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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

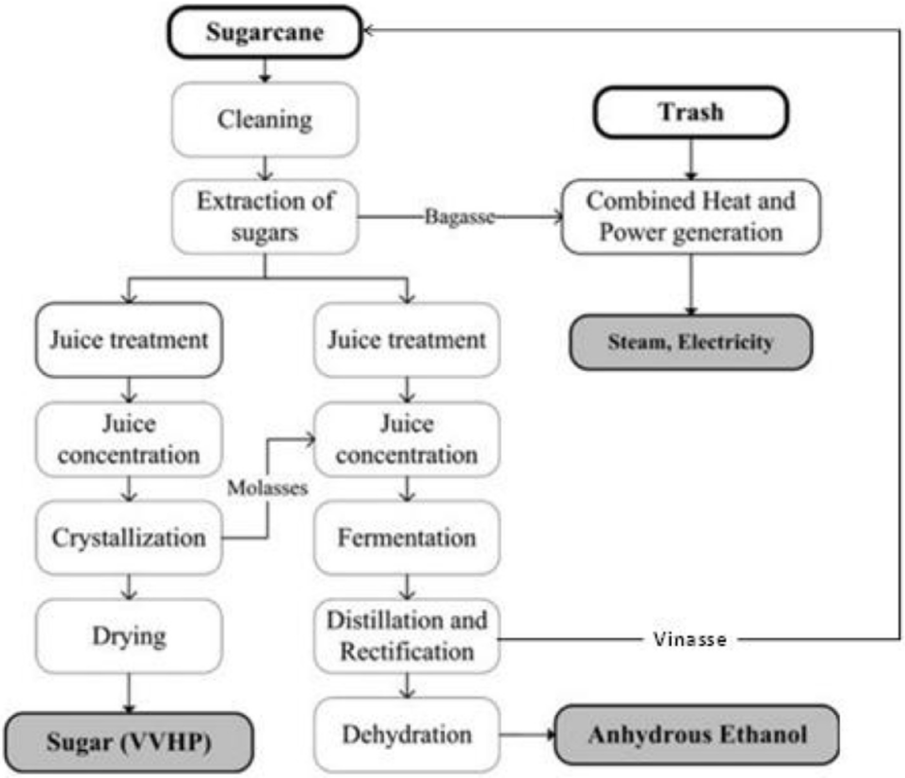

Fig. 1. Simplified flowsheet for an ethanol and sugar mill. Adapted from Cavalett et al. [26].

Table 1
Heating power of bagasse and straw [9,38–40].

Parameter	Bagasse	Straw
Moisture content (% wt, wet)	50.0	15.0
LHV (wet) kJ/kg	9,030–9,350	15,030

Table 3
Limits established for emission of particulate material by CONAMA [42,43].

Nominal thermal power (MW)[a]	PM emission limits (mg/Nm^3)[b]	
	Norm 382	Norm 436
Up to 10	280	520
10 to 75	230	450
Greater than 75	200	390

[a] Defined as $\dot{m}_{bag}.LHV$, where $\dot{m}_{bag}$ is the mass flowrate at which bagasse is fed to the boiler and LHV is the bagasse lower heating power.
[b] Measured in dry base with 8% O_2 excess.

matter due to bagasse burning, Brazilian environment regulations (CONAMA resolutions) limit its release to the atmosphere. Table 3 shows these limits.

2.2. *Production and use of biogas from vinasse biodigestion*

Biogas is mainly composed of CH_4 and CO_2, (the accurate composition depends greatly on the feedstock [44,45]). Vinasse is a suitable feedstock for biogas production, but there is scarcely any vinasse biodigestion practice in Brazil [19], which contrasts with a significant number of studies addressing the technology of vinasse digestion and biogas production. Nevertheless, there are two potential applications for the use of vinasse digestion rather than its simple disposal on the soil. One of them is the environmental one: the literature indicates that the biological process greatly reduces the organic content of vinasse (60–98% reduction in chemical oxygen demand – COD – and 80–92% reduction in biochemical oxygen demand – BOD – depending on the bioreactor technology chosen). Furthermore, the process also promotes a pH rise to neutral levels and there are no reports of significant reduction in the mineral content [46–48]. Therefore, producers can still use the bioreactor effluent in fertilization with the advantage of much lower environmental impacts.

Table 2
Evolution of technology for power generation in ethanol and sugar mills [7,38–41].

Scenario	Boiler thermal efficiency	Live steam conditions	Type of steam turbine	Steam consumed by the process	Generated EE
Past (no sell of surplus EE)	66–78%	2.3 MPa, 300 °C	CP SSP: 0.35 MPa	500 kg/t_{cane}	32.0–38.6 kWh/t_{cana}
Current (sell of surplus EE allowed)	85%	6.8 MPa, 480 °C	EC SSP- 0.35 MPa g, CS–0.114–0.112 MPa	360–500 kg/t_{cane}	74.0–111.0 kWh/t_{cana}
Current (sell of surplus EE allowed, best available technology)	85%	8-10 MPa, 520-530 °C	EC SSP- 0.35 MPa g, CS–0.114–0.112 MPa	280–360 kg/t_{cane}	115.6–121.2 kWh/t_{cana}

Obs: CP = counterpressure; EC = extraction-condensing; SSP = Sat. steam for process; CS = vac. pressure steam, for condensation.

