

Energy use of biogas generated in a sewage treatment plant: potential to reduce electricity costs and atmospheric emissions in northeast Brazil

Tuane Nascimento Mendes Aragão

Universidade Salvador

 0000-0002-9961-1199

tuane.aragao1@gmail.com

Gustavo Rafael Collere Possetti

Universidade Tecnológica Federal do Paraná

 0000-0001-8816-5632

Ícaro Thiago Andrade Moreira

Universidade Federal da Bahia

 0000-0002-3964-7368

Abstract: This research aimed to evaluate the management of a Sewage Treatment Plant (STP) and the existing biogas plant. A mathematical model was used to analyze the behavior of methane, biogas production and energy generation potential for a period of three years at the Jacuípe II Treatment Plant, located in northeastern Brazil. If the biogas plant were in operation, it would be possible to obtain autonomy for energy generation in the years 2016 and 2018. Greenhouse Gas Inventories - GHG, situational diagnosis of the biogas plant and scenario of financial losses with the deactivation of the plant were prepared. The results revealed that the emission of 1,958.38 tCH₄ could have been avoided with the use of an energy generator (85% less than that emitted) or 1,151.99 tCH₄ (50% less than emitted), if combustion by burner/flare. In addition, the financial loss due to the inactivity of the biogas plant resulted in US\$ 154,162.38, about 67% of the actual energy expenditure of the plant in the period from 2016 to 2018. The reactivation of the biogas plant present in this station will bring environmental benefits, since the emission of GHG will be mitigated, in addition to financial benefits, since the energy use of biogas in the plant will provide a reduction in the expenses with electricity from STP Jacuípe II, in line with the aspects of sustainability.

Keywords: Biogas plant; UASB; methane; electricity; greenhouse gases; emissions; inventories.

INTRODUCTION

The scenario of sanitary sewage in Brazil is marked by the low coverage index, presenting an average coverage of sewage treatment of only 46% for the estimate of sewage generated in 2018, according to data from the National Sanitation Information System (SNIS 2019).

The main challenges of the Sewage Treatment Plant - STP are the high demand for electricity, which is directly related to the type of treatment adopted; and sludge elimination (Di Fraia et al. 2018; Liu et al. 2018; Kalavrouziotis 2017). However, sustainable STPs capable of transforming sewage into resources with added value in a systematic, integrated and sustainable way, appear as a promising possibility (Rodriguez et al. 2019; Possetti, Requião 2018).

The use of energy is related to economic growth, thus, energy resources become significant worldwide, with emphasis on renewable sources, as their exploitation strengthens sustainable development (Kahia, Aïssaa, Lanouarb 2017; Aslan 2016).

Sewage sludge can be used as a renewable energy source due to its high volume of production and energy content, being a suitable material for energy recovery. Thus, it is important to develop cleaner technologies that value the use of this waste aligned with environmental planning and management (González-Arias et al. 2020; Hossain, Morni 2019). Anaerobic digestion (AD) is a favorable alternative to treat waste with biodegradable organic matter and simultaneously produce energy (Bakraoui et al. 2020; Santos-Clotas et al. 2019; Anjum et al. 2018; Laramée; Tilmans; Davis 2018; Liu et al. 2016; Deng et al. 2014; Pérez-Elvira; Diez; Fdz-Polanco 2006). In this treatment stage, the Upflow Anaerobic Sludge Blanket Digestion - UASB are widely used (Vassale et al. 2020), especially to treat sewage. According to Moreira (2014), 64% of the sewage treatment plant in Brazil use anaerobic sewage treatment. Among the most used systems in STP in Brazil is the UASB.

Some authors address the considerable potential of biogas production from anaerobic digestion and argue that converting biomass sources to biogas generation has been widely attracted huge attention through this technique (Antwi et al. 2017; Pantawong et al. 2015; Arhoun et al. 2013; Angenent et al. 2004). Biogas from anaerobic digestion of biomass can be a promising alternative for renewable energy, being mostly composed of methane and carbon dioxide (Unpaprom et al. 2020; le Saché et al. 2019). Biomethane produced by the treatment of biogas is also a promising source of green energy (Baena-Moreno et al. 2020). Biomethane can replace fossil fuels in various applications such as heat and power generation and the transportation sector (Atelge et al. 2018).

The more efficient the biological treatment stage, the greater the production of methane, one of the main Greenhouse Gases - GHG, and which gives biogas the calorific potential, resulting in the ability to obtain chemical energy (Deng et al. 2014; Jiang et al. 2013; CENBIO 2006). According to Valenti, Arcidiacono and Ruiz (2016), there is considerable potential for the production of biogas from anaerobic digestion. In view of the growing need for new energy sources and the need for adequate planning and management in the unitary sewage treatment processes, studies based on the use of biogas for energy purposes in STP have become a new perspective, which is already justified by the environmental function and which added to the economic issue, adds even more importance.

According to the Intergovernmental Panel on Climate Change (IPCC, 2007), methane gas, the main constituent of biogas, is considered the second largest contributor to global warming. In 2019, there was an increase of 9.6% in greenhouse gas emissions in Brazil, reflecting the emission of 2.17 billion tons of carbon dioxide equivalent (tCO₂e). The waste sector was responsible for the emission of around 96 million tCO₂e in 2019, with the treatment of domestic liquid effluents responsible for 26% of this portion. (SEEG 2020). The use of biogas energy can mitigate this scenario.

There are specific methods developed in order to estimate the production of methane, biogas and energy generation, among them are the mathematical model developed by Chernicharo (2007) that considers the mass balance of the Chemical Oxygen Demand - COD and presents equations that estimate a methane production ; the mathematical model developed by Lobato (2011) for calculating the COD mass balance and the energy potential of biogas from UASB reactors; ProBio 1.0, a computer program developed based on the mathematical model of Lobato (2011) for estimating biogas production in UASB reactors and energy generation potential (Possetti et al. 2015). These and other methods are presented as important tools for estimating energy generation from the recovery of biogas in STP.

This research contributes to the literature for some reasons: anaerobic sewage treatment plants in several countries do not yet have the use of biogas energy; therefore, the study aims to emphasize the importance of the biogas use in STPs, with better planning and environmental management. The second reason is the calculation of the financial loss due to non-operation of the biogas plant installed at the STP. Another reason is the possibility of sharing a regional experience to guide other managers of STP biogas plants in other countries. Finally, there is the dissemination of the practical use of a specific mathematical model to understand the theoretical energy potential of biogas from UASB reactors, enabling the adoption of strategic measures in the implantation or reactivation of biogas plants in STPs.

METHODOLOGY

The methodology consisted of a case study at STP Jacuípe II, located in the Northeast region of Brazil, with a population of 129,600.

The average monthly effluent flow in 2018 was 152.68 l.s^{-1} , with a monthly average of Chemical Oxygen Demand (COD) of 795 mg.l^{-1} . According to the History of Energy Consumption and Demand Report of STP Jacuípe II, the average monthly active energy consumption of STP between the months of november 2018 and october 2019 was 93,479.85 kWh, corresponding to an average monthly expense of US\$ 7,498.97. The total expense for the same period was approximately US\$ 89,987.62.

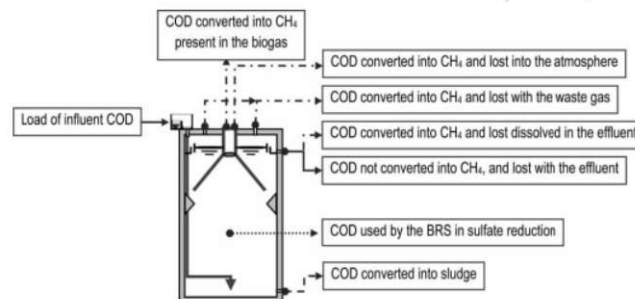
It is a conventional STP, with a nominal capacity of $1,296 \text{ m}^3.\text{h}^{-1}$, with preliminary/primary and secondary treatment. The decomposition of organic matter in that STP occurs in UASB reactors.

