THE PERSPECTIVES OF BIOMETHANE TO CONTRIBUTE TO INCREASE THE NATURAL GAS SUPPLY IN THE STATE OF SÃO PAULO

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ABSTRACT: The Intended Nationally Determined Contribution from Brazil presented in COP 21, ratified in 2016 by the Brazilian Congress, establishes goals regarding reduction of carbon emissions and increasing the share of biofuels by 2030. In this scenario, biogas and biomethane are suitable renewable fuels to meet such goals. Thus, the Bioenergy Research Group of the Institute of Energy and Environment at the University of São Paulo (GBIO/IEE/USP) developed "Project 27 - The biomethane contribution prospects to increase the supply of NG in São Paulo" - within the Research Center for Gas Innovation (RCGI/FAPESP/SHELL/USP). Project 27's objective is to map the production of biogas and biomethane in the state of São Paulo, where the most promising biogas potential in Brazil resides. In view of the above, this article aims to present the results obtained for biogas and biomethane potentials so far, to compare it to other estimates and to study the incentives for these biofuels in São Paulo. The results obtained diverge from other studies' estimates for biogas and biomethane in the state of São Paulo. Nonetheless, they show that the biogas and biomethane potential is São Paulo is largely underused. However, the state already has a number of policies and regulations aiming towards introducing biogas and biomethane to the energy matrix.
Keywords: biogas, biomethane, urban waste, agro-industrial residues, potential

1 INTRODUCTION

Biogas is the gaseous mixture produced by anaerobic digestion of biomass, mainly from organic waste in landfills, sewage treatment stations, animal residues and agro industries - such as vinasse, a byproduct from ethanol production. Biogas composition is mainly methane (CH_4) and carbon dioxide (CO_2), as well as other compounds such as moisture, H_2S [[1] and other impurities (in the case of biogas from landfills and sewage stations there are also the so-called siloxanes (1), compounds produced by the degradation of hygiene products and others) [2]. The exact composition of biogas depends greatly on the organic feedstock.

Biomethane is mainly composed of CH_4 and this denomination aims to highlight its renewable origin.

Biogas and biomethane may have different energy uses: electricity production, thermal purposes, replacing conventional fossil fuels in vehicles and substituting/complementing natural gas (NG) by biomethane injection in NG grids [2]. Biogas is transformed into biomethane by undergoing a cleaning process (which removes the contaminants mentioned above) and a upgrading processes (which removes CO_2) [3].

Uses for biogas include decentralized power generation with or without combined heat and power - CHP (cogeneration) systems. In the case of Brazil, it is possible to inject electricity surplus produced into the interlinked grid and sell it for other consumers. Another common use for biogas is for cooking, as it is observed in many countries. However, specifically for Brazil, this does not have much use (2), since in Brazil there is LPG (3) production and distribution in bottles all over the country for cooking purposes. [5]. Uses for biomethane include possible diesel replacement in agricultural equipment (tractors, trucks, etc.) or injection into the NG grid [6].

The use of biogas and biomethane as an energy source can contribute to attain the goals of the existing climate policies in Sao Paulo State and in Brazil. These goals are present on the recent NDC (Nationally Determined Contribution), signed by Brazil in the context of the Paris Agreement, and ratified on September 12, 2016 by Brazilian Federal Government. The main goals of NDC are as follows [7]:

- By 2025: reduction in carbon emissions by 37% compared to 2005.
- By 2030: reduction in carbon emissions by 43% compared to 2005.
- By 2030: increasing the share of biofuels in the Brazilian Energy Matrix to 18%.

The emissions from the Brazilian energy matrix have been increasing significantly in recent years [8]. This is due to the increased use of fossil fuel fired thermoelectric power plants and the increase in gasoline consumption.

This increase of gasoline consumption was due to the lack of ethanol economic competitiveness, since in 2014 the Brazilian Federal Government decided to control gasoline prices (ethanol prices were then informally controlled, since ethanol prices must be equal to a maximum of 70% of gasoline prices) [9]. Hence, biogas and biomethane may have a crucial role in achieving the above-mentioned goals.

