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Inovações e Soluções Sustentáveis em Engenharia Ambiental

Estimation of the energy recovery potential of biogas from UASB reactors in the state of Rio Grande do Sul

Estimativa do potencial de aproveitamento energético de biogás oriundo de reatores UASB no estado do Rio Grande do Sul

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ABSTRACT

The increase in sewage collection and treatment rates in Rio Grande do Sul (RS) should be guided by environmentally and economically sustainable practices. Anaerobic digestion, through UASB reactors, thus becomes potentially attractive because it allows, in addition to sewage treatment, the generation and collection of biogas - a biofuel with a high methane percentage. Therefore, the present work has investigated the scope of UASB reactors' operation in Rio Grande do Sul, identifying that 76.5% of its Sewage Treatment Plants (STPs) use anaerobic technology, with 1/3 having UASB reactors. Using self-monitoring data from the sectioned STPs and through the Chemical Oxygen Demand (COD) conversion methodology adapted from Lobato, Chernicharo, and Souza (2012) – incorporating a methane solubility fluctuation factor to better estimate losses in the liquid phase –, the energy potential of biogas generation in the state was estimated in three different scenarios. The results demonstrate that Rio Grande do Sul has low potential in this field due to the large number of small STPs, sewage with low COD concentration, and high methane losses in the liquid phase. Future individualized studies that address the financial viability are necessary, encompassing the perspective of less noble uses of biogas in order to provide additional revenue to the state's STPs.

Keywords: Wastewater treatment; Anaerobic digestion; Biogas

RESUMO

O aumento dos índices de coleta e tratamento de esgoto sanitário no Rio Grande do Sul, idealmente, deve ser pautado de forma ambiental e economicamente sustentável. A digestão anaeróbia, através de reatores UASB, torna-se, portanto, potencialmente atraente, por permitir, além do tratamento de esgoto, a geração e a coleta de biogás - biocombustível com alto teor de metano. Logo, o presente trabalho investigou a abrangência da operação de reatores UASB em território gaúcho, identificando-se que 76.5% de suas Estações de Tratamento de Esgotos (ETEs) se valem de tecnologia anaeróbia, com 1/3 possuindo reatores UASB. Utilizando dados de automonitoramento das ETEs secionadas e através de metodologia de conversão de DQO adaptada de Lobato, Chernicharo e Souza (2012) – com incorporação de fator de oscilação da solubilidade do metano para melhor estipular as perdas em fase líquida -, estimou-se o potencial energético de geração de biogás no Estado, em três cenários distintos. Os resultados demonstram que o Rio Grande do Sul apresenta baixo potencial na temática, em função do grande número de ETEs de pequeno porte, esgotos com baixa concentração de DQO e elevadas perdas de metano na fase líquida. Estudos futuros individualizados, que versem sobre a viabilidade financeira, são necessários, englobando a perspectiva de usos menos nobres do biogás, de forma a possibilitar aporte extra de receita às ETEs do Estado.

Palavras-chave: Tratamento de esgoto; Digestão anaeróbia; Biogás

1 INTRODUCTION

In 2022, approximately 56% of the Brazilian population had access to sewage collection services. Compared to 2010 (BRASIL, 2012), when only 46.2% benefited from such services, there has been a gradual progression toward universalization, as envisioned by the Federal Basic Sanitation Policy (2007) and the New Basic Sanitation Legal Framework (2020). In Rio Grande do Sul (RS), however, the subject matter is less developed: as of 2022, only 36% of the population was served by collection networks; consequently, a mere 26.6% of the sewage generated in the state was treated, compared to the national average of 52.2% (Brasil, 2023).

In the context of universalization, the goals of the National Basic Sanitation Plan (BRASIL, 2019) aim to increase the rate of treated sewage in Brazil to levels above 90% by 2033. In this expansion process, in addition to focusing on compliance with discharge standards, it is necessary to develop treatment systems sustainably from an environmental and economic point of view (Popovic, Kraslawski and Avramenko, 2013; Molinos-Senante et al., 2014). The correct management of by-products generated in STPs, for example, increases enterprises' potential for additional income while preventing their free disposal in the environment. In this context, anaerobic systems become potentially attractive (Probiogás, 2017; Bernal et al., 2017; Rosa et al., 2016).

Anaerobic treatment has certain advantages when compared to aerobic systems since it converts a large part of the biodegradable organic material into methane (CH_4) (50 to 70%), with a small portion being assimilated into biomass (5 to 15%) (Noyola, Moran-Sagatsume and López-Hernández, 2006; Mainardis, Buttazzoni, and Goi, 2020). The possibility of generating methane is decisive in this equation, considering that this gas has a lower calorific value of 35.9 MJ/Nm³, dictating the energy capacity of biogas (Probiogás, 2017).

Methane production results from a delicately balanced anaerobic metabolism, which depends on a consortium of microorganisms in four sequential stages (hydrolysis, acidogenesis, acetogenesis, and methanogenesis). The final phase – methanogenesis – removes organic carbon in the form of CH_4 and carbon dioxide (CO_2) in the liquid phase. Emphasis is also placed on sulfidogenesis, from which sulfur-reducing bacteria use sulfur-based compounds (mainly sulfate) as electron acceptors, reducing them into hydrogen sulfide (H_2S). This is an alternative route, competing with methanogenesis; therefore, if it occurs, there is less CH_4 production (Chernicharo, 2019).

Among the technologies that perform anaerobic digestion, upflow anaerobic sludge blanket (UASB) reactors stand out for liquid substrates. In addition to having favorable operational characteristics, such reactors allow the collection of biogas with a high CH_4 factor for subsequent use (Mainardis, Buttazzoni, and Goi 2020). Moreover, given that temperature is one of their most relevant requirements, UASB reactors have been widely accepted and disseminated in the Brazilian context (Probiogás, 2017).

