Estimates of Renewable Energy Recovery from Biogas in Residential Buildings: Economic Feasibility Analysis

Estimativa de recuperação de energia renovável a partir do biogás em edifícios residenciais: análise de viabilidade econômica

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Abstract

Increasing of energy demand and climate change have hampered sustainable development. This article aimed to study the potential of biogas recovery for energy generation from compact wastewater treatment plants in buildings. Three buildings were selected and an economic feasibility analysis was carried out. The net present value (NPV) was positive and the economic internal rate of return (EIRR) was higher than the minimum attractive rate in five of six cases, showing that energy savings were sufficient to cover implementation, operation, and maintenance costs, with two to four years of payback time for biogas structures. The anaerobic reactor was responsible for the main expenditure, which indicates the importance of developing low-cost and compact units for decentralized wastewater treatment. Finally, the results indicate that biogas may be a promising and viable energy source in residential buildings.

Keywords: UASB. Energy savings. Sustainability. Domestic wastewater. Decentralized wastewater systems.

Resumo

O aumento da demanda de energia associado às mudanças climáticas tem dificultado o desenvolvimento sustentável. Este artigo buscou avaliar o potencial de recuperação de biogás para geração de energia elétrica, a partir de estações compactas de tratamento de efluentes em edifícios. Foram selecionados três prédios e realizado um estudo de viabilidade econômica. O valor presente líquido (VPL) foi positivo e a taxa interna de retorno (TIR) foi superior à taxa mínima de atratividade em cinco dos seis casos analisados, mostrando que a economia de energia foi suficiente para cobrir os custos de implantação, operação e manutenção, com tempo de retorno de dois a quatro anos para as estruturas de biogás. O reator anaeróbio representou o maior custo, o que indica a importância do desenvolvimento de unidades compactas e de baixo custo para o tratamento descentralizado de águas residuais. Por fim, os resultados evidenciam que o biogás pode ser uma fonte viável de energia em edifícios residenciais.

Palavras-chave: *UASB. Economia de energia. Sustentabilidade. Esgoto doméstico. Sistemas de tratamento descentralizados.*

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1 INTRODUCTION

In the current situation of increasing energy demand and sustainable urban development, the use of biogas produced during sewage treatment will play an important role in the future (Angelidaki *et al*., 2018). Due to the presence of methane, biogas is considered a biofuel. Using this gas as a renewable fuel is important for three main reasons: first, it reduces of negative environmental impacts, since methane is a highly polluting greenhouse gas (GHG); second, biogas can be stored, which is an advantage compared with other renewable sources such as wind and solar; and third, biogas is a source of decentralized energy generation (Probiogás, 2015a).

Improving plant structures by implementing techniques for sewage by-products recovery, such as biogas, is an essential condition for sustainable development. Around the world, the biogas sector is increasing, despite biogas systems varying considerably, depending on the technology development of the country, policies, and cost structure. Centralised plants are concentrated in Europe and in the United States. However, in Asia and South America great opportunities might emerge due to the already existing high number of anaerobic digesters (Viancelli; Michelon; Elmahdy, 2019). Most of the small-scale (household) digesters are placed in rural communities of Asia. Also, the use of biogas for cooking and heating purposes in rural areas has increased in South America, using as substrates the waste from agricultural activities, cow manure, and domestic sewage. Studies, such as Garfí *et al*. (2019), Lansche and Muller (2017), Sfez, Meester, and Dewaulf (2017) and Wang *et al*. (2018), have analysed the impact of these low-cost digesters and have identified environmental benefits due to reduction of methane emissions, and soil and water pollution.

Brazil relies on the most abundant biogas production source in the world. This is mainly due to the agriculture sector, but also dur to the great population numbers and consequent solid waste/sewage production. Nevertheless, only a minimal fraction of the biogas produced in Brazil has been explored. For example, Brazil has the potential to produce 19 GW of electricity, but only 2% of this potential is used. Also, most plants in operation are concentrated in rural areas (farms) and in landfills (Associação Brasileira do Biogás, 2022; Kanda *et al*., 2022). Furthermore, Kanda *et al.* (2022) report that regulations for biogas regarding environmental technologies in the country has been mostly addressed by Brazilian states, which offer taxes discounts for decentralised electricity generation.

In terms of domestic sewage, Zhang *et al.* (2009) highlight that urban wastewater is usually treated in centralized large-scale plants, which might be a negative aspect for cities growing fast, in a disorderly manner, and with scarce water availability. Some factors have led to attempts and to the development of alternative forms to generate energy, such as increasing environmental awareness, rising energy prices, and attractive subsidy measures. Climate characteristics are also important, especially with anaerobic wastewater treatment processes. This aspect highlights the importance to evolve biogas technologies in developing countries, where tropical and subtropical climates are predominant and more favourable to biomass productivity (Barz; Delivand; Dinkler, 2019; Bogte *et al*., 1993), such as in the Northeast region of Brazil.