The other potential is the energetic one, which is due to biogas production. Technical studies show that the biological process yields 12.0–14.0 $m^3_{CH4}/m^3_{vinasse}$ (or 20.7–22.5 $m^3_{biogas}/m^3_{vinasse}$) [19,46,49]. The methane concentration ranges from 50% to 75% [31,49]. Although these figures greatly depend on the bioreactor technology chosen, an average value of 65% methane content is a recurring figure for biogas produced from "agricultural waste" [19,44].

For the final use of biogas, an upgrading step may be necessary. Works on biogas cleaning can be easily found in the literature [50–54] and will not be covered in depth in this paper. For burning purposes, only the removal of moisture and H_2S is necessary if the chosen power generation route involves gas turbines. This is so because these substances can corrode the turbine blades if not removed [55,56]. Should the sulfur content in the biogas be low enough, dry biogas may be burned in gas-fired steam boilers without any previous cleaning, as long as the exhaust temperature is higher than the dew point temperature of sulfuric acid and the boiler operates continuously [56,57].

2.3. 2G ethanol production

The lignocellulosic ethanol production process consists of breaking down the natural sugar polymers found in biomass (such as cellulose and hemicellulose) into fermentable sugars, which microorganisms will ferment, producing 2G ethanol [58–60]. However, the whole process, which includes pre-treatment, sugar polymer hydrolysis and fermentation of a wide range of sugars, still faces scale-up problems and is not economically feasible yet [61,62]. Currently, the literature points out that the typical yield for the whole process ranges from 0.11 to 0.27 m^3 per metric ton of dry agricultural residues [63]. Specifically for sugarcane bagasse, Dantas et al. report a 0.162 $m^3/t_{bagasse}$ yield for a laboratory scale plant [8].

The distillation of 2G ethanol produces vinasse, as does the 1G ethanol process. However, the literature is very scarce on 2G ethanol vinasse. This is because 2G ethanol production process is still at laboratory scale. Nevertheless, a few recent studies [64,65] show some useful results: these studies report that 2G ethanol vinasse contains a 38.6 kg/m^3 BOD, mainly distributed between non-hydrolyzed cellulose, non-fermented sugars (mainly pentose) and lignin. The vinasse yield is 7.8 $m^3_{vinasse}/m^3_{2Gethanol}$ and the biogas yield after biodigestion ranges from 10.25 to 10.95 $m^3_{CH4}/m^3_{vinasse}$.

Bagasse digestion is more difficult when compared to straw digestion due to its more complex chemical and physical structure [66,67]. However, it is preferred as the feedstock for 2G ethanol production because it is readily available in the mill, while most of the straw is left on the ground after the harvest for several reasons (a fraction is transported to the mill for burning alongside with the bagasse. In the case of the State of São Paulo, the mills burn greater fractions of straw along with bagasse) [68]. Furthermore, as straw has a lower apparent density, its transport cost is higher than that of bagasse [69], making it more interesting to just leave the straw on the plantation.

3. Materials and methods

Based on the current development and the relevance of solving the vinasse disposal problem, a new ethanol and sugar mill configuration is proposed. This new configuration contemplates both the digestion of 1G and 2G vinasse for producing biogas, its utilization for displacement of bagasse and the use of shifted biomass for 2G ethanol production. We take the current situation (bagasse burning in CHP systems) as a reference scenario or base case. It will be the reference for bagasse and straw consumption, heat and power generation and ethanol production. Other scenarios, representing future possible arrangements, have additional power generation using biogas in order to displace a fraction of the available bagasse. The non-displaced bagasse burning will be the same as in the reference scenario (in biomass-fired steam boilers).

3.1. Process modeling

The new proposed ethanol and sugar mill has all waste biomass used for energy production (Fig. 2). In all the scenarios proposed (henceforth called Generation Scenarios - GS), the objective is to generate a fixed amount of EE and maintain a fixed availability of steam for the ethanol and sugar production process, so that the energy balance of the plant does not differ from the parameters obtained in the reference scenario (RS).

Table 4 shows the description of the RS and GS, discriminating the power generation technology and operational conditions of each. A GS terminated in "A" has all the steam produced at high pressure and expanded in the steam turbine generating electrical power. A GS terminated in "B" has the steam produced from biogas burning generated at low pressure, serving only to supply the steam needed for the process, thus not being used to generate electrical power. The GS that only focuses on the generation through Brayton cycle does not produce steam from biogas firing, thus not having a "B" counterpart.

Since bagasse consumption will be reduced due to the displacement, low-pressure steam may lack for scenarios GS-1B, GS-2, GS-3A, GS-4B, GS-5 and GS-6A because of its design. Should this happen, additional bagasse straw is assumed to be consumed (higher straw consumption in biomass-fired boilers is suggested by Alves et al. [39] and Joppert et al. [71]) in order to keep the power generation constant. A turbine bypass containing a throttle valve is also assumed to feed low-pressure steam to the process if it lacks from the turbine lowpressure extraction.

Finally, scenarios GS-4A/B, GS-5 and GS-6A/B explore whether it is feasible to shift all of the bagasse for 2G ethanol production increasing the use of bagasse straw as an alternative fuel along with biogas, as mentioned by Joppert et al. [71].

