



encit 2020



18th Brazilian Congress of Thermal Sciences and Engineering  
November 16–20, 2020 (online)

ENC-2020-9999

## ENERGY AND CARBON CREDITS GENERATION FROM THE PRODUCTION OF BIOGAS FROM THE ETHANOL STILLAGE OF CORN AND SUGAR CANE

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**Abstract.** *In the alcohol industry, the main waste residues are stillage, sugarcane bagasse, and corn straw. The management of this waste is one of the critical points of the sector's highest development. An alternative to reduce environmental impacts and add value to waste, mainly stillage is its use for the generation of biogas and, consequently, energy. This work presents an estimate of the production of biogas and bioenergy from the anaerobic digestion of stillage from sugar cane and corn. The generation of carbon credits for the use of biogas helps to decrease the polluting impact of vinasse and combustion fossil fuels. Autonomous plants produce more bioenergy than the annexes because these plants have two very influential and decisive factors for the more generation of biogas and methane is the factor of generation efficiency and the factor ethanol generation efficiency. Considering 60% of methane in biogas and the season of 2019/20 sugarcane, the generation of bioenergy in autonomous plants was  $8.76E^6$  MWh/year, and for attached plants, it is  $4.17E^6$  MWh/year. Bioenergy from the corn plant, with 71.25% methane, resulted in the generation of  $7.35E^5$  MWh/year of bioenergy and generated millions of credits of carbon per year for both feedstocks.*

**Keywords:** Ethanol, Vinasse, sugar cane, corn, bioenergy.

### 1. INTRODUCTION

In Brazil, there is a large generation of biomass waste in the agro-industrial activities, which are still underutilized, and commonly left for natural decomposition, without using the energy contained in them and causing problems because they are environmental liabilities. Thus, the country's biomass needs more accurate assessments as to its potential for use as energy products.

The increase in energy demand currently causes higher consumption of fossil fuels. Still, there is a need to reduce emissions of greenhouse gases (GHG) in the order of 50% to 85% by 2050, making it possible to stabilize the atmospheric concentration of these gases in levels that make it possible to mitigate the effects of ongoing climate change (Edenhofer *et al.*, 2012). In this context, renewable fuels are standing out as alternative energy generation methods, thus meeting the demands of the industrial sector and environmental appeals. Organic waste also becomes an alternative source of energy generation, whether thermal, mechanical, or electrical. Biomass is the most important source of renewable energy in the world. When used for energy purposes, biomass is classified into three categories (Lúcia de Moraes *et al.*, 2017): forest energy biomass, its products and by-products or residues; agricultural energy biomass, agroenergy crops and residues and by-products from agricultural, agro-industrial, and animal production activities; and urban waste (pruning and sweeping).

According to the National Agroenergy Plan, three factors can be considered as determinants for the use of biomass as an energy source (Ministério da Agricultura, 2011): energy scarcity and the national energy matrix; environmental impacts and renewable energy sources; new business opportunity.

In this scenario, agro energy becomes the object of research and technological development in Brazil to use biomass better. This is due to growing concern about global climate change that, in the future, will converge to international pollution reduction policies; recognition of the importance of biomass energy to make the transition to a new energy matrix and to replace oil as raw material, in its use as a fuel or input for the chemical industry; and growing demand for energy and the current high rates of use of energy biomass.

In Brazil, the sugar and alcohol industry is one of the largest agro-industries; its raw material is sugarcane, which is very important for the Brazilian economy and primary commodities. In the Brazilian energy matrix, the use of biomass from sugarcane (bagasse) increased by about 20% in 2018 (EPE, 2019).

In Brazil, ethanol is predominantly from sugar cane, whereas in the USA it is from corn (Fig. 1a). Ethanol production is growing, and a total output of 33.8 billion liters is estimated in the 2019/2020 harvest (CONAB, 2020). In 2018, the use of ethanol in the transport energy matrix, it is increased by about 13% (EPE, 2019). But there is also a growing expectation

of ethanol production from corn in Brazil, which reached 1.69 billion liters in the 2019/2020 harvest (CONAB, 2020). The region that stands out most in ethanol-based corn is the Midwest, representing 95% of the national supply (CONAB, 2020). The growth in ethanol use in the world is evident; the production forecast for 2023 of 158 billion liters.