Nevertheless, in Brazil, the biogas generated in UASB reactors is typically flared to prevent its release into the atmosphere, representing a significant waste of its energy potential (Probiogás, 2017). According to the International Biogas Center (Cibiogás, 2022), as of 2022, only 11 STPs in Brazil utilized the biogas produced for electrical or thermal energy generation.

In wastewater treatment plants in Rio Grande do Sul, no UASB reactors are in operation producing biogas for energy generation. Additionally, in the state, primary studies addressing biogas mainly focus on agroforestry activities, sanitary landfills, and sludge codigestion, without taking UASB reactors into account. As an example, there is the Biomass Atlas of Rio Grande do Sul (Konrad et al., 2016), which sought to establish the energy potential of biogas generation in different regions of Rio Grande do Sul based on the biomass sources mentioned above without considering the possibility of using domestic sewage.

Consequently, focusing on this subject, this work has two objectives: first, to understand the adoption of anaerobic technologies for sewage treatment in Rio Grande do Sul. Then, based on secondary self-monitoring data, estimate the potential for energetic use of biogas generated in STPs with UASB reactors. To achieve this, the model developed by Lobato, Chernicharo, and Souza (2012) was used – with specific changes aimed to allow temperature variation – in order to estimate different scenarios of methane production.

2 MATERIAL AND METHODS

2.1 Collection of self-monitoring data from STPs

The data from the Rio Grande do Sul STPs were obtained through a usage agreement signed with the Henrique Luis Roessler State Foundation For Environmental Protection (FEPAM). Thus, data regarding the geographic distribution of all STPs in Rio Grande do Sul, the treatment technologies used, and their self-monitoring are available.

The following data were collected regarding the self-monitoring characteristics: influent flow (Q_i, in m^3/day) and influent COD (COD_i, in mg COD/L). The period covered by self-monitoring varies according to the STP, with the most recent data being from December 2021. Effluent data (the treated output from STPs) were not used since most STPs have treatments complementary to UASB; thus, the effluent COD values do not relate to the specific balance of organic load in the reactor. Furthermore, sulfate concentration is not a measurement commonly required by the environmental agency; therefore, it is not available.

The data not covered by monitoring were estimated through three different scenarios (Table 1), according to Lobato (2011) and Lopes et al (2020), covering the following parameters: E_{COD} (COD removal efficiency - %); Y (Sludge production coefficient - $kgCOD_{sludge}/kgCOD_{removed}$); C_{SO4} (Influent sulfate concentration - mg/L); E_{SO4} (SO_4^{-2} removal efficiency - %); Pw (CH_4 losses in the gas phase as residual gas - %); Po (other losses - %); Fs (CH_4 supersaturation factor in the liquid phase); and T (reactor operating temperature - °C).

Regarding the frequency of the data, in most cases, it was recorded weekly for COD and daily for flow, depending on the conditions imposed by the projects' licensing. Furthermore, for reasons of confidentiality of the state environmental agency, the names of the STPs involved were omitted, and the results were grouped by city.

Table 1 – Model input parameters

Scenario	E_{COD}	Y	C_{SO4}	E_{SO4}	Pw	Po	Fs	Q_i	COD_i	T
Pessimistic	60	0.213	20	80	7.5	7.5	1.7			
Typical	65	0.213	15	75	5.0	5.0	1.35	Varies by STP		Varies by city
Optimistic	70	0.213	10	70	2.5	2.5	1			

Source: adapted from Lobato (2011) and Lopes et al. (2020)

2.2 Steps for Model Application

The model proposed by Lobato (2011) and Lobato, Chernicharo, and Souza (2012) was used as a basis, model that had been validated on different scales (pilot, demonstration, and real) and which is condensed in the ProBio 1.0 software. However, the calculations were performed in a digital spreadsheet due to the need for specific adjustments, given that 1) the software does not allow COD concentrations below 180 mg/L, thus losing analytical power for diluted sewage, and 2) the program does not allow temperature variations to be included - there is an obligation to consider T = 25°C -, which is inadequate for a study on a large geographic scale and in a state with a subtropical climate.

Table 2 – Steps and respective equations of the model

(Continued)

Stage	Equations	Variables
1	$\mathbf{COD_{sludge} = Y_{COD} \times COD_{removed}}$	$\mathbf{COD_{sludge}}$: mass of COD converted into sludge ($\frac{kgCOD_{sludge}}{day}$) $\mathbf{Y_{COD}}$: solid production coefficient ($\frac{kgCOD_{sludge}}{kgCOD_{removed}}$) $\mathbf{COD_{removed}}$: mass of COD removed in the reactor ($\frac{kgCOD_{removed}}{day}$)
2	$\mathbf{CO_{SO_{4converted}} = Q_{av} \times C_{SO_4} \times E_{SO_4}}$ $\mathbf{COD_{SO_4} = CO_{SO_{4converted}} \times K_{COD-SO_4}}$	$\mathbf{CO_{SO_{4converted}}}$: mass of SO_4 converted to sulfide (kg $\frac{SO_4}{day}$) $\mathbf{Q_{av}}$: average influent flow rate ($\frac{m^3}{day}$) $\mathbf{C_{SO_4}}$: concentration of SO_4 in the influent (kg $\frac{SO_4}{m^3}$) $\mathbf{E_{SO_4}}$: efficiency of SO_4 reduction (%) $\mathbf{COD_{SO_4}}$: mass of COD used in sulfate reduction ($\frac{kgCOD_{SO_4}}{day}$) $\mathbf{K_{COD-SO_4}}$: COD consumed in sulfate reduction (0,667 $\frac{kgCOD}{kg\ SO_{4converted}}$)
3	$\mathbf{COD_{CH_4} = COD_{removed} - COD_{sludge} - COD_{SO_4}}$	$\mathbf{COD_{CH_4}}$: mass of COD converted into methane ($\frac{kgCOD_{CH_4}}{day}$)
4	$\mathbf{Q_{CH_4} = \frac{COD_{CH_4} \times R \times (273 + T)}{P \times K_{COD} \times 1000}}$	$\mathbf{Q_{CH_4}}$: volumetric methane production ($\frac{m^3}{day}$) $\mathbf{P}$: atmospheric pressure (1 atm) $\mathbf{K_{COD}}$: COD corresponding to 1 mole of methane ($\frac{0,064kgCOD_{CH_4}}{mol}$) $\mathbf{R}$: ideal gas constant (0,08206 atm.$\frac{L}{mol}$.K) $\mathbf{T}$: reactor's operational temperature (°C)
5	$\mathbf{\%_{CH_4}(1) = 2x10^{-7}COD^3 - 0,0004COD^2 + 0,2333COD + 18}$ $\mathbf{\%_{CH_4}(2) = 0,0059COD + 66,219}$	$\mathbf{\%_{CH_4}(1)}$: CH_4 in biogas (%), for a COD concentration of 100– 400 mg/L $\mathbf{\%_{CH_4}(2)}$: CH_4 in biogas (%), for a COD concentration of 400– 1000 mg/L
6	$\mathbf{Q_{biogas} = \frac{Q_{CH_4}}{\%_{CH_4}}}$	$\mathbf{Q_{biogas}}$: volumetric biogas production ($\frac{m^3}{day}$) $\mathbf{\%_{CH_4}}$: methane concentration in biogas (%)

