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Energy Integration of Biogas Production in an Integrated 1G2G Sugarcane Biorefinery: Modeling and Simulation

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Abstract
The integration of the first and second generation (1G2G) ethanol production promotes the increase of biofuel productivity per hectare of planted sugarcane, as well as the main liquid waste stream: vinasse, derived from ethanol distillation. As a sustainable way for it disposal, biogas production from anaerobic digestion (AD) promotes environmental suitability while enabling bioenergy generation. This work evaluated the potential energy generated from AD applied to vinasse within the context of an integrated 1G2G sugarcane biorefinery. Data from a literature survey based the scenario modeling and assessment, including economic and environmental indicators to compare the studied alternatives. AD allowed at least 68% increase of released bagasse for 2G ethanol production compared to 2G base scenario, being able to even double 2G ethanol productivity to 30 L t^{-1} cane. Organic matter removal efficiency of vinasse AD played an important role in 2G ethanol production so that higher the efficiency, larger the fraction of bagasse released for ethanol production. Economic indicators showed the unviability of 1G2G sugarcane mill including AD unit when considering the current technologies for 2G ethanol production in view of their high operational costs; however, with the envisaged technologies for 2025, the internal rate of return (IRR) of 14.3 and 17% was achieved, when considering conservative and optimistic data for vinasse AD efficiency, respectively. The results evidenced the importance of investment in R&D especially in 2G ethanol production but also in the AD of vinasse to reach the viability of this business.

Keywords 1G2G ethanol · Vinasse · Anaerobic digestion · Environmental indicators · Economic assessment

Introduction

Since the 1970s, many factors have boosted the search for renewable fuels, especially in field of biofuels. The worries regarding climate change and global warming, leading to mitigation measures to reduce greenhouse gas (GHG) emissions in the atmosphere and, also, local pollution, allied to the need for countries to decrease their dependence on the finite fossil fuels international market are among the main reasons. This last factor was even decisive to consolidate the global biofuels pursuit, in view of the large economic impacts on oil importing nations caused by the shocks of excessive prices increases [1].

In Brazil, ethanol is considered the "flagship" of biofuels, produced mostly from sucrose-based raw materials (first generation or 1G ethanol). Sugarcane is the main feedstock, with great availability in the country due to favorable climate conditions. Apart the environmental benefits, the sugarcane ethanol chain is an essential source of jobs and new business opportunities, being a relevant sector within the Brazilian economy [2, 3].

One of the most relevant advantage of producing ethanol from sugarcane is that all the biomass is utilized in the production process: the remaining bagasse from the juice extraction process is normally burned in co-generation systems, which provides the energy supply to the sugarcane mills. In some cases, excess energy is generated and it can feed the public electricity grid, enabling economic value generation. An alternative of the excess bagasse exploitation that has been lately drawing attention worldwide is the second generation (2G) ethanol production, i.e., ethanol produced from lignocellulosic feedstocks [4]. The production of 2G ethanol allows

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the increase of the biofuel productivity while maintaining the same sugarcane planted area [5]. In this context, Brazilian 2G ethanol has potential to replace significant crude oil use and reduce CO_2 globally [6].

Even with the whole exploitation of the feedstock, bioethanol production generates large amounts of liquid waste, so called vinasse or stillage. Within the 1G ethanol chain, vinasse is conventionally applied to sugarcane crops as fertilizer—practice known as fertirrigation—due to its high content of nutrients (especially potassium, nitrogen, and phosphorous). However, such application is controversial due to potential environmental impacts caused by the high organic content of vinasse [7–10]. In the case of 2G ethanol production, higher amounts of vinasse should be generated with a different and critical composition: much higher organic content and almost absence of nutrients [11]. This fact hampers its use for fertirrigation as well as further aggravate adverse impacts to the environment. On the other hand, such high organic amounts could be translated in extra-energy generation for the sugarcane mills in a more sustainable way if used correctly. Its chemical composition makes vinasse (1G or 2G) susceptible to energy production from biogas through the anaerobic digestion (AD) process. Digested 1G vinasse (or digestate) could still be used as fertilizer because only the organic matter content is reduced during the biological process, with the nutrients being retained. Additionally, the use of additional energy produced from AD to run the mill operation results in releasing extra bagasse for 2G ethanol production.

Thus, AD process applied to vinasse goes beyond its environmental suitability within the bioethanol production chain, being a potential source for energy production on the sugarcane mills which is usually wasted.

Bearing this in mind, this work evaluates the potential energy generated from AD applied to vinasse within the context of an integrated 1G2G sugarcane biorefinery. Data from a literature survey based the scenarios modeling and assessment, including economic and environmental indicators to compare the studied alternatives.

Methodology

Queries: Main Research Questions To Be Addressed and Motivation

The development of this research was based on main guiding questions regarding the use of bagasse for 2G ethanol production and how could AD contribute on it when applied to vinasse within the concept of an integrated 1G2G sugarcane biorefinery:

– How much bagasse can be released for 2G ethanol production without impairing the energy self-sufficiency of a sugarcane mill?
– What is the potential volume of 2G ethanol production from the surplus bagasse released from the co-generation system?
– What is the increase in the bagasse release because of the extra energy generation resulted from AD of vinasse?
– What are the economic aspects of the integration of ethanol production to a vinasse AD unit? How can they motivate the application of this alternative?
– What are the environmental benefits in terms of avoided emissions and equivalent pollution from this alternative?

The scenarios with the proposed improvements were compared with a standard scenario usually employed in Brazilian sugarcane mills, allowing a discussion regarding innovation possibilities to be employed in the bioethanol sector also considering economic and environmental benefits.

