also be addressed, such as climate change and biological diversity, with the creation of the United Nation Framework Convention on Climate Change (UNFCCC) and the Convention on Biological Diversity (CBD) at that Summit. While environmental legislation applied to the ethanol industry in Brazil often had the goal of improving sustainability as a whole, to date it has done so within a fragmented legal framework.

With the internationalisation of bioethanol as an energy commodity, and in the face of simultaneous Brazilian commitments to the UNFCCC process as a signatory of the Kyoto Protocol, other aspects of bioethanol production and usage came to the centre stage. Then, greenhouse gas emissions during the lifecycle of ethanol became the main benchmark of the contribution of biofuels to efforts to mitigate climate change. In this section we analyse the sustainability requirements for biofuels contained in European Directive 2009/28/EC. We then compare the European requirements with past innovation and the latest moves from the Brazilian ethanol industry.

European Directives and the sustainability criteria for biofuels

Amid general demands to improve multiple aspects of the European energy infrastructure, the European Commission (EC) redefined its initial biofuels strategy from 2003, and unified previous documents on the promotion of renewable energy into a single directive launched in 2009 (EC 2001; 2003; 2007; 2009). For most of 2007 the EC Directorate-General for Energy and Transport (DG TREN) spearheaded the policy-making process on biofuels sustainability, carrying out consultations and developing initial draft versions of the upcoming new renewable energy directive, which was finally put forward on 23rd January 2008 in Brussels and adopted on 17th December of the same year. The final version – 2009/28/EC was published in May 2009 (EC 2008; EC 2009).

The development of the new directive was closely watched by lobby organisations from Europe and abroad due to its potential effectively to change market conditions for the development of biofuels. The proposed target for 2020 - 10 per cent renewable energy in the transport sector – much of it likely to be fulfilled via biofuels - was accompanied by intense debate. As the production of first-generation biofuels is a land-intensive activity, the inevitable expansion of production to meet European demand has international repercussions on land use, as well as biodiversity and social systems. Responding to the debate on whether biofuels can de facto deliver positive results, the European Commission proposed a set of sustainability criteria to be followed to make biofuels eligible for the mandatory 10 per cent renewable energy target in the transport sector by 2020.

According to the adopted directive, only biofuels which are certified sustainable can be counted by European member states towards the mandatory 10 per cent share of renewable energy in the transport sector. Still according to the directive, biofuels counted towards this target should be certified sustainable irrespective of their origin (European Commission 2009: 36-38). According to the European criteria, biofuels: should deliver a minimum of 35 per cent savings in greenhouse gas emissions, when compared to lifecycles of their fossil-equivalents. These requirements are elevated to 50 per cent after 2017 and 60 per cent after 2018; cannot be produced in areas of high biodiversity; cannot be produced in untouched forests, areas of protection and highly biodiverse grasslands; should not be sourced from areas with high carbon stocks, wetlands and continuous forests; must be produced under work conditions which observe the Conventions of the International Labour Organization (ILO)

The sustainability scheme for biofuels was not adopted in the exact form initially proposed. While the proposal of the Renewable Energy Directive was being discussed in the European Parliament and the Council in 2008, the sustainability scheme was changed slightly. The final text adopted in May 2009 contained requirements for periodic reporting on labour conditions according to ILO Conventions and on the impacts of biofuel demand on food prices and land rights, especially regarding people living in developing countries.

Practical implementation of the sustainability criteria and verification schemes is an ongoing process as of 2011. Member states have their own task forces to adapt to the requirements, and the European Commission proposed implementation guidelines to help policy makers ensure national compliance and trade tracking of biofuel trade chains by issuing guidelines published in June 2010. Moreover, 13 voluntary certification schemes have been recognised by the Commisson to date. As it is unlikely that all biofuels will be produced under the same conditions, a mass-balance system may be implemented to weight the share of sustainable biofuels in each commercial shipment.

The European market is important for Brazilian ethanol producers given trade volumes with countries like Germany, Sweden and the Netherlands. In the face of this market interest, the sustainability criteria have exerted innovation pressures on the bioethanol industry. The areas where innovation will take place depend on the relative maturity of present technologies and pressures from the European requirements for change.

However, potential EU overregulation, as well as uncertainties, regarding the implementation of the sustainable biofuels criteria is causing major concern for the Brazilian ethanol industry and also potential new global ethanol producing countries, especially in Latin America and Africa. Common sense is needed in the European biofuels agenda, combined with science-based arguments, if innovation and the biofuels market are to be promoted worldwide, rather than weakening this important source of renewable energy in Europe or restricting the market only to domestic producers.

Perceived reactions from the Brazilian ethanol industry to the EU criteria: Three paths based on policy uncertainty

The European sustainability criteria for biofuels invoke market credibility, since adopted directives are binding to all EU27 member states. But while the European criteria are representative of a market of 500 million people, other markets such as the US are already large trade partners in bioethanol without sustainability requirements. According to statistics from the Brazilian Secretariat for Foreign Trade (Secex), ethanol exports to the US amounted to 4.38 billion litres between 2006 and 2009, while exports towards the EU amounted to 3.4 billion litres during the same period. Added to this, a number of other sustainability schemes for biofuels have been proposed at different levels (UNICA 2012). This puts the ethanol industry in an uncertain position prior to engaging in costly compliance investments. The lack of clear guidelines on sustainability criteria has been raised by bioenergy traders (Junginger et al. 2010). Even as the European Commission published guidelines for implementation and monitoring of the sustainability criteria in 2010, as well as an initial batch of 13 voluntary schemes recognised so far as meeting the sustainability requirements, the lack of definition in some aspects of implementation, as well as inaccurate cost estimations for different certification methods means uncertainty persists.[17]

Uncertainty is especially pronounced due to the two main pending points of the EC directive (RED): the approach to incorporate indirect land use change (Art. 19 §6) in the methodology for accounting of lifecycle emissions, as well as the definition of highly biodiverse grasslands (Art. 17 §3c). These two issues create strong uncertainty in critical market aspects, because they can render biofuels “sustainable” or not depending on the methodologies used.

Indirect Land Use Change (iLUC) caused by biofuels expansion is still a controversial issue and deserves further study and clarification about its potential effects before it can be incorporated into any sort of legislation. It means that an expansion of land for biofuels production onto agricultural land may lead the original crop indirectly to displace another land elsewhere. The International Energy Agency, through its Bioenergy Task Force 38, is conducting many international debates on this matter. However, results about a potential carbon-debt effect from iLUC still present high variation and uncertainty, depending on the methodology used, especially because the models are sensitive to the type of crop, country, yields, land availability, the agricultural and energy market dynamics, and other factors (see Akhurst et al. 2011 on iLUC multi-modelling analysis). The incorporation of iLUC criteria could, for example, render most types of biodiesel unfit to meet the minimum 35 per cent GHG threshold depending on the econometric parameters used (EBB 2011).