In obtaining alcohol, vinasse is generated in the distillation phase; its composition contains 93% water and 7% solids, with about 40% of organic matter (Carrilho *et al.*, 2016). According to CETESB (1985), the vinasse is the liquid derived from the distillation, which results from the fermentation of the juice of the sugar cane or molasses.

In 2023 estimates that 6 trillions liters of residue will generate (Fig.1b). Bearing in mind that approximately 9 to 24 liters of vinasse are generated for each liter of ethanol, forecasting about 6 trillion liters of this residue will need to be managed in 2023 Carrilho *et al.* (2016).



Figure 1. Projection of ethanol production among the largest producers scheduled (a) and projection of vinasse for 2023 (b) Carrilho *et al.* (2016)

According to CibioGás (2020), the sugarcane sector has the greatest potential, compared to the food and sanitation sector (Fig:2 a), and in 2017 biogas would be able to supply around 24% energy savings (Fig. 2 b).

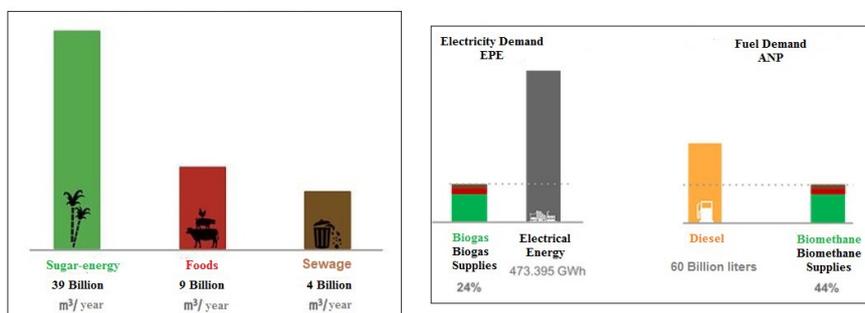


Figure 2. Brazilian Biogas Potential (a) and Potential for energy supply with biogas in 2017 (b).

In Brazil, there are 493 biogas units in operation; the total biogas production of the plants in operation is more than 1,329,672,161 m<sup>3</sup> / year, generating thermal, mechanical, and electrical energy (CibioGás, 2020). Brazil has 4 units that produce biogas in the sugar and alcohol sector, about 9 million m<sup>3</sup>/year. One medium-sized and three large, located in São Paulo (CibioGás, 2020). According to Neto (2016), Brazil already owns some ethanol plants with anaerobic biodigestion of vinasse; the São Martinho plant has operated with a thermophilic UASB reactor 1985.

In this context, this article aims to show the potential for generating bioenergy and biomethane based on the anaerobic digestion of vinasse from sugar cane and corn. Besides, this paper has demonstrated the generation of carbon credits generated by the use of biogas.

## 2. VINASSE AND BIOGAS

Vinasse is a liquid residue; it is a by-product of alcohol production. It is produced in many countries, from different raw materials, such as sugar cane, corn, beets, wine, etc. This effluent generally has a dark color and its composition consists basically of organic and mineral solids (7%) and water (93%). But its main component, independent of the raw material, is organic matter in the form of organic acids and, to a lesser extent, by cations such as K, Ca and Mg (Christofolletti *et al.*, 2013). Vinasse becomes 100 times more polluting than domestic sewage, as it is highly corrosive in nature and has an acidic pH (pH 3.5 and 5) (Salomon *et al.*, 2011).

Such characteristics make this affluent environmentally worrying (Carrilho *et al.*, 2016). A rich source of salts and organic contents, vinasse has minerals ranging from 24,000 to 80,000 mg/L and organic matter from 4,000 to 64,000

mg/L. In vinasse, it also contains a high potassium content, calcium, magnesium, sulfate, total phosphorus and nitrogen, and significant concentrations of heavy metals, such as copper, lead, zinc, among other metals (Carrilho *et al.*, 2016). Because of these vinasse conditions, it is considered harmful to fauna and contains high temperatures at the exit of distillers (Silva *et al.*, 2007).

Therefore, it is necessary to have the right destination for this waste. Nowadays, vinasse is used as fertilizer in crops. However, research on the use of vinasse for the production of biogas is being carried out. Biogas can be used to generate bioelectricity and fuel for vehicles.

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One of the most suitable technologies for handling vinasse in biorefineries is anaerobic digestion (AD) because through the controlled conversion of organic matter into biogas, it is possible to achieve energy efficiency and environmental adequacy without significant losses in the fertilizer potential of vinasse (Fuess *et al.*, 2017).