Fig. 3 and Fig. 4 show the reference power cycle and the proposed power cycles, respectively. The calculations were performed using PowerFNESS®, a Brazilian commercial engineering software that allows complete simulations of thermodynamic cycles for power generation. PowerFNESS® performs the mass, energy and entropy balances of any thermodynamic cycle given the boundary conditions. It has a built-in algorithm for the calculations, so that the user must only build the cycle on a user-friendly interface. PowerFNESS® also has an extensive database on properties of the substances used in the cycles (water, air, etc.) and of many fuels for the cycles. We chose this software due to its simplicity, easy to build interface and fast result yield.

3.2. Main assumptions

For the RS calculations, the steam boiler operation was that presented by Alves et al. [39], with an extraction-condensation turbine and steam provided from the turbine extraction. As suggested by Alves et al., only 90% of the available bagasse is burned (10% is stored for start-up and emergencies). Yet according to Alves et al., the straw consumption is only 10% of the available straw. Other premises assumed based on the literature review are shown in Table 5. Table 6 shows the additional premises assumed for the GS. Aside from the bagasse and straw consumption, live steam conditions and make-up water conditions, all the premises from Table 5 still stand and are thus not present in Table 6.

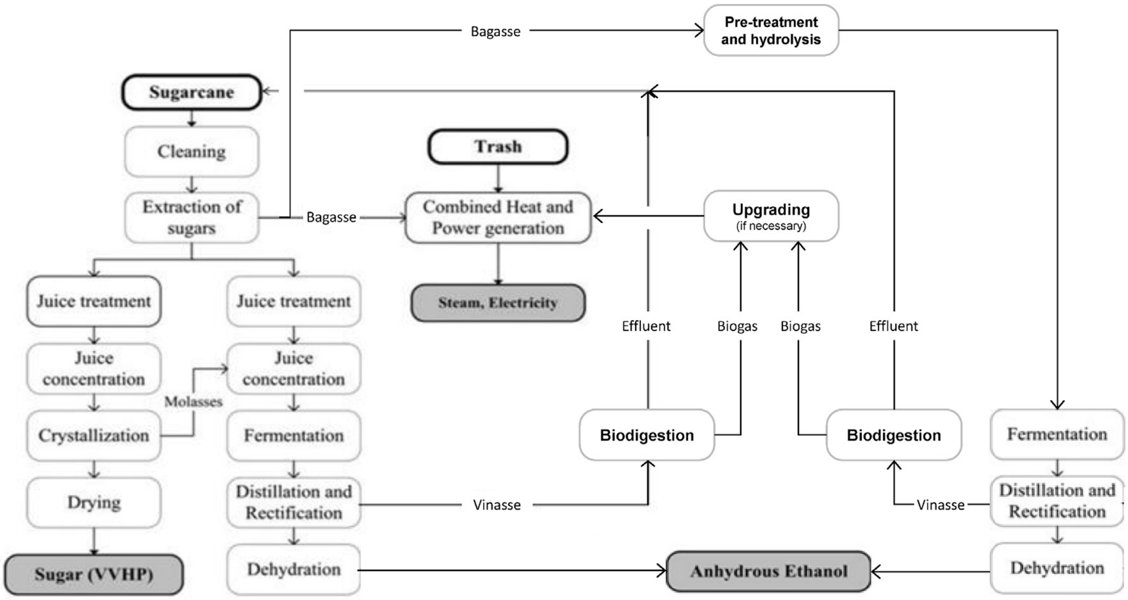

Fig. 2. Simplified flowsheet for the ethanol and sugar mill with vinasse biodigestion and 2G ethanol production.

Table 4
Scenarios summary.

Scenario	Technology for power generation		Steam produced from biogas-fired cycle pressure	Remarks
	Bagasse-fired	Biogas-fired		
RS	Rankine Cycle	N/A	N/A	Current plants scenario
GS-1A	Rankine Cycle	Rankine Cycle	HIgh	Use of 1G and 2G vinasse-produced biogas;
GS-1B	Rankine Cycle	Rankine Cycle	High	energy complementation by bagasse straw, if needed
GS-2	Rankine Cycle	Brayton Cycle	N/A	
GS-3A	Rankine Cycle	Combined Cycle	High	
GS-3B	Rankine Cycle	Combined Cycle	Low	
RS-4A	Rankine Cycle	Rankine Cycle	High	Use of 1G and 2G vinasse-produced biogas;
RS-4B	Rankine Cycle	Rankine Cycle	Low	Displacement of all bagasse. Energy complementation by bagasse straw
GS-5	Rankine Cycle	Brayton Cycle	N/A	
GS-6A	Rankine Cycle	Combined Cycle	High	
GS-6B	Rankine Cycle	Combined Cycle	Low	