In household establishments energy is usually provided by public supply network. Depending on number of properties within a building, energy consumption might be significant and represents a great annual expenditure. Thus, a decentralized unit in these locations with biogas managements seems both economic and environmental beneficial (Bauer; Mösle; Schwarz, 2006). Moreover, Glivin and Sekhar (2019) state that the main reasons for biogas development struggles lie on the lack of studies regarding biogas economic feasibility summed to the uncertainty of biogas production due to biomass heterogeneity. Thus, we address the research questions: is the biogas generated in compact wastewater treatment plants in urban household buildings sufficient to generate electricity? What are the economic implications of this technology?

To the best of our knowledge, the economic impacts of a proposed community biogas facility in an urban domestic environment was not yet assessed. Therefore, this work aimed to study the potential of biogas use for energy recovery in decentralized small-scale plants placed in residential buildings. This was achieved by designing a system model that includes a preliminary treatment, an upflow anaerobic sludge blanket (UASB) reactor and a biogas system. Also, the feasibility of the plant designed was analysed from an economic point of view.

2 MATERIAL AND METHODS

2.1 Study area and sewage characterization

Samples of sewage were collected from residential buildings in Aracaju, capital of the state of Sergipe, Brazil. The sewage was collected in the buildings' manhole structures with the aid of a rod to homogenously collect the material. These samplings were carried out weekly for five months with the purpose of analysing the influence of climate variation.

Aracaju is in the eastern coast of Sergipe (tropical climate zone). It has two characteristic periods: the dry season, with short duration, low frequency, and localized precipitations between September and February; and the rainy season, with constant and less intense precipitations from March to August. Thermal amplitude is minimal during the year, with temperatures varying from 24 to 30°C in spring/summer, and 22 to 29°C in autumn/winter (Climatempo, 2018).

The buildings where the samples were collected have the following characteristics: i) Building 1 (B1): middle-class building according to Brazilian patterns, with 105 properties currently occupied; ii) Building 2 (B2): horizontal condominium with higher social and economic level than B1 and 74 properties producing sewage; iii) Building 3 (B3): middle-class condominium with 300 properties occupied. This building was chosen mainly due to the large number of properties.

Aiming to preserve the characteristics of collected sewage, the sample bottles were placed inside a cooler with ice during transportation. The analysed parameters were: temperature, pH, total chemical oxygen demand (CODt), filtered COD (CODf), total solids (TS), total fixed solids (TFS), volatile solids (VS), total suspended solids (TSS), and total dissolved solids (TDS) in accordance with the procedure described in the Standard Methods for the Examination of Water and Wastewater (Eaton *et al.*, 2005).

2.2 Biogas estimates and energy recovery potential

The second methodology stage was about estimating biogas production and energy recovery potential using the software Probio 1.0 (Program of biogas production estimation in UASB reactors). This software is based on a mathematical model developed by the Federal University of Minas Gerais (UFMG) and Paraná Sanitation Company (SANEPAR) that estimates the production of biogas in UASB reactors treating domestic wastewater with a realistic mass-flow method, i.e., all methane losses identified during the process is accounted (Lobato, 2011).

Part of the input data for this software was calculated, such as population and influent flow rate of sewage (Q), whereas other data were obtained in laboratory or from typical values indicated in the software, as shown in Tables 1 and 2. Regarding the number of inhabitants, an average of 3.34 people was considered to live in the same property, which is the average value for Brazilian families (Instituto Brasileiro de Geografia e Estatística, 2010). Thus, the contributing population was calculated by multiplying this number by the quantity of properties occupied in each building, and the results were rounded to the nearest counting number. This calculation was necessary to preserve families' privacy.

The influent flow rate was determined considering a *per capita* water consumption for middle-class (272 L hab^{-1} day^{-1}) and upper-middle-class (239 L hab^{-1} day^{-1}) residential buildings according to results achieved by Oliveira and Lucas Filho (2004). The first was applied for the B1 and B3 buildings, and the second for the B2 condominium. This study was used as reference due to the climatic and economic similarity of the region. Also, a return coefficient of 0.8 was considered to obtain the correspondent sewage influent flow.

Table 1 – Input buildings data for software Probio 1.0.

Parameters	Buildings			Method
	B1	B2	B3	
Population (inhabitants)	350	247	1002	Calculated
Total COD (mg L^{-1})	583.7	539.4	493.8	Eaton *et al.*, 2005
Per capita COD contribution (kgCOD inhabitants^{-1} day^{-1})	0.11	0.12	0.09	Estimated
Temperature (ºC)	27.6	29.7	28.4	Thermometer
Sewage Inflow (m^3 day^{-1})	66.92	53.74	191.58	Calculated

Table 2 – Input data for software Probio 1.0 in each scenario.