Table 2 – Steps and respective equations of the model

(Conclusion)

Stage	Equations	Variables
7	$\mathbf{Q_{W-CH_4} = Q_{CH_4} \times p_w}$ $\mathbf{Q_{O-CH_4} = Q_{CH_4} \times p_o}$ $\mathbf{p_L = \frac{\%_{CH_4}}{100} \times K_h \times F_s}$ $\mathbf{Q_{L-CH_4} = Q_{av} \times (p_L \times 10^{-6}) \times f_{CH_4}(\frac{R \times (273+T)}{P \times K_{COD}})}$	$\mathbf{Q_{W-CH_4}}$: methane loss in the gas phase as residual gas $(\frac{m^3}{day})$ $\mathbf{p_W}$: percentage of methane loss in the gas phase as residual gas (%) $\mathbf{Q_{O-CH_4}}$: methane loss in the gas phase $(\frac{m^3}{day})$ $\mathbf{p_O}$: percentage of methane loss in the gas phase (%) $\mathbf{Q_{L-CH_4}}$: methane loss in the liquid phase $(\frac{m^3}{day})$ $\mathbf{p_L}$: methane concentration dissolved in the effluent (mg/L) $\mathbf{K_h}$ = Henry's constant $(\frac{mg}{L.atm})$ $\mathbf{F_s}$ = supersaturation factor of CH_4 in the liquid phase (atm) $\mathbf{f_{CH_4}}$: conversion factor of methane mass into COD mass $(4\frac{kgCOD}{kgCH_4})$
8	$\mathbf{Q_{real-CH_4} = Q_{CH_4} - Q_{W-CH_4} - Q_{O-CH_4} - Q_{L-CH_4}}$	$\mathbf{Q_{real-CH_4}}$: actual available methane production $(\frac{m^3}{day})$
9	$\mathbf{EP_{realCH_4} = Q_{real-CH_4} \times LCV}$	$\mathbf{EP_{realCH_4}}$: available energy potential $(\frac{kWh}{day})$ **LCV**: lower calorific value of biogas $(9.9722\ \frac{kWh}{Nm^3})$

Source: adapted from Lobato (2011)

The equations relevant to the model are presented in Table 2. Portions of organic matter conversion and methane losses from the system were considered in the equations in order not to overestimate the final production results. Firstly, using the input data, the rates of COD converted to sludge (1) and consumed in sulfate reduction (2) were estimated. Using these rates, the maximum COD converted to CH_4 (3) and its consequent maximum volumetric production (4) were determined. The composition of the biogas (in terms of methane percentage) was determined (6), the value of which varies according to the COD concentration of the influent sewage (5). The model includes the losses of CH_4 dissolved in the effluent and in the gas phase with the residual gas, in addition to other possible losses in the gas phase (7). After discounting these losses, the actual volumetric methane production was obtained (8), as well as the available energy potential (9).

2.3 Incorporation of Liquid Methane Losses Varying with Temperature

The “temperature” parameter is included in all equations of the model that use manipulations of the Ideal Gas Law - (4) and (7), from Table 2. However, the model is invariable at different temperatures when it comes to liquid methane losses (7) – the lost portion dissolved in the effluent. Therefore, a variable Henry’s constant[1] (kH) was added to the modeling of this work, which fluctuates with temperature.

For this purpose, standard reference data for the dissolution of methane in water, in the range of 0 to 55°C, compiled by the International Union of Pure and Applied Chemistry (IUPAC), were used. The variation in water density - in the same temperature range - was also considered (Hynes, 2014). In this way, an approximation of a polynomial representing a variable Henry’s constant (in mg/L.atm) was obtained according to the temperature of the UASB reactor, to automate the spreadsheet model.

In a second step, to allow temperature variations according to the spatial location of each city in Rio Grande do Sul, 30 meteorological monitoring stations of the National Institute of Meteorology (INMET) in the state were used as reference. The average annual temperatures referring to the climatological normal from 1961 to 1990 were then obtained – with more data than the most recent one (1991-2020). The results were incorporated into a vector file, which allowed the interpolation of its values throughout the state to form a raster map.

Thus, according to the geographic location of the UASB reactor, an average annual temperature value can be assumed. This value can be used to determine the Henry’s constant of methane, which dictates its solubility in water and its consequent liquid losses in the treated effluent.

[1] A constant that describes the solubility of a gas in a liquid as a function of the partial pressure of the gas above the liquid.

3 RESULTS AND DISCUSSION

3.1 Anaerobic technologies in Rio Grande do Sul

Of the 98 STPs analyzed in Rio Grande do Sul, 76.5% have anaerobic treatment in their process. UASB reactors are found in approximately 1/3 of them, which is similar to the data reported by Silva (2014), who mentioned that 35% of the STPs built in Brazil between 2007 and 2014 have UASB reactors.