Based on the available literature, it is likely that no scientific consensus on the iLUC issue will be met in the short-term or even the long-term, due to the high uncertainties associated with both complex agricultural dynamics in a globalised food market and energy scenarios worldwide. However, an innovation agenda using iLUC mitigation policies could already be implemented by biofuel-producing countries through best practice schemes, for example: increasing agricultural and industrial yields; stimulating the use of efficient crops and residues; promoting biofuels agroecological zonings and capacity building programmes.

Therefore, the European Commission recently decided not to make the introduction of iLUC criteria compulsory to determine biofuels sustainability, but limited to 5 per cent first generation biofuels out of the 10 per cent biofuels target by 2020. This restriction may attend to some NGOs claims and political concerns, but may also negatively affect the infant biofuels market worldwide, by, for example, not differentiating the types of bioenergy crops. In contrast to the USA, which considers sugarcane-based ethanol as an advanced biofuels, the EC simply generalised all types of biofuels in this recent decision. As an example of such a contradictory measure, first generation sugarcane-based ethanol currently has higher ethanol productivity than the possible second generation ethanol based on wheat. Moreover, the European Association of Farmers' Organisation (Copa-Cogeca), FEDIOL, ePURE, COCERAL and European Biodiesel Board stated that the 5 per cent cap is an irresponsible U-turn on the EU biofuels policy (Copa-Cogeca et al. 2012). This measure may undermine investors' confidence and therefore many organisations have been questioning the credibility of EU policy in respect of decarbonising transport.

With regards to the EU RED sustainability criterion on highly biodiverse grasslands, proposed as one of the no-go areas for biofuels crops, this measure may directly affect Brazil and many African countries with high potential for biofuels production. In Brazil grasslands already converted to agriculture especially for pasture are precisely those considered by the Brazilian legislation as one of the main potential areas for the expansion of bioethanol production with the lowest environmental impact. In addition, a potential enforcement from the EC in this regard has been seen as a tendentious policy, given the measure would be inequitable or unbalanced, since the European biomes' biodiversity are more damaged than third countries grasslands to date, but Europeans would not be directly affected by this criterion.

As the industry is faced with policy uncertainty, it could be seen as engaging in three non-exclusive strategies: (1) Adapting its innovation paths towards compliance with the EU criteria; (2) seeking market security by focusing innovation efforts on biorefinery models, diversifying its input-output strategy and risk; (3) and market leakage, by seeking less-regulated markets.

Adapting to the European Criteria

The past development of environmental legislation made Brazil achieve standards which generally ensure compliance with many of the European criteria for sustainable biofuels. Even though it is difficult to identify absolute causality between the EU sustainability scheme for biofuels and the current reactions from the Brazilian industry, there are recent events which indicate some level of possible influence:

Accounting of emissions

Part of the success of the Brazilian ethanol industry is the greenhouse gas balances of ethanol (Macedo et al. 2008). Methodologies have been established which measure GHG emissions in the production and usage of ethanol both as E100 and as E25 (blend with gasoline). The balance of GHG reductions in the usage of ethanol instead of gasoline vary between 80-90 per cent in the absence of significant land use change (Macedo 2004). Strong consensus is achieved on GHG savings thresholds, with studies ranking Brazilian ethanol far above the minimum of 35 per cent required by the EU. The directive itself provides a default value for ethanol production via sugarcane as delivering 71 per cent GHG savings compared to gasoline (European Commission 2009a: 52). Similar figures are presented by the US EPA (61 per cent), the IEA (90 per cent) and academics such as Macedo (85-91 per cent). (EPA 2010; IEA 2002: 13; Macedo et al. 2008: 11).

There are active efforts to reduce further the lifecycle emissions of sugarcane ethanol, as illustrated by recent efforts by the Brazilian Bioethanol Science and Technology Laboratory (CTBE) to develop low impact machinery and private sector investments on ethanol pipelines, which can further reduce the carbon intensity of ethanol.

The common practice of co-generating electricity at ethanol mills also helps to reduce the GHG footprints of biofuels. Modern cogeneration equipment, which produce both heat and power, has at present a very high efficiency level, overall ranging from 80 to 93 per cent (Kamate and Ganvati 2009; Andersen, 2009; Procknor, 2008). The cogeneration module provides power for the bioethanol plant and the excess electricity is fed into the national grid. This method of producing electricity, non-reliant on fossil inputs, is a fundamental reason behind the good energy balances associated with sugarcane ethanol (Goldemberg 2006). This fact is even recognised by sceptics of biofuels, such as Pimentel (2003). However, the high performance already achieved can limit further improvements, via decreased returns on investments. In addition, the possible emergence of second generation bioethanol might create internal competition for feedstock (sugarcane bagasse), today used for energy generation in the mills.

Since 2009 Brazil participates in the GlobalSoilMap initiative, an international consortium which aims to increase information on soil characteristics of different regions of the globe, which includes carbon stocks as required by the European Directive. The Brazilian Agricultural Research Corporation (EMBRAPA), through its soil research centre, is leading mapping efforts for Latin America and Caribbean.

Labour conditions

As a signatory to the ILO conventions, Brazil has a labour norm for agricultural field work (NR 31) which regulates safety and health standards of workplaces. Proper observance of NR 31 would be compatible with the ILO, which in principle would safeguard against negative labour assessments from the European Commission. On the other hand, as the European requirements only call for countries to be signatories to the ILO conventions, the effectiveness of this item is questionable. Signing is relatively easy and the directive does not go as far as specifying specific monitoring methodologies for reporting labour standards. This thus constitutes a weak source of innovation pressure in the industry.

As seen in the sections above, the Brazilian ethanol industry has been actively coordinating with government, private and research institutions to innovate towards reducing carbon footprints, gathering data about soil conditions and reinforcing labour standards. Some of the measures, especially those linked to carbon management and land mapping, correlate in time with the development of the European directive 2009/28/EC. Others such as forest and waterways protection, as well as labour protections were in place long before the European legislative process on biofuels. It can be said that the EU directive has been at least a partial motivator for the recent innovation processes which are developing in the Brazilian ethanol industry. Table 1 summarises the potential impacts of European legislation on the industry, assuming compliance with this legal framework.