The monthly reports of the sewage quality index for the years 2016, 2017 and 2018 were used. The monthly affluent and effluent COD concentrations were identified in the laboratory using the colorimetric method, following the Standard Methods standard for the Examination of Water and Wastewater (APHA 1998). The collection of effluent was carried out monthly at six different points: input of the STP, output of the UASB, output of the aeration tank, output of the STP, upstream and downstream of the point of discharge into the river. The points used in this research were entering and leaving the treatment plant.

The biogas plant of STP Jacuípe II consists of a capture system (closing of the biogas collection chambers of the reactors) and controlled burning of the biogas in flare type burners; biogas transport system; instrumentation consisting of measuring relative and absolute operating pressure, temperature, flow and biogas composition; storage system composed of a double membrane gasometer and a bio-sulfurization system (biological removal of hydrogen sulfide); biogas conditioning system for moisture removal (biogas cooler); and complementary removal of hydrogen sulfide (activated carbon filter).

A mathematical model was used to calculate the COD mass balance and the energy potential according to COD conversion routes and methane flow in UASB reactors, as shown in Figure 1 (Rosa, Lobato, Chernicharo 2020; Lobato, Chernicharo, Souza 2012; Lobato 2011).

Fig 1 COD conversion routes and methane flow in UASB reactors (Lobato, Chernicharo, Souza 2012)



In this model, the COD portions removed in the system and converted into sludge and consumed in the reduction of sulfate are estimated. Through the results of these plots, the portion of the maximum COD converted into methane and, consequently, the maximum volumetric production of methane was calculated. In order to calculate the volume of methane actually available for energy use, this mathematical model considers the losses of methane that was dissolved in the effluent and in the gas phase with the residual gas, in addition to other eventual losses in the gas phase. After the aforementioned steps, discounting the calculated losses, the amount of methane available in the biogas generated at the STP is obtained, that is, the potential for generating available electrical energy becomes known (Lobato 2011).

The inputs for the mathematical model are based on measured and unmeasured variables at the station, such as the temperature of the biological reactor, mean affluent flow, removal of COD, sulfate concentration in the effluent, among other parameters.

The results that will be presented in this work were found applying the less optimistic scenario of the mathematical model proposed by Lobato (2011), which is characterized by the lower energy potential in systems operating with more diluted sewage, higher concentrations of sulfate, less efficient removal of COD and higher rates of methane

loss. Knowing the methane portion, the equivalent of 65% of the biogas was adopted, thus estimating the biogas portion.

Other authors cited or used parameters and definitions adopted in this mathematical model (Campello et al. 2020; Centeno-Mora 2020; Mora, Chernicharo 2020; Bantacut 2019; Ferreira 2019; Nadaleti 2019; Do Amaral 2018; Silveira et al. 2018; Bressani-Ribeiro et al. 2017; Gontijo et al. 2017; Rosa et al. 2015). The equations used in the mathematical model are shown in Table 1.

Table 1 Equations of the mathematical model used.

Parameters	Equations	Variables
COD converted to biomass	$COD_{Lodo} = COD_{Remov} \times Y$	COD_{Lodo} : COD converted to biomass ($kgCOD_{Slude} \cdot day^{-1}$) COD_{Remov} : COD removed from the affluent ($kgCOD_{Remov} \cdot day^{-1}$) Y : Coefficient of solid production ($0,15 kgCOD_{Slude}/kgCOD_{Remov}$)
Sulfate converted to sulfide	$CO_{SO4-Conv} = Q_{Average} \times C_{SO4} \times Ef_{SO4}$	$CO_{SO4-Conv}$: Concentration of SO_4 converted to sulfide ($kgSO_4 \cdot day^{-1}$) $Q_{Average}$: average outflow of sewage ($m^3 \cdot day^{-1}$) C_{SO4} : Concentration of SO_4 in the affluent ($0,06 kgSO_4 \cdot m^{-3}$) Ef_{SO4} : Sulfate Reduction Efficiency (75,0%)
COD used to reduce sulfate	$COD_{SO4} = CO_{SO4-Conv} \times K_{COD-SO4}$	COD_{SO4} : COD ratio used by bacteria that SO_4 ($kgCOD_{SO4} \cdot day^{-1}$) $CO_{SO4-Conv}$: Concentration of SO_4 converted to sulfide ($kgSO_4 \cdot day^{-1}$) $K_{COD-SO4}$: COD consumed in the reduction of sulfate ($0,667 kgCOD_{SO4}/kgSO_4$)
COD converted to CH_4	$COD_{CH4} = COD_{Remov} - COD_{Lodo} - COD_{SO4}$	COD_{CH4} : COD convertida em CH_4 ($kgCOD_{CH4} \cdot day^{-1}$) COD_{SO4} : COD utilizada por bactérias redutoras de SO_4 ($kgCOD_{SO4} \cdot day^{-1}$)
	$Q_{CH4} = \frac{COD_{CH4} \times R \times (273 \pm T)}{P \times K_{COD} \times 1000}$	Q_{CH4} : Maximum volumetric production of CH_4 ($m^3 \cdot day^{-1}$) R : Gas constant ($0,08206 atm \cdot L \cdot mol^{-1} \cdot K^{-1}$) T : Operating temperature of the reactor ($27^\circ C$) P : Atmospheric pressure (1 atm) K_{COD} : COD to 1 mol of methane ($0,064 kgCOD_{CH4} \cdot mol^{-1}$)
Loss of CH_4	$Q_{W-CH4} = Q_{CH4} \times p_w$ $Q_{O-CH4} = Q_{CH4} \times p_o$ $Q_{L-CH4} = \frac{Q_{Average} \times p_L \times f_{CH4} \times R \times (273 \pm T)}{P \times K_{COD} \times 1000}$	Q_{W-CH4} e Q_{O-CH4} : Losses of CH_4 in the gas phase ($m^3 \cdot day^{-1}$) p_w e p_o : Losses of CH_4 in the gas phase (5,0%) <i>each</i> Q_{L-CH4} : Loss of CH_4 dissolved in effluent ($m^3 \cdot day^{-1}$) $Q_{Average}$: Average flow of sewage ($m^3 \cdot day^{-1}$) p_L : Loss of CH_4 dissolved in effluent ($0,020 kg \cdot m^{-3}$) f_{CH4} : Theoretical conversion factor of COD in CH_4 ($4,0 kgCOD/kgCH_4$)
Production of CH_4	$Q_{Real-CH4} = Q_{CH4} - Q_{W-CH4} - Q_{O-CH4} - Q_{L-CH4}$	$Q_{Real-CH4}$: Available flow rate ($m^3 \cdot day^{-1}$)
Power Generation Potential	$PCI_D = PE_{CH4} \times PCI_{CH4} \times K$	PCI_D : Lower calorific value available (kWh/Nm^3) (65% de CH_4) PE_{CH4} : Specific weight of CH_4 (kg/Nm^3) PCI_{CH4} : Lower calorific value of CH_4 ($kcal/kg$) K : 4,19 $kWh/3600$ (unit conversion)
	$PE = Q_{N-Real-CH4} \times PCI_D \times Ef$	$Q_{N-Real-CH4}$: Standardized flow available ($Nm^3 \cdot day^{-1}$) PE : Available electric power ($kWh \cdot day^{-1}$) Ef : conversion efficiency of thermal machines (25,0%)

An inventory of greenhouse gases from the sewage treatment plant used was prepared based on the operating characteristics of STP Jacuípe II. Among the different existing methodologies for carrying out greenhouse gas inventories, the GHG Protocol, originally developed in the United States in 1998, by the World Resources Institute (WRI), is the most used tool worldwide by companies and governments to understand, quantify and manage its emissions, following the guidelines determined by the Intergovernmental Panel on Climate Change - IPCC (GHG Protocol 2017).

For the calculation of financial losses, the electricity generation potential (kWh) was considered to supply all or part of the consumption that was recorded during peak hours and the residual of the electricity generation potential to supply part of the consumption off-peak hours. The tariffs for calculating financial losses were applied according to Table 2.