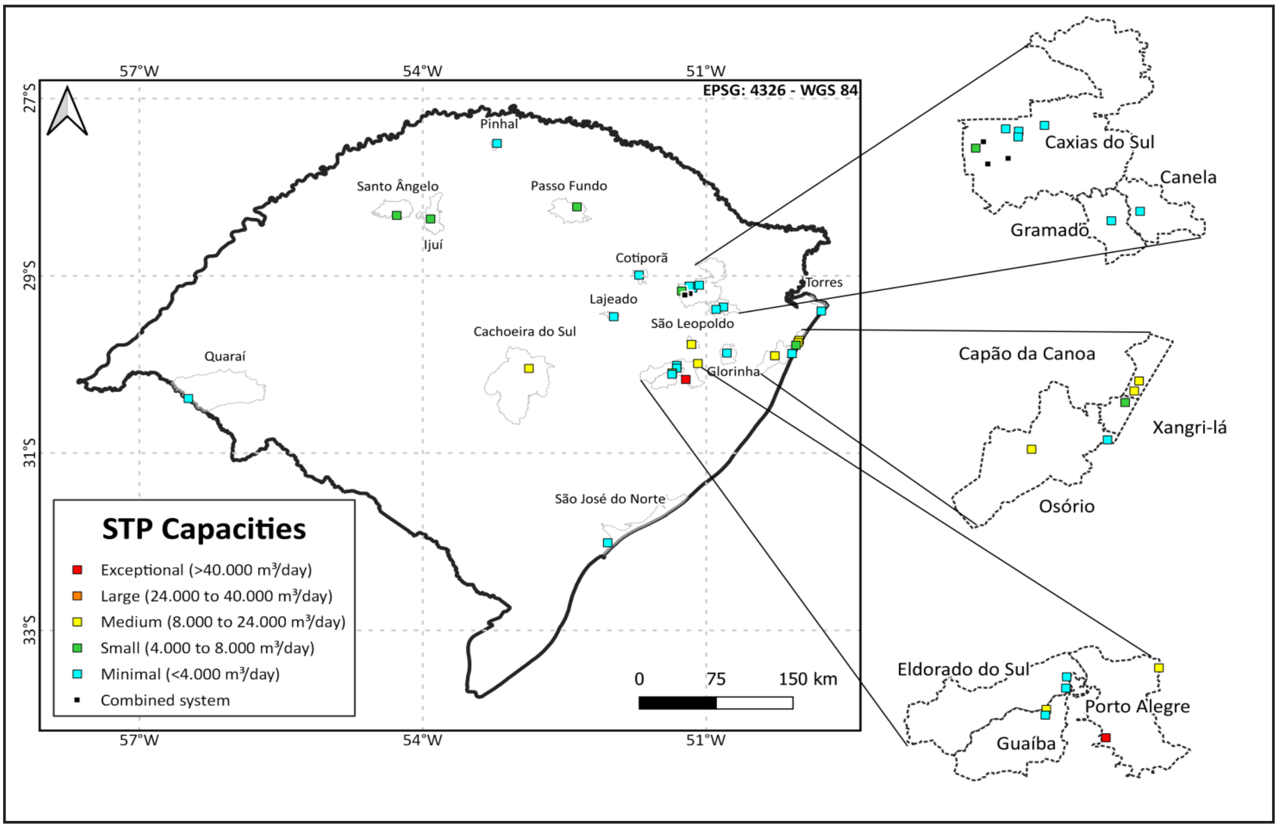
Chernicharo et al. (2018) similarly demonstrated that 40% of the 1,667 STPs inventoried in Brazil have UASB, unveiling the high acceptance of anaerobic technology as the first stage of the treatment process, regardless of the size of the plant. It is a fact that anaerobic technologies are adapted to the Brazilian reality due to the hot climate, small sludge production, low costs, and low energy demand, as well as operational simplicity, compensating for the scarcity of resources and qualified labor (Jordão, 2005; Lobato, 2011; Chernicharo, 2019). In 2020, according to a report by the National Water Agency (Ana, 2020), Brazil had 1,373 STPs with anaerobic reactors, representing the largest number of facilities in the world in this category.

This study aimed to evaluate the production of biogas from sewage with domestic characteristics and, therefore, originating from a separate sewer system. In this context, 20 cities have 33 projects with UASB reactors in the state (Figure 1). Out of them, 30 STPs receive sewage from a separate sewer system and three from combined systems.

Considering the STPs fed by a separator network, approximately 86.7% have polishing technology that complements the UASB. Thus: 56.6% (17) include a percolating biological filter; 13.3% (4) a submerged aerated biological filter; 10% (3) activated sludge; 3.3% (1) facultative lagoon; 3.3% (1) upflow aerated filter. Only four cases (13.3%) were observed in which the UASB is the only treatment stage. This corroborates the idea that to achieve the necessary removal efficiency, the anaerobic process is rarely sufficient in isolation, requiring post-treatment (Nair and Ahammed, 2015).

It is also worth noting that, for RS, using the classification criteria of CONSEMA Resolution n° 372/2018, there is a predominance of Minimum (51.5%), Medium (27.27%), and Small (15.15%) STPs, accounting for approximately 94% of the total number of projects. Only one Exceptional-sized STP was identified, and none were Large-sized.