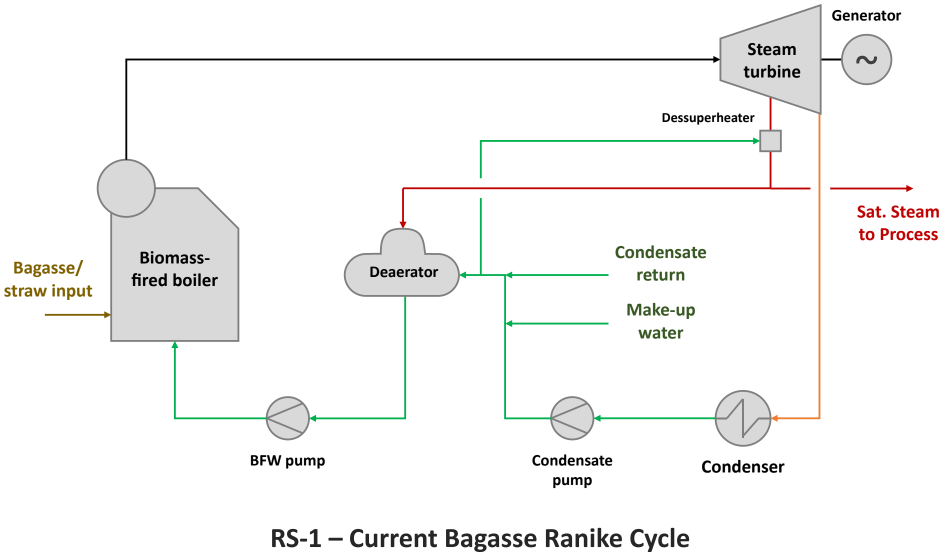

Fig. 3. Current ethanol and sugar mills power island (scenario RS-1).

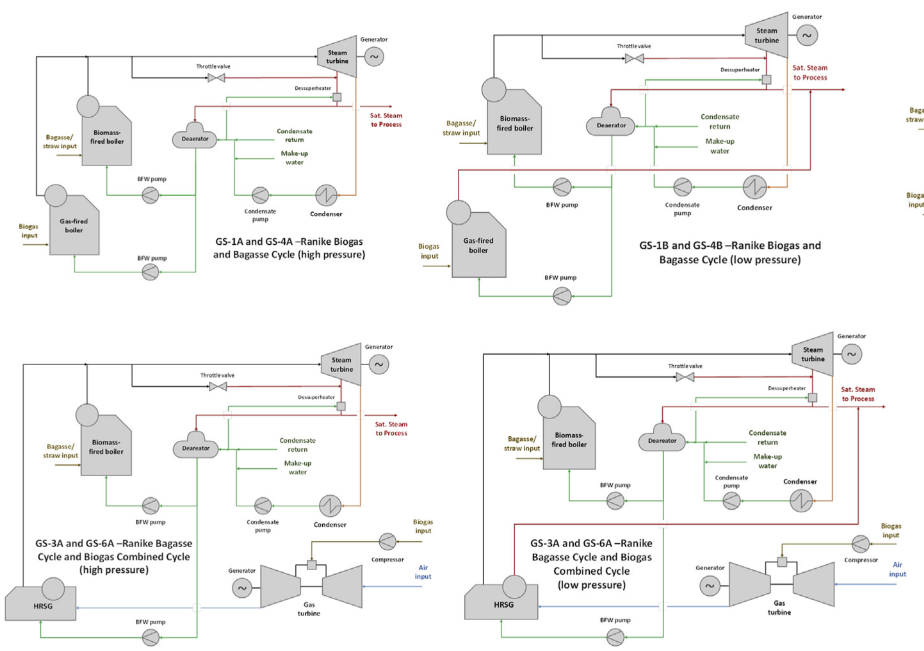

Fig. 4. Proposed power cycles.

Table 5
Main premises assumed for reference scenario RS.

	Consumption/ production	Properties of interest
Bagasse	252.0 kg/t$_{\text{cane}}$	Moisture content: 50% (wt%, wet) LHV: 9200.00 kJ/kg
Straw	16.5 kg/t$_{\text{cane}}$	Moisture content: 15% (wt%, wet) LHV: 15,00.00 kJ/kg
1G Ethanol	0.08 m^3/t$_{\text{cane}}$	–
1G Vinasse	1.04 m^3/t$_{\text{cane}}$	BOD: 56.5 kg/m^3
Live steam	–	T: 480 °C; P: 6.6 MPa
Steam for process	500,0 kg/t$_{\text{cane}}$	T: 140 °C; P: 0.35 MPa
Steam for condensation	–	P: 0.112 MPa
Condensate return	60% of steam for process	T: 110 °C; P: 0.3 MPa
Make-up water	–	T: 25 °C; P: 0.3 MPA
Boiler feed water		T: 138 °C; P: 7.6 MPa
EE consumption in process	28,0 kWh/t$_{\text{cane}}$	–

The remaining scenarios consider a few additional premises:

- In each of the GS, the electric power generation was kept at the same value as the one obtained in the RS and the low pressure steam production (0.35 MPa and 140 °C) was fixed at 500 kg/t$_{\text{cane}}$;
- There is a decrease in bagasse consumption due to the bagasse shift with biogas;
- In every GS, the steam produced from bagasse or straw burning is at 480 °C and 6.6 MPa. In "A" scenarios, this is also the condition for the steam produced from biogas burning; In "B" scenarios, the steam produced form biogas burning is at 140 °C and 0.35 MPa;
- In every GS, the particulate material emission is 2.10^{-4} kg/Nm^3, the most restrictive presented in Table 3 (CONAMA resolution 382);
- In every GS, the removal of BOD from vinasse biodigestion is 92%;
- In case the turbine bypass is turned on to supply steam to the process, it maintains a minimum flow rate for condensation (10% of the turbine total flow);
- Since scenarios GS-2, GS-3A/B, GS-5 and GS-6A/B involve the use of gas turbines, a biogas compression step is necessary, which generates a higher energy consumption at the power island. The estimation of this additional energy consumption considered a 60% isentropic efficiency [75]. Furthermore, for these scenarios, the removal of H_2S slightly reduces the biogas flowrate;
- Since scenarios GS-4A/B, GS-5 and GS-6A/B assume that all the bagasse will be shifted, they all have similar biogas consumption (which is the gas generated from 1G and 2G vinasse biodigestion);
- The bagasse shift, percentage increase in straw consumption and percentage increase in ethanol production were all calculated taking the figures obtained in the RS as a base case.