Studies on the formation of biogas are similar, but some authors differ in terms of the number of stages in the process. The production of biogas is done by bio digesting vinasse under anaerobic conditions, which basically takes place in four steps, hydrolysis, acidogenesis, acetogenesis and methanogenesis.

Bio digestion can be separated into monophasic or biphasic. Where monophasic occurs all the phases in a tank, and biphasic the last step to methanogenesis occurs in a separate tank.

According to Joppert (2019), the composition of biogas depends on the digested organic matter. However, biogas is mainly composed of  $CH_4$  and  $CO_2$ , and in smaller quantities  $O_2$  and  $N_2$ , hydrogen sulfide gas ( $H_2S$ ), and moisture. It is necessary that the biogas goes through a process called desulfurization. According to ANP (2017), the biomethane can be 90% of methane.

## 2.1 Vinasse from sugar cane

The growth of demand for products such as sugar and ethanol in Brazil increases the production and processing of sugarcane, and consequently, to a rise in industrial waste (Carrilho *et al.*, 2016). The vinasse is generated from the fermentation of cane juice, molasses, and the residue of sugar crystallization. Thus, the properties change, the type of plant and the kind of AD also influence. In this article, the values utilized are more consistent with the properties of vinasse by sugarcane juice, according to the values presented by Moraes *et al.* (2014) and Salomon and Silva Lora (2009). The vinasse from sugar cane comes out of distillation with a temperature of about  $107^\circ C$ . It is a dark brown colored liquid, naturally acid and has a strong smell, often reaching the smell of putrefaction (Joppert, 2019). The vinasse contains a high organic matter content, ranging from 10,973 to 14,801 mg/L of organic carbon. This residue also has high organic matter and biochemical oxygen demand (BOD) and chemical oxygen demand (COD) ranging from 6 to 25 and 15 to 65  $g/l_{O_2}$  (Carrilho *et al.*, 2016) respectively.

Tab. 1 Presents the main properties of vinasse from sugar cane ethanol to estimate biogas and bioenergy generated.

The vinasse is currently being used for fertirrigation, a technique that consists of applying vinasse to sugar cane cultivation. The pipes are transported to the sugarcane plantations, the vinasse collected from the stabilization ponds, and sprinkled (Joppert, 2019). This procedure is applied due to the high levels of organic matter and nutrients, especially potassium (Silva *et al.*, 2007).

The excess application of vinasse tends to reduce the soils' productive capacity, the yield of the harvest, and the quality of the surrounding waters (Fuess *et al.*, 2017).

This practice's challenge is the emissions associated with these channels; these emissions can reach  $455 g_{CO_2eq}/l$  (Bernal *et al.*, 2017). Studies also present the emission of nitrogen dioxide in these channels, even more, harmful since  $N_2O$  is 296 times more polluting than  $CO_2$  (Moraes *et al.*, 2014). Its highly corrosive nature makes this effluent approximately 100 times more polluting than domestic sewage (Salomon and Silva Lora, 2009). All these characteristics make vinasse a worrying waste for the environment.

Therefore, searching for a destination for this waste more suitable than fertirrigation is a current priority, and energy use is one of the possible techniques that stand out (Joppert, 2019).

## 2.2 Vinasse from corn

Corn is an agricultural product in abundance in the USA, so it is more common for ethanol to come from corn than sugarcane. Because of the co-products generated from corn in bioethanol production, corn fiber has recently become a biomass substrate of great interest (Eskicioglu *et al.*, 2011). Of this biomass, there is a residue known as vinasse produced in the distillation of the fermented corn mixture during the production process of bio-ethanol (Lee *et al.*, 2011).

In the bioethanol plant's traditional process, the subdivision between ethanol production consists of milling, hydrolysis, fermentation, distillation, and vinasse processing, which consists of evaporation of vinasse and distiller grains dry with soluble drying. In some ethanol plants, there is no separation of corn grains before fermentation. This process is

Table 1. Properties of vinasse from sugar cane.