Figure 1 – Geographical distribution of STPs with UASB reactors in Rio Grande do Sul



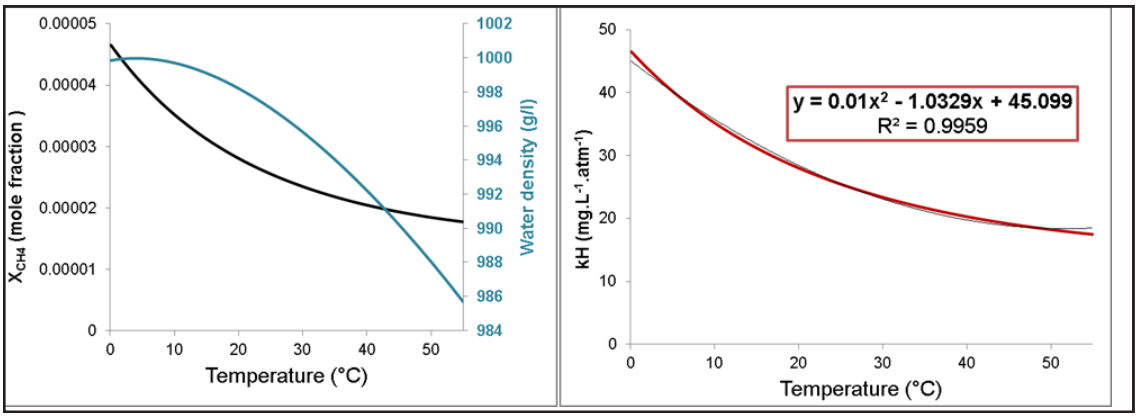
Source: Authors (2024)

3.2 Inserting the temperature factor

In Figure 2, on the left, we can see the variation in the solubility of methane gas in water (X_{ch4}, in molar fraction) and in the density of water (in g/L). On the right, we can see the curve obtained representing a variable Henry's constant (kH, in mg/ L.atm). The approximate polynomial for the curve (R^2 = 0.9959), therefore, allows for the automation of the Henry's constant ("y") from an average temperature ("x"). We can see that, for the range from 0 to 55°C, as temperature increases, the solubility of methane decreases, implying lower liquid losses at higher temperatures.

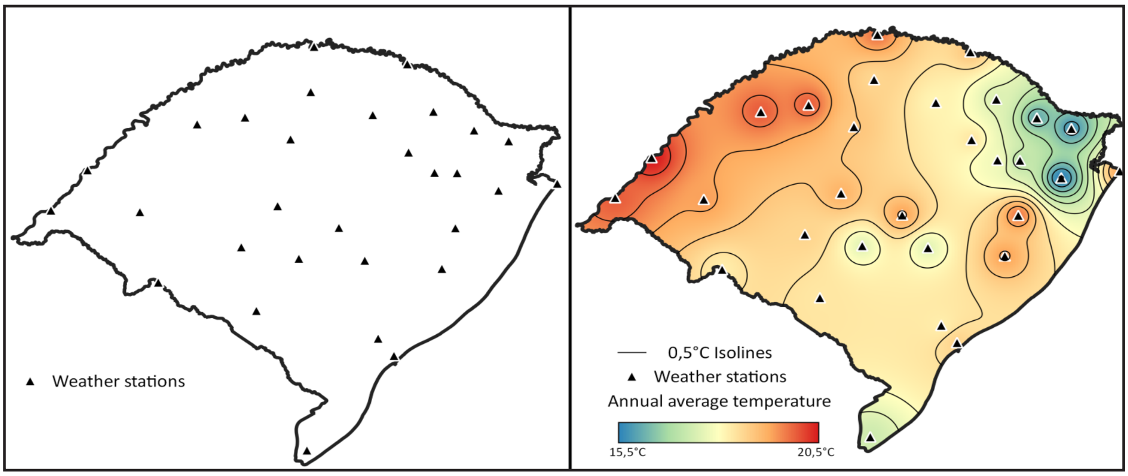
Figure 3 shows the representation of the INMET meteorological stations used for interpolation (right) and the resulting raster map (left), which allows for the discretization of average temperatures in the state according to location. There is a significant variation in average annual temperature between different regions, covering the range of 15.5°C to 20.5°C. This results in Henry's constants of 31.5 mg/L.atm and 28.13 mg/L.atm, respectively.

Figure 2 – Methane solubility and water density by temperature (left) and Henry's constant of methane by temperature (right)



Source: Authors (2024)

Figure 3 – INMET meteorological stations (left) and raster map of the average annual temperature in RS (right)



Source: Authors (2024)

3.3 Modelling results and discussion

The results obtained for the Pessimistic scenario – one in which the input parameters lead to lower COD removal, higher losses, and higher sulfate reduction rates – were unfavorable regarding methane production, generating zero production capacity in 40% of the cities (losses exceeded generation). For this scenario, the average loss in the liquid phase was 81% – exceeding the values reported in the literature. Souza (2010), for example, highlighted liquid methane losses of 30% of all methane generated in the UASB reactor; Lobato (2011) points out that several researchers had reported losses between 15% and 60%. Therefore, to evaluate the results, it was considered that the Pessimistic scenario was the least relevant.

The other scenarios - Typical and Optimistic, with average liquid phase losses of 67.5% and 51.3%, respectively – paint a picture more likely to represent the current situation and act as a possible guide for future studies and policies promoting biogas. Thus, Table 3 summarizes the results for the "Typical" and "Optimistic" scenarios, condensed into the following indices: Methane losses in the liquid phase (QL); Biogas production per capita (Qb); Volumetric methane production (QCH_4); Energy potential (EP); and Energy potential per volume treated (EPvt). Figure 4 illustrates the energy production potential for the Typical and Optimistic scenarios.

The overall analysis of the results allows us to understand the relationship between the generated indices. For example, the influent COD concentration is directly related to the per capita biogas flow rate (Qb) and inversely related to the liquid methane losses (QL). This is explained by the greater availability of substrate for bacterial metabolism. Biogas production, after all, depends on the conversion of the influent organic load to the reactor (PROBIOGÁS, 2017).