For other equipment, the simulation assumed the following premises, based on data available in the literature and technical brochures from the main manufacturers:

- Biomass-fired steam boiler thermal efficiency: 85% (power boiler) or 65% (heating boiler);

Table 6
Additional premises assumed for the remaining scenarios.

	Consumption/ production	Properties of interest
2G Ethanol	0.160 m^3/t_{bagsse}	–
2G Vinasse	1.248 $m^3/t_{bagasse}$	BOD: 38.6 g/l
Biogas	22.4 Nm^3/t_{cane} (1G) 19.2 $Nm^3/t_{bagasse}$ (2G)	Density: 1.08 kg/Nm^3[a] LHV: 20,543.5 kJ/kg[a] 65% CH_4, 32.5% CO_2, 0.3% H_2S (% vol)[a, b]
Live steam (Biogas/biomass boiler, scen. "A")	–	T: 480 °C; P: 6.6 MPa
Live steam (Biogas boiler, scen. "B")	–	T: 140 °C; P: 0.35 MPa
Boiler feed water (Biogas/biomass boiler, scen. "A")	–	T: 122 °C; P: 7.6 MPa
Boiler feed water (Biogas boiler, scen. "B")	–	Temp.: 120 °C; Press.: 1.35 MPa

[a] Figures for the dry "raw" biogas. For clean biogas, (98% H_2S removal), the composition becomes 65.2% CH_4, 32.6% CO_2, 60.2 ppm H_2S, the LHV becomes 20,567.5 kJ/kg and the availability reduces by 2.94%.

[b] The remainder of the composition is N_2.

- Steam turbo-generator global efficiency: 70.8%;
- Gas turbo-generator: global efficiency of 34.3%, heat rate of 10.500 kWh/kJ;
- Deaerator pressure: 0.3 MPa;
- Biogas compression pressure ratio: 12.5.

Additionally, In the case of the Rankine Cycle scenarios, dry biogas will be burned "as is", without any pre-treatment. The only constraint in this case will be to limit the flue gas exhaust temperature to be higher than the sulfuric acid dew point. In scenarios GS-1A and GS-4A, the flue gas exhaust temperature was estimated to be 151.7 °C. In order to avoid acid condensation, the exhaust temperature of the flue gases from the biogas-fired boiler was set to be 30 °C higher than the dew point temperature. This was achieved by setting this boiler efficiency to 90.4%. In scenarios GS-1B and GS-4B, there is also H_2S burning, but the boiler efficiency is set to 65%, thus having a higher exhaust temperature (570.9 °C), with no risk of acid condensation. In the case of Brayton and combined cycles scenarios, a H_2S removal pre-treatment is necessary. A 98% removal efficiency will be considered (this is feasible with the current technology [70]). In none of the scenarios was CO_2 removal employed, since the latter is inert for combustion purposes.

The dew point temperature was estimated by the classic Verhoff and Banchero correlation [72], given by Eq. (1).

$$\frac{10^3}{T_{dew}} = a + b.\ln\left(\frac{k.p_{SO2}}{133,32}\right) + c.\ln\left(\frac{p_{H2O}}{133,32}\right) + d.\ln\left(\frac{k.p_{SO2}}{133,32}\right).\ln\left(\frac{p_{H2O}}{133,32}\right) \tag{1}$$

Where T_{dew} (K) is the dewpoint temperature, p_{H2O} and p_{SO3} (Pa) are the H_2O and SO_2, partial pressures, $a,\ b, c, d$ are empirical constants ($a = 2.276; b = -0.0858; c = -0.02943; d = 0.0062$) and k is the conversion factor for the SO_2/SO_3 equilibrium, which can be assumed as 6% [73].

3.3. *Scenarios comparision*

The comparison of the scenarios will consider:

- the amount of shifted biomass;
- bagasse straw consumption;
- increase in ethanol production;
- Total energy production and consumption;
- The "energy efficiency" of cogeneration systems (expressed by the energy utilization factor - *EUF*) and
- Reduction of emissions (BOD disposal on the soil and particulate matter to the atmosphere).

The energy utilization factor (*EUF*) is commonly used to compare CHP systems. Its definition is [74] given by Eq. (2).

$$EUF = \frac{W + Q_u}{F} \tag{2}$$

where W is the useful work done by the CHP system, Q_u is the useful heat energy provided by the CHP system and F is the energy income to the CHP system in the fuel. Note that the magnitudes in Eq. (2) can also be in terms of time rate. In each scenario, W is the net electric power generation, Q_u is the net enthalpy flow of the low-pressure steam to the process (discharging and condensation enthalpy return), and F is the product between mass flowrate to the corresponding LHV (lower heating value) of bagasse, straw, or biogas, according to the employed fuel in consideration.

