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Diagnosis of the Sugar-Energy Sector in Paraná State and Assessment of its Potential for Producing Electricity and Biomethane from Biogas

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***Abstract*— *The sugar-energy sector is one of the main economic activities in Brazil and has a high availability of residues with the potential for biogas production. In this sense, the present study sought to analyze the characteristics of the sugarcane processing plants and to define a theoretical plant with the average characteristics for the state of Paraná, with the aim of identifying the biogas production potential of this unit and to evaluate the monetization strategy that presents the best results. The analysis performed shows that the state has 23 units in operation that have an installed capacity to process up to 246,530 tons of sugarcane per day; the biogas production potential of the theoretical plant would produce over 21,127 MWh.year-1 of electric energy or 6,302,463 Nm³.year-1 of biomethane. When analyzing the different monetization methods of biogas, the self-consumption of biomethane associated with the commercialization of the surplus portion presented a better financial performance (R$16.1 million.year^{-1}) when compared to the exclusive sale of biomethane (R$12.6 million.year^{-1}) or electricity (R$7.3 million.year^{-1}).*

I. INTRODUCTION

The sugar-alcohol sector was consolidated in Brazil in the 1970s from incentives offered by the National Alcohol Program (PROALCOOL). This federal government initiative offered reduced financing rates and made possible both the installation of plants dedicated to ethanol production and the construction of distilleries attached to existing sugar mills [1].

Brazil is currently the largest producer and exporter of sugar in the world [2] and the second largest producer of ethanol, accumulating 29.5% of world production [3]. According to [4] in the 2020/21 harvest, Brazil will produce approximately 41.5 million tons of sugar and 32.5 million m³ of ethanol.

Brazilian ethanol is mostly produced from sugarcane, however, the number of units using corn as a source of raw material is growing. Currently, there are 8 Flex[1] and 5 Full

[1] Combined processing of corn and sugarcane.

[2] Exclusive corn processing.

[2] plants in operation in the country, plus 2 Flex and 7 Full units under construction [5]. Using other sources of raw material for ethanol production occurs mainly because of the need to complement the supply of ethanol to the market between the months of December and March (off-season), a period in which sugarcane is not available [6].

Currently, 365 plants operate in Brazil, 96% of which use sugarcane to produce sugar and/or ethanol. Of these, 221 are annexed (producing sugar and ethanol), 114 are autonomous (dedicated to ethanol production) and 16 produce only sugar [5].

Despite being one of the main integrants of Brazil's agroindustry [7], the sugar-energy sector still faces some challenges to be solved, such as the management and treatment of its waste. During the sugarcane processing, high volumes of organic waste are generated, in the agricultural phase, the straw is generated, while in the industrial stage bagasse, vinasse and filter cake are obtained [8].

Straw is a substrate that became available after the beginning of the transition to mechanized harvesting, previously sugarcane plantations were set on fire to facilitate manual harvesting. Data regarding the 2019/20 harvest shows that the mechanized method is the most used for sugarcane harvesting in Brazil, representing 91.8% [2]. The main application of straw has been to cover the soil to control erosion, maintain moisture, promote soil biodiversity and control weed growth [9].

Bagasse is a residue got during the extraction phase of the sugarcane juice [10] for each ton of processed sugarcane, 260 kg of bagasse is obtained [8]. This waste is used as fuel for cogeneration plants in the mills themselves, which besides meeting the internal demand for steam and electricity, can often market the surplus electricity [11]. According to [12], the power licensed for the production of electric energy from sugarcane bagasse in Brazil is approximately 11.9 GW, which represents 6.8% of the country's electricity matrix.

Filter cake is a solid waste generated during the cleaning of sugarcane juice. For each ton of processed sugarcane, 35 to 40 kg of this waste is generated [8, 13]. Inorganic particles, residual sugars, bagasse fragments, and water composed this material. The filter cake is widely used as fertilizer in the sugar cane plantation areas [14].

The vinasse is a liquid waste, potentially polluting and generated on a large scale. Each liter of ethanol generated 12 liters of vinasse. The primary use of this waste is also as fertilizer, it is transported from the industrial units to the planting area where it is applied in natura [8].