Table 1: European Sustainability Criteria and potential signals for innovation

EU sustainability criteria for biofuels (in 2009/28/EC)	Brazilian bioethanol industry	Pressure for future innovation
Minimum of 35 per cent GHG savings	• GHG savings in the order of 50-90 per cent for sugarcane ethanol • Phase-out of crop fires (state of Sao Paulo Law 11.241/2002; Federal Law Project 6.077/2009)	• Incremental innovation on existing processes • Shift from truck-based to pipeline ethanol transport systems (planned) for long distances • Replace diesel by ethanol or biodiesel in field machinery
Land use restriction: High biodiversity	• Environmental law: minimum distance from water sources • Mandatory 20 per cent reserve in agricultural properties for native species • Agroecological zoning and ecological-economic zoning	• Clarification of status of different land in the country • Production and dissemination of information
Land use restriction: Protected areas	• Federal Law 12.651/2012 on environmental protection • Agroecological zoning and ecological-economic zoning	• Clarification of status of different land available in the country • Production and dissemination of information
Land use restriction: High carbon stocks	• GlobalSoilMap participation in initial stages • Agroecological zoning and ecological-economic zoning	• Map carbon stocks of land countrywide. • Clarification of status of different land-use in the country
Labour conditions	• Brazilian labour legislation e.g. NR31 and others. • National Sugarcane Labour Agreement	• Homogenisation of labour standards within industry • Better enforcement of existing labour norms compatible with ILO conventions of. • Capacity building for sugarcane manual harvest workers to have other job opportunities.

Risk-avoidance strategy

In the face of increasingly complex conditions – tariffs and sustainability mandates – present in international biofuel markets, the ethanol industry might steer innovation towards diversifying its activities. As Dahmén (1994) says, innovation occurs via the creation of new capacities and diversification of business risks. From the industry perspective, there is always uncertainty involved when shaping innovation paths due to the requirements of a single market. This has its roots in two main reasons. Firstly, the European Commission has to deliver periodic reports on environmental sustainability aspects. In principle, a country might be downgraded to unsustainable biofuels producer (in practice excluded from the market) if sustainability problems are uncovered in those reports;[18] secondly, it is not desirable to rely on one export product (bioethanol) for a single market. Experience with low-diversification monoculture brings back lessons from the decline of the coffee industry in Brazil after 1930. Additionally, given the amount of research interest in transport energy, it is plausible that new energy carriers might achieve price-parity with combustion engines, reducing demand for bioethanol somewhere in the future.

That said, the industry might respond to such signals by innovating in other ways, that is by expanding beyond the core ethanol business. This is the reason behind the concept of biorefineries. Given multiple raw inputs, a biorefinery yields a variety of outputs, from energy to chemicals, construction materials, food, biogas, plastics, among others (Ragauskas et al. 2006). In a biorefinery strategy, such as in a mixed portfolio of financial securities, multiple inputs (sugarcane, straw, wood) could be selected, and multiple end-products could be generated (ethanol, sugar, biomaterials, electricity, heat) depending on market conjunctures. Such a multi-product model is similar to the innovation strategy pursued by the pulp and paper industry for many years (Laestadius 2000).

Like the crisis of the Brazilian ethanol programme from 1989, when the so called “sugar chemistry” investigations focused on diversifying the output of sugar mills, the European directive might prompt such a renewal of this market-diversification behaviour. Just as sugar kept the ethanol industry alive during the 1990s and ethanol and electricity co-generation reinforced the sugar business after 2003, robustness tends to increase when a new output is added to the sugarcane mill (Andersen 2008: 27).

Market leakage

There is concern from developing countries that global environmental problems such as climate change might be used as an excuse for disguised trade barriers, known as green protectionism (UNCTAD 2010). Thus, sustainability criteria could be seen as a green conditionality or a non-tariff barrier to trade, leading countries to potential commercial litigation at the World Trade Organization (WTO). The bioethanol industry is expected to react, if necessary, to the European requirements proportional to the level of interest it has in that market, or if it believes the EU criteria will serve as a basis for global standards for biofuel sustainability. In other words, if member states do not uptake their biofuels usage in line with the directive´s targets, the absolute size of the European market will be smaller than once thought. Similarly, if other important trade partners (e.g. the USA) adopt very different approaches towards biofuel requirements, the incentive for compliance with the EU criteria could be weakened.

Given the characteristics of commodities such as bioethanol, international trade is highly dynamic, and fast entry of new producers and consumers is expected (UNCTAD 2009). In the presence of regulations, trade could be always directed to the market with lowest requirements. Given the existence of demand in alternative markets, sustainability has to command a price premium in Europe, although this has not been verified in practice yet, otherwise the end result might be trade diversion. As south-south trade volumes are on an ever-increasing trend, the Brazilian industry could soon bypass major destinations (such as US and the EU) looking instead to China, India and other countries interested in diversifying their transport fuel portfolios (Hira 2010). Japan and South Korea also represent potential strong consumer markets.

The United States has no comprehensive, nationwide sustainability scheme in line with the European directive. While EU ethanol production reached 4.3 billion litres in 2011, US production reached 54.2 billion litres in the same year (REN21 2012). In Europe, biofuels that are not certified as sustainable will not be banned from the market, but will not be counted towards the European mandatory target of 10 per cent by 2020. In this sense, biofuels which do not adhere to the EU criteria will struggle to find markets in Europe unless very advantageous in price compared to the fossil alternative. As restrictions are lower in the USA, unsustainable biofuels according to the European regulation might well be absorbed there. In global terms, this could mean a setback for efforts to improve the global transport energy infrastructure by promoting better biofuels. Here lies the importance of future coordinated policy on higher standards for biofuels in all relevant markets, avoiding market leakage which would reduce the efficiency of sustainability schemes applied to ethanol.

