Chapter 1

Assessment of Sugarcane-Based Ethanol Production

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Abstract

This chapter aims to explain how bio-ethanol has been drawn to become a successful alternative to partially replace petroleum as a source of liquid fuels in Brazil. A brief historical analysis about the production of bio-ethanol from sugarcane is presented. The motivation to start the production of the ethanol as biofuel in the 1970s and how the governmental policies have contributed to the ups and downs, successes, and failures of the sugarcane industry is shown. Then, the efficiency of the sector is addressed; firstly, the increasing efficiency of the agricultural sector is discussed, showing how the productivity per hectare has increased in the last decades and which improvements are further expected in a near future. Finally, the industrial process is discussed: the current efficiency in processing sugarcane to produce ethanol and the emerging technologies, not only to process sugarcane juice, but also to harness bagasse, vinasse, and sugarcane straw.

Keywords: Brazilian ethanol fuel, *Proálcool*, ethanol production, sugarcane ethanol, bio-ethanol

1. Introduction

The beginning of sugarcane cultivation in Brazil is related to the Portuguese occupation during the colonial period. Sugarcane crop met ideal soil and climate conditions, and it was used by the Portuguese to establish their settlement in Brazil. With the production of sugar, alcoholic beverages were produced by alcoholic fermentation of sucrose. The first studies on ethanol, as a fuel for internal combustion vehicles, started in the 1920s [1]. The characteristics of ethanol (liquid fuel, high-energy density, and relatively safe handling) made it an important substitute for liquid fuel from petroleum in the Brazilian energetic matrix. In fact, the world overwhelming dominance of gasoline, diesel, and jet fuel for transportation clearly shows the preference for liquid fuels due to their high-energy density. Except for the ethanol, most of the liquid fuels in the world are petroleum based. As petroleum is not renewable, in the long term, it must be substituted by other kind of energy. Aside from that, the use of fossil energy results in the releasing of greenhouse gas emission, which contributes for global warming. Hence, society in general is looking for alternatives to avoid global warming and thus replace petroleum. Biomass, like the sugarcane, clearly represents a sustainable and low-cost resource that can be converted into liquid fuels on a large scale to have a meaningful impact on petroleum use.

2. Why has bio-ethanol become a successful alternative to partially replace petroleum fuels? A short history

The beginning of the development of the ethanol fuel in Brazil is related to the petroleum shortage in Brazilian territory and the worldwide oil crisis. Brazil had few oil wells in 1970s, and the country was extremely vulnerable to international oil crisis. In 1973, during the first oil crisis, prices increased by 400%, which greatly affected the Brazilian economy in this way, and the Brazilian government began to seek an alternative to reduce its international dependence on oil. At that time, anhydrous ethanol, produced from sugarcane, had already been mixed to gasoline at a ratio of 5%, since 1931. In 1975, government created the Brazilian ethanol program, *Proálcool*, which involved many economical sectors to develop bio-ethanol as fuel to replace gasoline [2]. This program had massive governmental funds to develop feedstock and industry. In 1979, during the second oil crisis, Brazil presented the first ethanol fuel-powered car. At that time, Brazil had active state intervention over the price and the production of ethanol [3], which dictated the amount of sugar and ethanol to be produced. The ethanol price paid to the producers was a function of the sugar price. The price of ethanol and gasoline was established by the government at the fuel station. Therefore, the lower price of ethanol compared to gasoline led the population to choose ethanol-powered car instead of gasoline-powered one. As shown in **Figure 1**, the sales of ethanol cars skyrocketed, and in 1984, about 76% of the sales of cars using Otto cycle engines were ethanol fuel-based. At that time, most fuel stations in Brazil could offer ethanol as fuel.

At this point, it is worth defining “ethanol fuel” compared to anhydrous ethanol. “Ethanol fuel” is also known as “hydrous ethanol,” and it is basically composed of ethanol (92.5–94.6%wt) and water. Ethanol fuel is used straightly into car engines without any blend. Anhydrous ethanol consists of at most 0.7% water by weight, and it has been used mixed with gasoline in different blend levels. **Figure 2** shows the fraction of anhydrous ethanol mixed with gasoline over the years. Anhydrous ethanol is also used as anti-knock agent, substituting the additive added to gasoline to avoid getting ignited early before spark occurs. Many countries still use methyl tert-butyl ether (MTBE) as a gasoline additive instead of ethanol, despite the environmental and health concerns. In the United States, MTBE has been replaced by corn ethanol since 2005 [4]. In Europe, part of the MTBE has been substituted by ethyl-tertiary-butyl-ether (ETBE) which is an additive obtained by the reaction of isobutene with ethanol [5]. In Europe, the amount of ETBE used instead of MTBE is dependent on the price of ethanol.