Reference	Temp./R.	COD [kg/m <sup>3</sup> ]	% ECOD	pH	Fm [m <sup>3</sup> CH <sub>4</sub> / kgDQO <sub>rev</sub> ]	% CH <sub>4</sub>	Fev [Lvinhaca/Letanol]
Neto (2016)	M/UASB	23.8	80	3.5-4.9	0.5	60	12
Szymanski <i>et al.</i> (2010)	M/UASB	20-35	65	3.5-5.0	0.45	65	ND
Fuess <i>et al.</i> (2017) (an- nexed) 1 phase	T/UASB	29.6	60.7	4.5	0.23	58.4	10
Fuess <i>et al.</i> (2017) (an- nexed) 2 phases	T/ASTBRs	22.3	73.9	4.5	0.3	70	10
Bernal <i>et al.</i> (2017) (annexed)	M/UASB	37.5	74	ND	0.33	60	10.0-15.0
Bernal <i>et al.</i> (2017)(au- tonomous)	M/UASB	21	74	ND	0.33	60	10.0-15.0
Parsaee <i>et al.</i> (2019)	ND	27.5-299.2	79-81	2.8-8.6	0.31	60	8.0-20.0
Salomon and Silva Lora (2009)	M/UASB	120.22 (18.447)	91	3.895 (0.013)	0.26	67	10.0-12.0
Moraes <i>et al.</i> (2014)(an- nexed) 1 phase	T/UASB	33.6	72	ND	0.29	60	9.8
Moraes <i>et al.</i> (2014) (au- tonomous) 1 phase	T/UASB	21	72	2.9	0.29	60	10
Moraes <i>et al.</i> (2014) (Brazil)	T/UASB	30	72	ND	0.29	60	11.3

called dry grinding; it is different from wet grinding, where the corn grains are separated before fermentation (Eskicioglu *et al.*, 2011).

In the process, after the removal of the ethanol (where the residue is generated), the vinasse is centrifuged to separate the liquid fraction (fine vinasse) from the solid fraction (wet distilled grains). The fine vinasse passes through evaporators, where it is concentrated, forming a thick viscous syrup, then this syrup is mixed again with the distilled wet grains (WDG) to produce DDGS (dry grains distilled with solubles), which is used as cattle feed (Lee *et al.*, 2011). Each liter of corn ethanol produced about 20 liters of vinasse is generated, which implies a solution for vinasse management (Wilkie *et al.*, 2000).

Table 2 presents a summary of the literature regarding the properties of corn ethanol vinasse.

### 3. METHODOLOGY

#### 3.1 Prediction of the Biogas and Bioenergy

The methodology used to predict bioenergy from biogas is based on the mass conversion of sugarcane ( (Fuess *et al.*, 2017); (Moraes *et al.*, 2014); (Parsaee *et al.*, 2019)), utilized the season period 2019/20, for estimates the production the vinasse. The vinasse from corn uses the volume of ethanol produced in Brazil in 2019/20 to estimate the bioenergy.

The type of ethanol plant influences the prediction of bioenergy, DA system, whether single-phase or two-phase and the operating temperature of the reactor. In this article, the mesophilic temperature (32-37°C) was adopted, as it has a higher yield in UASB reactors, and less energy consumption (Bernal *et al.*, 2017); (Moraes *et al.*, 2015), and a single-phase system because it is the more common. Brazil has about 414 sugar and alcohol plants, all of which produce ethanol, and 150 of which produce sugar (Nova Cana, 2020); that is, 64% are autonomous plants, and the rest are attached. The vinasse flow rate,  $V_v$ , from sugar cane is described in Eq. (1), in [m<sup>3</sup>/h].

$$V_v = \frac{m_{sc} F_p F_{ev}}{T_s 24} \cdot 10^{-3} \quad (1)$$

The  $m_{sc}$ ,  $F_p$ ,  $F_{ev}$ ,  $T_s$  are respectively, the mass of the sugar cane, in tonnes per year [tc/year], the factor of productivity

Table 2. Main properties of corn vinasse for biogas estimation.

Reference	COD [ $kg/m^3$ ]	$E_{COD}$ [ $m^3/kg_{COD}$ ]	$F_m$ [ $m^3_{CH_4}/kg_{COD}$ ]	% $CH_4$	$F_p$ [ $L/t$ ]	$F_{ev}$ [ $L/kg$ ]
Loehr apud Wilkie <i>et al.</i> (2000)	56.0	97.3	ND	ND	379	6.29
Lee <i>et al.</i> (2011) (Mesophilic)	105-131	85	0.27	ND	ND	ND
Lee <i>et al.</i> (2011) (Thermophilic)	ND	ND	0.25	ND	ND	ND
Schaefer and Sung (2008)	100	89.8	0.33	59.5	ND	ND
Schaefer and Sung (2008)*	3.627	76	0.33	83	ND	9.4
Ganapathi apud Wilkie <i>et al.</i> (2000)	ND	ND	ND	ND	ND	ND
Dahab apud Wilkie <i>et al.</i> (2000)	59.4	ND	ND	ND	ND	ND
Stover apud Wilkie <i>et al.</i> (2000)	16	ND	ND	ND	ND	ND

\* UASB.

of cane processed in ethanol [ $L_{ethanol}/tc$ ], and the factor of productivity of ethanol in vinasse [ $L_{stillage}/L_{ethanol}$ ], season period in days.