Development and Operation of Simulation Platform

The proposed model was developed in Excel software through structured simulations using the Solver tool. The model was based on a simulated flowchart to evaluate three scenarios of bagasse distribution (with and without AD unit) against the base scenario, all described as follow:

a) Base: 100% of bagasse from 1G ethanol production is directed to combined heat and power (CHP) system to supply the plant's energy demand and for electric energy sale (Fig. 1). In this scenario, 100% of 1G vinasse is disposed to fertirrigation;
b) 2G: A fraction of bagasse from 1G ethanol production is directed to CHP system to supply the plant's energy demand and the surplus bagasse is directed to 2G ethanol production (Fig. 2);
c) 2G + AD: Different fractions of bagasse from 1G ethanol production are directed to CHP system to supply the plant's energy demand and to 2G ethanol production, taking account the energy from biogas generated through AD of 1G and 2G vinasse (Fig. 3). In this scenario, 100% of digestate is disposed to fertirrigation;
d) 2G + AD_Opt: Same as scenario 2G + AD (Fig. 3) but including supposed optimized data regarding AD of 2G vinasse. In this scenario, 100% of digestate is disposed to fertirrigation.

The developed model assessed the optimal bagasse distribution aiming at maximizing energy generation from the whole biomass use. The model primarily searched the energy self-sufficiency of sugarcane mill (i.e., enough steam

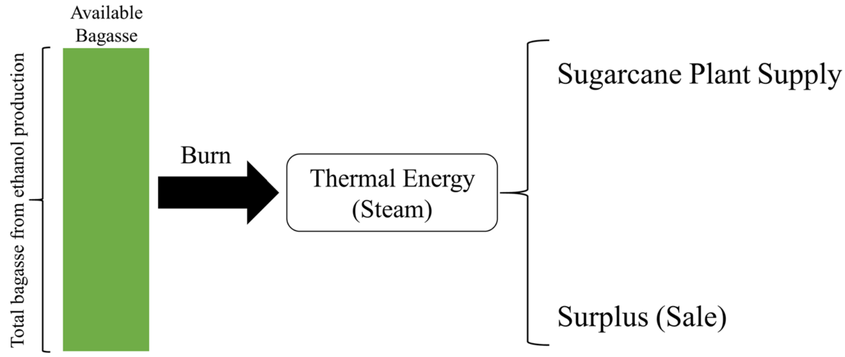

Fig. 1 Flowchart of base scenario

generation for supplying ethanol production), both in the scenario with or without AD. Then, the largest possible volume of ethanol produced is sought. The simulations allowed measuring the energy potential from vinasse and its impact in the sugarcane mill when exploited as a renewable energy source through AD. A deep literature survey provided the data for structuring model and the simulations.

Table 1 presents the main parameters of 1G2G sugarcane ethanol production that supported the model, as well as they were the basis for the model calculations. In all the scenarios, sugarcane mills were adopted as autonomous distilleries, with thermal integration and high-pressure systems for CHP (65 bar boilers) [14]. For the scenarios including 2G ethanol production, the distilleries were considered integrated to 1G ethanol production. The configuration of 2G process was based on the commercial technology of hydrolysis (DHR—Dedini rapid hydrolysis), in which the pre-treatment and hydrolysis occurs simultaneously in acid medium (steam explosion with H_2SO_4 addition) [17]. The fermentation of hydrolyzed from DHR processes was performed along with 1G juice. After fermentation, wine stream is sent to a series of distillation columns and dehydration processes where anhydrous ethanol (99.6 wt%) is obtained.

AD data are presented in Table 2. Although the generation of 1G2G vinasse occurs in a single stream in an 1G2G integrated sugarcane biorefinery, its composition and generation had to be considered separately, i.e., 1G vinasse and 2G vinasse, as no data in the literature was found. At the author's knowledge, there is only one sugarcane mill in Brazil operating on the integrated model. To take advantage of the existing facilities of the 1G plant, the generation of 1G and 2G vinasse does not occur separately, since the fermentation of sugarcane juice and C6 (hexoses) stream from bagasse pretreatment and hydrolysis occurs in the same vat. Information about the processes for 1G2G vinasse generation is not available due to confidentiality reasons from the 1G2G integrated sugarcane mill.

The optimization of the scenario (2G + AD_Opt) concerns the efficiency of AD process applied to 1G2G vinasse, i.e., the efficiency of COD removal to CH_4 production. The increase in this parameter is supposed to affect positively CH_4 production, and thus, allow more bagasse release for 2G ethanol process. At to the author's knowledge, there is no information about high-rate AD process applied to 1G sugarcane vinasse that could provide 90% COD removal efficiency, although there is promising research on it [20, 21]. Similarly, there is no data about AD applied to 2G sugarcane vinasse (optimized or not) in view of its novelty, but considering the higher recalcitrance than 1G vinasse [7], it has been assumed that the COD removal efficiency is lower. Thus, such values of efficiency were estimated.

Biogas Production from Vinasse: Energy Efficiency and Environmental Indicators

Thermal energy from biogas burning were based on studies carried out by Moraes et al. [15] and Junqueira et al. [16], considering values at the standard conditions for temperature

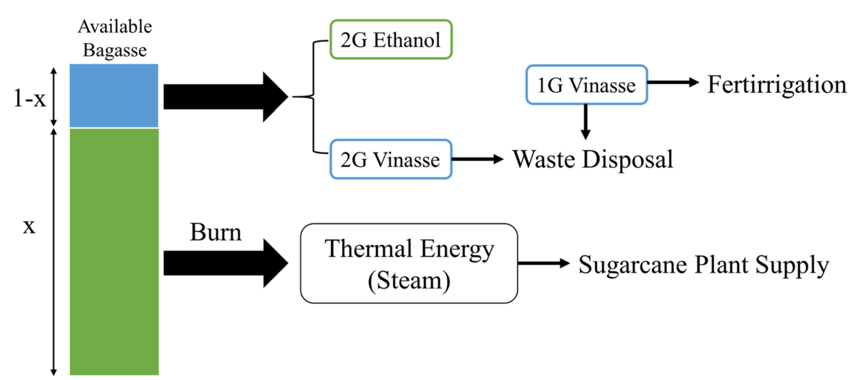

Fig. 2 Flowchart of scenario (2G) (X: % of bagasse directed to energy production to supply the sugarcane mill's energy demand; 1-X: % of bagasse directed to 2G ethanol production)