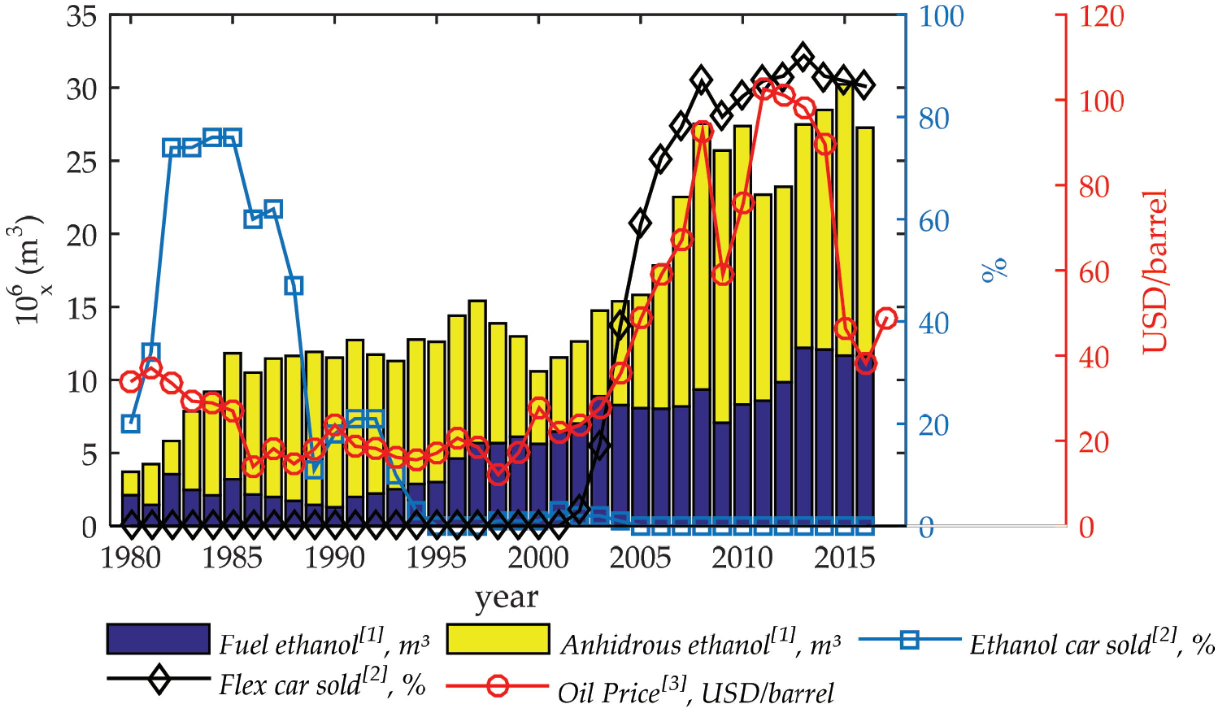

Figure 1. Fuel and anhydrous ethanol production; ethanol-powered car and flex fuel car sold in Brazil, and the price of the oil barrel. Source: [1] UNICA União da Indústria de Cana de Açúcar (2017); [2] ANFAVEA Associação Nacional dos Fabricantes de Veículos; Automotores; [3] eia U. S. Energy Information Administration.

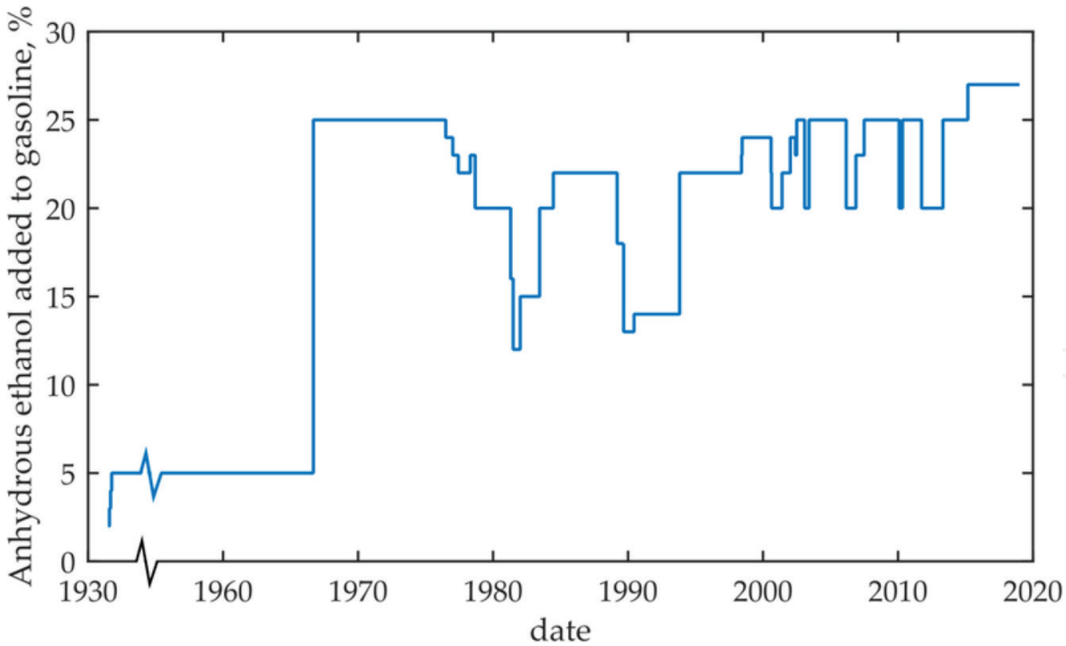

Figure 2. Fraction of anhydrous ethanol added to gasoline. Source: MME Brazilian Ministry of Mines and Energy.

In 1985, after government system changed to democracy, the congress changed the rules of public policy concerning ethanol to include stakeholders on the government decision. As a result, the government moved away from the sector and the bio-ethanol fuel development faced more challenges to overcome. Firstly, the oil price decreased and ethanol became economically noncompetitive compared to gasoline. Oil should cost more than U$ 45.00/barrel in order to let sugarcane ethanol to be competitive [6]. Then, in 1990, the government suspended the quote requirement on the mill to produce ethanol [7, 8]. In 1996, the price control on the fuel sector ended [9]. In 1999, government completely deregulated the sugarcane sector [10]. As a result, the ethanol consumption stopped rising, and the ethanol fuel sector suffered without government regulations and incentives.

Besides the end of the many subsidies, ethanol car technology had to deal with lack of consumer confidence, and so the sales of ethanol fuel-based car decreased. In 1984, ethanol car was still under development and, at that time, many problems were still unsolved such as the engine cold start. In 1989, due to the sugar price raising and the low oil price, sugarcane mills started to produce more sugar than ethanol. This resulted in a shortage of ethanol fuel, which led ethanol car users to stop using it. Besides, the ethanol engine, due to technical reasons, could not be easily converted to gasoline engine. For this reason, as shown in **Figure 1**, the ethanol car sales dropped from 76% to about 11% in Brazil, and 6 years later, no car manufacturer had ethanol fuel cars in its production lines. From 1995 to 2003, the ethanol demand was basically to supply fuel to the ethanol cars which had been sold before.