The volume of vinasse in [ $m^3/year$ ], by corn ethanol, is described in Eq. (2), this depends on the ethanol flow rate ( $V_e$ ) in [ $m^3/year$ ], and the factor of productivity of ethanol generates the vinasse ( $F_{ev}$ ).

$$V_v = V_e \cdot F_{ev} \quad (2)$$

The equations for biogas generation (3),  $V_b$  [ $m^3/h$ ], bioenergy (4) is the same for both raw materials.

$$V_b = \frac{V_v \cdot COD \cdot E_{CODmet} \cdot F_m}{\%CH_4} \quad (3)$$

The terms COD,  $E_{CODmet}$ ,  $F_m$ , %CH<sub>4</sub> are respectively, COD of stillage [ $Kg m^{-3}$ ], the removal efficiency of COD [%], efficiency generation methane [ $Nm^3_{CH_4}/Kg_{CODrem}$ ], the percentage of methane in biogas [%].

The estimated power generated,  $P_g$  em [MW], is displayed in Eq. (4).

In this study, stationary engines were considered for energy conversion, with an efficiency of 33%. MCI conversion rate is 43% for the production of electricity from biogas, regardless of LHV. But in Fuess and Marcelo (2018) work, the yield used to generate electricity in combined cycles was 56%, and for cogeneration, it was 30%.

The energy efficiency of the biogas produced from the vinasse in reciprocating combustion engines is 20%, while it is 32% in the gas turbines and micro-turbines (Parsaee *et al.*, 2019); (Salomon *et al.*, 2011)). Another consideration is the technology used to convert the biogas in electric energy. Some variations were observed in the engine efficiency value, which significantly influences the power generated by the biogas. In the work of Bernal *et al.* (2017) the amount used was 33% for a stationary engine, Parsaee *et al.* (2019), adopted 38% for a stationary engine, Szymanski *et al.* (2010), 35% for SI and Neto (2016) was 40% and did not measure engine type, this variation influence after in the prediction the electric energy generation.

$$P_g = \frac{V_b \cdot LHV_b \cdot \eta_e}{86400} \quad (4)$$

The lower heat value of biogas ( $LHV_b$ ) [ $MJ/Nm^3$ ], depends on the concentration of methane in the biogas, according to Fuess and Marcelo (2018) the biogas with 58.4% de  $CH_4$  has LHV of  $20 MJ/Nm^3$  when the AD is in one phase, the LHV for two phases where there is biogas with 70% of  $CH_4$ , this value is  $23.8 MJ/Nm^3$ . To establish a method, it will use the formulation of Okamura (2013) for the LHV prediction of biogas  $MJ/Nm^3$ , which varies with the percentage of methane, (Eq. ( 5)).

$$LHV = 35.7134.\%CH_4 \quad (5)$$

The prediction of electric energy,  $E_e$  in MWh is given by Eq. (6). The available bioenergy will be considering energy consumption from the 10% (Bernal *et al.*, 2017).

$$E_e = P_g.24.T_s \quad (6)$$

### 3.2 Credits of Carbon

The credits of carbon ( $ECO_2$ ) [ $tCO_{2eq}/y$ ] was calculated by three different methodologies, the first methodology, developed by Parsaee *et al.* (2019) is described in Eq. (7).

$$ECO_2 = V_b.\%CH_4.Ec.LHV_m \quad (7)$$

Where  $V_b$  [ $m^3/year$ ] is the volume of biogas,  $\%CH_4$  is the concentration of methane in the biogas, and  $Ec$  [ $tCO_{2eq}/TJ$ ] is the emission coefficient.