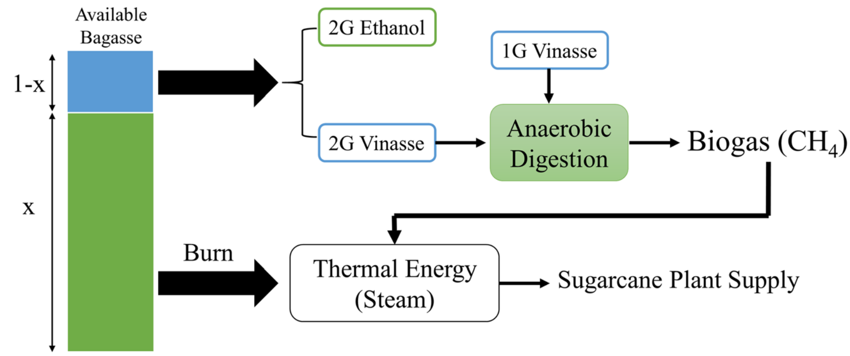

Fig. 3 Flowchart of scenarios (2G + AD) and (2G + AD_Opt) (X: % of bagasse directed to energy production to supply the sugarcane mill's energy demand; 1-X: % of bagasse directed to 2G ethanol production)

and pressure (STP). The amount of methane produced through vinasse AD ($VCH_4 = m^3\ CH_4\ t^{-1}$ cane) and its equivalence to bagasse in terms of energy (£bagasse = t bagasse $m^{-3}\ CH_4$) were calculated by Eqs. (1) and (2), respectively. Total steam produced by methane (CH_4 = kg steam t^{-1} cane) in terms of energy equivalency to bagasse burning in boilers at 65 bar was calculated by Eq. (3).

$$VCH_4 = \frac{\Omega_{CH_4} \cdot Qv \cdot C_{CODv} \cdot E_{CODv}}{M_{cane}} \quad (1)$$

$$£_{bagasse/CH4} = \frac{LHV_{CH4}}{LHV_{bagasse}} \quad (2)$$

$$\Sigma_{ch4} = VCH_4 \cdot £_{bagasse/CH4} \cdot P_{bagasse}. \quad (3)$$

In these expressions, ΩCH_4 is the CH_4 production per removed COD from vinasse ($m^3\ CH_4\ kg^{-1}$), Qv is the volumetric flow rate of vinasse ($m^3\ h^{-1}$), C_{CODv} is the vinasse COD ($kg\ m^{-3}$), E_{CODv} is the efficiency of COD removal, M_{cane} is the sugarcane production (t cane h^{-1}), LHV_{CH4} is the lower heating value of methane (kJ m^{-3} CH_4), $LHV_{bagasse}$ is the lower heating value of bagasse (kJ t^{-1} bagasse), and $P_{bagasse}$ is the steam production from bagasse burning (kg steam t^{-1} bagasse).

The environmental assessment accounted for effects of vinasse fertirrigation, involving indicators as equivalent population (EP) in terms of generated pollution and avoided emissions in terms of N_2O considering the effects of AD of vinasse, according to Moraes et al. [15]. Avoided emissions were calculated based on 1G vinasse solely since it was supposed that 2G vinasse would not be used as fertilizer in sugarcane crops due to its low nutrient content. The potential carbon credits resulting from avoided emissions were calculated in terms of tons of CO_2 equivalent (t $CO_{2(Eq)}$), considering the Global Warming Potential (GWP) of 310 for N_2O, for the time horizon of 100 years, according to IPCC [22].

Economic Indicators

A global economic assessment was performed for all scenarios considering current market prices (2015) and future estimates (2025) regarding 2G ethanol production costs, aiming at evaluating the impact of development level of such technology in the sugarcane mill. The main financial parameters are presented

Table 1 Data of 1G2G sugarcane ethanol production used in the simulations, considering autonomous distilleries

Parameter	Value	Source
Bagasse 50% humidity (kg t^{-1} cane)	276.0	[12]
Straw 15% humidity (kg t^{-1} cane)	140	[13]
1G ethanol production 1G (L t^{-1} cane)	81.80	[14]
Volume of 1G vinasse (L vinasse L^{-1} ethanol)	10.0	[15]
Volume of 2G vinasse (L vinasse L^{-1} ethanol)	10.0	Estimated
Steam demand (kg stream t^{-1} cane)	551.0	[14]
Steam produced by bagasse burning (kg t^{-1} cane)	618.0	[14]
Sugarcane processed (t cane h^{-1})	2.87×10^5	[15]
[a]Residual cellulignin from 2G ethanol production directed to CHP system (%)	35.0	[13]
Straw collected from the field directed to CHP system (%)	30	[13, 14]
Bagasse LHV, 50% humidity (kJ t^{-1} bagasse)	7.5×10^6	[16]
Straw LHV, 15% humidity (kJ t^{-1} straw)	15.1×10^6	[14]
CH_4 LHV (kJ m^{-3})	35.8×10^3	[15]

[a] Bagasse energy equivalent value

Table 2 Anaerobic digestion data used in the simulations

Parameter	2G + AD	2G + AD_Opt	Source
1G CH_4 production per COD removed (m^3 kg^{-1} COD removed)	0.31		[18]
2G CH_4 production per COD removed (m^3 kg^{-1} COD removed)	0.29		Estimated
COD 1G (kg m^{-3})	25.80		[18]
COD 2G (kg m^{-3})	92.30		[11]
1G COD removal efficiency	0.73	0.9	[18]; Estimated
2G COD removal efficiency	0.60	0.8	Estimated
1G vinasse production (m^3 h^{-1})	424.15		[15]
2G vinasse production (m^3 h^{-1})	149.20	224.55	[19]

in Table 3, considering a scale factor of 0.6. Incomes from carbon credit sale due to avoided emissions were added in the scenarios including AD units (2G + AD; 2G + AD_opt). Incremental cash flow analysis was also performed for these latter scenarios, for a 30-year project lifetime, being the results obtained in terms of internal rate of return (IRR), payback, and production costs, with an acceptable minimum rate of return of 12%. Working capital, annual depreciation, and tax rate (income and social contributions) were set as 10, 10, and 34%, respectively. The conversion rate for the US dollar and Euro was \$ 0.28 and \$ 0.31, respectively, per unit of Brazilian real, considering the average value from 2015.