Table 2 Tariffs applied to calculate financial losses (National Electric Energy Agency – ANEEL)

Years	Period	Tariff at Peak (US\$/kWh)	Tariff Off-Peak (US\$/kWh)	Effective Cycle	Homologatory Resolution ANEEL	Tariff Modality
2016	January - April	0.53	0.1	22/04/2015 - 21/04/2016	No. 1,878 - April 2015.	Green Horseasonal
	May - December	0.37	0.06	22/04/2016 - 21/04/2017	No. 2,066 - April 2016.	
2017	January - April					
	May - December					
2018	January - April	0.5	0.07	22/04/2018 - 21/04/2019	No. 2,382 - April 2018.	
	May - December					

Although STP Jacuípe II is in operation, the biogas plant is deactivated. After the start of operations in 2016, energy was generated for only 21 days, and due to various problems, such as the lack of adequate sealing of UASB reactors and specialized labor, the plant was deactivated. In a biogas plant in STP, it is fundamental to guarantee the complete tightness of the reactor, as well as in the capture of gas and in the other stages of transport and storage. However, it becomes much more complex to guarantee the airtightness in a biogas system that was not designed in conjunction with the STP project, as is the case with Jacuípe II, which after many years of operation, went through an adaptation process for the implementation of the biogas energy recovery system. Storage and capture of biogas are also extremely important factors. In general, a natural part of the biogas generated can involuntarily escape through these points. UASB reactors of STP Jacuípe II underwent some adaptations with the implementation of the project for the use of biogas in the STP, aiming to ensure tightness, such as the implantation of a size 80 x 80 cm cover, made of stainless steel material with rubber seal for airtight closure.

Another aspect that may have compromised the biogas plant of STP Jacuípe II is the dynamics of scum removal. According to Rosenfeldt et al. (2015), in order to make the use of biogas technically feasible, a scum removal system was developed and implemented using gutters inside the three-phase separation compartment, similar to the devices installed in COPASA's STP Onça and ETA Rio do Peixe's SAAE Itabira, presented by Chernicharo (2007). The recommended time interval for removing the foam must be very long, in order to allow the material to begin to harden at the bottom (Brasil 2015). Among the recommendations of the company responsible for the implantation of the plant, the highlight is the periodic foam removal with the lids closed, however, there is no guarantee that this procedure has occurred in this way, mainly due to the lack of specialized labor, a factor that will be reported below. It was also observed the absence of activated carbon in the filter responsible for the removal of moisture, which makes it impossible to treat biogas for energy generation. According to Matsui and Imamura (2010), activated carbon is the most widely used adsorbent support in filters for biogas purification, having demonstrated high removal efficiencies. However, a limiting factor is the high prices of this product (Cabrera- Codony et al. 2015), a fact that also caused the absence of the product in the filter present in the plant.

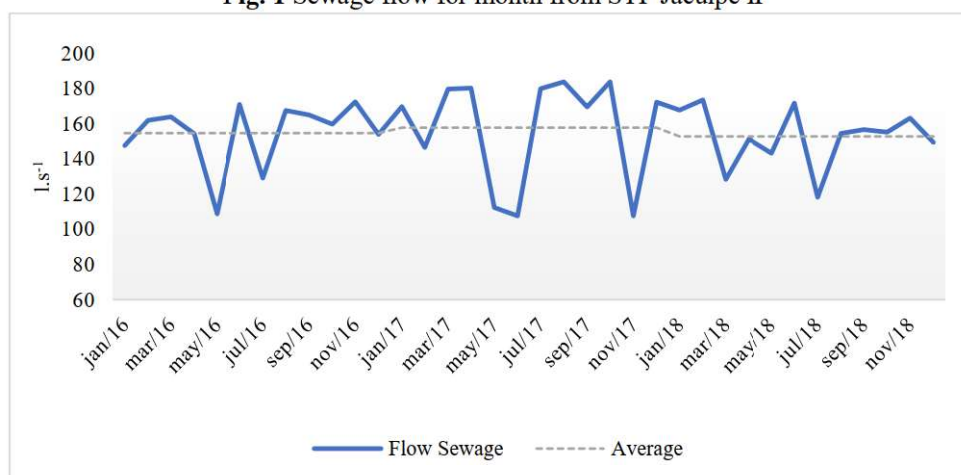
Among the activities required for this plant, some can be listed as main, such as reactor inspection, slag removal, removal of excess sludge, tests for checking the tightness of the system using specific leakage and biogas meters and inspection of system ducts transport of biogas, avoiding the occurrence of diversions that cause the accumulation of condensed water that hinder the passage of gas.

The designation of a manager is important, so that there is planning and environmental management of the system, in addition to making strategic decisions, one of which is the adequacy of the plant structure and the energy contract to the participation of the distributed generation system, allowing compensation of energy and even, in better situations, remote self-consumption contemplating other energy contracts from the sanitation company (Aragão, Possetti, Moreira 2019).

RESULTS AND DISCUSSION

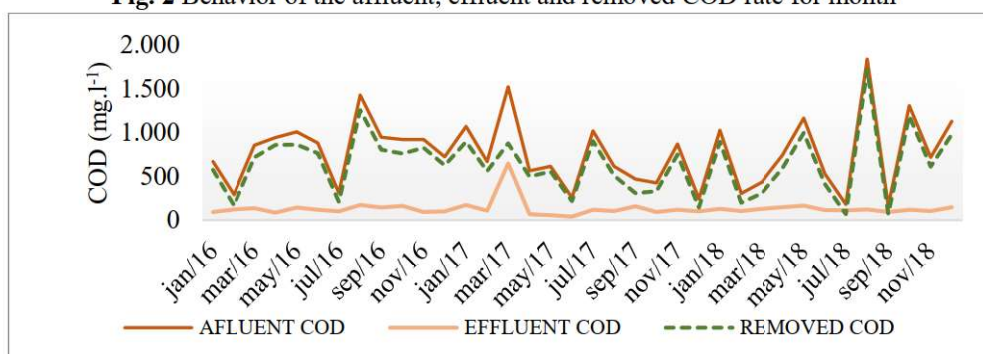
Initially, a temporal analysis of the flow of sewage was carried out over the evaluated period, as shown in Figure 1. The average flow of effluents was 154.50 l.s^{-1} ; 157.67 l.s^{-1} and 152.68 l.s^{-1} in the years 2016, 2017 and 2018, respectively. The annual averages did not show significant variation from the statistical point of view, however, it was observed that in the first four months of the three years analyzed, the flow rate was mostly above or very close to the average for each year. This behavior may have been influenced by the summer season, in which there is an increase in water consumption as it is the hottest season of the year and, consequently, in the greater domestic sewage production.

Fig. 1 Sewage flow for month from STP Jacuípe II



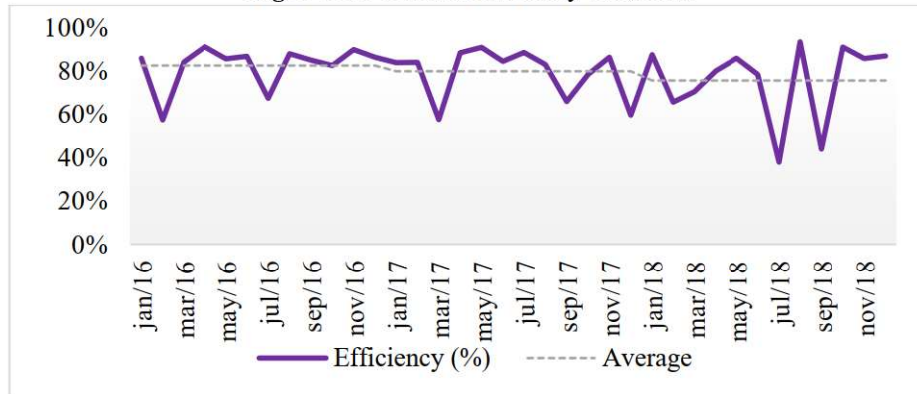
Regarding the COD parameter, through Figure 2, there was a predominance of an apparent oscillation in the affluent COD. The average affluent COD was 825 mg.l^{-1} ; 695 mg.l^{-1} and 795 mg.l^{-1} in the years analyzed, respectively. It can be noted that the portion of the removed COD has followed the same behavior as the incoming COD, corroborating the efficiency in the biological treatment of STP Jacuípe II.

Fig. 2 Behavior of the affluent, effluent and removed COD rate for month



The effluent COD showed an average of 123 mg.l^{-1} ; 149 mg.l^{-1} and 124 mg.l^{-1} in 2016, 2017 and 2018, respectively. These results, when compared to the average COD affluent, reflect the efficiency in the sewage treatment of the studied STP, as shown in Figure 3.