It is notable that the only residue of the sugar and alcohol sector that receives energy application is the bagasse, the others are used only as soil conditioning. In this sense, it is highlighted that the energy recovery of organic waste can be performed from the generation of biogas, through anaerobic digestion [15]. The production of energy through biodigestion is helpful because it makes it possible to recover the energy potential of the substrates without compromising their subsequent use as fertilizer.

Biogas comprises a mixture of gases composed mainly of methane (60 to 70%) carbon dioxide (30 to 40%) and other trace-level gases such as nitrogen, hydrogen sulfide, hydrogen, ammonia, and moisture [16].

Because of the high methane content this biofuel can be used for energy generation, the application with less technological complexity is the generation of heat from burning in boilers. In addition to thermal use, biogas has two other routes for energy use: (i) burning for combined heat and power, and (ii) purification to achieve quality levels comparable to natural gas [17]. In Brazil, purified biogas is commonly called biomethane or renewable natural gas.

In the State of Parana, the only biogas plant built to process residues from the sugar-energy sector has electricity as its main energy application. This industrial unit has an installed capacity of 10 MW and was the pioneer in Brazil to produce biogas on a commercial scale with this type of residue [12].

It is noteworthy that the State of Parana makes important contributions to Brazil's sugar-energy sector, being the third largest sugar producer in the country, the fifth in sugarcane processing and the sixth in ethanol production [4]. However, even with its high representation in the national scenario, Paraná has little information prepared specifically for the state, especially regarding sector characterization and projections of biogas production potential, a fact that explains the incipient diffusion of biogas projects in this sector in the state.

Thus, to enrich the technical literature on this subject for the state, the present study seeks to characterize the sugar-energy sector in Paraná and define a theoretical plant with the average characteristics for the state, in order to estimate the potential for biogas production for this unit and identify the energy application that presents the best revenue generation.

II. METHODOLOGY

2.1 CHARACTERIZATION OF THE SUGAR-ENERGY SECTOR IN PARANÁ

To carry out the diagnosis of the sector, the fundamental characteristics of the industrial units of the sugar-energy sector in Paraná were analyzed. The aspects evaluated were the number of mills by type (independent or annexed), their respective location, as well as their sugarcane processing and ethanol production capacities.

The Ministery of Agriculture, Supply and Livestock (MAPA) is the Brazilian agency that provides public information on sugarcane mills through the Sugarcane Production Monitoring System (SAPCANA). Thus, from SAPCANA it was possible to define the number of sugarcane mills in the State of Parana, as well as to perform the grouping according to their operational configuration (autonomous or annexed) [18].

The respective processing and ethanol production capacities per unit were determined based on public information made available by the National Petroleum, Natural Gas and Biofuels Agency through the public consultation center [19].

After evaluating the characteristics of the state a theoretical plant gathering the average characteristics of the state was estimated. The location of the theoretical unit was defined through an analysis that verified the Mesoregion of the State of Parana that concentrates the largest number of productive units. To define the type of plant, the units were grouped into annexed and autonomous, and the group with the largest number of units was selected to compose the configuration of the theoretical unit.

Finally, an analysis of the average among the mills allowed the definition of the sugarcane crushing capacity (tons.day^{-1}) and ethanol production capacity (m³.day^{-1}). It should be noted that the specific waste generation coefficients, as well as their respective biogas production potentials, were determined through information available in the literature.

2.2 ESTIMATED PRODUCTION OF BIOGAS, ELECTRIC ENERGY AND BIOMETHANE

Among the wastes available in the sugar and energy sector, in the present study vinasse and filter cake will be considered as substrates for biogas production, because of the greater biodegradability of these materials and the absence of competing uses, as suggested [20].

The strategy adopted to estimate the potential for biogas production consists in evaluating the co-digestion of these materials during the sugarcane harvest period (approximately 200 days per year) and maintaining the operation of the biodigestion system using filter cake during the off-season.