The investment and operational costs of AD unit were based on the technology applied to 1G vinasse, considering that the same applies to 1G2G vinasse. Optimization of AD technology considered only adjustments on operational parameters, assuming no significant difference between economic inputs Output sale prices of electric energy (U\$S 0.10 kWh^{-1}) and ethanol (U\$S 0.42 L^{-1}) were obtained from ANEEL [23] and CEPEA [24], respectively, considering the weighted average value from 2012 to 2017. Carbon credit price of US\$ 3.04 per ton of CO_2 equivalent from the last auction (2012) reported by BM & FBOVESPA [25] was adopted for the calculations.

Results and Discussion

Energy Assessment

Bagasse distribution and the resulting products in the assessed scenarios are presented in Table 4, as well as CH_4 generation from vinasse AD.

In the scenarios considering 2G ethanol, the employment of vinasse AD (2G + AD and 2G + AD_Opt) promoted higher values of 2G ethanol production due to better exploitation of biomass and the use of CH_4 as a source of thermal energy. In the case of 2G + AD scenario, CH_4 generated by AD of

Table 3 Main financial parameters for economic assessment considering current (2015) and improved (2025) technologies of 2G ethanol production processes

Parameter	Current technology (2015)[a]	Improved technology (2025)[b]	Reference
AD unit investment (US\$ million)	8.15	8.15	[15]
AD operation costs (US\$ m^{-3} vinasse)	0.26	0.26	[15]
2G ethanol facilities investment (US\$ million)	38.4	41.2	[17]
2G ethanol production cost (US\$ L^{-1} ethanol)	0.47	0.22	[17]
	Participation of production costs (%)		[17]
Civil works	0.33	0.47	
Equipment	56.10	49.00	
Labor	2.93	2.47	
Process inputs	35.44	43.22	
Others	5.20	4.84	

[a] DHR technology considering fermentation of hexoses; 48-h reaction; 2G ethanol yield of 151 m^3 day^{-1}

[b] DHR technology considering fermentation of hexoses and pentoses; 24-h reaction; 2G ethanol yield of 381 m^3 day^{-1}

Note: 1G ethanol production costs and investment were considered the same for all scenarios and thus were not accounted

Table 4 Distribution of bagasse and products generated in the assessed scenarios

	[a]Base	[b]2G	[c]2G+AD	[d]2G+AD_Opt
Methane generated by vinasse AD (m^3 t^{-1} cane)	0.00	0.00	12.57	15.64
Steam produced by methane burning (kg t^{-1} cane)	0.00	0.00	103.63	168.13
[e]Steam produced by bagasse burning (kg t^{-1} cane)	698.30	551.00	447.37	407.88
Bagasse directed to ethanol production (%)	0.00	51.00	86.00	100.00
Bagasse directed to energy production (%)	100.00	49.00	14.00	0.00
2G Ethanol produced (L t^{-1} cane)	0.00	15.00	26.00	30.00

[a] Bagasse directed to energy generation;

[b] Bagasse directed to 2G ethanol production and energy generation

[c] Bagasse directed to 2G ethanol and energy production considering the energy provided by conventional anaerobic digestion of vinasse

[d] Bagasse directed to 2G ethanol and energy production considering the energy provided by optimized anaerobic digestion of vinasse

[e] Considering residue use (straw and returned bagasse from 2G ethanol production)

vinasse caused a 68% increase of released bagasse for 2G ethanol production over the standard 2G scenario (2G). Thus, 2G ethanol productivity was enhanced by 73%. The energy demand of 2G scenario was supplied by burning part of the integral bagasse and the residual cellulignin (i.e., residual solids from the pre-treatment and hydrolysis of bagasse, composed of lignin and non-hydrolyzed cellulose and hemicellulose), accounting by 30% of collected straw from the field and the reuse of 35% of bagasse from 2G ethanol production process (i.e., residual cellulignin). The increment on such energy supply through biogas over aforementioned lignocellulosic materials was even enhanced by 24% when an optimized AD technology (2G + AD_Opt) was considered, providing extra 110-MJ t^{-1} cane in terms of produced CH_4 compared to (2G + AD) scenario. The increment of 15% on 2G ethanol production was consequently achieved. The positive effect of optimized AD technologies on energy generation within sugarcane ethanol production is been recently reported concerning 1G vinasse, presenting increments on energy potential of up to 30% [20, 21].

Figure 4 presents the thermal energy sources for supplying the unit according to the assessed scenarios. As 2G ethanol production increases, the amount of residual cellulignin is raised, favoring the use of integral bagasse to 2G ethanol production. This concept is inherent of integrated first and second generation ethanol biorefineries aiming at better utilization of the lignocellulosic biomass to improve the energy balance of the overall chain [5, 26]. Macrelli et al. [27] achieved 15.8% increase of ethanol productivity when combining the 2G to the 1G ethanol production, without mixing the material streams and considering the cogeneration of the solid residues from 2G ethanol production (lignin and non-hydrolyzed cellulose) plus the biogas from pentoses liquor AD. When leaves were added at a ratio of 50% of the total amount of bagasse based on dry weight to supplement 2G ethanol production, total ethanol productivity was 53.2% enhanced.