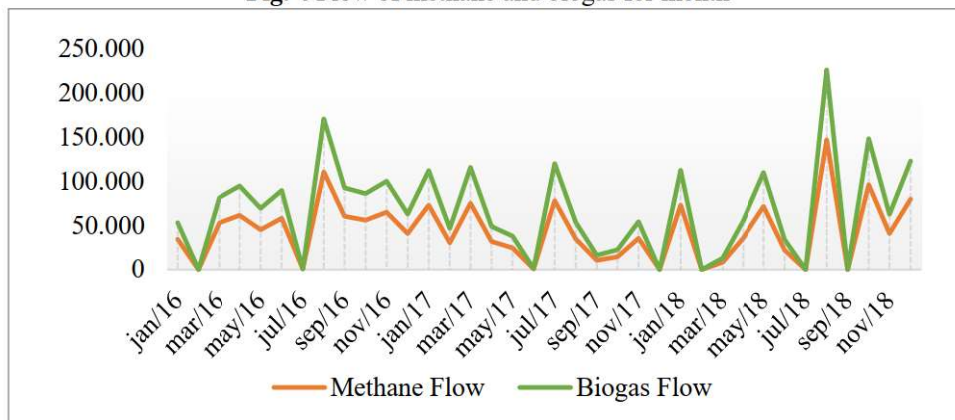
Fig. 3 COD removal efficiency for month



The COD removal efficiency remained above 85%. The typical efficiency range for COD removal in STP that have secondary and tertiary treatment, with the secondary comprising a UASB reactor, is 65 to 90% (Yetilmezsoy, Sapci-Zengin 2007; Oliveira, Von Sperling 2005; Keyser et al. 2003; Shivayogimath, Ramanujam 1999).

The theoretical production of methane was estimated under standardized conditions of temperature and pressure, in order to obtain the result in normal cubic meter (Nm³). The average results were 48,607.29 Nm³.month⁻¹ in 2016; 33,591.66 Nm³.month⁻¹ in 2017 and 46,070.43 Nm³.month⁻¹ in 2018. For biogas, the theoretical production showed average results of 74,780.44 Nm³.month⁻¹ in 2016; 51,679.47 Nm³.month⁻¹ in 2017 and 70,877.59 Nm³.month⁻¹ in 2018, as shown in Figure 4.

Fig. 4 Flow of methane and biogas for month

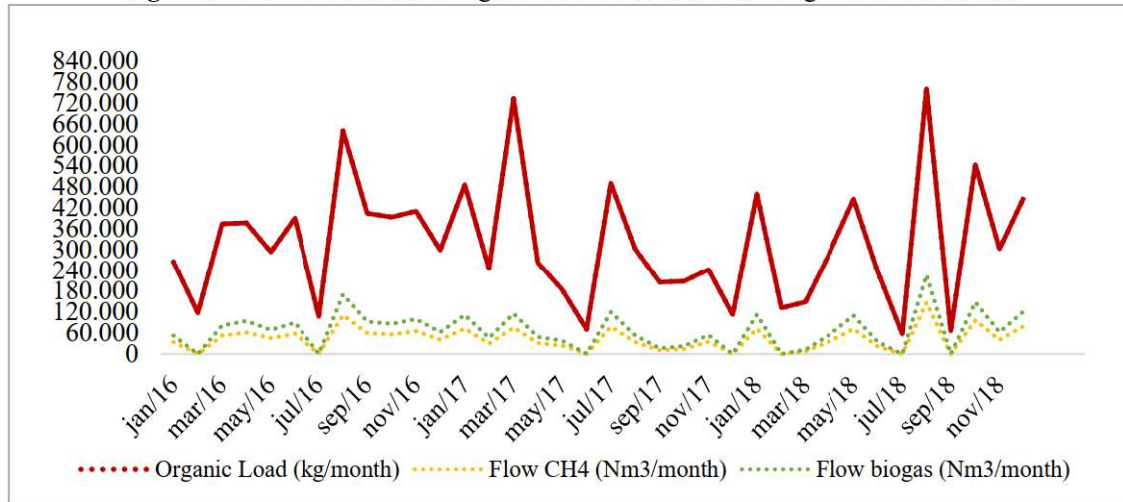


Biogas is considered a potential alternative to the global demand for energy and, at the same time, it reduces greenhouse gas emissions (Kapoor et al. 2019). The results presented in Figure 4 reinforce the possibility of using this by-product to meet the energy demanded in the sewage treatment, mitigating GHG emissions and reducing electricity costs.

According to Rosa, Lobato and Chernicharo (2020) several factors can contribute to an increase in biogas and, consequently, the energy potential from UASB reactors, such as a higher concentration of sewage, greater efficiency in the removal of COD and low rates of losses of methane.

There was a strong dependence on biogas flow in relation to sewage flow. However, it is noteworthy that this variable alone does not explain the flow of methane and biogas, and it is essential to make a relationship with the affluent organic load (product between the sewage flow and the affluent COD rate), which together explain it more consistent, as shown in Figure 5.

Fig. 5 Influence of the affluent organic load on methane and biogas flows for month



It is noted that there is a direct influence of the organic load with the production of methane and biogas, leading to verify that the variables that most influenced the production of methane and biogas were the affluent organic load and the COD removed, as also reported by Probiogás and others authors (De Freitas Melo 2020; Brasil 2016; Dobre, Nicolae, Matei 2014).

It is important to note that precipitation is a factor that can significantly reduce biogas production: the greater the intensity of the rain, the greater the dilution of the organic matter present in the effluent may be (Cabral 2016; Chernicharo et al. 2015; Silva 2015).

Possetti, et al. (2013), Silva (2015), Waiss and Possetti (2015) performed full-scale biogas measurements at other STP and identified that in rainy periods, biogas production tends to be reduced.

According to data from De Freitas Melo (2020), rainfall causes an increase (5–9%) in sewage flow, leading to a dilution in the organic load and, consequently, a decrease in biogas production (10 –20%), impairing the potential for electricity generation 20%, compromising the recovery of electricity.

In STP Jacuípe II, on days with a higher incidence of rain, sewage measurement is compromised, sometimes it is performed imprecisely or it may not even be performed. Therefore, there is no way to guarantee the influence of precipitation on the flow of sewage, available organic load or the flow of methane and biogas from that STP.

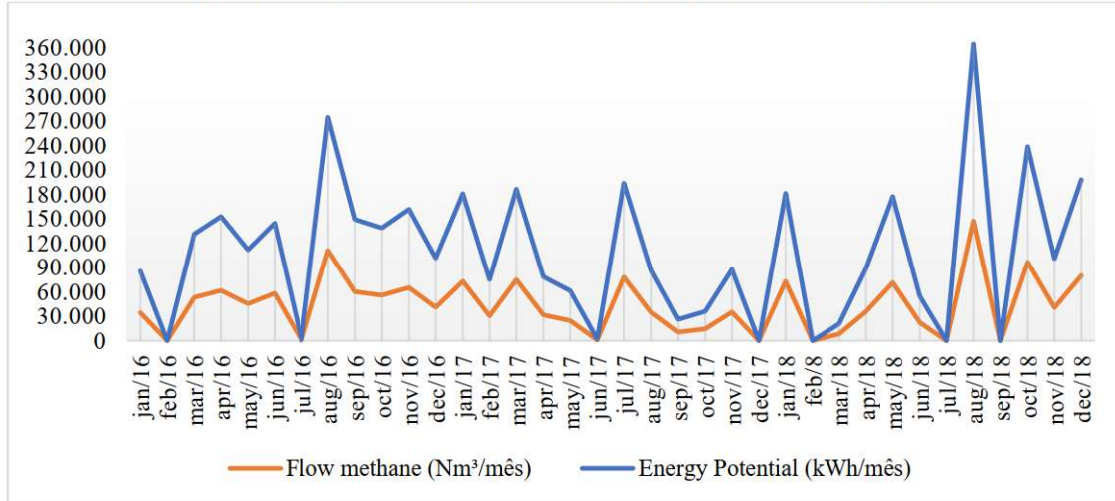
It is important to highlight that despite the variation of the affluent organic load shown in Figure 5, there was no statistically significant variability, according to Table 3.