CONCLUSION

Based on a broad review of recent literature as well as semi-structured interviews with academics and officials from both the Brazilian government and European Commission, this paper has explored the innovation mechanisms of the Brazilian ethanol industry and how these are likely to respond to the sustainability criteria for biofuels contained in the European Renewable Energy Directive proposed in 2009 (2009/28/EC). In its 37-year history, the Brazilian ethanol industry has shown itself to be highly innovative. While innovation has not been captured by patent statistics, the ethanol industry developed deep forward and backward linkages within the Brazilian economy, securing support from the government, financial institutions, farmers, the automobile industry and other sectors of society.[19]

The industry has shown rapid innovation capacity in a market facing constant change. Even as the Brazilian ethanol industry overcame difficulties in the 1990s, ethanol production costs kept falling. The domestic ethanol market expanded sharply after the introduction of flex-fuel technology in 2003. After 2005, with the coming into force of the Kyoto Protocol allied with climbing oil prices, ethanol came under the international spotlight, no longer as an example of successful national green energy policy but as a global energy commodity. Despite the complex national environmental and labour legislation, the sugarcane sector has been significantly progressed through innovative public policies, such as sugarcane agroecological zoning and the national labour agreement.

As ethanol attracted global attention, it was criticised for its potential dangers to ecosystems, to human health during production and to competition with foodstocks. Comprehensive sustainability criteria specific to biofuels were then introduced by the European Union as part of its Fuels Quality Directive (FQD) and Renewable Energy Directive (RED) adopted in 2009. However the effects of these legislations and further related bills on the Brazilian ethanol industry are still unclear. Potential agro-industrial innovations are expected to be undertaken in order to comply with European biofuels criteria, but at the same time an overregulation of this market could discourage the production of sugarcane-based ethanol to attend the European market, not only in Brazil, but in many other tropical countries too, especially in Africa.

Based on an examination of the historical development of the Brazilian bioethanol industry, it is clear that ethanol in Brazil was subject to strong innovation pressures between the early Proalcool Programme in 1975 to the present. Sources of innovation can be divided into two main categories: (1) endogenous; (2) and exogenous. Endogenous innovations were driven by the profit-seeking, competitive nature of the industry. The 1980s saw the adoption of multiple sugarcane varieties, the utilisation of production residues (vinasse) into fertiliser, biological controls and the establishment of technical standards (such as E100, along with its transport and blending infrastructures). The 1990s marked the optimisation of surplus electricity from bagasse-fired cogeneration, advances in automation and management, increases in the sugar exports as well as prospective multi-output models for the sugarcane mills. After 2000, the key innovations were the introduction of flex-fuel engines and the emergence of additional markets for sugarcane products, such as fibres and bioplastics, which hedged against fluctuations in ethanol prices and further contributed positively to the climate change agenda.

Exogenous innovations were introduced mainly in the form of regulations. Even though the Brazilian industry has been shown to have a long history of being subject to regulations – and has innovated accordingly – the introduction of internationally-applicable sustainability criteria by an external agent challenged the traditional domestic policy context in which the Brazilian ethanol industry operated. The European sustainability criteria adopted in 2009 called for minimum GHG savings, restrictions on usage of certain ecosystems for biofuel production and periodic reports on labour conditions and food supply primarily affecting populations in developing countries.

Sugarcane-based ethanol from Brazil was subject to similar requirements long before the European directive was introduced. These have facilitated some aspects of compliance. In recent years, federal and state laws were directed at watershed and wetland protection, the gradual phase-out of sugarcane crop fires and labour standards. The sugarcane agroecological zoning from 2009 also represented a major national step towards ethanol sustainability. All these regulations have been acting as external, although domestic, sources of innovation and were broadly incorporated by the industry to date. On the other hand, aiming to give further contribution and support to this progress in Brazil and other countries, the European indicators could be more objective, applicable, affordable and executive, respecting the reality and the specificities of different biofuels industries and also the economic viability for the implementation of such indicators worldwide. Moreover, biofuels is still an emerging industry in Africa for example and additional external costs may reduce its competitiveness and development.

In parallel, it is also important to highlight that there are no sustainability criteria for fossil fuels being regulated worldwide or at the EU level, representing unequal competition between renewable and non-renewable fuels. This especially favours the gasoline and diesel markets. If climate change is really a global concern, renewable sources of energy should compete on a level playing field with fossil fuels, to ensure that carbon-pricing schemes are extended to liquid fossil fuels sold within the EU and so better reflect their environmental impact. This paper has shown that while there are similarities between the EU sustainability criteria for biofuels and past national laws affecting the sugarcane ethanol industry in Brazil, there are clear differences in the objectives of past regulations introduced by national authorities and the new requirements implemented by the EU.

While national laws sought to regulate the sugarcane industry so as to steer innovation towards solving problems, the consequences of which affected Brazil itself, such as local damage to ecosystems, waterways, harsh labour conditions and pollutant emissions due to crop fires, those were all problems in which the negative externalities had observable local impact. The EU sustainability requirements, on the other hand, are primarily part of the European strategy for climate change and energy security, which seeks to diversify energy sources in Europe, favouring those with lower carbon intensity so as to help tackle climate change; which impacts may not affect a single country, but the entire globe. In addition local conditions are introduced by the EU such as the necessity of ratification of ILO conventions and monitoring food and fuel prices. Brazil already signed all the main ILO agreements and already monitors its food and fuel market.

The introduction of sustainability requirements for biofuels to be counted towards the mandated target of 10 per cent renewable energy in EU transport by 2020 sends three non-exclusive innovation signals to the industry. The first represents compliance with the introduced sustainability criteria on the innovation paths of the industry. This has already been taking place in a number of ongoing initiatives to minimise carbon intensities and environmental degradation about the production of ethanol, such as pipeline transportation, agroecological zoning and low impact machinery. While costly, adhering to the EU criteria signals the Brazilian industry is betting on new market conditions created by the EU strategy for climate change mitigation. The second signal sent to the industry is innovation towards risk-minimisation, as there are uncertainties about whether or not the EU criteria will develop into a dominant system for setting the rules for international trade of sustainable biofuels. By diversifying its input-output portfolio, the ethanol industry can expand beyond the trinity of sugar-ethanol-electricity which has characterised the core business model to date. This builds historically on the so-called "sugar and ethanol chemistry" attempts to diversify the industry in the 1990s. Bio-plastics, fibres and organic products are examples of alternative outputs that already work as a hedge against uncertainties in the bioethanol markets. The third signal would be plain market leakage. While a "race to the bottom" in environmental standards is unlikely due to the advanced status quo of the industry, high entry tariffs in the European market might gradually shift the industry away from compliance with EU sustainability criteria, adhering instead to requirements in other attractive markets such as the USA, India or China. All three signals for innovation are pursued simultaneously by market agents without a command-and-control structure, since production mills are decentralised and ownership is still fragmented.

While absolute causality cannot be established between the EU sustainability criteria and recent innovation efforts from the ethanol industry, the European directives coincided with many recent efforts from the industry towards reducing the lifecycle emissions of ethanol production, increasing transparency in the production process, enhancing accountability of production indicators and promoting greater scrutiny of its impacts on the environment and local societies.