In several states, there are already legislations to incentivize biomethane injection into the gas grid. Some worth mentioning are:

- Sao Paulo State Decree N. 58,659 from Dec 4, 2012, which creates the "*Paulista* Biogas Program" [10];
- Rio de Janeiro State Law N. 6,361 from Dec 19, 2012, which creates the "State Renewable Gas Program" [11];
- Espirito Santo State Decree 3453-R from Dec 2013, which creates the "State Policy for the Incentive of Renewable Energies" [12] and
- Rio Grande do Sul State Law N. 14,864 from May 2016., which creates the "*Gaúcho* Program of Incentive to the Generation and Use of Biogas" [13]

All these legislations have their base on the biomethane standards from the National Regulatory Agency on Oil, Gas and Biofuels (ANP). ANP's resolution n. 8/2015 standardizes biomethane derived from biogas produced from agro-industrial and forestry residues [14] and the more recent ANP's resolution n. 685/2017 standardizes biomethane derived from biogas produced on landfills and sewage treatment stations (focusing on the control of siloxanes in biomethane) [15]. Importantly, according to the ANP Resolution n. 8/2015 mentioned above, biomethane should have in its composition at least 96.5% methane.

The incentives for biogas and biomethane in Brazil are still timid and small compared to those observed in other countries. In European countries, biogas is already an important alternative fuel to NG. Europe uses NG mostly to provide electricity and heat and as fuel in industrial processes [16]. One important aspect of using NG is the fact that it produces less CO_2 per KWh than other fossil fuels, such as coal and oil [17]. However, being a fossil fuel, it is not carbon neutral. Furthermore, NG is responsible for about 24% of European energy consumption and the issue of energy security arises, as NG is not evenly distributed between countries [18].

Therefore, the European Union regards biomethane as a solution to both climate change and energy security. In these countries, biomethane uses include not only fueling for transport and electricity generation, but also injection into the NG grid; studies [19] have concluded that the biomethane injection into the NG grid would result in full use of the gas produced.

Europe has indeed presented strong political incentives to increase biogas and biomethane usage, especially after the Europe 2020 policy [20]. However, biomethane has yet to see full utilization across the European Union. This is due to technical, political and economic barriers and the scarce literature regarding the barriers of biomethane injection. As the rest of the world intends to learn from Europe about the use of renewable energy, the lack of information about barriers facing biogas use could be preventing the injection of biomethane into the NG grid globally.

Brazil has some plants that generate and use biogas. According to CIBIOGAS (International Center for Renewable Energy-Biogas*)* [21], there are currently 155 biogas plants in Brazil, 43.8% using biogas from animal residues and 28.4% from industrial (food, beverage and dairy) and agro-industrial waste (others come from landfills, sewage treatment and waste co-digestion). The biogas plants are mostly concentrated in the Southeastern and South regions of the country and use biogas mainly for power generation. The total number of biogas plants in Brazil is still quite low, considering that smaller countries, such as some European countries, have a much larger number of biogas plants. For instance, Germany has 10,212 plants, the United Kingdom has 913 plants and Switzerland, 615 plants [22].

In terms of power generation, according to the Brazilian Electric Energy Regulatory Agency (ANEEL) [23], out of the 155 biogas plants in Brazil, there are currently 35 producing and selling energy to the grid, with a total installed power of 137.36 MW. This amount represents only 0.08% of the total installed power for electricity generation in Brazil. Of these 35 plants, 96.0% use biogas from solid municipal waste (MSW), 3.3% use biogas from animal residues and only 0.7% use biogas from agricultural residues.

The situation in the state of São Paulo is not different. According to CIBIOGAS [21], there are only 23 biogas plants in São Paulo, mainly producing biogas from landfills (4 plants) and industrial and agro industrial residue (12 plants). In terms of power generation, according to ANEEL [23], there are only 9 biogas plants that suppy power to the grid, with a total installed power of 73.77 MW, which accounts for only 0.31% of the total installed power in the state. These figures show that biogas is still an emerging source in the energy sector in both São Paulo and Brazil as a whole.