Parameters	Scenarios			Reference
	Pessimistic	Typical	Optimistic	
COD removal efficiency (%)	60	65	70	Lobato (2011)
Sulphate-reducing efficiency (%)	80	75	70	Lobato (2011)
Solids production (kgslude kgCODrem-1)	0.11	0.17	0.23	Chernicharo (1997)
CH4 dissolved in effluent (kgCH4 m^{-3})	0.025	0.020	0.015	Chernicharo (2007)
CH4 loss as residual gas (%)	7.5	5.0	2.5	Chernicharo (2007)
CH4 eventual losses (%)	7.5	5.0	2.5	Chernicharo (2007)

2.3 Small-scale plant design

We assumed that a simplified preliminary treatment, a UASB and a system for collecting, transporting, storing, and using biogas are essential elements for the plant to operate properly.

Preliminary treatment aims to protect the operation of wastewater plants by removing coarse solids and other large material that can clog or damage pumps (Von Sperling, 2005). Since sanitation facilities inside a building avoid mixing sewage with rainwater, a relative amount of inert particles within wastewater is not expected. Therefore, a grit removal was not considered necessary and preliminary treatment would consist only of two coarse screenings.

The UASB reactor was designed following recommendations of Brazilian National Standards Organization (ABNT, 2011), Campos (1999) and guidelines about UASB hydraulic and kinetics typical values (Probiogás, 2015a; Chernicharo, 1997; Campos, 1999; Van Haandel; Lettinga, 1994). Moreover, orientations about biogas system implementation were gathered with Lobato (2011); Valente (2015) and Probiogás (2015b).

2.4 Economic feasibility

An economic analysis is important since it supports rational and informed decision making. The economic analysis was conducted in three different ways: net present value (NPV) (Equation 1), economic internal rate of return (EIRR) (Equation 2), and discounted payback period (DPP).

$$NVP = -C_o + \sum_{t=1}^{n} \frac{Bt - Ot}{(1 + iM)^t} \quad (1)$$

Where,

NVP = Net Present Value in BRL (real: Brazilian official currency);

C_o = capital expenditure (BRL);

Bt = benefits (energy savings) (BRL);

Ot = operation expenditure (BRL);

iM = minimum attractive rate (%);

t = period of time in which money was invested, starting from year 1.

n = period of project lifetime.

$$NVP = 0 = -C_o + \sum_{t=1}^{n} \frac{Bt - Ot}{(1 + EIRR)^t} \quad (2)$$

Where,

$EIRR$ = Economic Internal Rate of Return (%).

The first method (NPV) consists of measuring the difference between the present value of benefits and costs, considering a minimum attractive rate for investment. Thus, projects are considered economically feasible whenever benefits exceed costs or when NPV is higher than zero (Gordon; Loeb, 2006). The EIRR is the rate obtained by equalling NPV to zero, i.e., the difference between them is that NPV is presented in monetary values whereas EIRR is given in percentage. Thus, an EIRR above a minimum attractive rate means that the project is viable. Ultimately, DPP is defined by the period in which monetary benefits (positive values) are summed yearly until the expenditures are annulled (Tangvitoontham; Chaiwat, 2012).

3 RESULTS AND DISCUSSION

3.1 Sewage characterization

According to Shapiro-Wilk test, COD_t data follow a normal distribution with a 5% level of significance (Shapiro; Wilk, 1965). As can be seen in Figure 1, unlike total COD graph, filtered COD presented greater dispersion in B3 data, and the boxes were asymmetric in relation to the median, especially in B1. Comparing COD_t and COD_f blox-plots, the reduction in the median of total COD was less significant for B2 and B3 in relation to the median of their filtered COD, which varied from 569 to 439 mg L^{-1} in B2 and from 451 to 316 mg L^{-1} in B3, suggesting a greater presence of solids in total suspension (SST) in B1 (difference of 176 mg L^{-1} between COD_t and COD_f medians).

Metcalf and Eddy (2003) report that a sanitary sewage with a CDO_t of 1000 mg L^{-1} is classified as strong, and as average when it is 500 mg L^{-1}. In this case, the CDO_t medians (602, 569, and 451 mg L^{-1} respectively) indicate predominant characteristics of average organic matter content. Von Sperling and Chernicharo (2005) categorize that a CDO_t of domestic wastewater is usually around 600 mg L^{-1}.

Regarding pH (Figure 1), the results were close to neutral (pH = 7), what was already expected since this is domestic sewage. In addition, a large number of outliers was identified, which can be assumed by the sudden interference that may have happened in pH sewage caused by some household activity just before samples were collected, after all, degradation of domestic sewage substrates occurs somewhat slowly and pH and alkalinity are balanced after a while (Probiogás, 2016).