Both the size of STPs and the characteristics of the raw sewage demonstrate relevance for the volumetric production of methane – and, consequently, for the energy potential. However, the cities in Rio Grande do Sul showed sewage with low organic load, with 62% presenting average COD concentrations below 300 mg/L. Von Sperling (2007), for example, uses typical COD values close to 700 mg/L; Ribeiro and Botari (2022), in turn, reported COD values of 600-1,400 mg/L at the Paranavaí STP, Paraná/Brazil. Furthermore, there is a predominance of small-scale STPs (as shown in Figure 1), which suggests that most STPs with UASB reactors in the state produce limited quantities of biogas, potentially compromising the financial viability of its use for energy purposes.

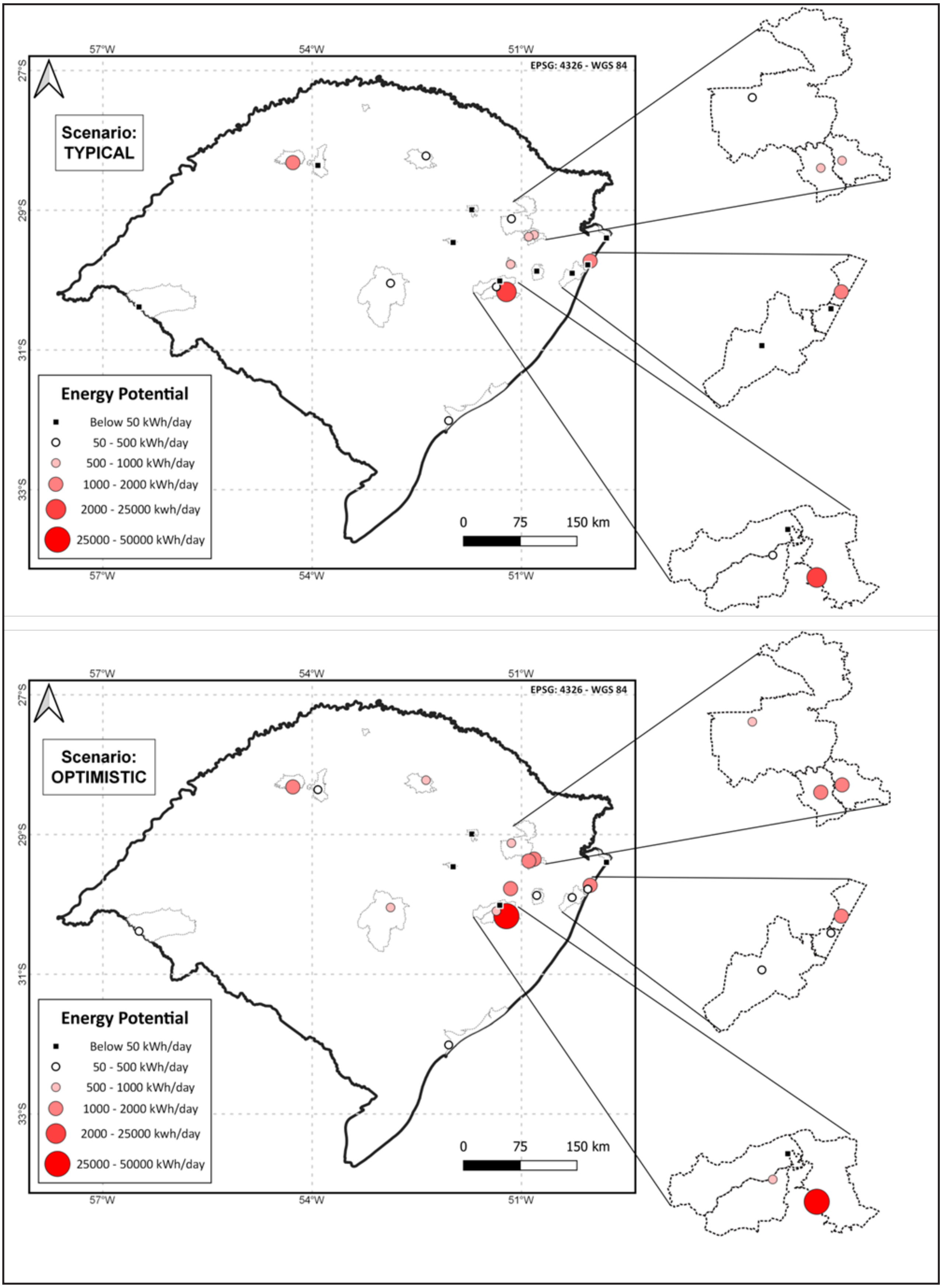
Table 3 – Summary of results for modelling the "Typical" and "Optimistic" scenarios