4. Results and discussion

4.1. *Reference scenario - RS*

Table 7 shows the results for the RS scenario or base case. The results for the net energy surplus obtained is 77.64 kWh/t_{cane}. Seabra and Macedo [6] reported a higher EE surplus, of 130.00 kWh/t_{cane}, because they considered a straw availability that is 4.125 times higher than the one considered in this study; Hosfetz and Silva [38] presented an electrical surplus of 45.66 kWh/t_{cane}. Even though the steam boiler temperature and pressure are similar to those considered in this study, any further assumptions (straw consumption, turbine extraction configuration) are not clear in the latter study. Alves et al. [39] achieved an EE surplus of 77.48 kWh/t_{cane}. These results are in accordance with the present study, since it

Table 7
Results for reference scenario RS.

Bagasse consumption	kg/t_{cane}	252.0
Straw consumption	kg/t_{cane}	16.5
Ethanol production	m^3/t_{cane}	0.08
Gross energy generation	kWh/t_{cane}	108.57
Power island EE consumption	kWh/t_{cane}	2.93
Net EE production	kWh/t_{cane}	105.64
Process EE consumption	kWh/t_{cane}	28.00
Surplus EE available	kWh/t_{cane}	77.64
Organic load disposed to the soil	kg/t_{cane}	58.76
Particulate material disposed at atmosphere	kg/t_{cane}	0.235

adopts the same main premises of Alves et al.'s study for establishing the RS.

4.2. Bagasse shift scenarios

Table 8 shows the results for the partial shift scenarios (GS-1A, GS-1B, GS-2, GS-3A and GS-3B). In GS-1A and GS-3B, the straw burning remained the same as in the RS. However, it doubled in GS-2 and GS-3A and increased threefold in GS-1B. The change in operating pressure with the Rankine cycle technology (GS-1A/1B) did not affect the ethanol production, but increased the straw consumption. The operating pressure had greater impact when using gas turbines (GS-3A/3B). Moreover, in scenarios with production of EE in steam and gas turbines (GS-2/3A/3B), a trend can be observed: 54% of the power production occurs at the steam turbine and 46% occurs in the gas turbines, regardless of the power generation cycle.

Table 9 shows the results for the total shift scenarios (GS-4A, GS-4B, GS-5, GS-6A and GS-6B). In these scenarios, all of the bagasse is available to 2G ethanol production, increasing the ethanol production by more than 50%, at the cost of increased straw burning in all of the scenarios. Differently for the partial shift scenarios, the share of power generation between gas turbines and steam turbines was practically the same in GS-5/6A/6B. The EE consumption in the power island and in biogas compression did not differ much when comparing the total shift scenarios with the partial sift scenarios.

The results show that it is possible to produce 2G ethanol and maintain the electric power output to supply the ethanol plant demand, opposing to the idea proposed by Macedo et al. [6]. According to their study, one would have to choose between power generation and 2G ethanol generation. As pointed out by Mariano et al. [24] burning biogas allows make bagasse available to 2G ethanol without compromising the power generation.

The results show that it is possible to shift up to all of the bagasse with biogas burning and an increased consumption of bagasse straw. The straw consumption may rise from 58.61% (scenario GS-6A) to practically 100% (scenario GS-4B) of the available straw. With reduced straw consumption, only up to 56.65% of the available bagasse can be shifted (scenario GS-6A). In any case, the results show that there are many ways in which on may produce 2G ethanol without changing the surplus 77.64 kWh/t_{cane} EE production at the mills power islands and the 500 kg/t_{cane} steam availability for the process.

Note that the straw appears as an important fuel in the ethanol and sugar mill, as well as a means of making 2G ethanol production feasible. However, the use of straw should be handled with care for many reasons, such as: the straw is much less dense than bagasse, thus making its transportation more expensive [69]; straw contains high low-melting point mineral content, which leads to increased slagging in boiler parts [39]; the importance of the straw in maintaining the soil moist and well-nourished [68].

Table 8
Results for the partial bagasse shift scenarios.

Relevant parameters	Units	Scenario				
		GS-1A	GS-1B	GS-2	GS-3A	GS-3B
Bagasse consumption	kg/t_{cane}	189.79	189.79	141.99	109.23	138.45
Shifted bagasse	%	24.69	24.69	43.65	56.65	45.00
Straw consumption	kg/t_{cane}	16.50	48.80	34.10	33.13	16.50
% straw consumption	%	10.0	29.58	20.67	20.08	10.0
Biogas consumption	Nm^3/t_{cane}	23.59	23.59	23.78	24.40	23.86
Ethanol production	m^3/t_{cane}	0.090	0.090	0.098	0.103	0.098
% increase in ethanol	%	12.44	12.44	21.69	28.50	22.55
Gross EE prod. (ST)	kWh/t_{cane}	108.57	108.57	61.79	60.60	61.38
Gross EE prod. (GT)	kWh/t_{cane}	N/A	N/A	50.32	51.62	50.48
Power island EE cons.	kWh/t_{cane}	2.92	2.74	1.96	1.95	1.71
Biogas compr. EE cons.	kWh/t_{cane}	N/A	N/A	4.50	4.61	4.51
Process EE cons.	kWh/t_{cane}	28.0	28.0	28.0	28.0	28.0
Surplus EE available	kWh/t_{cane}	77.64	77.83	77.64	77.64	77.64

Table 9
Results for the total bagasse shift scenarios.