The second methodology, adopted by Bernal *et al.* (2017), is described in Eq. (8)

$$ECO_2 = E_e.Ef \quad (8)$$

$Ef$  [ $tCO_{2eq}/MWh$ ] is the  $CO_2$  emission factor from Brazil

The third methodology, adopted by Szymanski *et al.* (2010), is described in Eq. (9). This method is used only for sugar cane vinasse, as it is adapted in open vinasse ducts, which does not happen with corn vinasse, since it is not in open ducts.

$$ECO_2[tCO_{2eq}] = \frac{V_v.Cc.AWR}{1000} \quad (9)$$

Where  $Cc$  is the Carbon content in vinasse and  $AWR$  is the Atomic Weight Ratio.

## 4. RESULTS AND CONCLUSIONS

### 4.1 Estimates of Biogas, Biomethane and Bioenergy

The Tables 3 and 4 shows the values utilized for this study. Some values are same both, engine efficiency,  $CH_4$  in biomethane, energy consumption at the plant.

Table 3. Main input data for each scenario for vinasse by corn.

Parameters	Values	References
Annual ethanol production [ $m^3/season$ ]	1690000	CONAB (2020)
COD vinasse [ $kg/m^3$ ]	67.5	Average values Tab.2
$E_{CODmet}$ [%]	87	Average values Tab.
$F_m$ [ $m^3_{CH_4}/kg_{DQOrem}$ ]	0.295	Average values Tab.2
$F_{ev}$ [ $L_{vinasse}/L_{ethanol}$ ]	20.69	Average values Tab.
$F_p$ [ $L_{ethanol}/tc$ ]	379	Average values Tab. 2
$CH_4$ in biogas [%]	71.25	Average values Tab. 2
LHV biogas [ $MJ/Nm^3$ ]	25.44	Eq. 5
Season period [days]	150	CONAB (2020)

The values used to make the average are for plants of one phase for DA and temperature of the mesophilic UASB reactor. The values of the parameters for Brazil were based on Szymanski *et al.* (2010), Neto (2016) e Parsaee *et al.* (2019).

From bioenergy, it was estimated the number of households that this energy could supply, the energy consumption per household was 254 kWh/month (EPE, 2019).

Table 4. Main input data for each scenario for vinasse by sugar cane.

Parameters	Annexed Plants	Autonomous Plants	Brazil	References
Mass of sugar cane [t/year]	$4.11E^8$	$2.31E^8$	$6.43E^8$	CONAB (2020)
COD vinasse [ $kg/m^3$ ]	37.50	25.57	25.65	Average value of Tab. 1
$E_{CODmet}$ [%]	74.00	74.00	75.00	Average value of Tab. 1
Fm [ $m^3CH_4/kgDQOrem$ ]	0.330	0.330	0.421	Average value of Tab. 1
$F_{ev}$ [ $L_{vinasse}/L_{ethanol}$ ]	12.50	11.93	13.00	Average value of Tab. 1
$F_p$ [ $L_{ethanol}/tc$ ]	53.40	82.90	66.55*	Average value of Tab. 1
$CH_4$ in biogas [%]	60	60	60	Average value of Tab. 1
$CH_4$ in biomethane [%]	90	90	90	ANP (2017)
LHV biomethane [ $MJ/Nm^3$ ]	32.14	32.14	32.14	Eq. 5
LHV methane [ $MJ/Nm^3$ ]	35.71	35.71	35.71	Eq. 5
LHV biogas [ $MJ/Nm^3$ ]	21.43	21.43	21.43	Eq. 5
Energy consumption at the plant [%]	10	10	10	Bernal <i>et al.</i> (2017)
Engine efficiency (%)	33	33	33	Average value of Tab. 1
Season period [days]	209	209	209	CONAB (2020)

\* Average values Nova Cana (2020).

Table 5. Results of biogas, biomethane and bioenergy generation from the vinasse from aucar cane and corn.

Parameters	Annexed Plant	Autonomous Plant	Sugar cane - Brazil	Corn
Biogas flow rate [ $m^3/h$ ]	$4.70E^5$	$8.44E^7$	$1.46E^6$	$8.52E^8$
Potential power generates from biogas [ $MW/year$ ]	$9.23E^2$	$1.66E^5$	$2.94E^5$	$2.27E^8$
Potential the bioenergy from biogas [ $MWh/year$ ]	$4.17E^6$	$7.49E^8$	$1.33E^9$	$7.35E^5$
Number of residences served from biogas	$1.37E^6$	$2.46E^8$	$4.36E^8$	$2.41E^5$
Biomethane flow rate [ $m^3/h$ ]	$3.13E^5$	$5.63E^7$	$9.99E^7$	$6.74E^8$
Potential power generates from biomethane [ $MW/year$ ]	$9.23E^2$	$1.66E^5$	$2.94E^5$	$2.27E^8$
Potential the bioenergy from biomethane [ $MWh/year$ ]	$4.17E^6$	$7.49E^8$	$1.33E^9$	$7.35E^5$
Number of residences served with biomethane	$1.37E^6$	$2.46E^8$	$4.36E^8$	$2.41E^5$

The vinasse results by sugarcane for generating biogas, biomethane e bioenergy by both are presented in Tab. 5.