In this context, this paper aims to present RCGI-Project 27 - "The perspectives of biomethane to contribute to increase the natural gas supply" within the Research Centre for Gas Innovation (RCGI) of the University of São Paulo. The scope of Project 27 is to analyze the perspectives, the corresponding benefits and potential barriers, as well as to propose adequate policies for integrated solutions using biomethane as a contributor to the offer of NG. It aims to analyze the contribution of those solutions to increase the offer of both biomethane and NG to the energy matrix of the São Paulo State. The project also includes the development of a GHG emission reduction framework for partial or full substitution of diesel oil by biomethane.

The objective of this paper is to present the preliminary results of Project 27 regarding biomethane potential estimates and to compare these results to the existing data regarding the use of biogas in the state of São Paulo.

2 BIOGAS SOURCES OVERVIEW

2.1 Landfills

Brazil still has only 58% of its solid residue (MSW) disposed of in an adequate way, with more than 1,500 dumping disposals, of which more than half are located in the Northeast region (the lowest HDI region in the country) [24].

Federal law 12,305/10 introduced the National Policy on Solid Residue (NPSR) [25], which establishes guidelines for the management of solid waste that reflect the non-generation, reduction, reuse, recycling, and treatment of solid waste and environmentally adequate proper disposal of waste. In light of this law, the adequate collection of biogas and its use as an energy source – or its transformation into biomethane through the upgrade process – surely can contribute to the economic feasibility of the adequate disposal of MSW. However, this legislation is still to be put in place, having been postponed several times and more recently it is expected to start in 2020 [26].

Landfills are the one of the most correct ways (4) of waste disposal considering environmental aspects, since they are designed to dispose of high quantities of waste at a low cost with potentially fewer environmental effects [27]. During the anaerobic digestion process of organic matter in municipal solid waste, there is the formation of two pollution vectors of the environment: slurry, a liquid pollutant, dark in color and with a nauseating odor, and biogas. The landfill must include the soil waterproofing adequate protection to prevent slurry infiltration into the soil. Additionally, there must be a biogas and slurry extraction system and within the landfill.

It is worth noting that the biogas extraction process in landfills greatly depends on the gas collection efficiency, which is a function of the type of coverage used on the landfill and time [28].

2.2 Sewage stations

Sanitation is a critical issue in terms of quality of life, because its absence causes pollution of water resources, harm to the health of the population and particularly increasing infant mortality. In addition to that, raw sewage dump brings a serious risk of disease spreading.

According to IBGE [29], only 3,069 of the 5,564 municipalities in Brazil (55.2%) collect sewage and only 1,587 (28.5%) provide adequate sewage treatment in wastewater treatment plants. Specifically in São Paulo, most municipalities have sewage disposal systems in practically every urban area. Many, however, do not yet have a sewage treatment system.

In Brazil, the municipalities use a wide variety of systems for the treatment of sewage. Nevertheless, a large portion of the waste generated still faces disposal directly into water bodies without any treatment. For sewage treatment, anaerobic digestion may play an important role in these municipalities, contributing to a significant reduction in pollution potential and allowing the recovery of energy in the form of biogas [30], [31].

Anaerobic digestion of organic material takes place in reactors called anaerobic biodigesters. The predominant technology related to anaerobic systems in Brazil is the UASB (Up-flow Anaerobic Sludge Blanket) reactor. This type of biodigester has a sludge layer that allows liquid to pass through and removes the organic nutrients, generating the gas phase [31].

Even though many sewage treatment plants do produce biogas through anaerobic digestion of the sludge, there is no energetic use of it: the common practice in the country is to flare the biogas generated in the process [31].

2.3 Animal residues

The high rate of greenhouse gas (GHG) emissions in Brazil is due to agricultural activity (methane emission by ruminants) and changes in land use (deforestation).

Agriculture contributes more than 35% to GHG emissions in the country [33], currently ranking first among the sectors involved (Energy, Industrial processes, Agricultural, Forests and Waste).

Extensive livestock is a major cause of environmental damage. Among the main impacts, one can include the elimination and/or reduction of native fauna and flora, because of deforestation areas for the pasture growth and production and GHG emissions. The activity is considered by environmental agencies to "potentially cause environmental degradation," being framed with a large pollution potential. According to the Brazilian Environmental Law [34], the producer can be held criminally responsible for any damage caused to the environment and the health of humans and animals.