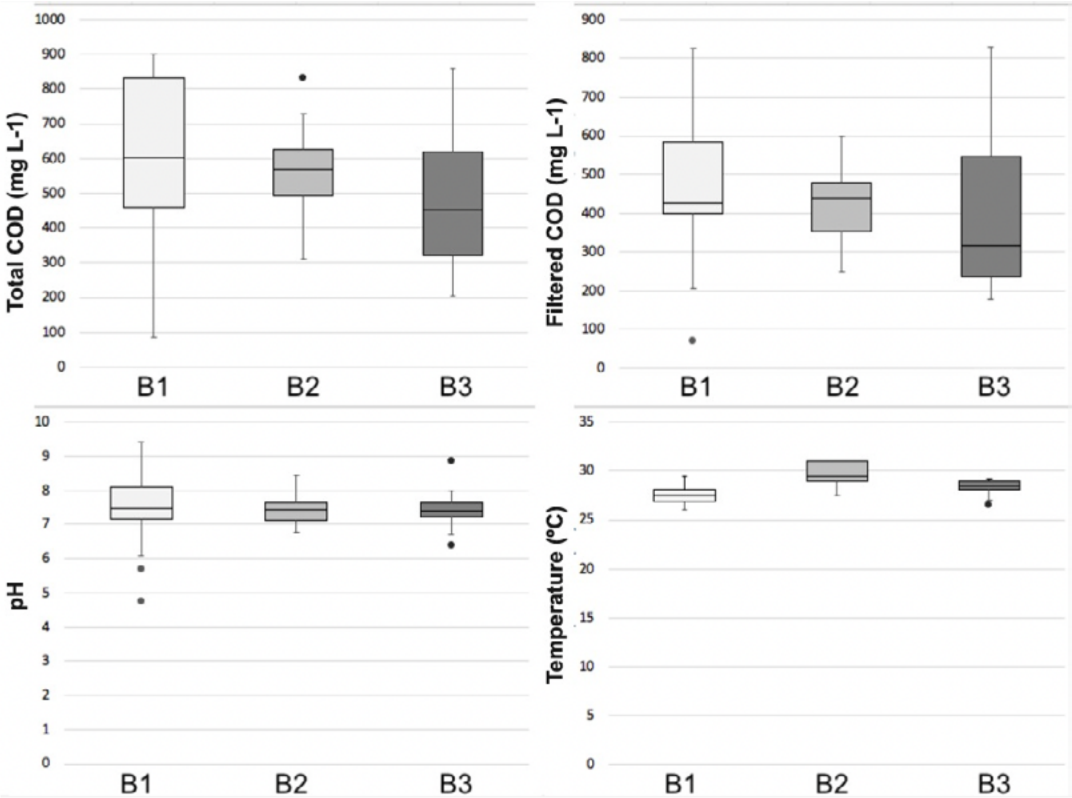

Figure 1 – Box-plots statistical results.

The mean values in Figure 1 for the temperature were 27.6 °C, 29.7 °C, and 28.4 °C for the B1, B2, and B3 respectively, and no data surpassed the amplitude of 26 to 31 °C. Thus, the digesters would be operating at great temperature, which indicates a satisfactory rate of hydrolysis and methane formation (Van Haandel; Lettinga, 1994).

The series of solids was calculated by descriptive statistics (arithmetic mean and standard deviation). High results for standard deviation were found, especially regarding B1 distribution, which reflects the spread shown in boxplot (Figure 1). Total suspended solids (TSS) represented the lowest part of total solids (TS), with means of 158.5 mg L^{-1} (B1), 108.1 mg L^{-1} (B2), and 141.9 mg L^{-1} (B3). That is, most of solids were dissolved. Furthermore, the average concentrations of solids for B1 and B2 was predominantly characteristic of medium to strong sewage and of B3 of medium to weak sewage, according to Metcalf and Eddy (2003) parameters.

3.2 Biogas estimation

Table 3 shows simulations of three scenarios were run in Probio 1.0 and the results for estimation of biogas.

The maximum volume of biogas formation was expected in B3 (21.6 m^3 day^{-1} in the optimistic scenario), as shown in the second line and third column of Table 3. On other hand, its composition was the one with smallest methane proportion (69.1% CH$_4$ yield in biogas). According to Lobato (2011), the average *per capita* volumetric production of biogas for a typical scenario is 14 N L hab^{-1} day^{-1}. In this study, the estimate pointed out to the following numbers in this scenario: 16.62 N L hab^{-1} day^{-1} (B1), 17.08 N L hab^{-1} day^{-1} (B2), and 14.86 NL hab^{-1} day^{-1} (B3). Namely, these estimations for the typical scenario (TS) indicated *per capita* biogas volumes above average, which may be caused by the favourable sewage temperature conditions that were higher than 25 °C, the standard temperature adopted in the mathematical model (Van Haandel; Lettinga, 1994).

The portion of CODt that is converted into methane and recovered into biogas corresponds to only 29.6% for B1, 28.9% for B2, and 31.1% for B3 in typical scenario, as shown in Figure 2. The remaining organic matter is converted into sludge, used by sulphate-reducing bacteria, and converted to methane and lost dissolved in the effluent, with residual gas, later released into atmosphere (Lobato, 2011).

These losses were not in accordance with Chernicharo (2007) numbers, which consider that 50 to 80% of the CODt that is converted into methane is recovered in biogas, 10 to 30% is lost in the effluent, and 5 to 15% is converted into sludge. The software Probio was modelled with data from a variety of domestic sewer plants in Brazil using UASB reactors, that is, evidencing that inefficient biogas capture systems and the non-release of methane from liquid sewage result in mediocre energy recovery face its potential.