By 2003, due to the rising of oil price, ethanol fuel regained its competitiveness. At this time, as a consequence of the ethanol production/demand occurred after 1985, automakers started manufacturing cars using flex fuel technology and, as a result, the demand for ethanol as fuel rose again. Due to the flex technology, the customers can decide whether to fuel their cars with ethanol or gasoline. So, there were no more customers concerns about purchasing ethanol-powered cars. Hence, it became a self-regulating market; for instance, during the sugarcane crop season, the ethanol fuel price decreases, which motivates the preferential use of ethanol instead of gasoline. By analogy, when the stock of ethanol fuel is low, the price of ethanol would rise and it could be preferable for customers to use gasoline instead. This also corrected the problems related to the possibility of ethanol shortage due to climate changes that would affect the sugarcane crop and the amount of sugarcane diverted to produce sugar instead of ethanol. Consequently, the flex technology seems to have solved most of the problems related to the use of ethanol as fuel.

Flex fuel technology consists in adjusting the engine to operate using both kinds of fuel, ethanol or gasoline, and their blend in any concentration. In an Otto cycle engine, each fuel has different operation characteristics such as air/fuel ratio, compression ratio, and ignition timing [11]. The air/fuel ratio issue has been solved by measuring the oxygen content of the exhaust gas by the lambda sensor, which supplies the necessary information for optimal air/fuel mixture to the engine control unit. Electronic ignition timing controller adjusts the ignition time for maximum torque and fuel conversion efficiency [12]. However, the compression ratio, which is the ratio of the volume of the combustion chamber from its largest to its smallest capacity, cannot be easily changed in an engine. Ethanol engine requires a higher compression ratio than the gasoline one; thereby, the commercial flex fuel car has an intermediate compression ratio, which is intermediate to the ideal one for both fuels. Automakers have worked in variable compression ratio engines, which would result in an increment of engine efficiency [13].

Nowadays, most of the cars sold in Brazil are flex fuel, and ethanol is easily found in every fuel station; thus, the customers are able to choose which fuel they want to use. It is worth noting that most Brazilians customers do not choose to use ethanol because it is environmentally friendly, but due to economic reasons. A survey carried out by the Brazilian Sugarcane Industry Association (UNICA) [14] shows that Brazilian consumers in general are not willing to pay more for ethanol than for gasoline even though the majority recognizes its environmental benefits. Even when ethanol has the same cost per driving kilometers (about 70% of the price of gasoline), 55% of the consumers choose to fuel the car with gasoline due to its higher autonomy. This behavior may be explained by "The Tragedy of the Commons" [15] in which the rational man finds that his share of the cost of the CO_2 he discharges into the commons is less than the cost of not releasing it individually. Consequently, the majority of the consumers choose the fuel taking into account only their own benefits. This means that ethanol can survive as an alternative fuel only if it is economically competitive when compared to gasoline or by law regulations.

Environmental and social concerns also have a beneficial impact on the fuel ethanol program: pressures from nongovernmental organization (NGO) and the United Nations (UN) about reduction of greenhouse gas emissions (GHGs), and some civil society organizations about the social impact of ethanol supply chain on the society. One action taken to support the claim for reducing GHG was the creation of a tax on the nonrenewable fuel [16], which aims to support environmental programs and natural disasters caused by GHG. This is based on the "beneficiary pays principle," whereby when purchasing fossil fuel, the beneficiaries should pay the bear costs on the environment, which are believed to contribute to climate change. This seems suitable; however, it is very difficult to precisely evaluate the impact on the environment. Moreover, in 2018, the Brazilian government created the *RenovaBio* [17]—a national biofuel policy to set rules to allow sustainable expansion of the Brazilian biofuel market. In fact, nowadays, ethanol supply chain is responsible for 950,000 direct jobs and 70,000 farmers [18] in the country. For each direct job, 2.39 indirect ones [19] are estimated, resulting in over 2.4 million jobs. For this reason, the ethanol fuel environmental and social benefits cannot be left at the mercy of the variations in petroleum price.

Besides its use as fuel, ethanol is used as a raw material to produce biopolyethylene. Polyethylene is one of the most popular plastics in the world. It is a polymer of ethylene and consists of a carbon backbone chain with pendant hydrogen atoms. Biopolyethylene is a polyethylene made from ethanol. The process consists in dehydrating ethanol to obtain ethylene prior to polymerization. The properties of this bioplastic are identical to the fossil-fuel based polymer. The main advantage of the polyethylene made from ethanol is that it captures and fixes CO_2 from the atmosphere.

Through this brief ethanol history, it is possible to infer that biofuel ethanol has undergone two different expansion phases: the first one is the *Proálcool* policy and the second one is the flex fuel car (concerning ethanol as liquid fuel). In these two expansion phases, the main claim was not the environmental one but an alternative fuel to the high price of petroleum. However, due to current global warming concerns, the world is looking for a renewable fuel to replace petroleum and reduce emissions. A number of alternatives are under development, and the question that arises is if the bio-ethanol is going to be "the fuel." In case of a positive answer, one may expect a new expansion phase in the ethanol production sector. Further, in this new expansion phase, not only an alternative fuel is expected, but also a fully environmentally friendly one. Thus, the process might be highly efficient in all steps of the production chain, from the crop to its final use. Therefore, the efficiency of the production of ethanol and some opportunities to improve the efficiency will be addressed subsequently in this chapter.

3. Efficiency of the sugarcane ethanol production and what is expected in a near future

Since the beginning of the ethanol fuel program in Brazil, an improvement in all production chain has been observed. With the emerging technologies, new improvements are expected. Hence, in this section, the recent enhancements in productivity and efficiency of the sector and what is expected in a near future are analyzed.