Like other energy sources biofuels might not be absolutely sustainable, but an attempt to improve their status with transparent, private and independent certification could be a positive step forward, using market power in a positive way for both the environment and societies seeking green development paths.

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[1] In Brazil ethanol surpassed gasoline as the main liquid fuel for light vehicle fleets since 2008.

[2] In late 2012 the European Commission limited to 5 per cent the total share of first generation biofuels out of the 10 per cent renewable energy target for transport by 2020. This reduction may significantly affect new investments in sugarcane industries with the view to supply ethanol from Brazil to Europe.

[3] For example the industrial lobbies which are often present in political arenas, trying to gather support for the creation of new markets or the adoption of support mechanisms which cater to the interests of their supporting industries.

[4] There are many ways an industry can bypass an entry tariff, such as by dumping, looking for alternative entry routes (product bundling), reducing profits, reducing costs, starting production locally, asking their national government to contest trade barriers through the World Trade Organization etc.

[5] In theory firms could earn higher profits with the introduction of regulations in the short term. One example of this occurring is when a regulation effectively lowers standards relative to former common practice. By downgrading (meeting the minimum necessary), an industry could engage in "regulated" markets at lower-than-usual costs. This is rather unusual and occurs mostly in specific circumstances given that regulations tend to be introduced when industrial trends are not internalising all relevant costs, such as environmental and health aspects.

[6] In July 2011, the European Commission published a list of seven recognised voluntary certification schemes for biofuels. The list currently has 13 recognised voluntary schemes. How different certificates will compete in the market is still unclear. See: http://ec.europa.eu/energy/renewables/biofuels/sustainability_schemes_en.htm

[7] Blending ratio recently re-established at 18 per cent by the bill (Medida Provisoria) 532/2011, which also gives additional power to the National Agency of Petroleum, Natural Gas and Biofuels (ANP) to regulate the ethanol market. Before this law the blending ratio varied between 20 per cent and 25 per cent.

[8] Most biofuels have a lower Energy Return on Investment (EROI) than oil. This makes biofuels more expensive than fossil equivalents, compared in free market conditions. The only biofuel that has been more price-attractive than gasoline is sugarcane-based bioethanol. High oil prices make gasoline more expensive, thus, the alternative (biofuels) become more price-attractive, with some correlations with the sugar market as well.

[9] As for example, the Brazilian company WEG ships electric generators to be used in boilers worldwide. Industrial infrastructure companies such as Renk-Zanini and Dedini are active exporters of bioethanol plant technology.

[10] São Paulo State law Nr. 11.241 of 19th September 2002.

[11] Mechanical harvesting accounted for 46.6 per cent of all sugarcane harvested in the major production state (Sao Paulo), for the harvest of 2007/2008, a 36 per cent increase compared to the 2006/2007 harvest (Aguiar *et al*, 2009). Additionally, wages in the sugarcane industry are among the highest in the agricultural sector of Brazil (Costa 2007).

[12] MAPA Ministerial Decree (Portaria) 333/2007.

[13] Presidential Decree 6.961/2009; MAPA Ministerial Decree (Portaria) 333/2007 Normative Instruction 57/2009; Bacen (Central Bank of Brazil) Resolutions 3.813/2009 and 3.814/2009; Federal Law Project 6.077/2009.

[14] SAP-Cana is an online official monitoring system of the Brazilian sugarcane industry, established and managed by the Department of Sugarcane and Agro-energy at the Ministry of Agriculture: www.agricultura.gov.br

[15] The Brazilian Ethanol Industry Association (UNICA) opened a representation office in Brussels in May 2008, following a similar move in Washington (late 2007). The Brussels office serves as a gathering point of regulatory matters of interest to the Brazilian ethanol industry.

[16] Crop fires were, but due to their detrimental effects to the health of populations in nearby areas.

[17] The voluntary schemes recognised by the European Commission can be seen at: http://ec.europa.eu/energy/renewables/biofuels/sustainability_criteria_en.htm

[18] The first report of 2011 foresees the assessment of issues such as food security and labour conditions in biofuel producing countries/regions.

[19] Patents were not analysed in depth in this study on purpose. This because patent statistics have a substantial weakness attributing the importance of each patent registration in total patent registries (many patents do not yield productive innovations), as well as due to different organisational cultures, as some patenting is much stronger in some regions (US, EU) than others (Brazil) and that has not been a good proxy for innovation, as Brazil had the lowest production cost for bioethanol as of 2010.

REFERENCES

Aguiar, Daniel Alves de; Rudorff, Bernardo Friedrich Theodor; Da Silva, Wagneer Fernando (2009) "Monitoramento do modo de colheita da cana-de-acucar no Estado de Sao Paulo – Brasil por meio de imagens de sensors orbitais em dois anos-safra". Brazilian National Institute for Space Research. Sao Jose dos Campos, pp. 1-10.

Akhurst, Mark; Kalas, Nicole; Woods, Jeremy (2011). "Synthesis of European Commission Biofuels Land Use Modelling". Science Insights for Biofuel Policy. 1, March 2011 LCA works and Porter Institute, Imperial College London, UK, pp. 1-6.

Andersen, Allan Dahl (2009) "A Natural Resource-based Development Path? The case of the Brazilian Sugarcane-Ethanol Industrial Complex". Working Paper for Globelics Conference Department of Business Studies, Aalborg: Aalborg University, pp. 3-20.

Andrade, Renata Marson Teixeira; Miccolis, Andrew (2010). "The expansion of Sugarcane-Ethanol in Brazil and Controversies surrounding Human Rights". In: Daniel Lee Kleinman, Jason Delborne, Karen A. Cloud-Hansen, and Jo Handelsman (eds.) Controversies in Science and Technology Volume 3: From evolution to Energy. USA: Mary Ann Liebert, pp. 214-220.

Araújo, Gisele Ferreira de; Strapasson, Alexandre Betinardi (2009). "Comparative Analysis of the Climate Change and Environmental Policies in Brazil: Challenges, Risks and Opportunities for the Amazon Region". Published at the United Kingdom Environmental Law Association (UKELA) and presented at a side event of the COP15/UNFCCC, Copenhagen - Denmark.

Arthur J. Ragauskas, et al. (2006). "The Path Forward for Biofuels and Biomaterials". Science, 311, pp 484-489.