It is noted that the production of vinasse by ethanol from corn is higher than that of sugarcane, as well as COD, which makes even the production of ethanol by corn is lower, the production of biogas is higher than that of sugarcane. But the harvest of corn is lower than that of sugarcane, so the electrical energy generated is lower.

Through the results presented, the potential for bioenergy generation in the sugar-energy sector is evident. The bioenergy generated serves millions of households. The annexed plants meet fewer requirements because it is only 36% of plants in Brazil and because it has a methane yield and the factor of productive ethanol per hectare higher. It is important to note that the bioenergy from biogas and biomethane is the same because in Eq. 3, the volume obtained is considering the methane concentration in the biogas.

The ethanol production of corn is still small compared to that of sugar cane, the generation of biogas by vinasse is also viable as shown in Tab. 5. But with a significant amount of electricity of 735 thousand MW/year, serving 241 thousand homes.

In order to present an estimate of the bioenergy produced by the sugar and alcohol industry, the Fig. 3 presents the electrical energy of the attached and autonomous plants according to the harvest CONAB (2020), of the last 10 years.

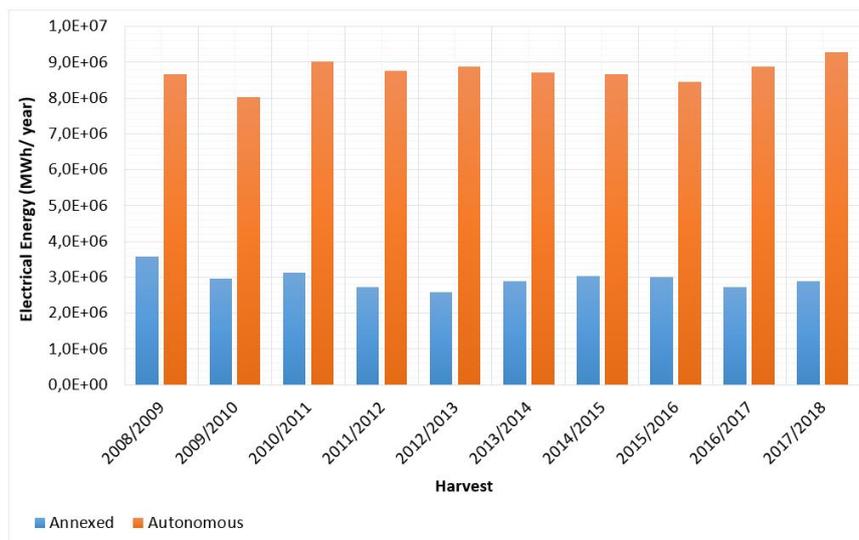


Figure 3. Prediction of bioenergy of the attached and autonomous plants during the last 10 years.

#### 4.1.1 Evaluation of bioenergy generation by different technologies

In order to assess the energy potential generated, three other technologies widely used in the industry were also analyzed. The technologies considered were the stationary engine, gas-turbine, cogeneration (biogas combustion in industrial boilers for steam and electricity cogeneration) and micro gas-turbine, the Tab. 6 show the values found in literature and the average value utilized in this results.

Table 6. The Efficiency of technologies analyzed.

Reference	Efficiency			
	Engine	Gas-turbine	Cogeneration	Micro Gas-turbine
Fuess and Marcelo (2018)	43	ND	30	ND
Moraes <i>et al.</i> (2014)	38	27	30	ND
Moraes <i>et al.</i> (2015)	38	ND	33	ND
Szymanski <i>et al.</i> (2010)	35	26	ND	ND
Joppert (2019)	ND	34.5	ND	33
Bernal <i>et al.</i> (2017)	33	ND	ND	ND
Salomon <i>et al.</i> (2011)	29	ND	ND	27
Average values	36	29	31	30

Figure 4 presents the electric energy coming from the autonomous and attached plants produced according to the different technologies and efficiencies.