Table 3 – Results for biogas estimates.

Parameter	Units	B1			B2			B3		
		PS.	TS.	OS.	PS.	TS.	OS.	PS.	TS.	OS.
CH4 yield in biogas	%	69.7	69.7	69.7	69.4	69.4	69.4	69.1	69.1	69.1
Real production of biogas	m^3 day^{-1}	4.3	6.4	8.7	3.1	4.7	6.4	11.7	16.4	21.6
Loss of energy potential	kWh day^{-1}	27.0	22.2	16.0	20.5	16.8	12.2	75.1	60.8	43.7
Available chemical energy	kWh day^{-1}	27.0	40.1	54.3	19.0	29.0	39.7	72.6	101.9	133.8
Unit volume of biogas produced	N L inhabitant^{-1} day^{-1}	11.2	16.6	22.5	11.2	17.1	23.4	10.6	14.9	19.5
	N m^3 m^3 sewage^{-1}	0.06	0.09	0.12	0.05	0.08	0.11	0.06	0.08	0.1
Unit energy recovery potential	kWh m^3 sewage^{-1}	0.4	0.6	0.8	0.4	0.5	0.7	0.4	0.5	0.7
	kWh inhabitant^{-1} day^{-1}	0.1	0.1	0.2	0.1	0.1	0.2	0.1	0.1	0.2

PS: pessimistic scenario (diluted sewage, high sulphate concentration, low COD removal efficiency, and high methane losses); TS: typical scenario (typical sewage, average sulphate concentration, average COD removal efficiency, and average methane losses); OS: optimistic scenario (concentrated sewage, low sulphate concentration, high COD removal efficiency, and low methane losses)

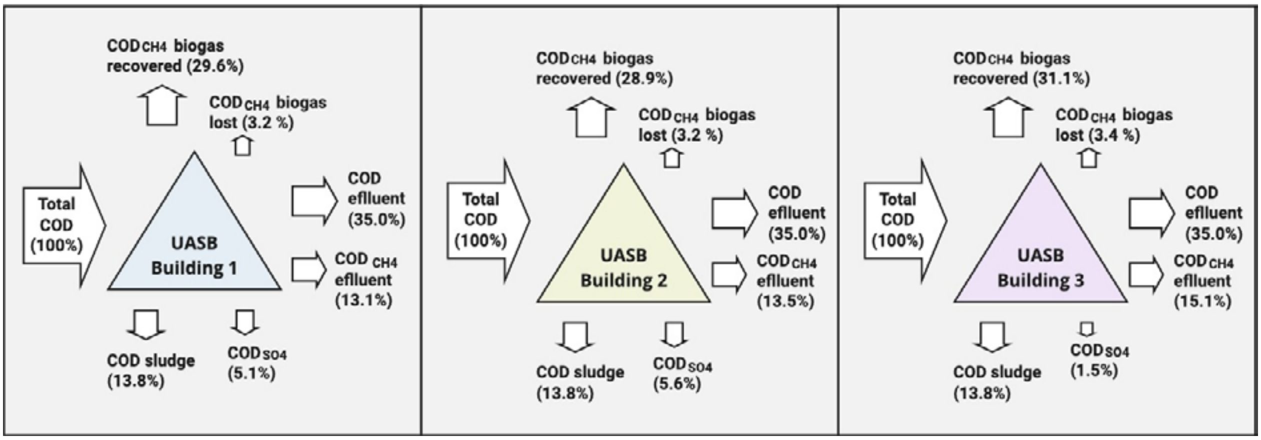

Figure 2 – COD mass balance in buildings B1, B2, and B3 for typical scenario (TS).

Reference: authors (2023) from results estimated in Probio 1.0.

There are ways to enhance biogas formation and methane yield. For example, non-porous membranes were very efficient in recovering up dissolved methane in UASB effluents as well as sequential down-flow hanging sponge (DHS) reactors (Crone *et al.*, 2016), and different treatments can remove the unwanted compounds from the biogas, expanding its range of applications (Angelidaki *et al.*, 2018). However, since this work aimed to evaluate the energy recovery potential considering the most practiced technology in the region, and not its improvement, the estimates were run as shown in the results, even though it could be better.

In addition, the influence of seasonality was not considered in biogas production due to rain. Rainfall events represents a decrease of biogas production in sewage treatment plants (10-20%) due to dilution in the organic loading rate (Melo *et al.*, 2020). Still, since the plant suggested would be located within buildings, i.e., the sewer pipeline would be directly connected to the reactor and none or few rainfall contribution is expected, this influence was considered irrelevant.

3.3 Small-scale plant components

A simplified preliminary treatment was proposed consisting of two screenings placed in sequence in an inlet channel, the first one with 30 mm in between its grids and the second one with 20 mm within its grids. After that, the wastewater should be directed to a shallow-well for pumping in a suction system, following to the UASB reactor. The pump should be adequate for influent flow, manometric head, and it must handle solids size up to 20 mm. At the reactor internal extreme of effluent pipelines, a tee fitting should be connected to the pipe to avoid scum mixing with treated effluent. No energy for heating the sewer was considered necessary since climate conditions are of high temperatures all year round.