The enhancement of AD process (2G + AD_Opt) allowed the use of bagasse exclusively for 2G ethanol production, improving the ethanol yield to 30 L t^{-1} cane, i.e., twice the value from the standard 2G scenario (2G) and 30% higher the value of (2G + AD). In that case, sugarcane plant's energy demand was obtained by burning CH4 from AD of vinasse, as well as the residual cellulignin from 2G ethanol production (lignin and non-hydrolyzed cellulose and hemicellulose) plus the straw fraction collected from the field. It is noteworthy that the value of organic matter removal efficiency adopted for AD of 2G vinasse was an estimate since no experimental values were found in the literature. This parameter played an important role in the 2G ethanol production so that higher the efficiency, larger the fraction of bagasse released for ethanol production, considering the methane yield proportional to the organic matter removed. The release of about 22% of bagasse from burning was achieved by the biogas use in the CHP system, when considering 80% of AD efficiency concerning 2G vinasse treatment (2G + AD_Opt). It could be expected an increment of about 10% in such released bagasse

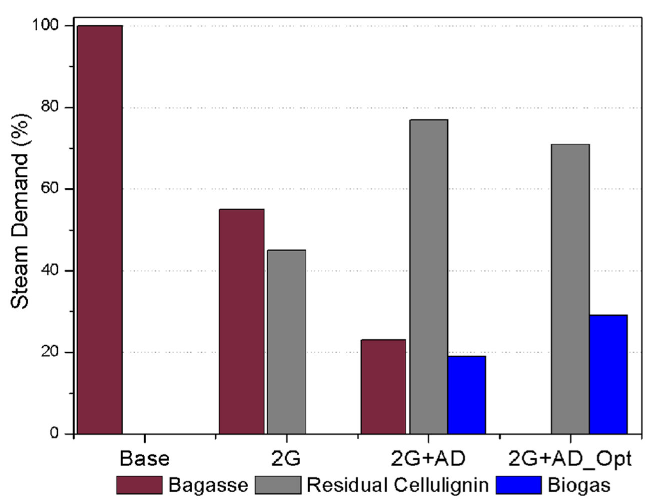

Fig. 4 Sources and contribution of energy supply of each scenario

percentage if the same AD efficiency of 1G vinasse treatment in the optimized scenario was achieved for 2G vinasse.

Environmental Assessment

AD of 1G2G vinasse could improve environmental aspects of bioethanol production. A more rational use of 1G vinasse as fertilizer could be provided since the impacts related to its organic matter content would be attenuated while the fertilizing capacity, i.e., nutrient content, would be preserved. In the case of 2G vinasse, AD arises as an option for disposal, since this stream has not enough nutrients to be used as fertilizer but must be correctly disposed to avoid major damage to the environment.

Environmental impact in terms of EP considering an autonomous sugarcane mill processing 2.87×10^6 tons of cane $year^{-1}$ is illustrated in Fig. 5. The annual application of *in natura* 1G vinasse to the sugarcane fields would generate pollution equivalent to the sewage generated by 1.5 million inhabitants (in terms of organic matter), e.g., approximately the population of Barcelona (1.6 million) for both scenarios (2G + AD and 2G + AD_Opt), since the improvements in 2G ethanol production do not impact the volume of 1G ethanol and, consequently, 1G vinasse generation. Considering the higher organic matter content of 2G vinasse, the avoided impact provided by AD treatment would be even higher: equivalent to 1.75 million inhabitants (scenario 2G + AD) and 2.94 million inhabitants (scenario 2G + AD_Opt), similar to populations of Hamburg (1.8 million) and Rome (2.8 million), respectively. For the scenario 2G + AD_Opt, the higher EP value is due to the higher volume of 2G vinasse generated as a result of improved productivity of 2G ethanol compared to scenario 2G + AD. Thus, a single 1G2G sugarcane biorefinery could generate a pollution load by fertirrigation with *in natura* 1G2G vinasse higher than the sewage generated by the population of Croacia (4.2 million) for example considering the scenario 2G + AD_Opt. These numbers highlight the need to find an environmental friendly destination for these streams, as the AD process.

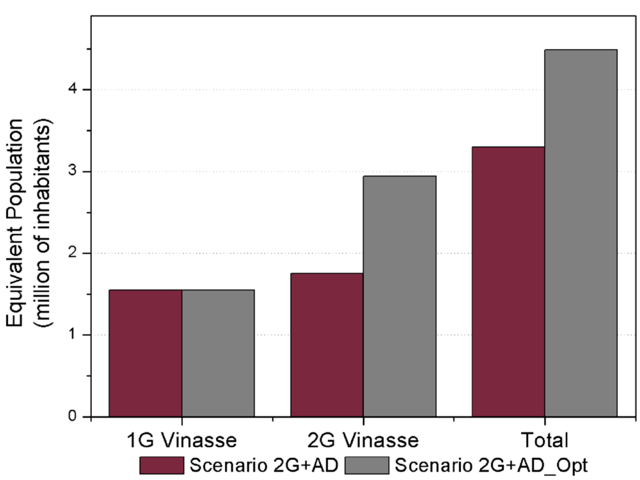

Fig. 5 Pollution load (accounted by organic matter) in terms of equivalent population of 1G vinasse, 2G vinasse, and total volume of vinasse (1G + 2G vinasse) considering the scenarios 2G + AD and 2G + AD_Opt

N_2O emissions accounted by fertirrigation with *in natura* 1G vinasse corresponded to 6.6×10^4 t $CO_{2(eq)}$ $season^{-1}$. Through the adopted premise that N_2O emissions from biodigested vinasse would resemble those of inorganic fertilizer emissions, the avoided emissions resulted in 3.3×10^4 t $CO_{2(Eq)}$ $season^{-1}$, i.e., 50% reduction in N_2O emissions could be achieved. Such estimated avoided emissions from a single sugarcane mill (processing capacity of 2.0×10^6 tons of sugarcane per year) represents the emissions caused by 14.3×10^3 inhabitants, considering the annual per capita emissions in Brazil (2.3 t CO_2) [28]. It is noteworthy these values are an estimate since no experimentation using biodigested sugarcane vinasse applied to field was found. Moraes et al. [10] reported reduction in GHG emissions when compared experimentally the application of sugar beet vinasse before and after AD treatment: between 48 and 78% mitigation on N_2O emissions was achieved when using digested vinasse.

Economic Assessment

Table 5 presents the financial inputs and outputs, as well as the gross operating profit, related to 2G ethanol production and vinasse AD, according to the assessed scenarios. The operational costs of electricity cogeneration unit (for both burning methane or bagasse) and of 1G ethanol production were considered the same for all scenarios, thus they were not accounted in this analysis.