The negative impacts caused by livestock correlates with the main production method adopted by Brazil, the extensive system, characterized by low investment in training and maintenance. This system is mainly observed in cattle breeding [35]. However, changes are already occurring in the breeding process, in which part of the fattening occurs by confinement, called intensive livestock. Animal production intensive systems consist of restricting the physical space for the breeding of animals and provide food and water troughs. The purpose of these systems is to increase productivity (to produce more in less physical space and time, reduce the age of slaughter, accelerate return on invested capital, and reduce idleness of refrigerators in the off season) [36], [37]

In this intensive creative process, factors related to the accumulation of waste and generation of liquid waste with high organic load concentrations could cause direct pollution to that location, with consequences in every area of indirect influence, affecting environmental quality, mainly due to the possibility of contamination of water resources [36]. Given the reality of the agricultural sector, the treatment of waste from animal creations becomes a necessity due to the high content of organic matter and the large amount generated by the activity. If these residues do not receive proper treatment, the risks to the environment are significant, causing pollution and eutrophication of water bodies, among others.

One of the solutions to solve the problems of this waste is anaerobic treatment. In rural areas, besides UASB biodigesters, it is also possible to use a biodigester model known as covered lagoon, which uses the geometry of the anaerobic treatment lagoons and applies a coverage in order to capture the biogas generated [38]. The anaerobic treatment of waste is possible in rural properties (swine, poultry and dairy and beef cattle) that employ the intensive system.

2.4 Agro-industries

The industrial sector in São Paulo State corresponds to 36% of the Brazilian industrial production, while agricultural sector in São Paulo is responsible for 12% of the agricultural income of Brazil [39].

The agribusiness sector has a significant share in São Paulo state, being the largest producer of orange, sugarcane and sugar/ethanol from sugarcane. The state also produces meat and other agricultural products. In general, the agro-industries process raw materials that generate solid wastes that can be treated anaerobically and produce biogas.

The ethanol and sugar sector are one of the most important in the agro-industriy of São Paulo. In the 2016/2017 harvest, the production of ethanol reached 13.2 billion liters, representing 48.4% of the total ethanol production of Brazil [40]. This sector has a huge potential for biogas generation from vinasse. Consequently, it has also a huge potential for producing biomethane from biogas.

Vinasse is a byproduct of ethanol distillation, produced in large amounts. Each cubic meter of ethanol produced generates around 10-14 cubic meters of vinasse [41]. During the first years of sugarcane ethanol production in Brazil, ethanol producers did not properly dispose of vinasse, as it occurred mainly in rivers, with severe pollution damages (death of aquatic life and water contamination [42]). Since then, strict environmental legislation and adequate enforcement forbidding this practice pushed towards other uses for vinasse, mainly fertigation. Since vinasse contains large amounts of potassium and other minerals, it is a significant environmental and economic option for fertilization and irrigation, replacing fertilizers from fossil origin [43].

Vinasse cannot be disposed of in high concentrations, or it may contaminate underground waters. Additionally, in soils with a high concentration of potassium, the application of vinasse is not recommended [44]. In Sao Paulo State, CETESB controls the amount of vinasse disposed in the soils [45].

More recently, a few mills have started to use vinasse biodigestion for energy conversion, such as *Geo Energética* [46] and the *Iracema* mill [47], but the process is not yet widely disseminated. Biogas from vinasse presents one of the highest potentials for energy generation, including biomethane production in Sao Paulo State. The high number of mills (180 operating mills [48]) in the state allows significant scenarios for biogas production. However, conservative behavior and lack of incentives do not allow the real development of such potential.

In the case of Sao Paulo State, in order to demonstrate the importance of organic waste generated, we can use the production of the 13.2 billion liters of ethanol in 2016/2017 in the state. To estimate the amount of vinasse produced. If we consider an average of 12 liters of vinasse per liter of ethanol [49], we can estimate the production of 158.4 billion liters of vinasse in the same year. The possibility of generating large amounts of biomethane makes the injection of the biomethane in gas distribution network economically viable. However, since most ethanol plants in the state of São Paulo are not near the existing NG pipelines, this is yet not the case. [50]

3 METHODOLOGY

This study takes into consideration the evaluation of biogas potential production in the state of São Paulo produced from four different sources: MSW in landfills, sewage treatment stations, animal residue and vinasse from ethanol production. The production of biogas was estimated using the amount of each source, obtained from official references from the Brazilian or São Paulo government and biomass conversion to biogas through the anaerobic digestion process rates, obtained from literature and technical reports.