SCENARIOS: TYPICAL // OPTIMISTIC							
Cities	**COD (mg/L)**	**Qa (L/s)**	**QL (%)**	**Qb[2] (NL/ inhab. day)**	**Q_{CH4} (Nm³/day)**	**EP (kwh/day)**	**EPvt (kWh/m³)**
Gramado	495	21.4	47.1 // 32	9.5 //14.0	75.8 // 112.2	755.5 // 1,118.5	0.41 // 0.6
Santo Ângelo	441	40.9	48.8 // 33	8.2 // 12.3	124.4 // 187.4	1240.6 // 1,869.1	0.35 // 0.53
Passo Fundo	400	13.8	56.3 // 38.1	6.3 // 10.4	32.3 // 52.8	321.9 // 526.6	0.27// 0.44
Canela	380	28.7	54.2 // 36.6	7.2 // 11.5	66.8 // 106.8	666.3 // 1,064.8	0.26 // 0.43
Capão da Canoa	362	54.1	54.8 // 37.0	6.8 // 10.9	118 // 190.2	1176.7 // 1,897.0	0.25 // 0.41
São José do Norte	356	3.9	54.4 // 36.7	6.8 // 11.8	8.5 // 13.6	84.8 // 136.0	0.25 // 0.40
Porto Alegre	305	1500	60.8 // 40.1	5.1 // 8.9	2,374.8// 4,153.3	23,682.3 // 41,417.8	0.18 // 0.32
São Leopoldo	286	65.0	65.4 // 44	4.3 // 8.0	85 // 160	847.5 // 1,595.4	0.15 // 0.28
Lajeado	283	0.9	66.7 // 44.9	4.1 // 7.8	1.1 // 2.1	10.9 // 21.0	0.14 // 0.28
Glorinha	266	4.5	70.7 // 47.5	3.4 // 7.1	4.6 // 9.7	46.2 //96.6	0.1 // 0.25
Torres	249	0.4	71.6 // 48	3.2 // 6.7	0.38 // 0.8	3.8 // 8.1	0.1 // 0.23
Cotiporã	247	1.1	74.2 // 49.7	2.9 // 6.5	0.9 // 2.1	8.99 // 20.4	0.1 // 0.22
Caxias do Sul	229	34.7	80.6 // 53.9	2.0 // 5.6	20.1 // 55.9	200.7 // 556.9	0.07 // 0.19
Guaíba	180	90.1	89.4 // 59.2	0.95 // 4.3	22.1 // 99.9	220.7 // 996.3	0.03 // 0.13
Cachoeira do Sul	180	45.5	89.4 // 59.2	0.95 // 4.3	11.1 // 50.4	111.0 // 502.7	0.03 // 0.13
Xangri-lá	175	16.5	95 // 62.9	0.45 // 3.8	1.8 // 16.2	11.3 // 161.1	0.01 // 0.11
Ijuí	140	16.2	100 // 69.6	0.0 // 2.7	0.0 // 10.3	0.0 // 102.5	0.0 // 0.07
Quaraí	134	26.7	100 // 71.9	0.0 // 2.4	0.0 // 14.9	0.0 // 148.6	0.0 // 0.06
Eldorado do Sul	123	2.9	100 // 75.3	0.0 // 2.1	0.0 // 1.3	0.0 // 13.0	0.0 // 0.05
Osório	110	155	100 // 85.6	0.0 // 1.1	0.0 // 35.7	0.0 // 355.9	0.0 // 0.03

Source: Organized by the authors

[2] A contribution of 160 L/inhabitant.day was considered to estimate per capita production.

Figure 4 – Biogas energy potential for Typical and Optimistic scenarios



Source: Authors (2024)

Similarly, Camelo et al. (2024) - in a study involving statistical analysis of influent sewage to Rio Grande do Sul's STPs fed by separator networks - highlighted characteristics of more significant dilution observed in the state's sewage, with COD values significantly lower than those reported in other studies in Brazil.

Among the possible hypotheses meant to explain such behavior, the following stand out: local climate conditions; the residents' dietary structure; lower return coefficients; clandestine contributions; and accidental interceptions, such as rain infiltration into the soil (Camelo et al., 2024). Therefore, individual assessments are necessary in several cities in the state. This urgency is justified by the fact that sewage with higher COD allows for greater biogas production potential.

For example, Rosa et al. (2018) monitored an average volumetric production of 390.1 Nm³/day of biogas (78.2% CH_4) for the Laboreaux STPs (MG) using 78 L/s of sewage (average COD of 537.7 mg/L). They estimated an energy potential of 3,045 kWh/day and the possibility of generating 914 kWh/day of electricity – using an internal combustion engine with 30% efficiency – enough to meet 57.6% of the STP electricity consumption. It is worth noting that the volumetric production of biogas exceeds that of all RS cities, except Porto Alegre, in addition to having a higher CH_4 content than that estimated for the present study (Table 4).

Table 4 – Estimated CH_4 content of biogas of cities in Rio Grande do Sul

City	CH_4 (%)	City	CH_4 (%)	City	CH_4 (%)	City	CH_4 (%)
Gramado	69.1	São José do Norte	59.4	Torres	54.4	Xangri-lá	47.7
Santo Ângelo	68.8	Porto Alegre	57.6	Cotiporã	54.2	Ijuí	43.4
Passo Fundo	68.6	São Leopoldo	56.7	Caxias do Sul	52.9	Quaraí	42.6
Canela	59.9	Lajeado	56.5	Guaíba	48.2	Eldorado do Sul	41.0
Capão da Canoa	59.5	Glorinha	55.5	Cachoeira do Sul	48.2	Osório	39.1

Source: Organized by the authors

Likewise, higher treatment fluxes increase the volume of biofuel generated. For example, Lopes et al. (2020) assessed the energy potential of STPs in Paraná - the state with the most significant number of UASB-based plants in the country, totaling 182 STPs (out of 239). Out of them, 61 were classified as small (less than 56 L/s), 99 as medium-sized (57 to 434 L/s), and 22 as large (greater than 435 L/s). In a Typical scenario, the authors estimated a total energy potential of 2,256 MWh/day – significantly higher than the total value estimated in this study for the same scenario (29 MWh/day, considering the sum of all cities in Rio Grande do Sul).

Therefore, Lopes et al. (2020) concluded that using an electrical converter with 30% efficiency, the state of Paraná could generate 677 MWh/d of electrical energy, enough to meet the energy demand of 111,000 inhabitants. In this case, the precise impact of the size of the STPs is demonstrated: while in Paraná, 121 STPs (with UASB) with flow rates greater than 57 L/s were registered, in RS, only four were registered.

Part of this is due to Paraná's progress in terms of universalization: 76.3% of the population is served by sewage collection, with 75.9% of the total sewage being treated, which greatly contrast with the rates in Rio Grande do Sul, with only 26.6% of the population served and 26.6% treated (Brasil, 2022). There is, therefore, a vast field for the expansion of Rio Grande do Sul's STPs, which must be based on principles of self-sustainability.

During this universalization process, it is essential to pay due attention to the liquid phase losses of methane in the treated effluent, which exceeded, on average, more than 50% of the total produced in anaerobic digestion, even for the most optimistic scenario. In addition to the reduction in energy potential, the loss by the liquid phase implies the release of dissolved methane from the treated effluent into the atmosphere – due to the decrease in partial pressure.