A mass balance was performed to estimate the flow rate, solids content, and biogas production of the unit. The calculation of total solids concentration was performed from (1), adapted from [21]:

$$C_0 = \frac{\sum_{i=1}^{n} Q_i * C_i}{\sum_{i=1}^{n} Q_i} \quad (1)$$

whereby

C_0 = Total solids concentration of the mixture (%),

C_i = Concentration of the mixture component (%),

Q_i = Flow of the mixture component (m³.day^{-1}),

n = Number of components in the mixture,

The estimation of methane production was performed using (2), adapted from [22]:

$$Q_{CH4} = Q_S * C_{COD} * BMP * E_{COD} \quad (2)$$

whereby

Q_{CH4} = Methane flow (Nm³.day^{-1}),

Q_S = Substrate flow rate (m³.day^{-1}),

C_{COD} = COD in the substrate (kg.m^{-3}),

BMP = methanogenic potential of the substrate (Nm³.kg$_{COD}^{-1}$),

E_{COD} = Conversion efficiency of COD to biogas (%),

(3) [23], was used to estimate the daily biogas flow rate:

$$Q_{Biogas} = \frac{Q_{CH4}}{C_{CH4}} \quad (3)$$

Q_{Biogas} = Biogas flow (Nm³.day^{-1}),

Q_{CH4} = Methane flow (Nm³.day^{-1}),

C_{CH4} = methane concentration in the biogas (%),

The estimate of electric energy production was performed considering the multiplication between the lower calorific value of the biogas, the flow rate, and the electrical efficiency of the selected generator. The electrical efficiency refers to the efficiency that the generator set has to convert biogas into electricity.

On the other hand, the estimation of biomethane production potential was performed by the multiplication of the biogas flow and a conversion factor from biogas to biomethane, which considers the methane content present in the biofuel and the losses involved in the process.

The electricity revenue estimate was made considering the price of R$ 347.5 per MWh commercialized, which corresponds to the updated value of the price achieved in the last energy auction won by a biogas plant in Brazil [24]. For biomethane it was considered as an assumption the commercialization with a price of R$ 2 per m³ of renewable molecule.

Furthermore, the avoided cost with diesel that could be replaced by biomethane in the truck fleet that performs the agricultural logistics during the harvest was also evaluated. For this, the price of diesel was considered to be R$ 6.5 per liter and the specific consumption of diesel was considered to be 1.04 $L_{diesel}.Ton_{cana}^{-1}$ [25] to estimate the total demand. It was also considered that 35% of the diesel demand could be replaced by biomethane if the fleet were converted to the combined use of diesel and gas [26].

III. RESULTS

3.1 CHARACTERIZATION OF THE SUGAR-ENERGY SECTOR IN PARANÁ

Paraná has 24 plants allowed to produce ethanol, however, one of them produces ethanol from soy, and for this reason was disregarded, so 23 units were accounted for in this study. Altogether the state can process 246,530 tons of sugar cane per day [19].

Fig. 1 shows the distribution of the number of mills by daily processing capacity.

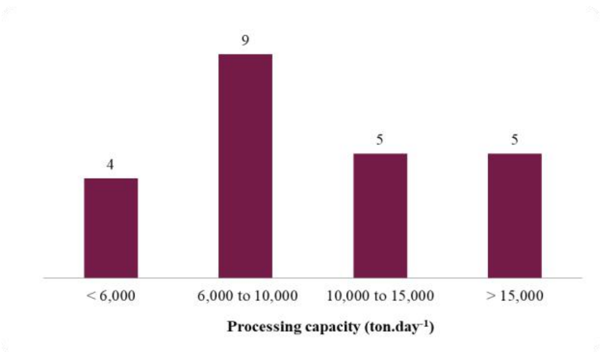

Fig. 1: Number of mills by processing capacity.

From the analysis carried out, it was found that approximately 39% of the mills in the state analyzed have a daily processing capacity of 6,000 to 10,000 tons of sugarcane, and, therefore, this is the range that brings together the largest number of units.

The territorial layout of the ethanol plants in Paraná is illustrated in Fig. 2.