Although biofuel selling price is 165% higher than that of electricity, the costs of 2G ethanol production are also higher and further increased in the cases including the AD unit. Thus, annual gross profit obtained for these scenarios was lower than for the base scenario considering the existing technologies of 2015. Nevertheless, with the expected improvements in the process up to 2025 (e.g., development of more productive enzymes, microorganisms capable of fermenting the complex sugars, more efficient process of bagasse pre-treatment [29]), a considerable decrease in the production costs is envisaged, resulting in a considerable impact the economic results: up to three times higher the annual gross revenues when compared to the current technology. Independently of the technological degree of 2G ethanol production (2015 or 2025), its operational costs were as higher as the optimization degree of AD process due to the increase of 2G ethanol production volume. It causes an expansion of the sugarcane mill capacity, intensifying the operations. Even though, larger capacities for producing 2G ethanol provided higher incomes from ethanol sales, resulting in the best economic benefits for the scenario (2G + AD_Opt).

Table 5 Operation costs and products sale related to the studied scenarios

	Base		2G		2G + AD		2G + AD_Opt	
	2015	2025	2015	2025	2015	2025	2015	2025
Total annual 2G ethanol sale (million US\$ year^{-1})	0.00		10.45		18.12		20.91	
Total annual energy sale (million US\$ year^{-1})	3.92		0.00		0.00		0.66	
[a]Total annual carbon credits sale (million US\$ year^{-1})	0.00		0.00		0.10		0.10	
Operation costs of 2G ethanol production (million US\$ year^{-1})	0.00		11.83	6.40	16.46	8.90	17.93	9.70
Operation costs of vinasse AD (million US\$ year^{-1})	0.00		0.00		0.49		0.54	
Annual gross profit (million US\$ year^{-1})	3.92		− 1.38	4.05	1.28	8.83	3.21	11.44

[a] Considering the minimum selling price

Financial incomes obtained from the environmental benefits could also enhance the results, as the case of carbon credits. According to the latest carbon credit auction [25], the minimum selling price was US\$ 3.04 t^{-1} CO_2, which would result in a minimum income of US\$ 100,000 season^{-1} for the scenarios including the AD unit. In a hypothetical scenario in which such selling price reaches US\$ 10.15 t^{-1} CO_2, the operating costs of AD unit could be fully covered by the carbon credit sale. Thus, this market represents an alternative with potential to enhance profitability while improving the environmental sustainability of sugarcane mills. However, the carbon credit price is so far below the US\$ 15.99 t^{-1} CO_2 quoted at the height of the carbon market, almost 10 years ago [30]. Since then, the declining credit prices portray the low priority that has been given to carbon market and, thus, their contribution cannot be decisive in the analysis of investment.

Figure 6 presents the incremental cash flow analysis of the scenarios including the AD unit in the sugarcane mills operating with the current technologies of 2G ethanol production (year 2015) and the envisaged improvements in 2025.

The improvements foreseen for the technologies of 2G ethanol production had an important impact on the economic viability of the assessed scenarios, revealing that their current operational costs make the 1G2G sugarcane mill with AD unit an unfeasible business. The IRR was only higher than the minimum acceptable rate of return for the scenarios of 2025 (Fig. 7), with an increase of 19% in such economic indicator when considering the optimization of AD process applied to 1G2G vinasse (2G + AD_Opt). The upgrade in the AD process also allowed the payback of the investment 1 year before when compared with the standard AD treatment. However, the major impact was due to the upgrade in 2G ethanol production, providing a payback 7 years earlier than that obtained with the technologies of 2015, regardless of the AD level. [31] also reported that the high costs associated with 2G technology rely on the current choices of industrial routes and equipment design (such as those dedicated to pretreatment area) that may evolve over the years. The authors estimated a reduction about 50% over 2G ethanol production costs in medium term (2021–2025), which would allow the lignocellulosic ethanol to be competitive with 1G ethanol.

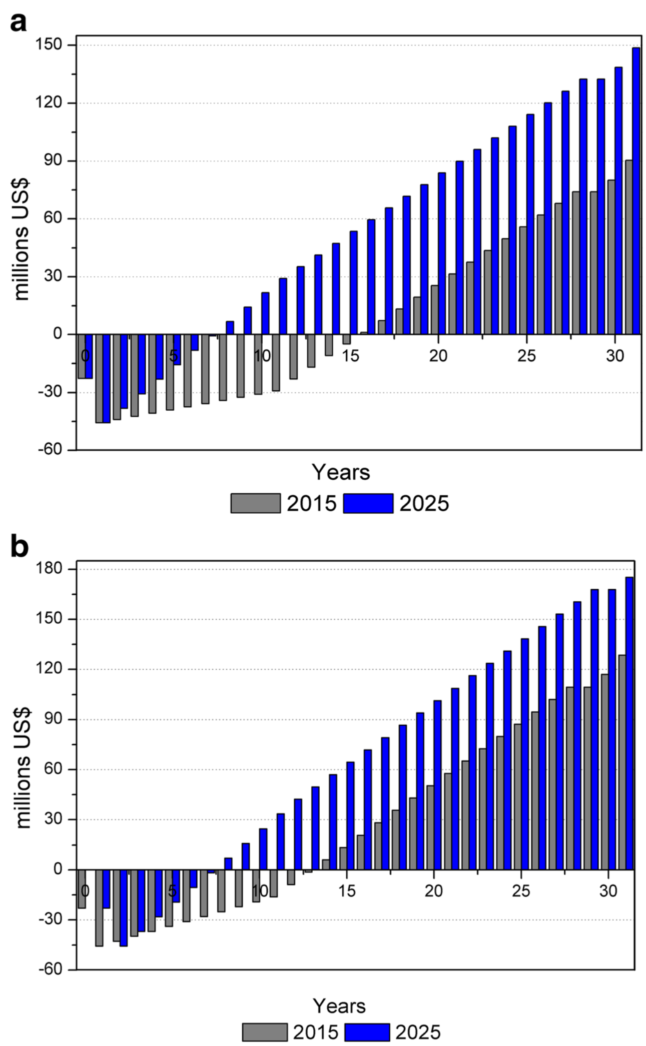

Fig. 6 Incremental cash flow analysis for the scenarios of 2G ethanol production applying traditional (year 2015) and improved (year 2025) technologies, integrated to biogas production from vinasse according to the efficiency of AD process: **a** standard AD process (2G + AD), **b** optimized AD process (2G + AD_Opt)