3.1. Sugarcane crop

During the last decade, the principal change in crop management was the mechanization. One of the main reason for mechanizing the sugarcane crop is concerned environment protection. The traditional harvest was done manually and the sugarcane leaves had to be burned in the field. The consequence was high particle and CO_2 emissions, which led the Brazilian legislation to prohibit the burning of sugarcane leaves in the field [20]. This provided an opportunity to the sector to use this leaves (straw) as an additional feedstock to the ethanol process, producing electricity or second-generation ethanol. Yet this has also increased the amount of pesticides needed to control sugarcane bugs and diseases [21, 22] that are kept in the field for the next crop. It is important to mention that sugarcane is a semi-perennial crop, which means that the same plant may be harvested (without uprooting the plant) and re-grown for up to 5 years. In addition, mechanical harvest and crop have reduced the production cost; however, the amount of dirt brought with the cane to the refinery has increased, thus affecting the industrial process [23].

The productivity in Brazil is uneven concerning the region of the country, for example, in the 2016/2017 crop, the average productivity in the south, southeast, and central regions was 75.3 tonne/ha while in the north and northeast it was 48.6 tonne/ha [24]. In addition, some regions in Brazil, such as the southeast, can reach an avarange production yield higher than 100 tonne/ha [25]. Nowadays, in a good climate condition scenario, a national average productivity of at least 80 tonne/ha is expected [26]. The average sugarcane productivity and planted area have increased since 1980. There was a rapid acceleration in productivity growth in the 1980s, which is mainly due to the investments from the *Proálcool* program. **Figure 3** shows the productivity and planted area from 2005 to 2015 [24]. Nyko [26] studied the recent drop in the sugarcane productivity (2010/11 harvest) and concluded that mechanization of sugarcane planting and harvesting were the main cause, besides climate change and the lower

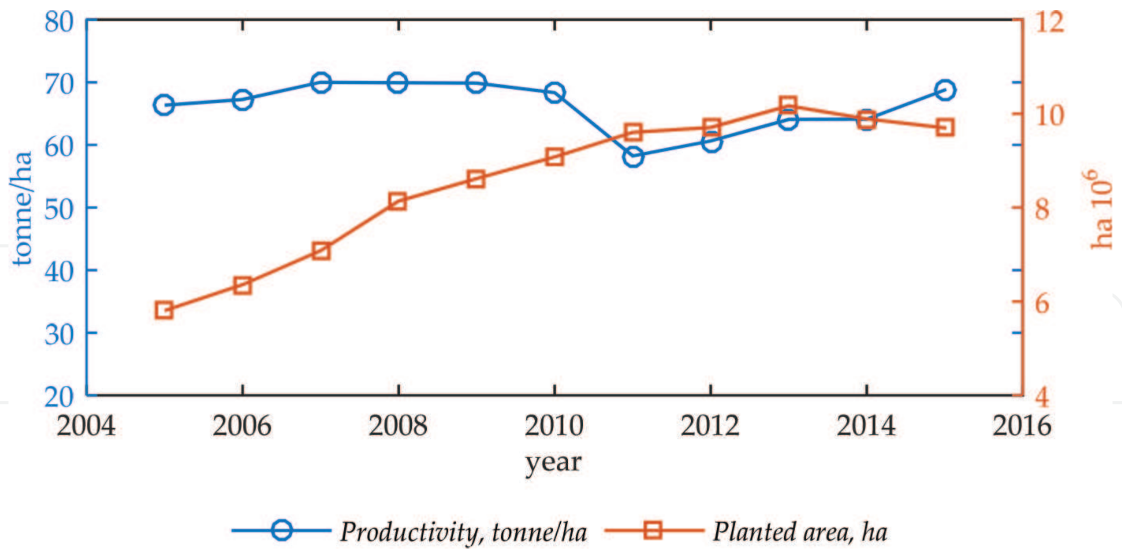

Figure 3. Productivity of sugarcane and planted area. Source: UNICA União da Indústria de Cana de Açúcar.

investment in the agricultural field due to the lower price of sugar and alcohol in this crop season. In fact, mechanization is a relatively new technology for some industries in Brazil, and they might have to adapt to the mechanical crop management and a learning curve is required. In addition, some researches in genetic-modified sugarcane have been carried out to increase the yield, and pest and disease resistance [27]. Consequently, the average productivity is expected to increase in the near future.

3.2. Sugarcane transportation

Transportation plays a crucial role in the cost of sugarcane production, owing to the multiple transport facilities and time-consuming activities involved in the delivery process. For instance, the total average cost of sugarcane production in São Paulo, in 2016/2017, was R$ 49.56 (U$ 14.57) per tonne of sugarcane [28]. In order to evaluate how much the delivery represents on the total cost, Françoso et al. [29] studied two cities in the same state and in the same crop season, and the cost of cutting, loading, and transportation of sugarcane from the farm to the mill gate 25-km away varied from R$ 26.77 (U$ 7.87) to R$ 37.25 (U$ 10.96) which represents 54–75% of the total production cost, respectively. The great variation in the transportation costs of sugarcane is due to the region topography, quality of roads, and technology employed in the transportation. So, the role of sugarcane transportation on the cost of bio-ethanol cannot be overlooked.

The most economical way of transporting sugarcane from field to the industry is the two semi-trailers attached to a tractor unit. The distance from the farm to the sugar mill is about 25 km. Different ways to transport sugar have been tested, from railroad, rivers, and road [30]. Until 2017, the largest truck licensed was nine axles with the total length of 30 m and a load of 74 tonne, which was the most economical way of bringing sugarcane from the field to the industry [31]. This kind of transport allows drivers to disconnect the tractor from the full trailer on arrival in the mill and then connect to an empty trailer and get back to the field without waiting to unload. As from 2017, the department responsible for monitoring the road traffic has authorized 11 axles, two semi-trailers attached to a tractor unit with the same length, and a total load of 91 tonne [32]. To the best of our knowledge, there are no studies on the viability of this transport mode; however, this might be the most efficient transport mode since this is a claim made by sugarcane producers.