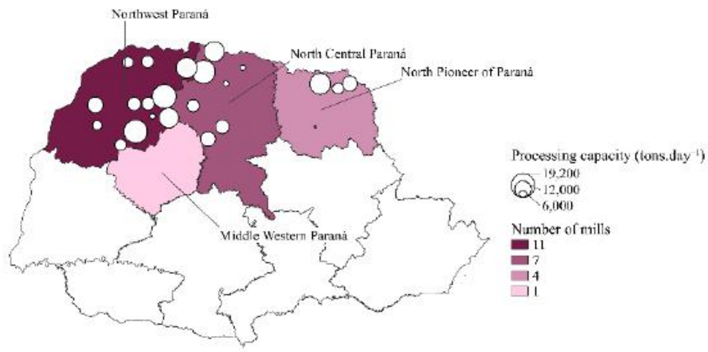

Fig. 2: Territorial arrangement of the sugarcane mills in Paraná.

Source: Own preparation based on data from [19].

The Mesoregion of Northwest Paraná, besides concentrating the largest number of mills, also aggregates the largest processing capacity. Altogether this region can process 126,040 tons of sugarcane daily, equivalent to 51% of the state capacity.

Besides understanding the location of the plants, it is also necessary to analyze their respective production characteristics. Fig. 3 presents the number of mills by type of configuration.

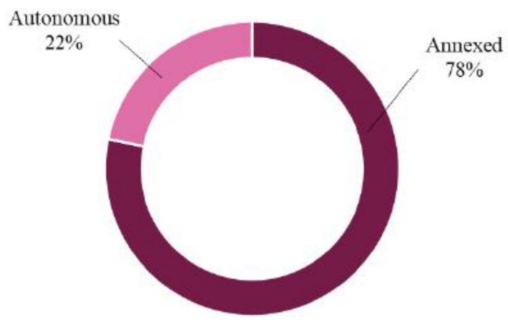

Fig. 3: Number of mills by type.

Source: Own preparation based on data from [18].

The predominance of annexed mills is explained given the vocation of the State of Parana in the sugar sector. This federative unit is the third largest producer of sugar in Brazil, behind only São Paulo and Minas Gerais. In the 2019/20 harvest, the state produced approximately 2 million tons of this commodity [4], which corresponds to 7% of the national production.

The aforementioned information defined the main characteristics of the state to configure a theoretical plant that represents the average parameters of Paraná.

Therefore, the theoretical mill that best represents the average characteristics for Paraná is located in the Northwest region of Paraná, is annexed and can process

10,719 tons per day, a value that is equivalent to the average sugarcane processing capacity in the state. The estimated total ethanol production capacity is 880 m³ per day.

3.2 WASTE GENERATION ESTIMATE

Among the waste from the sugar and ethanol sector, vinasse and filter cake were the substrates selected for the estimation of the biogas production potential, because of their high availability and for presenting physical-chemical characteristics that propitiate the energy recovery of this material through anaerobic digestion, as observed by [20].

Table 1 shows the estimated waste generation for the unit under analysis.

Table. 1: Estimated waste generation

	Input/Output	Unit	Source
Operational Days	200	$days.year^{-1}$	[27]
Specific generation of vinasse	11.84	$m^3_{vinasse}.m^3_{ethanol}{}^{-1}$	[8]
Specific generation of filter cake	35	$kg_{filter\ cake}.ton_{cane}{}^{-1}$	[8]
Daily generation of vinasse (volume)	3,248	$m^3_{vinasse}.day^{-1}$	-
Vinasse Density	1.14	$ton.m^{-3}$	[28]
Daily generation of vinasse (mass)	3,713	$ton_{vinasse}.days^{-1}$	-
Daily generation of filter cake	264.71	$Ton_{filter\ cake}.day^{-1}$	-
Generation of vinasse by harvest	742,702	$ton_{vinasse}.harvest^{-1}$	-
Generation of filter cake by harvest	52,943	$ton_{filter\ cake}.harvest^{-1}$	-

The vinasse production was estimated from its respective specific generation and the total ethanol production capacity, however, the maximum capacity was not considered because it was found that the mills in Paraná use, on average, only 31% of the available capacity. This rate was calculated from the ratio between the volume of ethanol produced in the 2020/21 harvest, 6,305 $m^3.day^{-1}$ [4], and the total capacity of the state, 20,220 $m^3.day^{-1}$ [19].