Bastos, Milton Briquet (2007). "Brazil´s Ethanol Program – An Insider´s View". Energy Tribune. Available at: http://www.energytribune.com/articles.cfm?aid=534 Last accessed 12.12.2012.

Barzelay, Michael (1986). "The Politicized Market Economy: Alcohol in Brazil's Energy Strategy." Berkeley: University of California Press.

Bertelli, Luiz Gonzaga. (2005) "Urbano Ernesto Stumpf, o pai do motor a álcool". União da Indústria de cana-de-açúcar – UNICA. Available at: http://www.unica.com.br/opiniao/show.asp?msgCode=%7B86A7307D-21A2-455E-8E82-0D83A24ADD68%7D Last accessed 12.12.2012.

BNDES (2008). "Sugarcane-based Bioethanol: Energy for Sustainable Development". Rio de Janeiro. pp 5-304.

BCG (2009). "The Innovation Imperative in Manufacturing. How the United States can restore its edge". Boston: The Boston Consulting Group, pp.1-10.

BRASKEM (2009). Institutional Website. Available at: www.braskem.com.br under link "Plastico Verde" (Green Plastic). Sao Paulo.

Brito Cruz, Carlos H. (2009). "Bioenergy in Brazil". The São Paulo Research Foundation, FAPESP. Presentation for FAPESP bioenergy programme. Sao Paulo.

Cançado, José Eduardo Delfini (2007). "Hospital admissions in a sugar cane plantation area in Brazil". Journal of Epidemiology and Community Health, 61, pp. 395-400.

Cassiolato, José Eduardo; Soares, Maria Clara Couto (2009). "Description and Dynamics of the Brazilian Innovation System". Federal University of Rio de Janeiro. RedeSist, pp 1-30.

Copa-Cogeca; Coceral; ePURE; FEDIOL; COCERAL; EBB (2012). Open letter: Irresponsible U-turn on biofuels policy kills sustainable growth and jobs. Brussels, October 2012. pp 1-3.

Costa, Henrique Silva Pacini (2007). “Ethanol and the European Union: Potential and Implications. Master Thesis”. Bremen, Hochschule Bremen, pp 1-64.

Correlje, Aad.; Van der Linde, Coby. (2006). “Energy supply security and geopolitics: A European perspective”. Energy Policy, 34, 5, pp 532-543.

Cortez, Luiz Augusto Barbosa (2010). “Sugarcane bioethanol – R&D for Productivity and Sustainability”. Sao Paulo: Edgar Blucher, pp. 1-994.

Dahmén, Erik (1994). “The Dynamics of Entrepreneurship”. Dynamics of Entrepreneurship, Technology and Institutions. Lund: Lund Institute of Economic Research, pp. 1-61.

Desplechin, Emmanuel (2010). “The Brazilian ethanol industry´s approach to certification”. Brazilian Sugarcane Industry Association (UNICA). Available at: http://english.unica.com.br/opiniao/show.asp?msgCode=%7BCB4605EE-B672-4D2C-9480-6A6EC339AFD2%7D Last accessed 12.12.2012.

De Souza, Taynah Lopes; Hasenclever, Lia (2008). “The Brazilian System of Innovation for Ethanol Fuel: An Essay on the Strategic Role of the Standardization Process”. VI Globelics Conference, Mexico City.

EBB (2011). “Latest developments in the Indirect Land-Use Change (ILUC) debate”. European Biodiesel Board.

Embrapa (2010). Geoportal da Embrapa Solos. Available at: http://mapoteca.cnps.embrapa.br Last accessed 12.12.2012.

EPA (2010). “Greenhouse gas reduction thresholds from renewable fuels”. United States Environmental Protection Agency. Available at: http://www.epa.gov/OMS/renewablefuels/420f10007.pdf Last accessed 12.12.2012.

European Commission (2001). “Directive on the promotion of electricity produced from renewable energy sources in the internal electricity market 2001/77/EC”. Brussels, pp. 1-8.

European Commission (2003). “Promotion of the use of biofuels and other renewable fuels for transport”. Directive 2003/30/EC. Brussels, pp. 1-12.

European Commission (2007). “An Energy Policy for Europe” COM (2007) 1 final. Brussels, pp. 1-27.

European Commission (2008). “Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources” COM (2008) 30 final. Brussels, pp. 1-45.

European Commission (2009a). “Directive 2009/28/EC of the European Parliament and the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.” Brussels, pp. 1-46.

European Commission (2009b). Tender process. TREN/D1/389/2009. Brussels.

Finguerut, J. (2004). Produção de Álcool: Pesquisa e Desenvolvimento. Piracicaba, SP, Brazil: CTC, pp 8-17.

Folha de São Paulo (2009). Lula vetará o plantio de cana em 50% do paìs. Folha. Available at : http://www1.folha.uol.com.br/fsp/dinheiro/fi0709200902.htm Last accessed 12.12.2012.

Furtado, Andre Tosi; Scandiffio, Mirna Ivonne Gaya; Cortez, Luiz Augusto Barbosa (2011). “The Brazilian sugarcane innovation system”. Energy Policy, 39, 1, pp. 156-166.

Goldemberg, José; Guardabassi, Patricia (2009). “Are biofuels a feasible option?”. Energy Policy, 37, 1, pp. 10-14.

Goldemberg, José (2006). “The Ethanol program in Brazil”. Environmental Research Letters. Universidade de Sao Paulo, pp 1-5.

Goldemberg, José; Teixeira Coelho, Suani; Nastari, Plinio Mario; Lucon, Oswaldo (2004). “Ethanol Learning Curve – The Brazilian Experience”. Biomass and Bioenergy, 26, pp. 301-304.

Harari, Elena (2008). “Bioethanol and Technological Innovation Systems. A comparative analysis between the U.S. and Brazil”. Paper presented at the Science, Technology and Innovation Policy Conference. Atlanta. pp 1-3. Available at: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=04472886 Last accessed 12.12.2012.

Hira, Anil; Oliveira, Luiz Guilherme de (2009). “No substitute for oil? How Brazil developed its ethanol industry”. Energy Policy, 37, pp. 2450-2456.

Hira, Anil (2010). “Sugar rush: Prospects for a global ethanol market”. Energy Policy. 39, 11 pp. 6925-6935.

Hirschman, Albert O. (1958). “The Strategy of Economic Development”. Yale: Yale University Press. Pp. 1-251.

IEA (2002). Biofuels for transport. An international perspective. OECD. pp.1-13. Available at: http://www.iea.org/textbase/nppdf/free/2004/biofuels2004.pdf Last accessed 12.12.2012.