3.3. Cane reception preparation and extraction

The farmers are rewarded according to the quality of the sugarcane supplied to the industry. When the sugarcane arrives at the mill by a truck, it is weighed, and then the load is drilled in order to collect a sample. The quality of the sugarcane undergoes standardized analysis of the sample. The responsible for the standard is *Consecana* and *ABNT NBR 16271*. The payment is made in accordance with a coefficient called “total recoverable sugar,” which is proportional to the sugarcane sucrose content. With the recent use of bagasse to produce electricity and the possibility to produce second-generation ethanol, the possibility of rewarding the producer for the amount of fiber in the sugarcane is under discussion by the agricultural and by the industrial sector [33]. Besides, new varieties, aiming to produce more fiber than sugar, have been developed by BioVertix®. Consequently, the sugarcane payment is expected to soon take into account the sugarcane fiber in addition to the amount of sugar.

An appropriate sampling method is fundamental to correctly evaluate the shipment. The collection of samples is usually done by drilling the shipment with mechanical oblique probe samplers. This kind of sampler was introduced in 2007 and has undoubted advantages over the method formerly used because it allows the sample to be taken from the top to the bottom of the truck load. Before the oblique probe, sugarcane was sampled using a horizontal probe or randomly samples were taken at three different points of the shipments.

Mechanization has increased the level of dirt brought with the sugarcane to the industrial process, so a cleaning process has become necessary. When sugarcane was harvested manually, it was possible to wash it before its being forward to an industrial-cutting shredder and milling process. However, because of mechanization, sugarcane arrived at the industry in small stalks since the harvester already cut the sugarcane. Sugarcane in small pieces cannot be washed due to the fact that a lot of sugar would be lost by the stalk-cutting edge. For this reason, a dry-cleaning technology has been adopted by many industries to avoid dirt from entering the industrial process. Increasing 1 kg of dirt per 100 kg of sugarcane is expected to a decrease in the sugar recovery at the industrial process by 0.1% [23]. The loss of sugar occurs with bagasse and filter cake during the sugar juice treatment step. However, the dry-cleaning system consumes about 0.5–1.0 kW per tonne of cane. Because electricity and sugar are products sold by the refinery, there is a feasible balance between profit and loss, that is, the cost of the electricity used to clean the sugarcane should be lower than the cost of the sugar lost due to the dirt. In fact, as shown by some suppliers [34], the dry cleaning system would be feasible when the sugarcane leaves (straw) are intentionally brought with the sugarcane to be burnt in the boiler. In this case, straw is easily collected with cane by lowering the speed of the harvester clean blower. Thus, the dry-cleaning process would separate straw from stalks before the extraction process and then would mix the straw and bagasse after milling. In fact, this is not a consolidated technology, since some industries prefer to harvest the straw on the field and bring it separately. Thus, the implementation of the sugarcane dry cleaner method will depend on the manner of straw handling.

The next process applied to the sugarcane is the extraction, which is done by the mill or diffuser. The aim is to separate fiber, a solid stream, from sugar in a liquid stream. In this process, sugarcane is first reduced into small pieces and the sugar-bearing cells are ruptured to facilitate the subsequent extraction process. This is basically a mechanical process whereby size reduction is generally achieved through the use of rotating knives and swing hammer shredder in the cane-conveying system. In the case of billeted cane, mechanically harvested, it can be fed directly into a shredder without any additional cutting. For cane juice extraction, there are many studies comparing milling and diffuser [30, 35, 36]. The main advantage of a diffuser over mill is the greater extraction of sugar; however, a diffuser uses more imbibition water and steam than a mill. As a result, there is a dilemma to the industrials: to increase sugar extraction, more thermal energy is spent. In Brazil, the preference has been for the use of mills, which consists of a set of four to six mill units. A new extraction technology called "Hydrodynamic Extraction" or "Rivière Juice Extractor" is under development and aims to achieve the same level of diffuser extraction using less imbibition water with a lower cost of installation and maintenance when compared to both technologies [37]; however, to the best of our knowledge, there is no commercial plant using this technology.

Sugarcane milling did not change much during the last two decades, except for the driving system. Two driving systems are the mostly used in Brazil: steam turbine and electric motor. Even when an electric motor is used, the electricity is produced using a steam turbo-generator, that is, in both cases, the primary energy to drive the extraction process is the bagasse, which is burned in a boiler to produce steam. The driving system with steam turbine is the most widely used, mainly in old industries. This system consists of a low-efficiency steam turbine working around 22 bar and 350°C admission, and 2.5 bar exhaust, so, in this system, steam energy is converted into a mechanical energy to the mill. The electric drive system consist of an electric motor attached to each roll of the mill unit. Even with the double transformation of energy, the overall efficiency of the electric drive is higher than the work done by a single-stage turbine. These become an issue for the sugar mill, since the surplus electricity becomes a profitable product for the mills. As from 2002 when the government has regulated the commercialization of electricity by the private sector using biomass [38], many sugar mills have invested in higher-pressure boilers (65–100 bar) and high-efficiency cogeneration systems.

3.4. Juice treatment

After being milled, the juice contains several impurities, which must be removed prior to fermentation or concentration. These impurities are removed using a set of unit operations, which basically consist of heating, adjusting the pH, settling the precipitate formed in the body juice, and filtering.