Table 3 Affluent organic load - descriptive statistics and significance tests.

Variable	Year	Minimum	Maximum	Average	Median	Standard deviation	Significance (Kruskal-Wallis p-value)	Significance (Levene p-value)
Organic Load (kg.month ⁻¹)	2016	107,844	640,758	339,633	375,870	141,573	0.671	0.381
	2017	71,358	733,264	295,513	243,712	186,938		
	2018	57,608	761,098	324,842	296,920	213,785		

Similar to the flow of methane and biogas, the results of the potential for electricity generation in the Jacuípe II STP showed apparently variable behavior, as shown in Figure 6.

Fig. 6 Flow of methane and potential for electricity generation for month



The potential for generating electricity is a direct reflection of the methane flow, justifying the direct relationship between the variables. The oscillations shown in the figures are being treated as apparent because they do not present statistically significant variability, as shown in Table 4.

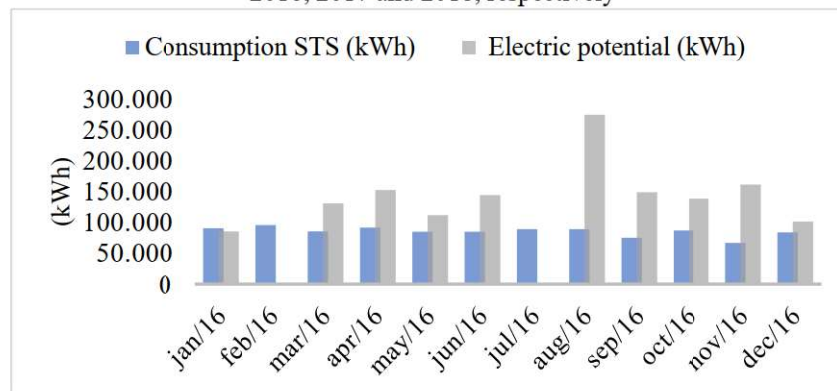
Table 4 Energy potential: descriptive statistics and significance tests

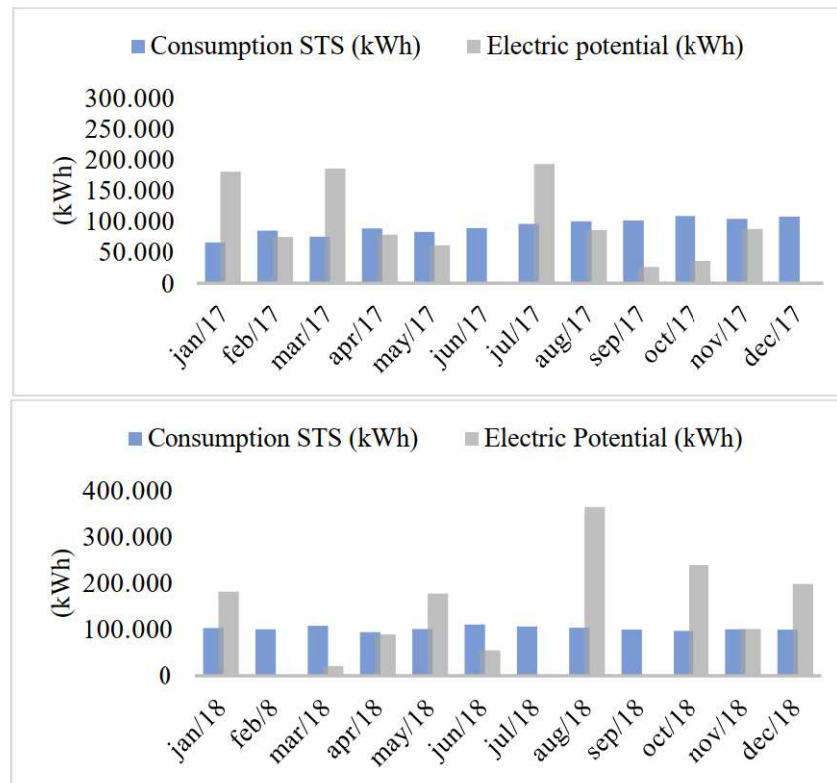
Variable	Year	Minimum	Maximum	Average	Median	Standard deviation	Significance (Kruskal-Wallis <i>p</i> -valor)	Significance (Levene <i>p</i> -valor)
Energy potential (kWh. month ⁻¹)	2016	1,416	274,622	132,033	138,509	65,334	0.214	0.192
	2017	1,855	193,476	92,133	78,654	66,390		
	2018	20,801	364,331	158,318	177,211	105,515		

It is noteworthy that even in the face of the high standard deviation in 2018, which reflects a greater dispersion of data in relation to the average, Levene's significance test showed a "*p*-value" much larger than 5%, corroborating the absence of large variations for this variable. Likewise, the Kruskal-Wallis test of significance demonstrated that there is no significant fluctuation between the averages of the different years analyzed.

According to Kalavrouziotis (2017), the operation of conventional STP is costly energy intensive and has high environmental footprint. Figures 7 (a), (b) and (c) show the real electricity consumption of the STP Jacuípe II and the potential for theoretical electricity generation from the biogas generated at the STP.

Fig. 7 (a), (b), (c) Electricity consumption and estimated electricity generation from biogas in the years 2016, 2017 and 2018, respectively





There is an apparent variation in the estimated electric power generation potential, however, it has nevertheless proved capable of supplying the actual energy consumption of that station in several months of the three years analyzed.

In the study carried out by Shirado (2014) with the STP Santa Quitéria, the energy autonomy of the STP for the year 2013 was also assessed. The author found that during the year of analysis there was autonomy in 5 months. In the study by Koga (2016) at the STP located in Curitiba, the greatest energy autonomy occurred in August 2015, resulting in 80.61%. In the present study of STP Jacuípe II, the year with the lowest estimated autonomy was 2017, and approached STP Santa Quitéria in the number of months with energy autonomy, presenting three months of autonomy; in 2016 the most favorable year of the study, there was autonomy in nine months, and in 2018, six months.

The study by Campello et al. (2020) showed that the use of biogas from STP is shown to be viable, and the larger the population of the municipalities, the more economically viable the project will be. The authors point out that an option to expand the attractiveness of lower cities is the combined use of biogas from sewage treatment plants with biogas from landfills for municipal solid waste. In addition, the potential for electricity generation in the state of Minas Gerais - Brazil was approximately 47,140 MWh per year.

Even with the favorable scenario for energy generation in the different years analyzed, the apparent fluctuation of the affluent organic load and the COD removal efficiency corroborate the intermittency that can occur in biogas production systems and consequently in the generation of energy, causing that there is insecurity in the generation of energy in similar projects. However, the possibility of distributed generation established by ANEEL through Normative Resolutions No. 482/2012 and No. 687/2015, is an important ally for these power generation systems that present such fluctuation, as the compensation Electricity credits allow the producer to offset the surplus energy, using it in the same unit or in another consumer unit under the same corporate management.

GHG EMISSIONS INVENTORY

The GHG inventories prepared for STP Jacuípe II presented the portions of methane and tonne carbon dioxide equivalent (tCO₂e) emissions from the sewage treatment in the years 2016, 2017 and 2018 carried out at that station. Table 5 shows the total emissions from the effluent treatment in the three years analyzed. According to Amazon Environmental Research Institute (IPAM 2018), the carbon dioxide equivalent

(CO₂e) it is a metric measure used to compare emissions of various greenhouse gases based on the global warming potential of each one of them.

Table 5 Total emissions from wastewater treatment (GHG Protocol Program 2018)

PHASES	2016	2017	2018
Quantity of liquid effluent generated in the year of the inventory (m³/ year)	4,880,603.58	4,993,455.91	4,821,611.49
Degradable organic component of the effluent (kgCOD/m³)	0.84	0.71	0.81
CH₄ emissions from wastewater treatment (tCH₄/year)	815.12	709.23	779.62
CO₂e emissions from wastewater treatment (tCO₂e/year)	20,378.00	17,730.80	19,490.50

Observations: The effluent is submitted to a type of anaerobic treatment (UASB Reactors) and a type of aerobic treatment (Activated Sludge). The Methane Conversion Factor (MCF1) used was 0.8.