ISO, International Sugar Organization (2010). “Sugar Yearbook 2010 edition”. London, pp. 1-50.

Jank, Marcos S. (2011) “Coragem para retomar o etanol”. Estado de São Paulo, 20th Sep 2011, Special page A2. Sao Paulo.

Jaffe, Adam B.; Lerner, Josh; Stern, Scott (2005). “Innovation Policy and the Economy. Vol. 5”. National Bureau of Economic Research. Cambridge, pp. 1-250.

Junginger, Martin; Van Dam, Jinke; Zarrilli, Simonetta; Ali Mohammed, Fatin; Marchal, Didier; Faaij, Andre (2010). “Opportunities and barriers for international bioenergy trade”. Energy Policy, 39, 4, pp, 2028-2048.

Kamate, S.C.; Gangavati, P.B. (2009). “Exergy analysis of cogeneration power plants in sugar industries”. Applied Thermal Engineering, 29, pp 1-7.

Kamis, Ronald; Joshi, Mandar (2008). “Biofuel patents are booming.” Cleantech Group LLC. San Francisco. Available at: http://cleantech.com/news/2329/biofuel-patents-are-booming Last accessed 12.12.2012.

Karmarkar-Deshmukh, Rupa; Pray, Carl E. (2009). “Private Sector Innovation in Biofuels in the United States: Induced by Prices or Policies?” The journal of Agrobiotechnology Management and Economics. pp 141-148. Available at: http://agbioforum.org/v12n1/v12n1a13-deshmukh.htm Last accessed 12.12.2012.

KPMG (2008). International / CIES Survey 2008. Available at: http://www.kpmg.com.au/Portals/0/KPMG%20CIES%20Survey.pdf Last accessed 12.12.2012.

Krugman, Paul; Obstfeld, Maurice (2008). “International Economics. Theory and Policy.” 8th edition. Boston: Addison-Wesley, pp. 1-736.

Lachenmaier, Stefan; Woessmann, Ludger (2004). “Does innovation cause exports? Evidence from exogenous innovation impulses and obstacles using German Micro Data.” CESIFO Working Paper 1178. Munich, p 317-350.

Laestadius, Staffan (2000). “Biotechnology and the Potential for a Radical Shift of Technology in Forest Industry”. Technology Analysis & Strategic Management, 12, 2 pp. 10-13.

Lima, Gilberto Tadeu (2002). “Endogenous technological innovation, capital accumulation and distributional dynamics.” Metroeconomica, 55, 4, pp 386-408.

Macedo, Isaías C.; Seabra, Joaquim E.A.; Silva, João E.A.R. (2008). "Green house gases emissions in the production and use of ethanol from sugarcane in Brazil: The 2005/2006 averages and a prediction for 2020". Biomass & Bioenergy, 32, pp 582-595.

Macedo, Isaías. (2004). "Assessment of greenhouse gas emissions in the production and use of fuel ethanol in Brazil". Report from the government of the State of São Paulo. pp. 1-32. Available at: http://www.wilsoncenter.org/sites/default/files/brazil.unicamp.macedo.greenhousegas.pdf Last accessed 12.12.2012.

Macedo, Isaias. (2007). "The current situation and prospects for ethanol". Advanced Studies of the University of Sao Paulo, 21, 59, pp. 157-165. Available at: http://www.scielo.br/pdf/ea/v21n59/en_a11v2159.pdf Last accessed 12.12.2012.

Manzatto, Celso Vainer; Assad, Eduardo Delgado; Bacca, Jesus Fernando Mansilla; Zaroni, Maria Jose; Pereira, Sandro Eduardo Marschhausen. (2009). "Zoneamento Agroecológico da Cana-de-açúcar: Technical Report." MAPA and Embrapa joint publication. Brasilia, pp 1-58. Available at: http://www.cnps.embrapa.br/zoneamento_cana_de_acucar/ZonCana.pdf Last accessed 12.12.2012.

MAPA, Ministry of Agriculture, Livestock and Food Supply of Brazil (2009a). "Brazilian Agrienergy Yearbook". In A.B. Strapasson et al. (eds.) Brasilia, MAPA/SPAE, pp 1-162.

MAPA (2009b). "Ementário Nacional da Agroindústria Canavieira". In F. M. Marinho et al. (eds.) Brasilia, MAPA/SPAE.

MAPA and Embrapa (2006). "Brazilian Agroenergy Plan: 2006-2011. 2nd edition". Brasilia: Embrapa Publishing, pp. 1-118.

Brasilia, Martinelli, Luiz., Filoso, Solange (2008). "Expansion of sugarcane ethanol production in Brazil: Environmental and Social challenges." Ecological Applications, 18, 4, pp. 895-896.

Mayerhoff, Zea Duque Vieira Luna (2006). "Patentes em bioetanol evidenciam desenvolvimento brasileiro." Inovação Uniemp, 2, 2..

MTE (2011) "NR31 Work Safety Regulation – Safety at agriculture, livestock, forestry and fisheries sector". (In Portuguese) Brazilian Ministry for work and employment. Available at: http://portal.mte.gov.br/data/files/8A7C812D33EF459C0134561C307E1E94/NR-31%20%28atualizada%202011%29.pdf Last accessed 12.12.2012.

Pacini, Henrique; Silveira, Semida (2010a). "Consumer choice between ethanol and gasoline: Lessons from Brazil and Sweden". Energy Policy, 39, 11 pp. 6936-6942.

Pacini, Henrique; Silveira, Semida (2010b). "Ethanol or gasoline? Consumer choice in face of different fuel pricing systems in Brazil and Sweden", Biofuels, 1, 5, pp. 685-695.

PECEGE (2011) "Ethanol production costs. Annual reports from 2007-2010. Piracicaba. Available at: http://www.pecege.esalq.usp.br/2010/?Area=9 Last accessed 12.12.2012.

Pimentel, David (2003). "Ethanol fuels: Energy balance, economics, and environmental impacts are negative. Natural Resources Research, 12, pp.127-134.

Pimentel, David; Patzek, Tad W. (2005). "Ethanol Production Using Corn, Switchgrass, and Wood; Biodiesel Production Using Soybean and Sunflower. Natural Resources Research, 14, 1, pp 1-5.

Piringer, Otto G.; Baner, Albert L. (2008). "Plastic Packaging: Interactions with food and Pharmaceuticals." 2nd edition. Weinheim: Wiley-YCH, pp 1-48.