Biogas potentials were estimated considering the potential electricity generation per year and the potential installed power from burning biogas in gas engines. To calculate the potential available power, it was adopted an Otto-engine, with a 28% efficiency and a biogas LHV equal to 5,500 kcal/Nm³ (considering an average methane content of 50-55%). As for the available energy, it was adopted that the Otto-engines would operate all-year round, with the exception of the ones burning biogas from vinasse (which has only 5856 operation hours per year, due to the period of sugarcane harvesting season in the SE region and Sao Paulo as well). The load factor considered for the reciprocating engines was 87%.

Biomethane potentials were estimated considering biogas upgrade following ANP standards.

Another point studied was the current legislation, regulation and incentives for biogas and biomethane in the state of São Paulo, in order to perceive the perspectives for these biofuels in the near future.

This study implements a distinct methodological approach for estimation of biogas potential for each source, as follows:

3.1 Landfills

To evaluate the theoretical potential of biogas/biomethane production, the first step was to obtain a figure of the estimated population in 2016 to every municipality in the state of São Paulo. The information source was SEADE estimation for the 2016 population in the state of São Paulo [51]. For quantification of MSW in the municipalities analyzed in this study, the study considers the MSW per capita generation rate in São Paulo to be 1.1 kg/person.day [52]. With the MSW generation rate and the resident population in the municipalities of São Paulo, it was possible to calculate the estimated amount of MSW produced in 2016 for each municipality.

To estimate the amount of MSW collected, this study used the amount of MSW generated and the coverage area presented in the Atlas of Human Development in Brazil [53], which is an open-platform with the Human Development Index of Brazilian municipalities.

To evaluate biogas generation potential from landfills, the methodologies applied are those suggested by the IPCC [54]. The calculation of the potential methane generation from MSW considers the total population of each municipality and the average MSW generation per capita of Brazil, in addition to data provided by the IPCC, as described above.

It should be noted that the generation of methane from solid waste disposal varies over time, as it increases or decreases with the disposal of organic matter. Thus, the calculation of methane generation potential refers to the potential generated methane over a year array, excluding methane that may have previously be emitted from the waste deposited. The amount of methane emitted may increase with the increase of waste contained in the landfill in the course of time and vice versa, as the curve of methane generation has an increasing trend during the period in which the landfill receives waste (each new ton of deposited waste sums up new potential for biogas generation). The peak of the curve occurs in the final year of waste disposal in landfills and, from this point, the curve is driven by the decay constant, related to the degradation of organic matter over time [55].

For biomethane produced in each municipality, it was considered that 50% of the volume of biogas produced becomes biomethane after the cleaning and upgrading process.

3.2 Sewage stations

The information for the 2016 population of each municipality of São Paulo came, once again, from SEADE [51]. To quantify the sewage produced in the municipalities analyzed in this study, we adopted an average sewage produced per day, per person of 0.16 m³ (or 58.4 m^3 in the span of a year) [56].

With the sewage generation rate and the resident population in the municipalities of the state of São Paulo, it was possible to calculate the estimated amount of sewage produced in 2016 for each municipality. This study calculates the amount of collected sewage from the amount of generated sewage and coverage area presented in the Atlas of Human Development in Brazil [53].

To calculate the amount of methane generated in wastewater treatment plants, this study uses the methodology defined by CENBIO/IEE/USP [56]. For biomethane produced in each municipality, we consider once again that 50% of the volume of biogas produced becomes biomethane after the cleaning and upgrading process.

3.3 Animal residues

In the case of animal residues, preliminary results were based on COLUNA [57]. The author's methodology was adapted for this paper.