In view of the GHG inventories presented, it was observed that the anaerobic treatment of STP Jacuípe II may have been responsible for the emission of 2,303.97 tCH₄ without energy use over the three years analyzed, equivalent to 57,599.30 tCO₂e. It is noted, therefore, the importance of projects aimed at the energy use of biogas in STP, enabling not only the mitigation of GHG emissions, but also the generation of energy and reduction of expenses. In the Jacuípe II STP, for example, which already has a structure for such use, the emissions could have been significantly lower, since the methane generated during the treatment would be used as an input for generating electricity in the STP. According to Parravicini, Svardal, Krampe (2016), anaerobic digesters and anaerobic sludge storage tanks can become a relevant source of direct methane emissions, fact reinforced by the results presented.

The study carried out by Santos (2015), referring to the GHG emissions inventory of the same sanitation company, revealed that the emissions from the sewage treatment of the Biological Oxygen Demand (BOD) removed by the stations in 2012 resulted in 448,858 tCO₂e. Thus, based on this study, it can be associated that the results found for STP Jacuípe II in the years 2016, 2017 and 2018 were equivalent to 5%, 4% and 4.4% (respectively) of the total treatment emissions sewage system of this sanitation company in 2012.

The results obtained by Campello et al. (2020) demonstrated the potential for reducing GHG derivatives with a potential reduction of around 325,800 tCO₂e/ year with the implementation of energy methane recovery system at STP in the state of Minas Gerais, Brazil.

New trends are even inclined towards the quantification of avoided methane emissions in processes that generate biogas, when performing the recovery of methane for energy production. The avoided emission of methane is fully aligned with the guidelines established by the National Policy on Climate Change (Brazilian law 12.187/2009), and can therefore be used as a Clean Development Mechanism (CDM) (Aragão and Moreira 2020).

Tables 6 and 7 show the potential for reducing GHG emissions considering the use of a Generator Motor Group- GMG, with an average use of methane of 85% in combustion (adopted), and an open type flare, as it is the most usual in station and due to its low acquisition cost, presenting methane destruction efficiency of 50% (Fokal 2015).

Table 6 Scenario 1: Methane emission considering the use of a generator

Annual methane emission without recovery (tCH ₄ /year)	Efficiency in combustion of methane (%)	Emission of methane with energy use (tCH ₄ /year)	Avoided methane emissions (tCH ₄ /year)
815.12 (2016)	85%	122.27	692.85
709.23 (2017)		106.38	602.85
779.62 (2018)		116.94	662.68

With the use of the energy generator, emissions could have been reduced by up to 85% in the years analyzed, as shown in Table 6.

Table 7 Scenario 2: Methane emission considering the use of open flare

Annual methane emission without recovery (tCH ₄ /year)	Efficiency in combustion of methane (%)	Emission of methane with energy use (tCH ₄ /year)	Avoided methane emissions (tCH ₄ /year)
815.12 (2016)	50%	407.56	407.56
709.23 (2017)		354.62	354.62
779.62 (2018)		389.81	389.81

It is observed that the potential for reducing GHG emissions using a GMG is substantially greater in relation to the use of the open type burner, corroborating the need to reactivate the system to mitigate methane emissions to the atmosphere, using it as an input for energy generation through the generator group, significantly reducing atmospheric emissions from the sewage treatment of STP Jacuípe II and generating electricity.

FINANCIAL LOSSES WITH THE DEAD BIOGAS PLANT

The scenario presented for the three disadvantaged years shows that the estimated financial loss was US\$ 137,063.40 (without monetary restatement) and US\$ 154,162.38 with monetary restatement based on the Broad Consumer Price Index - IPCA. This result represents only the financial loss due to the biogas system of STP Jacuípe II being inoperative in the years 2016, 2017 and 2018 (considering only energy consumption). If biogas has a concentration greater than 65% in its composition, which was considered in the estimates, this loss may have been even greater.

Of this amount of estimated financial losses, 2016 was the most representative year, resulting in US\$ 50,412.27 (US\$ 59,965.35 with correction), followed by 2018 which resulted in US\$ 45,499.39 (US\$ 49,461.82 with correction) and finally 2017, with losses of US\$ 41,151.74 (US\$ 44,735.53 with monetary correction).

The total expenditure on electricity from STP Jacuípe II in the three years analyzed, including demand and energy consumption, demand for overtaking, excess reactive, in addition to other miscellaneous charges, resulted in US\$ 229,426.02. The estimated financial loss considering the monetary restatement, represented 67% of the total expenditure of this period, a very significant result.

CONCLUSION

The results presented are relevant and may contribute as a subsidy for the adoption of strategic measures in the sanitation companies of the countries regarding the planning and environmental management in the sewage treatment plants, even allowing the implementation of similar projects and efficient management in other station. In this case, the scope becomes even greater, given the possibility of motivation on the part of the sanitation companies that prioritize the implantation of sewage treatment plants that already have the biogas energy use since its conception.

Given the estimates of electricity generation from biogas, it was found that this by-product could have supplied 100% of the energy consumption of STP Jacuípe II in the years 2016 and 2018, and 92% of the year 2017. The gas inventories of greenhouse effect revealed a portion of emission from the anaerobic sewage treatment of about 2,303.97 tCH₄, equivalent to 57,599.30 tCO₂e in the analyzed period. If the plant were in operation and the methane produced was used to generate electricity through the existing Otto cycle generator set, the avoided methane emission could reach 85%. The financial loss resulted in US\$ 154,162.38 due to non-operation of the biogas plant. The effective use of biogas energy will result in environmental benefits, as it will reduce GHG emissions to the atmosphere; and also in financial benefits, due to the reduction in expenses with electricity, which currently represent the second largest expense of sanitation service providers.

It is essential that there is an update of the understanding about the function of sewage systems, so that from this paradigm break, the by-products generated in the sewage treatment unit processes have better planning and environmental management and start to have added value, constituting themselves in inputs for other processes, reducing negative impacts on the environment, with the scope of the circular economy.