Relevant parameters	Units	Scenario				
		GS-4A	GS-4B	GS-5	GS-6A	GS-6B
Bagasse consumption	kg/t_{cane}	0.0	0.0	0.0	0.0	0.0
Shifted bagasse	%	100.0	100.0	100.0	100.0	100.0
Straw consumption	kg/t_{cane}	128.02	164.49	118.84	96.71	94.91
% straw consumption	%	77.59	99.69	72.02	58.61	57.52
Biogas consumption	Nm^3/t_{cane}	27.24	27.24	26.44	26.44	26.44
Ethanol production	m^3/t_{cane}	0.120	0.120	0.120	0.120	0.120
% increase in ethanol	%	50.40	50.40	50.40	50.40	50.40
Gross EE prod. (ST)	kWh/t_{cane}	108.57	108.57	56.65	56.64	56.51
Gross EE prod. (GT)	kWh/t_{cane}	N/A	N/A	55.93	55.93	55.93
Power island EE cons.	kWh/t_{cane}	2.92	2.72	1.94	1.92	1.70
Biogas compr. EE cons.	kWh/t_{cane}	N/A	N/A	5.00	5.00	5.00
Process EE cons.	kWh/t_{cane}	28.0	28.0	28.0	28.0	28.0
Surplus EE available	kWh/t_{cane}	77.64	77.83	77.64	77.64	77.64

In terms of technology, the combined cycle resulted in greater displacement, followed by the Brayton and Rankine cycles. As for the operation condition, it is possible to shift higher amounts of bagasse when operating only with high-pressure steam. These results agree with the literature: the overall efficiency of a combined cycle is higher than the Brayton cycle efficiency, which, in turn, is higher than that of the Rankine cycle [76], so that similar CHP systems are expected to have similar results. The Rankine cycle efficiency increases by operating at higher temperatures and pressures [8], so that the utilization factor should be lower for the scenarios with low-pressure Rankine cycles. Even though economic analysis is out of the scope of this paper, a reverse trend exists for the cycles CAPEX. The installation costs of a Brayton and combined cycle can be up to 5 and 10 times higher than those of the Rankine cycle, respectively [24,77]. Furthermore, installation costs are also lower for lower pressure operating conditions.

Table 10 shows the results for the EUF for each scenario studied. A closer inspection of the EUF can provide insights in which way the energy provided by biogas, bagasse, and straw converts to heat and power. The results for scenario RS indicate that 28.9% of the energy does not convert to useful heat or power in the current situation. While the use of the Rankine cycle for bagasse shift did result in some displacement, it did not significantly increase the EUF in scenarios GS-1A and GS-4A, even being reduced in scenarios GS-1B and GS-4B. Scenario GS-2 and GS-5 present slightly higher EUF, whereas the highest figures are present in scenarios GS-3B, GS-3A, GS-6A, and GS-6B, respectively. While the operation condition seems to have great importance for the Rankine cycle, combined cycles do not seem to differ much in terms of overall efficiency regarding the operational conditions. However, producing steam from biogas firing at a lower pressure allows a more flexible operation, since the ethanol and sugar mill may revert to only using bagasse and straw as fuel if the biogas boiler is not available due to maintenance or untimely stops.

Regarding the increase in ethanol production, the results show that it is possible to produce up to 50.4% more ethanol when the total shift occurs. When there is only partial shifting, the maximum increase in ethanol production was 28.5% (scenario GS-3A). Note that, from scenario GS-1A to scenario GS-3B, it was possible to increase the bagasse shift by 2.3 times, thus increasing the extra ethanol production in the same proportion. Furthermore, an increase of 675% in straw consumption allowed a 76.8% increase in

Table 10
EUF for each of the scenarios simulated.

Scenario	W (kWh/t_{cane})	Q_u (kWh/t_{cane})	F (kWh/t_{cane})	EUF
RS	77.64	429.27	712.75	0.711
GS-1A	77.64	429.27	699.18	0.725
GS-1B	77.83	429.27	833.85	0.608
GS-2	77.64	429.27	651.75	0.778
GS-3A	77.64	429.27	567.75	0.893
GS-3B	77.64	429.27	569.77	0.890
GS-4A	77.64	429.27	701.29	0.723
GS-4B	77.83	429.27	853.25	0.594
GS-5	77.64	429.27	658.29	0.770
GS-6A	77.64	429.27	566.08	0.895
GS-6B	77.64	429.27	558.58	0.907

Table 11
Emissions of the simulated scenarios.

Scenario	Organic load		Particulate material	
	Emissions (kg/t_{cane})	Reduction	Emissions (kg/t_{cane})	Reduction
RS	58.760	–	0.235	–
GS-1A	4.941	91.59%	0.181	23.17%
GS-1B	4.941	91.59%	0.209	11.13%
GS-2	5.125	91.28%	0.154	34.42%
GS-3A	5.251	91.06%	0.125	46.98%
GS-3B	5.138	91.26%	0.136	42.29%
GS-4A	5.672	90.35%	0.112	52.32%
GS-4B	5.672	90.35%	0.144	38.74%
GS-5	5.672	90.35%	0.104	55.74%
GS-6A	5.672	90.35%	0.085	63.98%
GS-6B	5.672	90.35%	0.083	64.65%

extra ethanol production if one compares scenarios GS-3B and GS-6B.