IBGE provides the number of heads of swine breeding [58]. The data for the number of heads of bovine farming (in confinement) came from ASOCON's census of confined cattle [59]. Based on these figures, it was evaluated the methane production from cattle and swine production, using the methodologies from CETESB [60] and from IPCC [54].

This study considers the residue called "poultry litter" to evaluate the potential of waste from cutting poultry breeding. Some studies have shown that poultry waste presents a higher potential for biogas production when compared to others. Therefore, they present a high methane content, what makes this waste more interesting [61], [62].

For the estimate of the amount of biomethane obtained from the biogas purification, it was considered the concentration of methane in biogas from cattle and poultry (60%) and in swine (66%) and assumed that the methane losses in the process are negligible (i.e. the volume of biomethane is exactly the volume of methane present in the biogas).

3.4 Agro-industries

Due to the major share of the ethanol and sugarcane industry in the state of São Paulo, the preliminary estimates will focus on biogas produced from anaerobic digestion of sugarcane vinasse for the estimate of biogas potential production from agro-industries.

According to MOREDA [64] the anaerobic digestion of organic waste (in this case, vinasse) depends on the conditions under which the process is carried out, as well as several factors such as type of reactor, residence time (for the cases where the system is continuous or batch), temperature, mixing performance, kind of microorganisms, presence of antibiotics, etc. The experiments carried out in different conditions and at different scales allow the determination of optimal conditions of degradation and, consequently, the potential for anaerobic digestion. The values for different categories of waste are obtained in literature. With these values, is possible to estimate the degradation of waste in terms of the reduction of Chemical Oxygen Demand (COD) or Volatile Suspended Solids (VSS).

It is important to notice that the specific amount of biogas produced (per waste unit), as well as the total waste generation and the maximum theoretical potential for biogas production can be calculated for each type of waste. However, only a fraction of the total waste generated may be used for the production of biogas. As discussed in POVEDA [40], there are often restrictions that inhibit the full use of the waste, or there are alternative uses for waste.

For the estimation of biogas and biomethane potentials, this study considers the following figures:

- Removed COD to biogas conversion factor of 0.45 Nm^3/kg_{COD} [65];
- Sugarcane vinasse COD varying between 40,000 - 65,000 mg/l;
- Vinasse to ethanol yield varying between 10-15 m^3/m^3 [49], [66];
- Anaerobic process COD removal efficiency ranging between 0.65-0.70 and resulting biogas with 57.5% CH_4 [67], [67];
- The production of ethanol in the state of São Paulo ranges, historically, between 11.5-16 million m^3/year [40].

To obtain an average value for the biogas potential, a Monte Carlo simulation was performed using the above-mentioned figures, using the software @risk.

4 RESULTS AND DISCUSSIONS

Table I presents the preliminary results of biogas and biomethane production of theoretical potential in the state of São Paulo.

From the inspection of Table I, one can assess that the main contributions for biomethane in the state of São Paulo would be from landfills and vinasse biodigestion: biomethane from vinasse is responsible for 50.2% of the estimated potential, whereas landfill stands for 40.4% of the total biomethane production.

Table I: Biogas and biomethane potential for the state of São Paulo.

Biogas Source	Biogas potential (10^9 m^3/year)	Biomethane potential (10^9 m^3/year)
Landfill	2.419	1.210
Sewage treatment	0.431	0.215
Vinasse	2.610	1.501
Animal residues	0.133	0.066
Total	5.593	2.992

Since biomethane is a substitute for NG, it is interesting to assess how much of this fuel consumption could be replaced by biomethane. According to the São Paulo State Energy Balance for the year 2016 [68], the consumption of NG was 6.008 10^9 m^3/year. Thus, the results show that the biomethane production could replace 48 % of NG consumption in São Paulo State.

From the biogas production, it was possible perform the calculations for power (kW) and energy (kWh/year) that would be available from this fuel.

Table II shows the power and energy available from biogas obtained from sources analyzed in this study.

Table II: Potential power production and electric energy generation in São Paulo state from biogas.

Biogas Source	Potential power (MW)	Electric energy (GWh/yr)
Landfill	495	3,769
Sewage treatment	88	671
Vinasse	798	4,067
Animal residues	26	207
Total	1,407	8,714

Considering that the electricity consumption in São Paulo State in 2015 was 150,723 GWh/year [68] the electricity produced could be 5.8% of electricity consumption in São Paulo state.