Only small changes on these processes were adopted during the last decades. In the heating, most industries prefer vertical shell-and-tube steam heaters. Despite the higher overall heat transfer coefficient in the horizontal one, the vertical one is easier to clean. The extracted sugarcane juice has a pH of about 5.3, and needs to be adjusted to 7 before clarification. For this, lime Ca(OH) is added, which is the most widespread process used. For refineries that produce sugar in addition to ethanol, processes such as sulfitation, phosphatation, and carbonation [36] are also used, aiming to lower the color and turbidity. After the pH adjustment, the juice is sent to a clarifier to settle the insoluble part of the juice. Before the use of chemical products (flocculants and polymer) and instruments to control the flow and dosing, the most popular installation used multi-tray clarifiers. The main disadvantage of multi-tray is the retention time of about 3 h. Single-tray clarifiers, known as "rapid clarifiers," became possible with the development of chemicals that promotes the mud coagulation and settling. The retention time in this case is about 1 h. The main advantages of the rapid clarifiers over the multi-tray ones are the lower installation costs, and the small retention time, which reduces the degradation of sugars [30]. There are not many research works carried out recently about juice treatment, and consequently, great changes in this process are not expected in a near future.

3.5. Juice concentration

Ethanol can be produced in an autonomous distillery, producing only ethanol, or in an attached distillery, which produces sugar and ethanol. In the second case, ethanol can be produced only from molasses, a residue from the sugar production process, or a mixture of molasses and juice, depending on the amount of juice diverted to produce ethanol. When sugar is produced, the juice destined to the sugar process must be concentrated to achieve a suitable brix to start the crystallization process at about 60% sucrose by weight. This concentration is obtained using multiple-effect evaporators (MEVs), which reduces the required steam to concentrate the juice, since each effect produces lower-pressure steam, which is used in the next effect to evaporate more water and so on. In this way, only the first-effect evaporator uses the exhaust steam from turbines. Saving the exhaust steam is crucial for industries that have condensation turbine installed or for refineries that want to save bagasse for other purposes, such as second-generation ethanol or just selling bagasse as a product.

When sugar and ethanol are produced in a refinery, there is a synergistic effect that reduces the total consumption of steam. Since large amount of water must be taken off from the juice in order to concentrate it in the crystallization process, this water is withdrawn as steam in an MEV. This steam from MEV is used in the ethanol process. In this manner, steam from MEV replaces the necessity of using exhaust steam. Combining ethanol and sugar production, results in an energy efficient refinery.

3.6. Fermentation

Alcoholic fermentation is a biological process, which converts sugars such as glucose, fructose, and sucrose into cellular energy, producing ethanol and carbon dioxide as a side effect. The overall chemical reaction for alcoholic fermentation is as follows:

$$\underset{sucrose}{C_{12}H_{22}O_{11}} + H_2O + enzyme \rightarrow \underset{fructose\ and\ glucose}{2\ C_6H_{12}O_6} \rightarrow 4\ \underset{ethanol}{C_2H_5OH} + 4\ CO_2 \quad (1)$$

Sucrose is a dimer of glucose and fructose molecules. In the first step of alcoholic fermentation, the enzyme invertase cleaves the glycolic linkage between the glucose and fructose molecules. When the fermentation finishes, the fermented liquor is centrifuged to remove east (*Saccharomyces cerevisiae*), which is recycled to fermentation. The product from the centrifugation (a stream with about 8º GL ethanol content) is sent to the distillation process.

There are two types of process for alcoholic fermentation commonly used to produce ethanol. The majority of the sugar mills use a fed-batch fermentation process. Continuous process is also used by some industries; however, despite the lower installation cost, continuous fermentation results in lower efficiency in the production of ethanol. The lower efficiency is a result of bacterial contamination since, in a continuous process, the fermenter cannot be as frequently cleaned as in a fed batch, in which cleaning can be carried out after each batch.

The main disadvantage of the fed-batch process is related to the large size of the fermenters. Many technologies are under development to reduce this size. There are many problems in the operation of such large equipment: high cost of installation, difficulty to control parameters, such as contamination, mixing, and temperature, which can cause temperature gradients and dead zones inside the fermenter. To reduce these problems, the total volume of broth under process must be reduced. Therefore, the proposed technologies aim to increase the concentration of reactants and products. Removing ethanol during the fermentation process is one possibility, since a high concentration of ethanol is toxic to yeast. There are some studies of pervaporation [39] and stripping [40] to take ethanol off the fermentation broth during the ethanol fermentation. The high cost of pervaporation membranes and the difficulty in recovering ethanol from CO_2 make this technology unfeasible nowadays. Reducing the temperature of the fermentation broth using a chiller is also an option under development, and there are some commercial-scale units [41]. At a lower temperature, yeast would resist a higher concentration of ethanol, but reducing the temperature would also reduce the reaction rate. By now, the best available technology continues to be the fed batch cooled by cooling towers.

3.7. Downstream processing

The recent development in downstream process did not aim to improve the ethanol recovery efficiency but to save the energy demand by the process. Downstream consists of the separation of ethanol from the other components in the fermented wine; the first step is the centrifugation of wine, which recovers yeast to the next fermentation fed batch. There are two main components at the centrifuged wine: water and ethanol. Fuel ethanol also called "hydrous ethanol" (ethanol 92.5–94.6 wt%) is obtained by distillation. Due to the azeotropic point in the mixture ethanol-water, anhydrous ethanol cannot be obtained using a common distillation process. Anhydrous ethanol (99.3 wt%) must be produced in order to be used in a mixture with gasoline. There are two common dehydration systems used in Brazil: azeotropic distillation with cyclohexane or monoethyleneglycol, and, more recently, absorption on molecular sieves. The main advantage of using molecular sieves is that steam consumption is about one-third of those in the azeotropic distillation. Pervaporation is a process that could significantly reduce the energy demand; however, the high cost of membranes makes it unfeasible to be used in a commercial scale.

3.8. Vinasse and biogas

Vinasse is the final by-product of the ethanol distillation and is the main effluent of the ethanol process. About 12 liters of vinasse are produced per liter of hydrous ethanol. Most industries use the vinasse without any treatment as a fertilizer and, it is simultaneous used for irrigation due to its high amount of water (fertirrigation). The vinasse produced in a distillery is a stream composed basically of water, organic matter, and inorganic salts. Therefore, there are many possibilities to utilize this vinasse: as biogas obtained by conversion of the organic matter into gas, and as fertilizer through using the inorganic salts (phosphorus, potassium, and nitrogen) to partially replace synthetic fertilizers derived from the petroleum industry.