REFERENCES

- Angenent LT, Karim K, Al-Dahhan MH, Wrenn BA, Domínguez-Espinosa R (2004) Production of bioenergy and biochemicals from industrial and agricultural wastewater. *Trends Biotechnol.* <https://doi.org/10.1016/j.tibtech.2004.07.001>
- Anjum M, Al-Talhi HA, Mohamed SA, Kumar R, Barakat MA (2018) Visible light photocatalytic disintegration of waste activated sludge for enhancing biogas production. *J Environ Manage.* <https://doi.org/10.1016/j.jenvman.2017.07.064>
- Antwi P, Li J, Boadi PO, Meng J, Shi E, Deng K (2017) Estimation of biogas and methane yields in an UASB treating potato starch processing wastewater with backpropagation artificial neural network. *Bioresour Technol.* <https://doi.org/10.1016/j.biortech.2016.12.045>
- APHA American Public Health Association (1998) Standard methods for the examination of water and wastewater. Washington (USA)
- Aragão TNM, Moreira ÍTA (2020) Evaluation of the potential for the generation of energy from biogas and estimated emission avoided of methane in a sewage treatment station. *Brazilian Journal of Development.* <https://doi.org/10.34117/bjdv6n5-448>
- Aragão TNM, Possetti GRC, Moreira ÍTA (2019) Geração de energia elétrica a partir do aproveitamento do biogás proveniente de reatores anaeróbios: estudo de caso na estação de tratamento de esgoto Jacuípe II – Bahia. Dissertação, Universidade Salvador – UNIFACS. (In Portuguese)
- Arhoun B, Bakkali A, El Mail R, Rodríguez-Maroto J, García-Herruzo F (2013) Biogas production from pear residues using sludge from a wastewater treatment plant digester. Influence of the feed delivery procedure. *Bioresour Technol.* <https://doi.org/10.1016/j.biortech.2012.09.075>
- Aslan A (2016) The causal relationship between biomass energy use and economic growth in the United States. *Renew Sust Energ Rev.* <http://dx.doi.org/10.1016/j.rser.2015.12.109>
- Atelge MR, David K, Gopalakrishnan K, Cigdem E, Dinh Duc N, Soon Woong C, Alaa HAM (2018) Biogas Production from Organic Waste: Recent Progress and Perspectives. *Waste Biomass Valorization.* <https://doi.org/10.1007/s12649-018-00546-0>
- Baena-Moreno FM, le Saché E, Pastor-Pérez L, Reina TR (2020) Membrane-based technologies for biogas upgrading: a review. *Environ Chem Lett.* <https://doi.org/10.1007/s10311-020-01036-3>
- Bakraoui M, Karouach F, Ouhammou B, Aggour M, Essamri A, El Bari H (2020) Biogas production from recycled paper mill wastewater by UASB digester: Optimal and mesophilic conditions. *Biotechnol Rep.* <https://doi.org/10.1016/j.btre.2019.e00402>
- Bantacut T, Aulia AN (2019) Assessment of Chemical Oxygen Demand Balance for Energy Harvesting in Sugar Mills Wastewater Treatment. *Nat Environ Pollut Technol*, 2: 413-423
- Brasil (2016) Secretaria Nacional de Saneamento Ambiental. Probiogás. Resultados do projeto de medições de biogás em reatores anaeróbios. Brasília, DF: Ministério das Cidades. (In Portuguese)
- Brasil (2015) Secretaria Nacional de Saneamento Ambiental. Probiogás. Guia técnico de aproveitamento energético de biogás em estações de tratamento de esgoto. Brasília, DF: Ministério das Cidades. (In Portuguese)
- Bressani-Ribeiro T, Brandt EMF, Gutierrez KG, Díaz CA, Garcia GB, Chernicharo CAL (2017) Potential of resource recovery in UASB/trickling filter systems treating domestic sewage in developing countries. *Water Sci Technol.* <https://doi.org/10.2166/wst.2017.038>
- Cabral CBG (2016) Avaliação da produção de biogás para fins energéticos em reatores anaeróbios tratando esgoto sanitário. Dissertação, Universidade Federal de Santa Catarina. (In Portuguese)
- Campello LD, Barros RM, Tiago Filho GL, dos Santos IFS (2020) Analysis of the economic viability of the use of biogas produced in wastewater treatment plants to generate electrical energy. *Environ Dev Sustain.* <https://doi.org/10.1007/s10668-020-00689-y>
- CENBIO Centro Nacional de Referência em Biomassa (2000) Medidas mitigadoras para a redução de emissões de gases de efeito estufa na geração termelétrica. Brasília. (In Portuguese).

- Centeno-Mora E, Fonseca PR, Andreão WL, Brandt EMF, de Souza CL, Chernicharo CAL (2020) Mitigation of diffuse CH₄ and H₂S emissions from the liquid phase of UASB-based sewage treatment plants: challenges, techniques, and perspectives. *Environ Sci Pollut Res*. <https://doi.org/10.1007/s11356-020-08644-0>
- Chernicharo CAL (2007). *Princípios do Tratamento Biológico de Águas Residuárias – Reatores Anaeróbios*. Belo Horizonte, Minas Gerais. (in Portuguese)
- Chernicharo CAL, van Lier JB, Noyola A, Bressani Ribeiro T (2015) Anaerobic sewage treatment: state of the art, constraints and challenges. *Rev Environ Sci Bio*. <https://doi.org/10.1007/s11157-015-9377-3>
- Costa DF (2006) Geração de energia elétrica a partir do biogás do tratamento de esgoto. Dissertação, Universidade de São Paulo (in Portuguese).
- Crone BC, Garland JL, Sorial GA, Vane LM (2016) Significance of dissolved methane in effluents of anaerobically treated low strength wastewater and potential for recovery as an energy product: A review. *Water Res*. <https://doi.org/10.1016/j.watres.2016.08.019>
- De Freitas Melo D, Neves PN, Bressani-Ribeiro T, Chernicharo CAL, Passos F (2020) The effect of seasonality in biogas production in full-scale UASB reactors treating sewage in long-term assessment. *Int J Sustain Energy*. <https://doi.org/10.1080/14786451.2020.1797741>
- Deng Y, Xu J, Liu Y, Mancl K (2014) Biogas as a sustainable energy source in China: Regional development strategy application and decision making. *Renew Sust Energ Rev*. <https://doi.org/10.1016/j.rser.2014.04.031>
- Do Amaral KC, Aisse MM, Possetti GRC, Prado MR (2018) Use of life cycle assessment to evaluate environmental impacts associated with the management of sludge and biogas. *Water Sci Technol*. <https://doi.org/10.2166/wst.2018.146>
- Dobre P, Nicolae F, Matei F (2014) Main factors affecting biogas production-an overview. *Rom Biotechnol Lett* 19(3): 9283-9296
- Ferreira SF, Buller LS, Berni MD, Bajay SV, Forster-Carneiro T (2019) An integrated approach to explore UASB reactors for energy recycling in pulp and paper industry: a case study in Brazil. *Biofuel Res J*. <https://doi.org/10.18331/BRJ2019.6.3.4>
- GHG Protocol (2017) Programa Brasileiro do Protocolo de Gases de Efeito Estufa. <https://www.ghgprotocolbrasil.com.br/o-programa-brasileiro-ghg-protocol?locale=pt-br> Access in 23 august 2020 (in Portuguese)
- Gontijo JC, Wagner LG, Souza MED, Possetti GRC (2018) Sanitation and drying of sewage sludge on radiant floors using solar energy and biogas: comparison between different thicknesses of deposited mass. *Braz Arch Biol Technol*. <https://doi.org/10.1590/1678-4324-smart-2018000037>
- González-Arias J, Gil MV, Fernández RÁ, Martínez EJ, Fernández C, Papaharalabos G, Gómez X (2020) Integrating anaerobic digestion and pyrolysis for treating digestates derived from sewage sludge and fat wastes. *Environ Sci and Pollut*. <https://doi.org/10.1007/s11356-020-09461-1>
- Hossain N, Morni NAH (2019) Co-pelletization of microalgae-sewage sludge blend with sub-bituminous coal as solid fuel feedstock. *Bioenergy Res*. <https://doi.org/10.1007/s12155-019-10061-2>
- IPAM (2018) CO₂ equivalent (CO₂e). <https://ipam.org.br/glossario/co2-equivalent-co2e/#> Access in 29 november 2020.
- IPCC (2007) Fourth Assessment Report: Climate Change 2007 (AR4). https://www.ipcc.ch/site/assets/uploads/2018/02/ar4_syr_full_report.pdf Access in 8 jun. 2020.
- Jiang X, Hayashi J, Sun ZY, Yang L, Tang YQ, Oshibe H, Osaka N, Kida K (2013) Improving biogas production from protein-rich distillery wastewater by decreasing ammonia inhibition. *Process Biochem*. <https://doi.org/10.1016/j.procbio.2013.08.014>
- Kalavrouziotis IK (2017) *Wastewater and Biosolids Management*. 1^a ed. IWA Publishing.
- Kapoor R, Ghosh P, Kumar M, Vijay VK (2019) Evaluation of biogas upgrading technologies and future perspectives: a review. *Environ Sci and Pollut R*. <https://doi.org/10.1007/s11356-019-04767-1>

