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Research paper

Energetic shift of sugarcane bagasse using biogas produced from sugarcane vinasse in Brazilian ethanol plants

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ABSTRACT

Worldwide environmental policies demand each time more biofuel consumption and less emission. In this context, this work presents a 2G ethanol study as a mean to increase bioethanol production and availability. Currently, technologies use sugarcane bagasse for lignocellulosic ethanol production, which may unbalance the ethanol and sugar mill energy matrix, since bagasse and straw are the main fuel for power and steam generation. A possible solution is using biogas produced from vinasse biodigestion as a fuel instead of using biomass, enabling to shift a fraction of the sugarcane bagasse to 2G ethanol production and, at the same time, keeping power and steam production constant. This paper assesses that energy shift by analyzing ten different scenarios for power generation, comparing the amount of bagasse shifted, the increase in straw consumption, the increase in ethanol production and the reduction of environmental emissions in each scenario. The results show that, at least from the technical and environmental perspective, a combined cycle operating at a high pressure is the best alternative. It is possible to shift from 56.5% to 100% of the available bagasse using the combined cycle technology, which is also followed by an increase in straw consumption. In addition to that, the ethanol availability increase ranges from 28.5 to 50.4%. Moreover, the organic load disposal to the ground also decreases more than 90% compared to the conventional process due to the introduction of vinasse biodigestion.

1. Introduction

Ethanol produced from sugarcane powers a considerable share of the light vehicle fleet in Brazil, a country that holds the second position as producer of that fuel in the world [1]. About 82% of the Brazilian vehicles produced in 2015 (more than 2.4 million automobile units) were of the *flex type*, meaning they can use either ethanol or gasoline alone or any blend of these two fuels [2]. Furthermore, about 30% of the fuel for light motor vehicles consumed in Brazil in 2015 was hydrous ethanol [3]. The success of ethanol as a fuel in Brazil is due to the *PróÁlcool* policy, in force from 1975 to 1990 [4], that boosted the production of ethanol and made it possible for sugarcane ethanol to be a highly competitive fuel against gasoline [5]. Finally, sugarcane ethanol is a fuel with low overall net carbon emissions. It is not completely zero, because fossil fuel is still used to power agricultural machinery [6].

The Brazilian ethanol and sugar industry also stands out in the electric sector. Currently, ethanol and sugar plants are energy-independent thanks to their efficient operation in the cogeneration mode; sugarcane bagasse and straw are fuels for producing the steam used in the ethanol and sugar production process as well as to power turbines. Any electrical energy (EE) surplus is sold to the power grid, which is allowed by the Brazilian government to tackle the seasonality of hydropower and to supplement the EE demand in drought times [7]. Therefore, ethanol and sugar plants seek efficient technologies for burning the bagasse and straw (boilers at high operating pressure and temperature) [8]. In 2006, the sugar and ethanol sector generated 11.3 TWh EE, which represented 3% of the national production that year [6]; in 2015, the use of bagasse and straw generated 144.98 TWh EE, now representing 45.4% of the national production [9]. Despite the mentioned highlights in the

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energy sector and CO_2 emissions, sugarcane ethanol plants present two main environmental issues regarding waste generation [10]: the disposal of vinasse on the soil (fertigation [11]), due to its nutrient contents, the disposal of particulate matter from bagasse and green cane burning to the environment.

Recent environmental policies, such as the Paris Agreement [12], demand less pollution and even more biofuel availability. Recent local policies limit the amount of vinasse disposed on the soil [13] and forbid green cane burning before harvesting [14]. This pressure for more biofuels and less environmental impacts leads to the search of more noble energy uses for bagasse and vinasse. A way to achieve that is to shift from using biomass energy to producing biofuels from biomass or wastes [15]. For instance, bagasse gasification generates a gaseous fuel; bagasse digestion generates lignocellulosic ethanol (or 2G ethanol) [8,16]. As for vinasse, biodigestion is a possibility. The biological process yields a fuel gas (biogas), and an effluent with the same nutrient content of vinasse nutrients, but with reduced organic content, which is suitable for fertilization with reduced environmental impacts of application on the soil [17–19].

Biogas has many final uses in an ethanol and sugar plant, such as powering machines and direct heat generation by burning [11] or, after an upgrading process, the resulting gas (biomethane) can either be injected on gas pipelines [20] or be compressed and used as a fuel for automotive vehicles or even for the agricultural machinery used in sugar cane plantations. Regardless of the final use of biogas, its use strongly depends on the existence of a gas pipeline network or highways in the vicinity area.

Seeking to meet the goals imposed by environmental policies, there is a growing interest throughout the world regarding 2G ethanol. However, even though lignocellulosic ethanol would generate an increase in ethanol production, the use of bagasse for this sole purpose would generate an imbalance in the energy matrix of ethanol and sugar mills. This is so because ethanol plants use all the available bagasse to supply energy to the process and commercialize surplus EE, which generates revenue to the plant [21]. In the current situation, the mill must choose between producing either more EE or 2G ethanol [6].