The biogas system was defined in accordance with technologies available in the region. It was composed of a set of elements responsible for its transportation, purification, and storage, and an electric power generation unit. These comprise a simplified H2S filter with two horizontal tubes filled up with stainless steel sponges, a biogas gasometer of 8 m^3, a compressor, a biogas generator, a biogas transport pipeline, and security devices. Figure 3 shows a schematic representation of all elements of the plant.

3.4 Energy recovery potential

After biogas estimates and definition of small-scale structures for buildings adopted as examples, the potential energy available in each situation could be calculated (Table 4). The number of hours per day in which biogas generators would work depended on biogas volume available and generator consumption – 1.7 N m³ h^{-1} (Lobato, 2011).

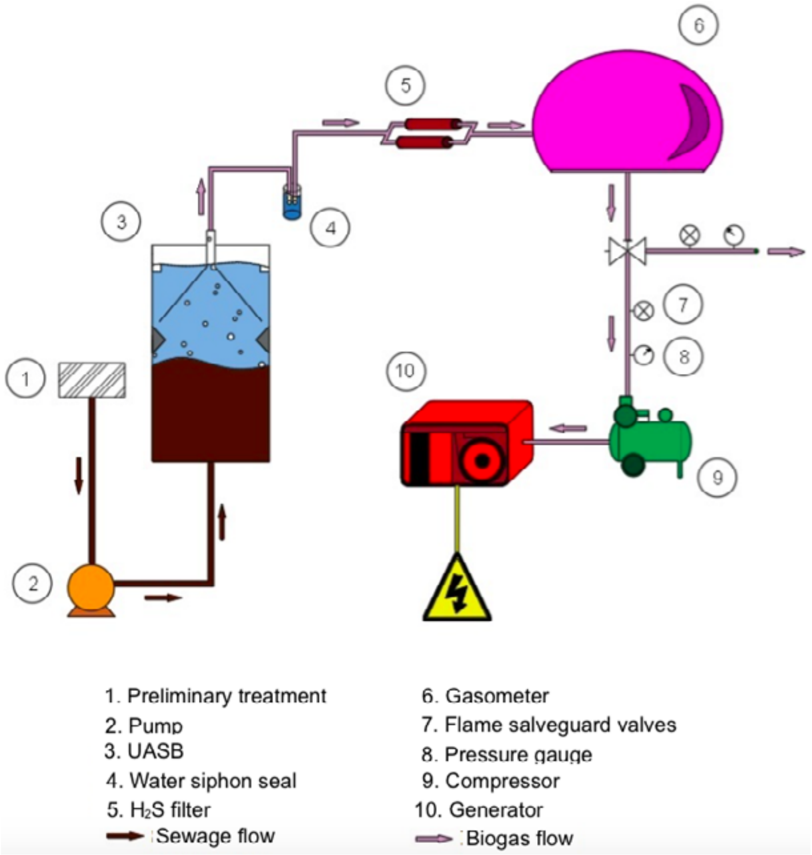

Figure 3 – Schematic representation of plant designed.

Reference: Adapted from Lobato (2011).

The savings in energy costs was determined by multiplying energy tariff (in kWh) by electricity generated (kWh.day^{-1}). The energy in the place of study is supplied by the municipal company. According to Brazilian National Energy Agency, a model of tariff (white tariff) indicates to consumers the variation of tariff charges depending on day and time of energy consumption (Agência Nacional de Energia Elétrica, 2022). That means energy prices vary for peak, off-peak, and intermediate periods. Peak tariffs are charged during greater load of supplier electrical system and it refers to a period of three consecutive hours on weekdays, excluding national holidays. The intermediate period corresponds to one hour before and after the peak time, also charged only for weekdays and non-national-holidays. Lastly, off-peak tariff is the one charged during complementary hours in weekdays and during weekends and holidays (ANEEL, 2016).

Table 4 shows tariff charges for residential buildings in this modality, and the current monthly electricity buildings' expenses were obtained with the respective managers. These expenditures refer to energy consumed in the building common areas, thus the benefits are for supplying buildings' amenities and not individual properties within the buildings.

To calculate money savings after biogas usage, we deliberated that biogas generators would operate preferably during peak times and, when there was still biogas available, during intermediate and off-peak periods. This happened for increasing savings as much as possible, since energy generation at peak hours decreases condominiums' energy consumption from supplier during the period in which tariff is more expensive. Also, a 30-day month was considered, where eight days corresponded to weekends and one day to a national holiday (when there is no peak time charges).

The energy savings in Table 4 demonstrate that biogas production was not enough to supply all energy demand. However, annual savings were considerably satisfactory, resulting in a saving equivalent to more than one-month consummation in B1, more than two months in B2, and R$ 6,269.99 in B3.

Table 4 – Estimates of energy available and energy savings after biogas usage for the optimistic scenario after Probio 1.0 (Lobato, 2011).