The amount of filter cake produced was estimated similarly. For this calculation, the specific generation of filter cake and the cane processing capacity were considered, adjusted by the average occupancy rate of the Paraná mills (71%). The occupancy rate corresponds to the ratio between the amount of processed cane 173,950 $ton.day^{-1}$ [19] and the state's processing capacity 246,530 $ton.day^{-1}$ [19]. According to [5] the occupancy rate of the sugar-alcohol sector in Brazil in 2020 was 90%, therefore, it is possible to observe that the State of Parana has an utilization rate of its installed capacity lower than the national average.

3.3 ESTIMATION OF BIOGAS PRODUCTION

In this sense, using the assumptions presented so far, a mass balance was performed (Table 2) to estimate the amount of cake to be stored (in order to ensure the generation of biogas in the off-season), to estimate the physical-chemical characteristics of the mixture and its potential for biogas production.

Table. 2: Mass balance for harvest and off-season.

	Substrate	**Flow rate ($ton.day^{-1}$)**	**TS [a] (%FM)**	**Methanogenic Potential ($Nm^3.ton^{-1}$) [a]**	**Methane (%v/v) [b]**	**Biogas Production ($Nm^3.day^{-1}$)**
Harvest	Vinasse	3,713	3.44%	8.15	57.67%	52,480
	Filter Cake	150	28.90%	54	57.67%	14,046
	Digestate	1,000	2%	-	-	-
	Mix	**4,863**	**3.93%**			**66,526**
Off-Season	Filter Cake	139	28.90%	54	57.67%	13,021
	Digestate	2,000	2%	-	-	-
	Mix	**2,139**	**3.75%**			**13,021**

Source: [a] [29], [b] [30]; TS – Total Solids, FM - FRESH MATTER

The mass balance performed needed to equalize the amount of stored cake and the volume of vinasse available to estimate the characteristics of the mixture that will be co-digested. In this context, the quantities considered for the composition of the mixture were calculated strategically so that the content of total solids (ST) did not exceed 4%, and for this reason it was necessary to consider the use of digestate (recirculated) as a diluent to increase the moisture of the mixture. The maximum value of 4% was determined, imagining that the biodigestion system would be a covered lagoon reactor.

Co-digestion of substrates is beneficial for biogas production, [31] when analyzing the associated digestion of waste from the sugar-energy sector observed higher potential for methane production compared to mono-digestion of the same materials. [32] they report that co-digestion confers greater stability to the process, favors the balance of nutrients and promotes better adaptation of microorganisms to the substrate. In addition, the authors state that co-digestion favors the solids content of the mixture to suit the parameters of the biodigestion system.

The estimated potential biogas production is 66.5 thousand $Nm^3_{biogas}.day^{-1}$ for the harvest and approximately 13 thousand $Nm^3_{biogas}.day^{-1}$ in the off-season. The notable difference is expected because vinasse accumulates 79% of the volume of biogas that can be produced daily during the operational period of the plant, and it is not available for the off-season. The total volume of filter cake to be stored for the off-season is 22,943 tons, a material that allows for the feeding of 139 tons per day when there is no generation of effluents by the sugar and ethanol mill.

It is noteworthy that the proposed biodigestion system has a conversion efficiency of organic matter into biogas equal to 70% [33]. For this reason, the effective volume of biogas produced during the harvest would be 46,569 $Nm^3_{biogas}.day^{-1}$ and 9,114 $Nm^3_{biogas}.day^{-1}$ in the off-season.

3.4 BIOGAS MONETIZATION

From the volume of biogas estimated for the theoretical plant, the respective potential for production of electricity and biomethane was evaluated. Table 3 gathers the results got during the estimation of the potential for electricity and biomethane production.

Table. 3: Estimated potential for electricity and biomethane production.

	Harvest	Off-season	Unit
Biogas production potential	46,569	9,114	$Nm^3_{biogas}.day^{-1}$
	Electricity Assessment		
Lower Heating Value biogas	4.5		$kWh.Nm^{-3}$
Electrical Performance	43.4%		-
Electricity Generation	90,948	17,801	$kWh.day^{-1}$
	Biomethane Assessment		
Conversion Factor	0.58		$Nm^3_{biomethane}.Nm^{-3}_{biogas}$
Biomethane Production	27,131	5,310	$Nm^3_{biomethane}.day^{-1}$

The value of 43.4% refers to the conversion efficiency of biogas into electric energy of the J620 engine manufactured by INNIO company, while the conversion factor of 0.58 $Nm^3_{biomethane}.Nm^{-3}_{biogas}$ was calculated considering that the methane content in biomethane is 97% and that there are losses of 2% of the processed methane [34].