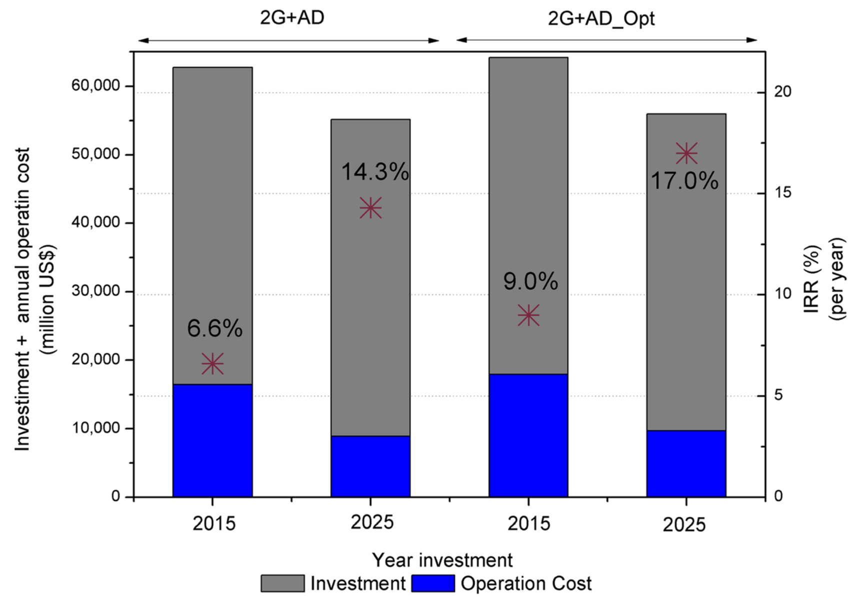

Fig. 7 Economic assessment of scenarios (2G + AD) and (2G + AD_Opt)

The results evidence the importance of investment in research and development especially in 2G ethanol production but also in the AD of vinasse. The development of new technologies in all stages of the 2G ethanol production process, from the selection of feedstock for biomass production to the development of microorganisms capable of fermenting the sugars from this complex material [29], seems to be the key of reducing ethanol production costs and, thus, provide the reality of integrated 1G2G sugarcane mills. Further AD developments in this sector may also provide considerable economic increments if more noble biogas uses were assessed, as the case of biomethane, i.e., purified biogas rich in CH_4 (> 96.5% *v*/*v*). It could optimize costs of energy production when considering the replacement of diesel, which plays an important role in the energy inputs of sugarcane mills, causing significant effects on production costs [32]. Studies have shown the viability with the best economic results for 1G sugarcane mills including AD unit when biomethane is directed to partially replace diesel used in sugarcane agricultural and transport operations, or when it is launched in the natural gas grid [15, 16]. Those applications in an integrated 1G2G sugarcane biorefinery may improve its profitability, although such supposition must still be explored.

Conclusion

The integrated 1G2G sugarcane biorefinery scenarios evaluated in this work highlighted several benefits derived from the energy integration of biogas production by vinasse AD. The inclusion of an upgraded AD unit for the treatment of 1G2G vinasse allowed the use of bagasse exclusively for 2G ethanol production, accounting for twice the 2G ethanol yield compared to a standard 2G ethanol sugarcane mill without vinasse AD. Environmental impacts of 1G2G ethanol production were also representative with the AD unit inclusion, especially by the mitigation of 50% in the N_2O emissions caused by the application of digested vinasse in the sugarcane fields. The efficiency of AD process was a critical parameter for the economic viability of an integrated 1G2G sugarcane biorefinery, but the technological level of 2G ethanol production was even more decisive: the prohibitive operational costs of current technologies make the 1G2G sugarcane mill with AD unit an unfeasible business, achieving its profitability only with the envisaged technologies for 2025. A successful energetic integration using AD vinasse is directly related to public environmental policies that encourage the development of sustainable technologies.

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References

1. Clark JH, Luque R, Matharu AS (2012) Green chemistry, biofuels, and biorefinery. Annu Rev Chem Biomol Eng 3:183–207. https://doi.org/10.1146/annurev-chembioeng-062011-081014
2. Bonomi A, Cavallet O, da Cunha MP, Lima MAP (2015) Virtual biorefinery: an optimization strategy for renewable carbon valorization. In: 1st ed. Springer, p 285
3. Cortez LAB (2010) Sugarcane bioethanol: R&D for productivity and sustainability, 1st edn. Edgard Blücher Ltda, São Paulo
4. Hamelinck CN, Van Hooijdonk G, Faaij APC (2005) Ethanol from lignocellulosic biomass: techno-economic performance in short-,