Biogas has a great potential opportunity for using the vinasse. Many studies have been carried out about the bio-digestion of vinasse [42–44]. Biogas is an easy to handle fuel since it can be transported in high-pressure cylinders, or by pipeline, and can fuel farm machinery and trucks to partially replace diesel [45]. Biogas can also be obtained from sugarcane trash (bagasse and straw) [46] in a bio-digester blended with vinasse. This is also an opportunity to the use of bagasse, that is, bagasse, as well as straw, can be converted into biogas instead of producing electricity or 2G ethanol. There are also many sugar mills close to the gas pipeline network in Brazil, which would raise the feasibility of implementing a biogas facility. Besides the high cost of installation, a great challenge to implementing biogas facilities is to deal with an unstable vinasse supply. Vinasse is not produced continuously, since industry interrupts its operation relatively frequently due to the rain, which stops the harvest, or due to the maintenance or the braking of equipment.

Another possibility is to concentrate vinasse and to recover water to be used in the process. In this case, the concentrated vinasse can be transported to longer distances to be used as liquid fertilizer. Concentrated vinasse can also be burned into the boiler; in this case, the higher the concentration, the higher its net calorific value. The main disadvantage in this process is the steam demand to concentrate vinasse.

After biodigestion, water can be withdrawn from vinasse using commercial technologies such as evaporator or ultra-filtration membrane. Reducing the use of water has a positive environmental impact, but the cost of these processes may be higher than the intake of water from natural sources (mainly rivers). So, only few refineries in Brazil are withdrawn water from vinasse to be used in the process.

3.9. Combined heat and power

What makes ethanol from sugarcane superior to that from other feedstocks (e.g., corn) is the bagasse that comes with the sugarcane. First-generation ethanol processes from sugarcane have a positive energetic balance, which means that it is not only self-sufficient on energy, but it can export the surplus energy usually as electricity. Using the combined heat and power (CHP) process is the most efficient way to produce electricity. In the CHP, high-pressure steam (between 65 and 100 bar) is expanded in turbines coupled with electric generators, and the exhaust steam from the turbines is used as thermal energy for the process. A high-efficient process, that is, a process which consumes small amount of thermal energy, results in surplus bagasse that can be used as feedstock to another process, such as second-generation ethanol, or to produce surplus steam—the steam produced by the boiler and not condensed in the process. The surplus steam can be expanded in condensation steam turbines to allow maximizing the electricity production.

The condensation turbine used to produce electricity with the steam competes with the cellulosic ethanol. The condensation turbine cannot be classified as CHP, since only power is

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produced and the exhaust steam is condensed by cooling water, that is, heat is not used in the process. Despite the fact that it maximizes the production of electricity, an energetic analysis shows that the larger enthalpy jump occurs in the condenser and not in the turbo-generator expansion. Thus, the energy to condense the steam is released to the surrounding cooling tower.

Sugarcane bagasse has become a valuable product for sugarcane refineries, and it is really an important source of energy for the Brazilian economy. Before the possibility of exporting electricity to the grid [38], most sugarcane mills had low pressure and inefficient boiler and turbo-generator (about 22 bar 350°C). This allows the refinery to be self-sufficient in electricity, however, without the possibility to export to the grid. Some sugarcane mills are still running using this old technology. High-pressure and high-efficiency boiler and turbines allow the refinery to export electricity. For instance, in a scenario in which a refinery has a higher-efficiency boiler, counter-pressure and condensation turbine, and electrified mill, it is possible to export about 79.7 kW·h per tonne of sugarcane. The parameter and efficiency of this scenario are shown in **Table 1**. To verify the potential of the bagasse in Brazil, in 2016, the country produced 666.8 million tonne of sugarcane [47] and in the same year produced 35,236 GW·h of electricity from sugarcane bagasse [48]. If every sugar mill was prepared to export electricity as described in this scenario, this number could have been 53,135 GW·h. Further, considering the possibility of bringing 50% of the sugarcane straw (leaves and tips) which yields about 140 kg per tonne of sugarcane (15% humidity) [49], it would be possible to export 135,470 GW·h per year. For an idea of the order of magnitude, Itaipu, the biggest hydroelectric power plant in Brazil, in the same year, produced 103,098 GW·h.

3.10. Second-generation ethanol

The conventional ethanol production utilizes a fermentation process to convert sugars, such as starch, sucrose, glucose, and fructose, into ethanol. Second-generation biofuels, also commonly known as advanced biofuels, utilize agricultural residues or other feedstock that cannot be straightly used as food for humans. Cellulose is an important structural material for plants (along with lignin), and it is made up of many repeating sugar units. These repeating sugar units can be broken down by various processes into the component sugars, which can finely be fermented into ethanol.