Parameters		**B1**	**B2**	**B3**
Real production of biogas (m^3 day^{-1})		8.70	6.40	21.60
Generator performance (%)		23.5	23.5	23.5
Generator operation in weekdays (hours day^{-1})	Peak time	3	3	3
	Intermediate time	2	0.76	2
	Off-peak time	0.12	0	7.71
Generator operation in weekends and holidays (hours day^{-1})	Off-peak time	5.12	3.76	12.71
Electricity generated monthly (kWh month^{-1})	Peak time	157.1	156.1	155.9
	Intermediate time	104.7	39.8	103.9
	Off-peak time	121.0	84.0	683.4
White tariff charges (BRL kWh^{-1})	Peak time	1.07697		
	Intermediate time	0.67335		
	Off-peak time	0.41643		
Monthly savings (BRL month^{-1})		343.05	429.24	522.50
Monthly mean energy consumption in the common areas (BRL month^{-1})		3,005.83	1,240.30	8,865.29
Energy self-sufficiency (%)		9.65	18.54	5.89
Annual savings (BRL year^{-1})		3,481.00	2,758.83	6,269.99

3.5 Economic feasibility

Table 5 shows a summary of the small-scale plants capital expenditures (CAPEX) and operation expenditures (OPEX). The costs for CAPEX were gathered in three different ways: i) from Sergipe Construction Budget System (ORSE) towards suction systems, UASB concrete structures, sewage pipelines, and H2S filter; ii) with local suppliers regarding expenditures for sludge inoculation and UASB three-phase separator; and iii) consulting reliable websites for the remaining features. In this last situation, several websites were reviewed to compose final costs, avoiding off-market prices.

The economic viability analysis was based on 25-year of project lifetime. Thus, some elements with a shorter lifetime should be substituted at least one time during system operation. These are: pump, gasometer, biogas generator, and the concrete sealing service for protecting UASB reactors from corrosion.

Table 5 – Summary of total capital expenditures (CAPEX) and operation expenditures (OPEX) of the designed plants.

Cost	Unit	B1	B2	B3
CAPEX	BRL	30,031.00	27,701.82	50,011.64
OPEX	BRL year^{-1}	1,596.07	1,211.66	3,964.61
CAPEX *per capita*	BRL inhabitant^{-1}	85.80	112.15	49.91
OPEX *per capita*	BRL inhabitant^{-1} year^{-1}	4.56	4.91	3.96

In the CAPEX composition, most costs were due to UASB reactors construction (approximately 60 to 80%). The main reason for this were the great expenses with concrete and the three-phase separator. The preliminary treatment costs were higher for B1 and B2 than for B3, since in B3 the pump would be used close to its maximum capacity. In other words, as sewage inflow is considerably low in B1 and B2, the pump would be working oversized.

Finally, expenditures with the biogas system were calculated to cost 27.41%, 29.71%, and 16.46% of the total CAPEX value for B1, B2, and B3 respectively. The proportion of expenses with biogas structure was inferior for B3 since the system assumed was the same for all three projects. Consequently, the largest CAPEX parcel in this building was due to UASB, which should be bigger to meet inflow demand in this building, and not the biogas system, which can meet the three situations' needs.

For the OPEX estimates (Table 5), the costs for one year of activities was considered, which should persist during project lifetime. The UASB's OPEX were calculated according to Von Sperling (2005), which provides an average annual expense of R$ 3.00 per inhabitant, and the biogas system OPEX was based on values presented in Brazil (Rosenfeldt *et al.*, 2017). Also, a visit of a skilled operator twice a year for maintenance was accounted for. For the components of preliminary treatment, we admitted that a local worker could perform operation and maintenance, since the main activity is simply a manual cleaning.

Regarding CAPEX and OPEX, total *per capita* expenditure in a year was calculated, considering the number of inhabitants in each building. Table 5 shows the *per capita* values, and if each resident spends nearly 5.00 to 10.00 BRL monthly, the project could be built and maintained. This does not necessarily mean that the plant is economically feasible, yet, it is believed that this project has great potential for implementation.

The minimum attractive rate (iM) adopted for the economic parameters' analysis was 2.56% and Table 6 shows the NPV, EIRR, and DPP results.

From the economic parameters calculated the B1 and B2 systems were both economic feasible since NPV was above zero and EIRR higher than. Then, we understand that the savings obtained from biogas utilization were enough to cover all implementation and operation expenditures. The same cannot be said for B3. One reason for this may be due to the period in which its generator would be working. Although biogas volume was greater in this establishment and the generator would operate during more hours, after peak and intermediate period was exceeded, the generator would be working with cheaper tariff (off-peak). Meanwhile, savings in the other buildings would be occurring, most of the time, during peak times. Consequently, B3 savings were higher in terms of absolute values, but lower in proportion to its annual expenses. Regarding DPP, despite economic viability, B1 and B2 results were quite unsatisfactory (21 and 25 years). Nonetheless, annual *per capita* costs were minimal, so these expenditures could be easily distributed by residents.