From the estimates made (Table 3) it was found that the potential for electricity generation is 21,127 $MWh.year^{-1}$ while the estimate made for biomethane indicates a potential of 6,302,463 $Nm^3_{biomethane}.year^{-1}$. However, to define which alternative is more attractive, it was necessary to evaluate them in terms of the possible financial gains that both can generate.

In this sense, Fig. 4 presents the estimated realized revenues for both energy sources.

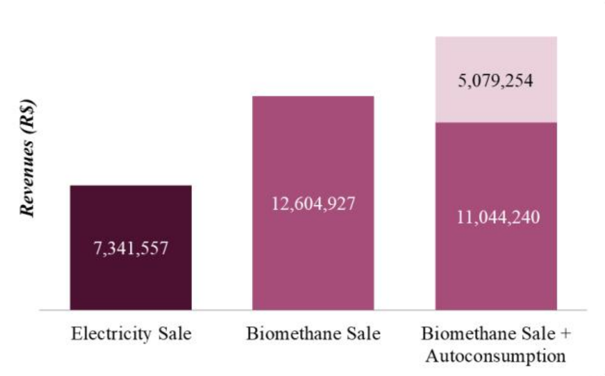

Fig. 4: Estimated revenues for biomethane and electricity.

The sale of biomethane combined with its use as a substitute for diesel is the one with the highest annual revenue generation, R$ 16,123,494, followed by the exclusive sale of biomethane. [35] when analyzing the different factors that influence the economic viability of biogas projects using vinasse as a substrate source, they concluded biomethane was the energy application with the best economic performance compared to electricity.

Besides the higher revenue generation compared to electricity, another factor motivating the purification of biogas to biomethane is the National Biofuels Policy (RenovaBio), instituted by Law No. 13,576 of 2017. RenovaBio seeks to boost biofuels in Brazil by remunerating producers through Decarbonization Credits (CBIOs), a financial asset that is issued according to the environmental energy efficiency of the producing unit, traded through the stock exchange in the country [36]. On average, a biomethane plant emits 0.028 CBIOs per cubic meter of the renewable molecule, if we consider the average price of CBIO equal to R$ 94.94 [37]. It is estimated that an additional gain with CBIOs of R$ 1,697,923 could be generated for the theoretical plant analyzed.

IV. CONCLUSION

Biodigestion is an interesting alternative for treating the residues available in the sugar-energy sector and recovering them energetically from biogas. In this sense, it was verified that the State of Parana has 23 sugar-alcohol mills predominantly annexed, and that they are mainly located in the northwest region of the state, it is also highlighted that over 39% of the identified mills can process from 6,000 to 10,000 tons of sugarcane per day.

It was found that a plant with the average characteristics of the state evaluated, has a potential for biogas production equal to 46,569 $Nm^3_{biogas}.day^{-1}$ in the harvest and 9,114 $Nm^3_{biogas}. day^{-1}$ in the off-season. This volume suffices to produce up to 21,127 $MWh.year^{-1}$ of electric energy or 6,302,463 $Nm^3.year^{-1}$ of biomethane.

When analyzing the possible financial gains from each of the energy applications, it was found that the commercialization of biomethane combined with the use of this energy source as a substitute for diesel is the one that presents the best performance, R$16,123,494 per year.

The financial results got are linked to the current geopolitical situation of Brazil and the world, because the fossil fuels are tied to international indicators that are on the rise because of the moment of global instability created by the pandemic of COVID-19 and which were driven again by the war between Russia and Ukraine. Therefore, biomethane as an energy source analogous to natural gas and a potential substitute for diesel in logistics, ends up benefiting from the rise of its fossil counterparts and generates more attractive revenues for the projects.

Besides this, the use of biogas to produce biomethane is also positive because this is an alternative energy source that could be included in the product portfolio of the Paraná mills, since electricity is already a widespread product in this sector. As a suggestion for future works, the authors suggest evaluating not only the revenues but also the expenses related to biomethane production to assertively verify the economic feasibility of implementing this type of project.

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