Finally, taking the comparison to the environmental sphere, Table 11 shows the result the emissions of organic load and particulate matter of the scenarios simulated. The bagasse shift provided a reduction of both organic matter disposal to the soil and particulate matter to the atmosphere with more efficient use of bioenergy. The emissions experienced great reduction in most of the scenarios: more than 50% reduction in particulate matter emission in scenarios GS-4A, GS-5, GS-6A e GS-6B when compared to the reference scenario. The more efficient the cycle is, the less particulate matter it will dispose, as expected. Therefore, the greater reductions are in the combined cycle scenarios. Note that, even with a 5.75 times greater straw consumption from scenario GS-3B to scenario GS-6B, the latter has greater reduction in emissions, since all of the available bagasse is shifted.

The reduction in organic matter disposal ranged from 90.35% to 91.59% due to the biodigestion process, which is coherent with the reductions pointed out in the literature [46–48]. All the scenarios have similar reductions in organic load disposal, since it depends very little on the thermodynamic cycle chosen. The reductions range from 53 a 54 kg_{BOD}/t_{cane}. It is important to highlight that the cane plantation is not impaired by any means because of the BOD reduction, since the mineral content of the vinasse is not altered by the biological process, providing a nutrient-rich effluent that can still be used for fertilization [48]. These results can help to push forward the use of biogas/bagasse energy shift, since environmental laws and accords are increasingly demanding more biofuels and fewer emissions.

5. Conclusions

The objective of this paper was to assess the amount of bagasse that could be shifted to 2G ethanol production by vinasse-produced biogas, aiming not to alter the energy matrix of the ethanol and sugar mill. Simulations of different thermodynamic cycles were performed to achieve it.

From technical and environmental aspects, the results seem to indicate the following highlights:

- It is possible to displace a fraction of the bagasse towards 2G ethanol using biogas produced from vinasse;
- Increasing straw firing in steam boilers can further increase the amount of bagasse shifted to 2G ethanol production. It is possible to shift all of the bagasse available if from 58.61% (scenario GS-6A) to practically 100% (scenario GS-4B) of the available straw is fired instead of the bagasse. However, there are issues regarding increased straw firing;
- The combined cycle technology (scenarios GSS-3A/B and GS-6A/B) would be the best choice for burning biogas, providing the bagasse shift. There is little increase in EUF by choosing between “A” or “B” operational modes in those scenarios.
- It is possible to produce up to 50.4% more ethanol when shifting all of the available bagasse. When there is only partial shifting, the maximum increase in ethanol production is almost halved.
- Bagasse shifting also promotes environmental benefits, such as a reduction of more than 50% in the emission of particulate matter and 90.35%–91.59% reduction of organic load on the soil.

Even though the use of the Rankine cycle based on bagasse burning is the simplest and most widely available and accepted technology in Brazil, it is the least efficient. Using biomass energy instead of using a biofuel produced from biomass is the source of this paradigm – and it can thus be changed with the use of biogas to provide energy more efficiently, allowing bagasse to be used for 2G ethanol production. In this sense, it does not seem reasonable, at least from an energy point-of-view, to use the Rankine cycle to burn biogas – even if this result in some bagasse shift - since burning biogas instead of bagasse allows using a more efficient technology, such as the Brayton and combined cycles.

Regarding the increase in straw consumption as a fuel, a very reasonable question would be: since there are technical issues concerning burning the straw, why not similarly transform it into biofuel, instead of using it as a mere biomass burning source of energy, allowing for more 2G ethanol and biogas production? Further studies considering the digestion of bagasse straw in the energy balance should be developed to further assess whether ethanol and sugar mills can be free of biomass energy or if they will still be dependent of biomass firing.

Finally, aside from the results presented, one must take the economic variable into consideration for a true decision making when performing further studies. Relevant aspects regarding economic analysis of the scenarios would include:

- Even though it is less efficient, the CAPEX for the Rankine Cycle is significantly lower than the CAPEX for Brayton and combined cycles. This is so because of its technical simplicity, but also for the strong adoption of this technology by the Brazilian ethanol and sugar mills;
- The choice of the operating condition also has different CAPEX (lower pressure being cheaper), but it may also lead to different OPEX, since at a lower pressure, the operation provides more flexibility and great process availability;
- Lower particulate matter emissions means that smaller or less efficient dust removal equipment may be used, thus reducing the CAPEX for the gas cleaning system;
- The 2G ethanol production currently has low efficiency and high costs. The literature indicates that 2G ethanol may be

competitive with 1G starch ethanol, even without subsidy [78], but this will hardly be the situation when comparing to 1G sugarcane ethanol [8]. This is likely because the 2G technology is still incipient and facing scaling-up issues. There are different technological and economic challenges, such as the digestion of pentose and the price of the pre-treatment enzymes to make 2G ethanol commercially viable.

- The literature regarding 2G ethanol yields presents a wide range of figures for process yields, vinasse production and digestion. This is the major source of uncertainty for this study.

Hence, future studies on bagasse shift should focus on assessing the trade-off between increased bagasse shift and CAPEX/OPEX of the scenarios, considering what the cost of 2G ethanol production should be for the results presented in this paper to be also economically feasible.

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