Procknor Engineering Services (2005). Institutional presentation, pp. 4-5. Sao Paulo. Available at: http://www.saneamento.sp.gov.br/bio_apresen/Procknor.pdf Last accessed 12.12.2012.

REN21 (2012). "Renewables 2012: Global Status Report." Renewable Energy Policy Network, pp 1-172. Available at: http://www.ren21.net Last accessed 12.12.2012.

Robertson, Paul; Pol, Eduardo; Carroll, Peter (2003). “Receptive capacity of established industries as a limiting factor in the economy´s rate of innovation”. Industry & Innovation, 10,4, pp. 457-474.

Schumpeter, Joseph. (1934). “The theory of economic development. An inquiry into profits, capital, credit and business cycles.” Harvard: Harvard University Press, pp. 1-18.

Scopinho, Roseimeire Aparecida; Eid, Farid; Vian, Carlos Eduardo de Freitas; Silva, Paulo Roberto Correia (1999). “New technologies and worker´s health: Mechanization of sugarcane harvesting.” Rio de Janeiro: Caderno de Saúde Pública, pp. 147-161.

SMA (2011). “Resultados do Protocolo Agroambiental para a Proteção de Recursos Hídricos no Estado de São Paulo.” Secretaria do Meio Ambiente do Estado de Sao Paulo Etanol Verde: Notícias, Março de 2011. Sao Paulo. Available at: http://www.ambiente.sp.gov.br/etanolverde/23_acoes.php Last accessed 12.12.2012.

Smith, Keith (2002). “What is the Knowledge Economy? Knowledge Intensity and Distributed Knowledge Bases”. Discussion Paper Series, United Nations University INTECH, pp. 1-15.

Smith, Keith (2008). “Climate change and radical energy innovation: the policy issues.” Report to Garnaut Commission on Climate Change. Sidney, pp. 1-175.

SPPT – Sociedade Paulista de Pneumologia e Tisiologia (2005). “Queimada da cana-de-açúcar é responsável por doenças respiratórias em crianças e idosos.” Notícias. (In portuguese). Sao Paulo. Available at: http://www.sppt.org.br/v2/noticia_completa.php?id_noticia=108 Last accessed 12.12.2012.

Sperling, Daniel (1987). “Brazil, Ethanol and the Process of System Change”. Energy, 12, pp. 11-23.

Sperling, Daniel (1988). “New Transportation Fuels: A Strategic Approach to Technological Change”. Berkeley: University of California Press, pp. 1-34.

Strapasson, Alexandre., Job, Luis Carlos (2007). “Ethanol, Environment and Technology: Reflections on the Brazilian Experience”. In: Revista de Política Agrícola (Journal of Agricultural Policy). English version, 3, XVI, July/Ago/Sep, 2007. MAPA. Brasília/Brazil, pp. 50-63.

Strapasson, Alexandre B. (2008). “Cogeração com Bagaço de Cana-de-açúcar: A Energia do Campo”. Revista Opiniões (Opiniões Review). Ribeirão Preto, Brazi:l WDS publishing house, pp. 12-14.

Strapasson, Alexandre B.; Ramalho Filho, Antônio; Ferreira, Denilson; Vieira, José Nilton de S.; Job, Luís Carlos M. A. (2012). “Agroecological Zoning and Biofuels: the Brazilian experience and the potential application in Africa.” In Francis X. Johnson and Vikram Seebaluck (eds.) Bioenergy and Sustainable Development: the Role of Sugar Cane in Africa. USA and Canada: Routledge, pp. 48-65.

Tonelli, Dany Flavio; Zambalde, Andre Luiz; De Brito, Mozar Jose.; Figueira, Mariane (2010) “Endogenous and exogenous features of innovation processes in Brazil : two case studies at a Brazilian university.” International Journal of Technology Transfer and Commercialisation, 9, 2, pp. 133-149.

UNCTAD (2009) “The Biofuels Market: Current Situation and Alternative Scenarios.” Geneva: UNCTAD, pp. 15-28.

UNCTAD (2010) “The Green Economy: Trade and Sustainable Development Implications”. Geneva: United Nations Conference on Trade and Development. Available at: http://www.unctad.org/en/docs/ditcted20102_en.pdf Last accessed 12.12.2012.

UNICA (2011). Statistics on ethanol exports. Available at: http://english.unica.com.br/dadosCotacao/estatistica/ Last accessed 12.12.2012.

UNICA (2012) Map of sustainability schemes applicable to biofuels. Sao Paulo. Available at: http://english.unica.com.br/opiniao/show.asp?msgCode=%7BCB4605EE-B672-4D2C-9480-6A6EC339AFD2%7D Last accessed 12.12.2012.

United States Congress (2007). “Energy Independence and Security Act Pub.L.”. Washington D.C. Available at: http://hdl.loc.gov/loc.uscongress/legislation.110hr6 Last accessed 12.12.2012.

Uriarte, Maria; Yackulic, Charles B.; Cooper, Tamar; Flynn, Dan; Cortes, Marina; Crk, Tanja; Cullman, Georgina; McGinty, Meghan; Sircely, Jason (2009). “Expansion of sugarcane production in São Paulo, Brazil: Implications for fire occurrence and respiratory health.” Agriculture, Ecosystems and Environment 132, pp. 48-56.

Velho, Lea; Velho, Paulo (2006). “Innovation in Resource-Based Technology Clusters. Investigating the Lateral Migration Thesis. The development of a sugar-based plastic in Brazil”. Department of Science and Technology Policy – University of Campinas, pp. 28-77.

Walter, Arnaldo (2009). “Bio-Ethanol Development(s) in Brazil”. In W. Soetaert and E.J. Vandamme (eds.) Biofuels, Chichester, U.K., John Wiley & Sons Ltd., pp. 15-34.

Warhurst, Michael (2005). “Environmental regulation, innovation and competitiveness – making the link”. HESA newsletter. October 2005 No. 28. Germany.

Watanabe, Chihiro; Tsuji, Youichirou S.; Griffy-Brown, Charla (2001). “Patent statistics: deciphering a “real” versus a “pseudo” proxy of innovation”. Technovation, 21, pp 783-790.

Wilkinson, John; Herrera, Selena (2008). “Agrofuels in Brazil: what is the outlook for its farming sector?”. CPDA/UFRRJ. Rio de Janeiro, pp. 15-18 Available at: http://www.boell-latinoamerica.org/downloads/Wilkinson__Herrera_Ing_Final_Nov20081.pdf Last accessed 12.12.2012.