Other institutions have also evaluated similar figures to those presented on this paper. Table III shows a comparison between the results obtained in this study and studies performed by the regulatory the Secretariat of Energy of the state of São Paulo (SESP) in 2012 [69] and the sugarcane sector consulting company DATAGRO in 2017 [70].

Table III illustrates that the scenarios by the São Paulo state Energy and Mining Secretariat (*Secretaria de Energia e Mineração do Estado de Sao Paulo* - SEMSP) and DATAGRO are more optimistic than the ones obtained in this study, except for the biogas produced from landfills. SEMSP, in particular, forecasts a power output 2.4 times higher than the one predicted by this study. DATAGRO predicts an electrical energy output for biogas produced from vinasse biodigestion 4.76 times greater than the one predicted here.

Table III: Biogas potential power production in Sao Paulo State: comparison of results from existing studies.

Biogas Source	Potential power (MW)		
	This study	SEMSP	DATAGRO
Landfill	495	354	-
Sewage treatment	88	370	-
Vinasse	798	2,247	3,800
Animal residues	26	440	
Total	1,407	3,411	-

The differences observed are mainly due to different methodological approaches adopted by each study, along with the data sources for the calculation of biomethane potentials. Nevertheless, all studies point out the potential of biogas from vinasse as the major potential for power generation in the state.

Another interesting potential if the biomethane production from biogas upgrade. Therefore, it is interesting to compare the estimated biogas production and power generation from biogas with the actual figures observed in the state of São Paulo for each of the sources considered in this study. Table IV compares the estimated potential production of biogas with the actual production reported by CIBIOGAS [21] in the state of São Paulo.

Table V shows the comparison of the results of this study with data from ANEEL [23] for the installed power in power plants of the state of São Paulo that use biogas as fuel.

Tables IV and V show how underused is the biogas potential in the state of São Paulo. The existing production of biogas in the states represents only 5.83% of the total estimated potential biogas production. Regarding the installed power, it represents only 0.05% of the estimated potential power from biogas. Since the total potentials estimated in this study are more conservative than studies from other institutions, it is safe to say that the state of São Paulo still has a long way to go regarding the insertion of biogas and biomethane in its energy matrix.

Table IV: Potential production of biogas and average biogas production the state of São Paulo.

Biogas Source	Biogas potential (10^9 m^3/year)	Average biogas production (10^9 m^3/year)
Landfill	2.419	0.259
Sewage treatment	0.431	0.020
Vinasse	2.610	0.026
Animal residues	0.133	0
Other*	-	0.020
Total	5.593	0.326

*Biogas produced from beverage and food industry residues and co-digestion of other residues.

Table V: Potential power from biogas and installed power from biogas in the state of São Paulo.

Biogas Source	Potential power (MW)	Installed power (MW)
Landfill	495	72.92
Sewage treatment	88	0
Vinasse	798	0
Animal residues	26	0
Other*	-	0.85
Total	1,407	73.77

*Biogas produced from food industry residues.

Table IV also makes it evident how underused is the biggest potential of biogas for São Paulo (biogas from vinasse). The current production of biogas from vinasse is only less than 1% of the estimated potential. On the other hand, the production of biogas from MSW in landfills stands out, representing more than 10% of the estimated potential.

Another use for biogas from vinasse is for power generation (since most of the ethanol plants are already connected to the national grid), which is already starting to happen. Recently, the sugar and ethanol mill *Bonfim* has won an electric energy generation auction promoted by ANEEL, where the mill shall produce 20.9 MW from biogas produced from vinasse biodigestion by 2020 [71]. Another possibility is diesel replacement by biomethane in agricultural machines (mechanical harvesting machines, tractors and trucks). One recent research also evaluates burning biogas in boilers replacing bagasse to make it available for 2G ethanol production [72].

The most promising use for biogas from vinasse is the injection of biomethane (biogas after the cleaning and upgrading process) into the existing NG pipelines in the state of São Paulo. However, many ethanol plants are not located near the existing NG infrastructure. Figure 1 shows the NG pipeline and the ethanol mills location.