- Keyser M, Witthuhn RC, Ronquest LC, Britz TJ (2003) Treatment of winery effluent with upflow anaerobic sludge blanket (UASB) – granular sludges enriched with *Enterobacter sakazakii*. *Biotechnol Lett*. <https://doi.org/10.1023/B:BILE.0000003978.72266.96>
- Koga P (2016) Geração de energia renovável a partir dos subprodutos de uma estação de tratamento anaeróbia de esgotos. Dissertação, Universidade Federal do Paraná, Serviço Nacional de Aprendizagem Industrial, Universidade de Stuttgart. (in Portuguese)
- Laramée J, Tilmans S, Davis J (2018) Costs and benefits of biogas recovery from communal anaerobic digesters treating domestic wastewater: Evidence from peri-urban Zambia. *J Environ Manage*. <https://doi.org/10.1016/j.jenvman.2017.12.064>
- Le Saché E, Johnson S, Pastor-Pérez L, Amini Horri B, Reina T R (2019) Biogas upgrading via dry reforming over a Ni–Sn/CeO₂–Al₂O₃ catalyst: influence of the biogas source. *Energies*. <https://doi.org/10.3390/en12061007>
- Liu J, Yu D, Zhang J, Yang M, Wang Y, Wei Y, Tong J (2016) Rheological properties of sewage sludge during enhanced anaerobic digestion with microwave - H₂O₂ pretreatment. *Water Res*. <https://doi.org/10.1016/j.watres.2016.03.073>
- Liu S, Yang G, Fu J, Zhang G (2018) Synchronously enhancing biogas production, sludge reduction, biogas desulfurization, and digestate treatment in sludge anaerobic digestion by adding K₂FeO₄. *Environ Sci and Pollut*. <https://doi.org/10.1007/s11356-018-3438-4>
- Lobato LCS (2011) Aproveitamento energético de biogás gerado em reatores UASB tratando esgoto doméstico. Tese, Universidade Federal de Minas Gerais. (in Portuguese)
- Lobato LCS, Chernicharo CAL, Souza CL (2012) Estimates of methane loss and energy recovery potential in anaerobic reactors treating domestic wastewater. *Water Sci Technol*. <https://doi.org/10.2166/wst.2012.514>
- Matsui T, Imamura S (2010) Removal of siloxane from digestion gas of sewage sludge. *Bioresour Technol*. <https://doi.org/10.1016/j.biortech.2009.05.037>
- Mora EC, Chernicharo CAL (2020) Use of membrane contactors for removing and recovering dissolved methane from anaerobic reactors effluents: state-of-the-art, challenges, and perspectives. *Rev Environ Sci Biotechnol*. <https://doi.org/10.1007/s11157-020-09546-w>
- Nadaleti WC (2019) Utilization of residues from rice parboiling industries in southern Brazil for biogas and hydrogen-syngas generation: heat, electricity and energy planning. *Renew Energ*. <https://doi.org/10.1016/j.renene.2018.07.014>
- Oliveira SMAC, Von Sperling M (2005) Avaliação de 166 ETEs em operação no país, compreendendo diversas tecnologias. Parte 1: análise de desempenho. *Eng. Sanit. Ambient*. <https://doi.org/10.1590/S1413-41522005000400011>. (in Portuguese)
- Pantawong R, Chuanchai A, Thipbunrat P, Unpaprom Y, Ramaraj R (2015) Experimental investigation of biogas production from water lettuce, *Pistia stratiotes* L. *Emer Life Sci Res* 2: 41-46
- Parraviciniak V, Svardala K, Krampea J (2016) Greenhouse gas emissions from wastewater treatment plants. *Energy Procedia*. <https://doi.org/10.1016/j.egypro.2016.10.067>
- Possetti GRC, Chernicharo CAL, Carneiro C, Rietow JC, Luckow RF, Waiss TCF, Souza CL, Lobato LCS. ProBio 1.0 - Programa de estimativa de produção de biogás em reatores UASB. Manual do Usuário. (in Portuguese)
- Possetti GRC, Jasinski VP, Mesquita NC, Kriguel K, Carneiro C (2013) Medições em tempo real do biogás produzido em reatores UASB alimentados com esgoto doméstico. <http://abes.locaweb.com.br/XP/XP-EasyArtigos/Site/Uploads/Evento22/TrabalhosCompletoPDF/II-106.pdf> Access in 10 august 2020. (in Portuguese)
- Possetti GRC, Requião GM (2019) O futuro do saneamento na valorização do esgoto. <https://www.saneamentobasico.com.br/saneamento-valorizacao-esgoto/> Access in 5 march 2019. (in Portuguese)
- Rodríguez DJ, Serrano HA, Delgado A, Nolasco D, Saltiel G (2019) From Waste to Resource: Shifting paradigms for smarter wastewater interventions in Latin America and the Caribbean. World Bank, Washington, DC.

- Rosa AP, Conesa JA, Fullana A, Melo GCB, Borges JM, Chernicharo CAL (2015) Energy potential and alternative usages of biogas and sludge from UASB reactors: case study of the Laboreaux wastewater treatment plant. *Water Sci Technol*. <https://doi.org/10.2166/wst.2015.643>
- Rosa AP, Lobato LCS, Chernicharo CAL (2020) Mathematical model to predict the energy potential of UASB-based sewage treatment plants. *Brazilian J Chem Eng*. <https://doi.org/10.1007/s43153-020-00012-2>
- Rosenfeldt S, Cabral CBG, Platzer CJ, Hoffmann H, Araújo RA (2015) Avaliação da viabilidade econômica do aproveitamento energético do biogás por meio de motor-gerador em uma estação de tratamento de esgoto. 1ª ed. Brasília, Distrito Federal. (in Portuguese)
- Santos JO (2015) Inventário das emissões de gases de efeito estufa (GEE) na Embasa: oportunidades para o aprimoramento da gestão das emissões. Tese, Universidade Federal da Bahia. (in Portuguese)
- Santos-Clotas E, Cabrera-Codony A, Ruiz B, Fuente E, Martín MJ (2019) Sewage biogas efficient purification by means of lignocellulosic waste-based activated carbons. *Bioresour Technol*. <https://doi.org/10.1016/j.biortech.2018.12.060>
- SEEG Sistema de Estimativas de Emissões e Remoções de Gases de Efeito Estufa (2020) Análise das emissões brasileiras de gases de efeito estufa e suas implicações para as metas do Brasil. http://www.observatoriodoclima.eco.br/wp-content/uploads/2020/11/OC_RelatorioSEEG2020_final.pdf Access in 28 november 2020. (in Portuguese).
- Shirado J (2014) Análise dos fluxos de materiais e de energia como ferramenta de gestão para uma estação de tratamento anaeróbio de esgoto doméstico Dissertação, Universidade Federal do Paraná - UFP. (in Portuguese)
- Shivayogimath CB, Ramanujam TK (1999) Treatment of distillery spentwash by hybrid UASB reactor. *Biotechnol Bioprocess Eng*. <https://doi.org/10.1007/s004490050673>
- Silva TCF (2015) Utilização de biogás de estações de tratamento de esgoto para fins energéticos. Dissertação Universidade de São Paulo. (in Portuguese)
- Silveira ARR, Nadaleti WC, Przybyla G, Belli Filho P (2018) Potential use of methane and syngas from residues generated in rice industries of Pelotas, Rio Grande do Sul: Thermal and electrical energy. *Renew Energ*. <https://doi.org/10.1016/j.renene.2018.11.063>
- SNIS Sistema Nacional de Informações sobre Saneamento (2019) Diagnóstico dos serviços de água e esgotos – ano base 2017. Brasília, Distrito Federal.
- Unpaprom Y, Pimpimol T, Whangchai K, Ramaraj R (2020) Sustainability assessment of water hyacinth with swine dung for biogas production, methane enhancement, and biofertilizer. *Biomass Convers Biorefin*. <https://doi.org/10.1007/s13399-020-00850-7>
- Valenti G, Arcidiacono A., Ruiz JAN (2016) Assessment of membrane plants for biogas upgrading to biomethane at zero methane emission. *Biomass Bioenergy*. <https://doi.org/10.1016/j.biombioe.2015.11.020>
- Waiss TCF, Posseti GRC (2015) Influência de eventos de chuva na produção de biogás de reatores anaeróbios alimentados com esgoto doméstico. <http://abes.locaweb.com.br/XP/XP-EasyArtigos/Site/Uploads/Evento29/TrabalhosCompletoPDF/II-590.pdf> Access in 23 february 2019. (in Portuguese).
- Xu S, Zhang L, Huang S, Zeeman G, Rijnaarts H, Liu Y (2018) Improving the energy efficiency of a pilot-scale UASB-digester for low temperature domestic wastewater treatment. *Biochem Eng J*. <https://doi.org/10.1016/j.bej.2018.04.003>
- Yetilmezsoy K, Sapci-Zengin Z (2007) Stochastic modeling applications for the prediction of COD removal efficiency of UASB reactors treating diluted real cotton textile wastewater. *Stoch Environ Res Risk Assess*. <https://doi.org/10.1007/s00477-007-0191-5>