Many investments on the development of ethanol from cellulosic material have been made, and some industrial-scale plants have been built; however, it has been taken longer than expected for cellulosic ethanol to succeed. In the United States, for instance, there are at least four commercial plants (DuPont Cellulosic Ethanol, Poet Project Liberty, Abengoa Bioenergy Biomass, Alliance Bio-Products INEOS) with an installed capacity of 121, 88, 110, and 35 million liters per year, respectively. In Brazil, there are two commercial plants, Granbio and Raizen, with an installed capacity of 82 and 40 million liters per year, respectively. In addition, in Italy, the first cellulosic plant, Crescentino, a Mossi & Ghisolfi group company, has an installed capacity of 31 million liters per year. Most of them started their operation in 2014, but not all has been well: in 2017, DuPont decided to close its plant and announced that it will sell the company's ethanol facility in Nevada, Iowa. Abengoa announced bankruptcy and financial restructuring in 2016 and, in the same year, the cellulosic biofuel plant was bought by Sinatra-Bio. In the end of 2017, Crescentino also applied for *concordato preventivo*

Bagasse produced per kg of sugarcane	0.276 kg
Bagasse losses due to degradation and boiler startup	5%
Net calorific value of bagasse	7300 kJ/kg
Boiler temperature	520°C
Boiler pressure	68 bar
Boiler efficiency	85%
Counter-pressure turbo-generator efficiency	83.5%
Condensation-pressure turbo-generator efficiency	78.3%
Steam consumption in the first-generation process per kg of sugarcane	0.4 kg
Electricity consumption per tonne of sugarcane	32 kW
Sugarcane straw brought with sugarcane per kg of sugarcane	0.140 kg
Net calorific value of sugarcane straw	12,900 kJ/kg

Table 1. Parameters used to obtain the electricity production from sugarcane bagasse.

in accordance to local bankruptcy Law. Granbio, in 2016, stopped producing ethanol and it is only burning bagasse to produce electricity. In January 2018, Frankens Energy LLC bought INEOS cellulosic plant in Florida, which had been closed at the end of 2016 [50]. Conversely, Poet announced in 2017, on its website press release, the achievement of the major breakthrough in cellulosic biofuels production and its intention to build an onsite enzyme manufacturing facility to directly pipe DSM enzymes into the process. Also, Ek Laboratories, Inc., a subsidiary of Alliance BioEnergy and owner of the CTS® patent whose process makes the pretreatment without using enzymes, started the operation of a demonstration plant processing 2.5 tonne/day, in 2015 [51]. In fact, by 2018, the cellulosic ethanol process has not been shown to be completely commercially feasible yet, but it has still a great potential to convert low-value feedstocks for increasing the production of biofuel.

3.11. Second-generation ethanol versus CHP

Surplus bagasse can be used to produce more electricity or second-generation ethanol. Both fuels can be used in light vehicles. For instance, take two commercial cars where car "A" being sold in the USA and uses electricity and car "B" being sold in Brazil and using a flex fuel engine (it can use ethanol or gasoline). Knowing that surplus bagasse can be converted into electricity or second-generation ethanol, it is possible to draw two hypothetical scenarios where scenario 1 consists in a refinery processing 1 tonne of sugarcane to produce ethanol in the first-generation process and electricity using a condensation turbine as described in **Table 1**, and scenario 2, in which the same 1 tonne of sugarcane is used to produce second-generation ethanol from surplus bagasse besides first-generation ethanol. The parameters and efficiency adopted for second-generation ethanol is described in **Table 2**. **Table 3** compares both scenarios side by side to obtain the distance driven in each scenario.

Looking through these results, it would be possible to infer that, considering these parameters and efficiency, it is better to produce electricity instead of ethanol since the distance driven in scenario 1 is higher than in scenario 2. However, this is not a conclusive result since to reach a reliable best scenario, studies such as live cycle analysis, return on investment, energy storage method, concentrated versus dispersed emissions, autonomy, and the preferable fuel by customers are needed.

Parameter and efficiency adopted	Second-generation ethanol plant
Steam consumed per tonne of bagasse at second-generation process.	451 kg [52]
Electricity consumed per tonne of bagasse at second-generation process.	155 kW·h [52]
Lignin per kg of bagasse (dry basis).	0.264 kg [53]
Glucan group per kg of bagasse (dry basis).	0.405 kg [53]
Xylan group per kg of bagasse (dry basis).	0.197 kg [53]
Net calorific value of lignin (35% moisture).	12671.8 kJ/kg [54]
Pretreatment efficiency.	90%
Sucrose and glucose fermentation efficiency.	90%
Xylose fermentation efficiency.	80%
Distillation efficiency.	97%

Table 2. Parameters used to obtain the consumption rating of two vehicles.

Parameter	Scenario	
	First scenario	Second scenario
Surplus electricity	79.7 kW·h	38 kW·h
Ethanol	90 L	104.3 L
City consumption ratings car "A"	6.20 km/kW·h	
Highway consumption ratings car "A"	4.90 km/kW·h	
City consumption ratings car "B"	8.34 km/L	
Highway consumption ratings car "B"	9.9 km/L	
Distance driven in a city using car "A"	494 km	237 km
Distance driven in a highway using car "A"	390 km	186 km
Distance driven in a city using car "B"	750 km	870 km
Distance driven in a highway using car "B"	891 km	1072 km
Total distance driven in a city	1245 km	1107 km
Total distance driven in a highway	1281 km	1258 km

Table 3. Parameters used to obtain the consumption rating of two vehicles.

4. Conclusion

A new era with a clean worldwide energy matrix is expected nowadays. Ethanol has been shown to be a fuel with great potential to meet this world's aspiration. In this new phase, the fuel needs to be recognized by its environmental benefits and not only by the energy that it contains. Consequently, it has to be rewarded according to the benefits it brings to the society. For this in recent years, the sugarcane industry has positioned itself not only as a food industry but also as an energy industry. Having a look into the sugarcane feedstock, bringing a different viewpoint, one could say that it produces three different kinds of energy: sugar—energy for human beings; ethanol—energy for transportation; and electricity—energy for a variety of uses. As an energy company, the process itself cannot be energetically wasteful. So, recent improvements in the process have aimed to maximize its efficiency; meaning that using less energy in the process itself results in more energy left to be sold as a product. However, many questions, such as the destination of the use of straw, bagasse, and vinasse, are still unanswered and will depend on the next technology improvement. This new era will result in increasing the demand for ethanol, which must be met not only by the increase in the production but also in the productivity and efficiency. Nevertheless, many technologies, with notorious performances, are not applied to the production of ethanol nowadays because of their low feasibility. They would become feasible, however, if ethanol was rewarded for its environmental benefits.

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