Figure 1: Existing NG infrastructure in São Paulo and sugar/ethanol mill distant up to 20 km from it [73].

EPE (Energy Research Company - *Empresa de Pesquisa Energética*) [73] evaluates that there are 66 mills located in a distance of up to 20 km from the existing NG pipelines, with a potential production of 3.0 million Nm^3 of biomethane per day, corresponding to 20% of NG consumption of Sao Paulo State.

Considering the huge potential of biogas and biomethane in Sao Paulo, the state government has been improving the state legislation related to biogas policy. In 2012, the state government, through the Decree N. 58,659 from Dec 4, 2012, created the "*Paulista* Biogas Program", which focuses mainly on biogas from sugarcane industry residue (vinasse), but also addressing other residues.

In 2012, in consonance with its own biogas program, the "PPE 2020" (Sao Paulo Energy Program - *Programa Paulista de Energia – 2020*) [66] was issued, recognizing the potential for biogas derived from vinasse, sewer treatment and landfills. Even though the PPE 2020 did not include the injection of biogas on the NG grid, it did not take long for the state government to seek to regulate it.

The Energy Regulation agency of the State São Paulo (ARSESP) started developing the regulation for biomethane injection in the state of São Paulo, which went to public consultancy in 2017 [74] and then was approved by the State Energy Council on June of the same year.

Other factors that may positively influence the biogas market in the state of São Paulo include:

- The Paris Agreement;
- ANEEL's resolution n. 482, (which provides regulation to distributed micro and mini generation of electricity and energy compensation systems [75]);
- Brazil Federal Government brand new renewable energy incentive program, RENOVABIO [76] and
- Private and civil society initiatives such as ABIOGAS and CIBIOGAS [77].

5 CONCLUSIONS

Our results have pointed out that the potential from the different sources in Sao Paulo state presents a $5{,}594{,}10^9$ m^3/year biogas production and a $2{,}992.10^9$ m^3/year biomethane production, which represents 49.8% of the consumption of NG in the state of São Paulo in 2016. In terms of electric energy, it was estimated that 8,714 GWh/year could be produced using biogas and biomethane, which represents 5.8% of the electricity consumption in São Paulo in 2015. However, we have found great divergences by comparing our results to those shown by other important institutions in the field of energy and bioenergy in the state of São Paulo. Those differences are due to distinct methodological approaches.

Regardless of the source of potentials estimations, biogas from vinasse stands out as the most promising source of biogas for the state of São Paulo. While it may yet not be possible to inject biomethane derived from this biogas in the existing NG pipeline, it is possible to burn biogas to increase the energy surplus of the sugar and ethanol mill or substitute diesel oil by biomethane in agricultural machinery.

By comparing the results obtained with the actual production of biogas and with the installed power using biogas in São Paulo, the chasm between the potential of biogas and its use in the state becomes evident especially for biogas produced from sugarcane vinasse. However, the government of São Paulo and the regulatory agencies are already acting to make the environment suitable for the expansion of biogas.

Moreover, the preliminary results show the important contribution of biogas and biomethane to reduce carbon emissions in Brazil and to reach the goals of the Paris Agreement. In this sense, Project 27 team has been continuously collaborating with ANP and with the state government in regulatory issues regarding mandatory share of biomethane in the gas grid and prices to be paid to producers (feed-in-tariffs).

Project 27 future activities include a better refinement of the presented results, based on consultation with all stakeholders involved, aiming to standardize the methodological approaches, the development of the geo-referenced mapping with the biogas and biomethane potential, among several other activities. Further and updated information on this project can be found at www.usp.br/rcgi and www.iee.usp.br/gbio.

6 NOTES

(1) The term "siloxanes" comes from this substance composition (silicon, oxygen and alkanes).
(2) Biogas is used in some farms in Parana State, in a local project funded by Itaipu Co.
(3) LPG - liquefied petroleum gas.
(4) With the recent policy expected to start in 2020, it will not be possible to dispose in natura waste in landfills but only the final residue from the different processes defined by the legislation. However, for the moment, the biggest challenge is to dispose MSW in an adequate way (in landfills) and not in dumps.

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