Analyzing Fig. 4, it is noticeable that the engine is the most viable technology as it is more efficient. The bioenergy generated using the engine is about 19% more than a gas-turbine, 35% more than cogeneration and 10% more than a micro gas-turbine. Many studies show that the engine has better investment and lower returns than other technologies.

#### 4.2 Credits of Carbon

The data for realized this estimated are in Tab. 7, and the results of the carbon credits are presented in Table 8. Two methodologies are in the function the bioenergy, and method 3 is the emission carbon evited in open kennels of stillage by sugar cane.

Analyzing the results, in three methodologies applied, the importance of generating carbon credits using biogas as fuel is evident. As well as emissions avoided in the open channels of sugar cane vinasse. The carbon credits generation in Brazil is at minimum van be 154 million  $tCO_{2e}q/y$  for the sugar and alcohol industries. The generation of carbon credits from corn vinasse is also very attractive, at a minimum of 429 thousand  $tCO_{2e}q/y$ .

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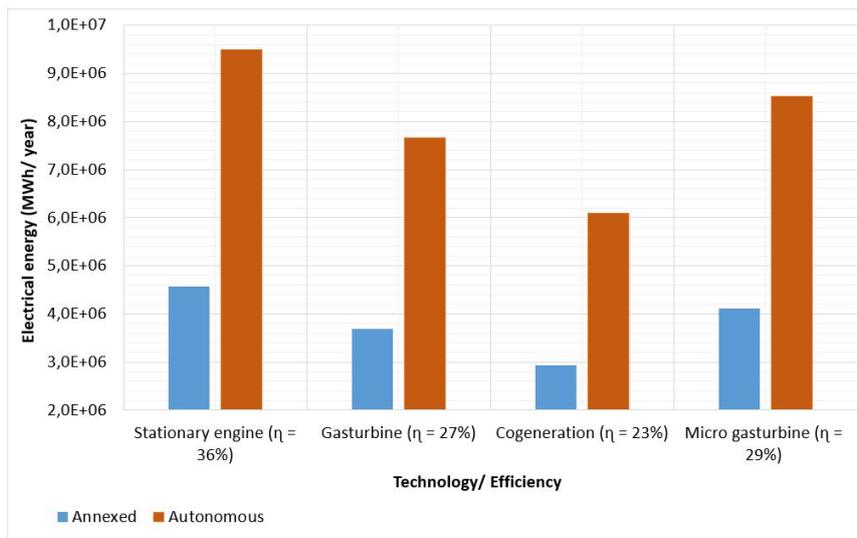


Figure 4. Prediction of bioenergy for each technology

Table 7. Main input data for each scenario for credits of carbon.

Parameter	Value	Reference
$CO_2$ Emission factor from Brazil [ $t_{CO_2eq}/MWh$ ]	0.5836	Bernal <i>et al.</i> (2017)
Emission Coefficient [ $t_{CO_2eq}/TJ$ ]	56.10	Parsaee <i>et al.</i> (2019)
Carbon content in vinasse	3.00	Szymanski <i>et al.</i> (2010)
Atomic Weight Ratio $CO_2$	3.67	Szymanski <i>et al.</i> (2010)

Table 8. Results of the prediction of carbon credits.

Stillage of	Methodology 1	Methodology 2	Methodology 3
Carbon credits $E_{CO_2}$ [ $t_{CO_2eq}/y$ ]			
Sugar cane (Annexed plant)	$4.95E^6$	$2.43E^6$	$1.70E^6$
Sugar cane (Autonomous plant)	$1.04E^7$	$5.11E^6$	$4.48E^6$
Sugar cane (Brazil)	$1.54E^7$	$2.54E^8$	$6.12E^6$
Corn	$1.22E^6$	$4.29E^5$	ND

in Brazil is no minimum van be 154 millions  $tCO_2eq/y$  for sugar and alcohol industry.

The generation of carbon credits from corn vinasse is also very attractive at least 429 thousand  $tCO_2eq/y$ .

Stillage is the waste with large potential for generating biogas and bioelectricity through all the results presented, both feedstocks analyzed. The generation of carbon credits is essential for sustainable development. The stillage from corn is less used today than vinasse from sugar cane. Still, research on its use is being studied more thoroughly since it presents favorable conditions for biogas and bioenergy production.

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