Therefore, such a relevant environmental impact must be solved, for methane's global warming potential (GWP) is 28 times greater than CO_2 on a time scale of 100 years (Akpasi et al., 2024). According to Souza (2010), one solution to this problem would be the use of a dissipation chamber after the UASB reactor, aiming to remove methane in the liquid phase, which could achieve an efficiency of around 60%.

Regarding the possibility of its electrical use, according to the National Basic Sanitation Information System (SNIS), for 2022, the electricity consumption rate in sewage systems for the South region was 0.31 kWh for each m^3 of treated sewage. Thus, considering the results obtained from “Energy potential per treated volume” (PEvt), values close to or even higher than this rate are noted – especially in the Optimistic scenario, with more than 30% of cities exceeding it – which, preliminarily, could suggest the feasibility of supplying all or a large part of the electricity demand of their STPs.

However, as Rosa et al. (2018) and Lopes et al. (2020) considered in their studies, it should be taken into account that the estimated energy potential is not readily available for electricity generation, requiring electrical conversion devices, whose efficiency varies typically from 30 to 40% (Mertins & Wawer, 2022). Thus, even the cities with the most significant energy potential per volume treated in the State would not have the capacity to meet the electrical demand of their STPs.

Furthermore, more than a simple verification between the calculated electrical potential and the operating costs of a STP is necessary in order to conclude on the viability of using its biogas. This is because, in addition to the costs of electrical converters, a prior biogas treatment stage is usually necessary (Lobato, 2011). Therefore, the feasibility analysis must include a financial analysis covering the equipment to be installed and the entire useful life of the system.

Nogueira and Gaspar (2020), for example, assessed the feasibility of using biogas produced at the São José STP in Varginha, Minas Gerais, which operates with a UASB reactor with a flow rate of 229 L/s and an influent COD of 489 mg/L. Through a financial analysis – covering the cost of implementation and operation based on an internal combustion engine – the authors concluded that this possibility would be unfeasible, given the price of imported equipment and the low volume of biogas produced. Thus, it is clear that the financial analysis may make the project unfeasible, even if the energy potential appears to represent a cost reduction.

Most cities in Rio Grande do Sul do not have the feasibility of using such energy, mainly because they are small-scale STPs, where financial support is unlikely to be a reality. This is in line with the findings of Noyola, Morgan-Sagastume, and López-Hernández (2006) and the results of Valente (2015). The latter estimated that STPs serving a population of fewer than 50,000 inhabitants do not find any arrangement (electricity generation, cogeneration, or thermal treatment) viable.

Considering the opportunities arising from the New Legal Framework for Basic Sanitation (Law n° 14,026/2020) – which seeks to expand the private sector's participation in sanitation services – the possibility of public-private partnerships could bring investments that increase the viability of biogas projects, even in small cities, reversing this scenario of the predominance of small-scale STPs in the State.

In addition to this problem, the highly diluted sewage in the cities of Rio Grande do Sul led to deficient per capita biogas production – well below the average value of 14 L/inhab.d presented by Valente (2015) – with low methane content and high losses. Thus, it is even questioned whether the small amount of biogas produced could sustain a flame, as, for example, biogas must have a minimum methane content of 50% to be used in boilers (Probiogás, 2017).

Those STPs where the highest organic concentration of influent sewage was observed – in Gramado, Santo Ângelo, Passo Fundo, and Canela, for example – although due to their size they probably did not find financial viability for the generation and cogeneration of electrical energy, showed the highest value of biogas per capita among other cities, as well as a byproduct with a higher methane content.

A more detailed examination of such locations is needed, including alternatives that require lower treatment costs, such as direct combustion – heat generation or sale for cooking (Mertins and Wawer, 2022). Bressani-Ribeiro et al. (2019), for example, suggested two technological routes for biogas recovery in small and medium-sized

STPs, respectively: 1) cooking food or as fuel for heating water in the vicinity and 2) drying sludge or as thermal energy for disinfection. Both routes are characterized by thermal energy from biogas based on a certain constructive and operational simplicity, representing lower costs.

According to Souza et al. (2019), the potential for energy application in cooking – particularly recommended for small-scale STPs – is highly beneficial for surrounding communities, creating opportunities for local economic development through the training of residents. Araújo (2019), for example, when evaluating UASB reactors in the State of Ceará and carrying out a financial analysis of alternatives for the energy use of biogas, concluded that there is great viability for cooking food in appropriate stoves.

Finally, an individual assessment must also be made for Porto Alegre – which represents the largest generation of biogas due to its exceptional STP – covering different operating modes, such as base load, peak load, and emergency power.

4 FINAL CONSIDERATIONS

Following the national trend, most STPs in the Rio Grande do Sul use anaerobic technology to treat domestic sewage. UASB reactors have also proven to be recurrent and essential in treating domestic sewage in Rio Grande do Sul.

The adapted model allowed for a study on a large geographic scale to estimate biogas production in the state. Based on the variation in the solubility of methane in the liquid phase, the climatic characteristics of each city were included. Regarding the results, the Typical and Optimistic scenarios were judged to be the most appropriate.

Even so, the estimated energy production could have been more significant, mainly due to the highly dilute characteristics of the raw sewage, the predominance of small-scale STPs, and the high losses of dissolved methane in the treated effluent. These are the main obstacles that must be overcome to make biogas more attractive in Rio Grande do Sul.

Although in some cities energy production per volume of treated sewage appears to be sufficient to meet the operating electrical demand, generating electrical energy requires conversion devices with limited efficiencies, reducing most of the estimated potential.

Likewise, the biogas generated typically requires treatment steps to remove impurities. Installing such devices – both for conversion and conditioning – requires financial resources for their acquisition and maintenance, so a financial analysis tends to make the electrical use of biogas for small-scale STPs unfeasible.

For future work, it is recommended that each case be individually understood through a financial study that can identify the investment required to implement the biogas utilization system and the return time for this investment, considering expenses and savings, including the possibility of less noble uses of biogas, such as direct burning or cooking food.

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