middle- and long-term. Biomass Bioenergy 28:384–410. https://doi.org/10.1016/j.biombioe.2004.09.002
5. Dias MOS, Junqueira TL, Cavalett O, Cunha MP, Jesus CDF, Rossell CEV, Maciel Filho R, Bonomi A (2012) Integrated versus stand-alone second generation ethanol production from sugarcane bagasse and trash. Bioresour Technol 103:152–161. https://doi.org/10.1016/j.biortech.2011.09.120
6. Jaiswal D, De Souza AP, Larsen S et al (2017) Brazilian sugarcane ethanol as an expandable green alternative to crude oil use. Nat Clim Chang 7:788–792. https://doi.org/10.1038/nclimate3410
7. Moraes BS, Zaiat M, Bonomi A (2015) Anaerobic digestion of vinasse from sugarcane ethanol production in Brazil: challenges and perspectives. Renew Sust Energ Rev 44:888–903. https://doi.org/10.1016/j.rser.2015.01.023
8. Wilkie AC, Riedesel KJ, Owens JM (2000) Stillage characterization and anaerobic treatment of ethanol stillage from conventional and cellulosic feedstocks. Biomass Bioenergy 19:63–102. https://doi.org/10.1016/S0961-9534(00)00017-9
9. de Oliveira BG, Nunes Carvalho JL, Pellegrino Cerri CE et al (2015) Greenhouse gas emissions from sugarcane vinasse transportation by open channel: a case study in Brazil. J Clean Prod 94:102–107. https://doi.org/10.1016/j.jclepro.2015.02.025
10. Moraes BS, Petersen SO, Zaiat M, Sommer SG, Triolo JM (2016) Reduction in greenhouse gas emissions from vinasse through anaerobic digestion. Appl Energy 189:21–30. https://doi.org/10.1016/j.apenergy.2016.12.009
11. Groposo Silveira CJ, Melo Santa Aanna LM, de Machado Castro A, et al (2012) Method for producing energy-rich gases from lignocellulosic material streams. International Patent Application No. WO 2012/003556 A1
12. Leite RC, De C, Leal MR (2007) O biocombustível no Brasil
13. Furlan FF, Filho RT, Pinto FH et al (2013) Bioelectricity versus bioethanol from sugarcane bagasse: is it worth being flexible? Biotechnol Biofuels 6:142. https://doi.org/10.1186/1754-6834-6-142
14. Dias MOS, Junqueira TL, Jesus CDF, Rossell CEV, Maciel Filho R, Bonomi A (2012) Improving second generation ethanol production through optimization of first generation production process from sugarcane. Energy 43:246–252. https://doi.org/10.1016/j.energy.2012.04.034
15. Moraes BS, Junqueira TL, Pavanello LG, Cavalett O, Mantelatto PE, Bonomi A, Zaiat M (2014) Anaerobic digestion of vinasse from sugarcane biorefineries in Brazil from energy, environmental, and economic perspectives: profit or expense? Appl Energy 113:825–835. https://doi.org/10.1016/j.apenergy.2013.07.018
16. Junqueira TL, Moraes BS, Gouveia VLR et al (2015) Use of VSB to plan research programs and public policies. green energy and technology. In: Bonomi A, Cavalett O, Pereira da Cunha M, Lima M (eds) Virtual biorefinery: an optimization strategy for renewable carbon valorization. Springer, Campinas
17. NovaCana (2015) Implantação da hidrólise nas usinas de etanol e açúcar (Implantation of hydrolysis in ethanol and sugar mills). NovaCana database: www.novacana.com. Accessed 15 Jan 2015
18. Ferraz Júnior ADN, Koyama MH, de Araújo Júnior MM, Zaiat M (2016) Thermophilic anaerobic digestion of raw sugarcane vinasse. Renew Energy 89:245–252
19. Bonomi A, Mariano AP, de Jesus CDF, et al (2011) The Virtual Sugarcane Biorefinery (VSB)
20. Fuess LT, Kiyuna LSM, Ferraz ADN et al (2017) Thermophilic two-phase anaerobic digestion using an innovative fixed-bed reactor for enhanced organic matter removal and bioenergy recovery from sugarcane vinasse. Appl Energy 189:480–491. https://doi.org/10.1016/j.apenergy.2016.12.071
21. Fuess LT, Klein BC, Chagas MF, Alves Ferreira Rezende MC, Garcia ML, Bonomi A, Zaiat M (2018) Diversifying the technological strategies for recovering bioenergy from the two-phase anaerobic digestion of sugarcane vinasse: an integrated techno-economic and environmental approach. Renew Energy 122:674–687. https://doi.org/10.1016/j.renene.2018.02.003
22. IPCC (2014) Climate change 2014: mitigation of climate change. Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change
23. ANEEL (2015) Brazilian Electricity Regulatory Agency (Agência Nacional de Energia Elétrica). http://www.aneel.gov.br/
24. CEPEA (2015) Indicador Semanal Etanol Anidro. In: Cent. Estud. Avançados em Econ. Apl. https://www.cepea.esalq.usp.br/br/indicador/etanol.aspx
25. BM&F_BOVESPA (2012) Leilão de Venda de Reduções Certificadas de Emissão. Edital no. 1/2012 (12/06/2012)
26. Khatiwada D, Leduc S, Silveira S, McCallum I (2016) Optimizing ethanol and bioelectricity production in sugarcane biorefineries in Brazil. Renew Energy 85:371–386. https://doi.org/10.1016/j.renene.2015.06.009
27. Macrelli S, Mogensen J, Zacchi G (2012) Techno-economic evaluation of 2nd generation bioethanol production from sugar cane bagasse and leaves integrated with the sugar-based ethanol process. Biotechnol Biofuels 5:22. https://doi.org/10.1186/1754-6834-5-22
28. Olivier JGJ (PBL), Janssens-Maenhout G (EC-J) Muntean M (EC-J), Peters JAHW (PBL) (2016) Trends in global CO_2 emissions: 2016 report. PBL Netherlands Environ Assess Agency Eur Comm Jt Res Cent
29. dos Santos LV, de Barros Grassi MC, Gallardo JCM, Pirolla RAS, Calderón LL, de Carvalho-Netto OV, Parreiras LS, Camargo ELO, Drezza AL, Missawa SK, Teixeira GS, Lunardi I, Bressiani J, Pereira GAG (2016) Second-generation ethanol: the need is becoming a reality. Ind Biotechnol 12:40–57. https://doi.org/10.1089/ind.2015.0017
30. BM&F_BOVESPA (2008) Leilão de Venda de Reduções Certificadas de Emissão. Edital no. 001/2008 (12/06/2008)
31. Junqueira TL, Chagas MF, Gouveia VLR, Rezende MCAF, Watanabe MDB, Jesus CDF, Cavalett O, Milanez AY, Bonomi A (2017) Techno-economic analysis and climate change impacts of sugarcane biorefineries considering different time horizons. Biotechnol Biofuels 10:50. https://doi.org/10.1186/s13068-017-0722-3
32. Chen X, Nuñez HM, Xu B (2015) Explaining the reductions in Brazilian sugarcane ethanol production costs: importance of technological change. GCB Bioenergy 7:468–478. https://doi.org/10.1111/gcbb.12163