One possibility to avoid this issue is the use of an alternative fuel to replace bagasse as an energy source in the process, thereby increasing its availability for producing 2G ethanol. The choice of a gaseous fuel stands out for this purpose, since the switch of oil, coal or biomass-fired boilers for gas-fired boilers usually has sensitive economic gains coupled with a significant reduction in emission values of local pollutants [22].

Natural gas may seem as a potential fuel for the energy shift of bagasse. However, there are two hindrances regarding the use of that fuel. One is that the use of a fossil fuel for power generation would produce a higher CO_2 emission balance than the current one [21]. The other one is the fact that most of the ethanol and sugar mills are not located in areas next to natural gas pipelines infrastructure [20]. For overcoming these hurdles, an alternative way is using biogas to shift the bagasse to 2G ethanol production.

A literature review presents few papers addressing the issue of 2G ethanol and the ethanol and sugar energy matrix as proposed in this paper. Some previous works involving 2G ethanol suggest the use of a bagasse pre-treatment and hydrolysis process residues as feedstock for biogas. Dias et al.'s [23] objective was to produce 2G ethanol and to use unreacted solids and biogas (from 2G residues digestion) to produce the same amount of power required by the process. Mariano et al. [24] provided a technical and economic study regarding the use of pentose sugars obtained from 2G ethanol production to produce biogas and to complement the plant energy income. Even though it is not the objective of their work, the authors mention the use of biogas for displacing bagasse towards a 2G ethanol production in their conclusion. Galbe and Zachi [25] mention the production of biogas as an opportunity to utilize the liquid phase of bagasse pre-treatment residues.

Due to the lack of studies involving bagasse shift as described here, this paper aims at carrying out a technical and scientific analysis of biogas and 2G ethanol viability. We thus present operational results from the use of vinasse-produced biogas as an alternative fuel to bagasse in ethanol and sugar plants, which can then make that biomass available for 2G ethanol production. The goal is to compare the energy productivity that Brazilian sugarcane mills currently achieve with the energy productivity possible to achieve using biogas for power generation at various operational modes and technologies. It is also our objective to compare air and soil emissions related to the current and to the proposed scenarios.

2. State-of-the-art

2.1. Ethanol and sugar mills

The commercial scale production of sugar and ethanol from sugarcane is well established in Brazil (Fig. 1), where most plants can produce both ethanol and sugar [26], at a ratio that ranges from 50% to 60% of ethanol, in terms of total reducible sugars [27]. In terms of process yield, the literature reports a production of 0.075–0.090 m^3 ethanol per metric ton of processed cane [28,29].

As shown in Fig. 1, ethanol distillation yields vinasse as a byproduct. Vinasse is the most abundant waste generated in that process. The literature reports this wastewater to be a dark-brown colored liquid with a foul and pungent stench, presenting high organic load (10–65 g_{BOD}/l), low pH (3.5–5.0) and high mineral content [30]. Typically, 10.0–15.0 m^3 vinasse are produced for each cubic meter of ethanol produced. The 13.0 m^3/m^3 yield is a common average value [30–32].

Due to its high mineral content (most remarkably, potassium), producers use vinasse as a source of nutrients for the cane plantation (fertigation) [33,34]. According to the literature, this is currently the most technically easy and cost effective way to dispose this effluent [33], but there are many issues regarding using vinasse as a fertilizer due to its pollutant potential. Environmental impacts include emission of greenhouse gases (GHG) from *in situ* anaerobic and aerobic decomposition, contamination of the soil and underground water due to organic matter, soil leaching due to the accumulation of inorganic components, among others [35]. The literature indicates that there is no proof that underground water contamination occurs if the concentration of the application is less than 30.000 m^3/km^2 [32,36]. As for GHG, according to Oliveira et al. [37], the application of vinasse to the soil accounts for the emission of 4.94–7.46 kg_{CO2eq}/m^3 in the form of CO_2 and N_2O.

Fig. 1 also shows the use of bagasse and straw for power and steam generation in a CHP (combined heat and power) system. According to the literature, bagasse production ranges from 260 to 280 kg per metric ton of processed sugarcane, with a moisture content of 50% [28,29,38] and straw production ranges from 66 to 165 kg per metric ton of processed sugarcane, with a moisture content of 15% [39]. Table 1 shows the heat of combustion for bagasse and straw. Despite having relatively low energy content, the biomass high availability justifies its use in the CHP system.

Table 2 shows the main CHP configurations found in the literature for ethanol and sugar mills. Currently, most steam boilers have high efficiency since it is desirable to produce not only EE for the process itself, but also to sell the surplus to the power grid. It is rare to find low efficiency CHP cycles in moderns mills, although a few work with the best available technology.

Finally, the literature indicates 28 kWh/t_{cane} EE consumption in all the drives of the process [7,39]. As for the emission of particulate