Table 6 – Results of economic feasibility for the optimistic scenario.

Economic feasibility considering total plant costs	B1	B2	B3
NPV	BRL 4,460.51	BRL 590.87	−BRL 7,826.50
EIRR	3.82%	2.75%	1.12%
DPP	21 years	25 years	Investment is not paid
Economic feasibility considering biogas system costs	B1	B2	B3
NPV	BRL 45,473.83	BRL 33,639.05	BRL 88,959.44
EIRR	35.64%	27.74%	64.53%
DPP	3 years	4 years	2 years

Furthermore, another situation was analysed. As stated before, growing consciousness and modification in legislations have stimulated a more seriously approach to sanitation issues. Thus, we may consider a circumstance where sewage treatment implementation occurred during building construction, that is, only the biogas system expenses would be transferred to future building owners. Given this situation, a new economic feasibility was assessed.

Table 6 demonstrates that all plants were economically viable in the alternative situation presented, with fairly short DPP (2, 3, and 4 years). This shows that benefits from energy generation were sufficient to pay implementation and operation of biogas systems' costs in a slightly period. In addition, the annual *per capita* costs for this conjecture, including CAPEX and OPEX, would be only: BRL 25.08 (B1), BRL 35.23 (B2), and BRL 9.17 (B3).

Anaerobic procedures might be ideal for local systems due to their low or null energy consumption, small area requirement, and simple project execution (Lohani; Bakke; Khanal, 2015). In terms of municipalities, Campello *et al.* (2021) state that a methane recovery system is viable for cities with more than 250,000 inhabitants, with a payback time of 1.25 years. However, decentralized units are necessary specially in cities with lower population and low density, as is the case of many cities of the north of Brazil.

In addition, despite these advantages, developing countries still struggle with unavailability of low-cost technologies of compact sewer structures, which increases the investment expenditure. For example, the technology stage for the biogas system is less developed in the locality. Even though Brazil has a great number of anaerobic treatment plants in operation, biogas use is still incipient in this country. Specific policies related to biogas are lacking, and high import taxes usually difficult investors in this field (Probiogás, 2016). Thus, obtaining information about equipment's specification, especially regarding biogas generators of small electrical power, was difficult, which may be a common problem for emerging countries with more recent technological development.

As for operation and maintenance of sewage treatment systems, both designers and construction workers have consolidated theoretical and technical skills. Nonetheless, technical competence becomes a challenge when innovative approaches are projected, such as the biogas system presented in this work. Although energy recovery is frequent in rural biodigesters around the world, implementing structures for biogas production and utilization for power generation in residential buildings is not usual. Consequently, doubts and uncertainties are expected at the beginning of biogas systems implementation within urban areas.

Another important factor for discussion is that this economic analysis might give an approximation of the costs with compact domestic sewer plant that can be constructed to attend a group of residences in a certain area that not necessarily form a condominium, but that can be used as an alternative to serve regions that are hard to access or that are localized in a way that forms groups of houses, such as some riverside communities, favelas, etc.

Thus, this study shows that the economic feasibility of energy recovery from biogas was favourable for household establishments with 247 to 1002 inhabitants (number of residents in the buildings evaluated in this study). What most affected the analysis, resulting even in economic unviability of one of the systems in the first situation, was UASB's implementation expenses. Thus, encouraging inclusion of efficient compact wastewater plants in buildings' future projects as well as adapting existing ones is important, contributing to a more sustainable urban development, and favouring installation of energy recovery systems such as biogas.

In conclusion, although the economic results were mainly positive, this study is an indicative of economic feasibility, since costs might vary from one region to another depending on technological progress, culture, climate, income, etc. Besides, it developed an estimative of biogas with the help of the software Probio, which gives us a great prediction of biogas formation and, consequently, of the plant economic viability. However, additional studies applied to a greater quantity and variety of buildings are necessary, as well in full-scale projects, to establish a better understanding about financial returns.

4 CONCLUSION

This article assumed that anaerobic compact systems for domestic wastewater treatment in household buildings were feasible, with advantages beyond environmental benefits, that is, allowing reduction of energy expenditures with a simplified biogas energy recovery plant.

Installation, operation, and maintenance costs of the small-scale plants designed were affordable for each inhabitant within buildings, i.e., the benefits from energy savings were higher than systems' expenditures, except for one situation. The greatest complexity identified was regarding technical features for assembling biogas structures, due to the lack of a specific guideline including local aspects for professionals to design and operate these systems, besides the small biogas trade development in the region.

Therefore, encouraging architects and engineers to include more efficient wastewater treatment plants during building designs is recommended, so that energy and economic recovery is favoured, also contributing for an environment friendly urban development. Finally, since environmental benefits are enough motive to include sustainable processes in new constructions and the projects resulted in low *per capita* annual expenditures, we understand that the system presented great potential of application.

5 AUTHORS' CONTRIBUTION

Investigation, Methodology, Writing & Editing – First version: Andrade-Barbosa, T; **Conceptualisation, Review and Supervision:** Lima, DMF.

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