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On-Site Power Generation Using Biogas in Sewage Treatment Plants: A Techno-Economic Assessment of a Brazilian UASB Facility

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Abstract

Small sewage treatment plants (STPs) in developing regions often flare the biogas produced in their upflow anaerobic sludge blanket (UASB) reactors, giving away a cost-effective energy source. This study tests whether on-site biogas-to-energy can pay for itself in approximately 2 years, even in plants treating less than 30 l s^{-1}. A small-scale STP in Angra dos Reis, Brazil (25 L/s), was studied, with an average biogas flow of 9.7 m^3/h; electricity generation was modeled for an engine generator unit with an efficiency of 30%. The techno-economic results show that the actual system would generate 125 MWh/year at a levelized cost of 0.017–0.023 USD/kWh, covering 47% of the plant's electricity demand. At a discount rate of 8%, the net present value was + 9.3 k US$, and the simple payback period was 2 years for the initial investment. Additionally, extrapolating the results to account for future expansion of the sewage treatment plant based on the total population in the region served by the system reveals even more promising results, with a suggested payback period of 1 year and 1 month of operation, covering approximately 57% of electricity demand. Scaling this retrofit to the approximately 18,000 comparable UASB-based STPs worldwide at low capital cost could reduce electricity bills by approximately 40% and avoid ~ 450 tons of CO_2-eq. per plant per year through methane capture and displacement of electricity from the grid. These results confirm that decentralized biogas power generation on a small scale is not only technically feasible, but also financially attractive and ecologically beneficial for operators of sewage and wastewater treatment plants and municipalities.

Keywords Sewage treatment plant · Biogas · Energy production · Renewable energy

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Introduction

Bioenergy derived from biogas has established itself as a relevant component of the global energy matrix [1, 2]. Recent reports estimate that all anaerobic digesters in operation will produce ≈ 445 TWh of energy in 2022, following a cumulative growth of 19% since 2017, with Europe accounting for almost half of this and Germany alone for around 20% [3]. In terms of installed capacity, the global market for biogas plants reached 23.3 GW in 2024 and is expected to exceed 40 GW by 2033 if the projected compound annual growth rate of 5.8% is maintained [4].

In the European Union alone, the combined production of biogas and biomethane reached 22 billion m^3 in 2023, which corresponds to around 7% of regional natural gas demand [5]. Capacities are still distributed, but heavily concentrated in a few countries: Germany (~ 87 TWh/yr), China (~ 81 TWh/yr), the UK (32 TWh/yr), and France (25 TWh/yr) are leading, while Brazil, despite its significant potential, still produces around 12 TWh per year [6].

This global panorama coexists with initiatives that put biogas back at the center of circular economy strategies. The integration of biogas plants in agro-industrial parks, food processing centers, and landfills leads to cascading synergies: organic waste becomes a source of heat, electricity, and biogenic carbon dioxide, which in turn can feed into e-fuel routes or carbon capture and storage processes [7]. Several countries are setting up regional bioenergy clusters to exploit precisely this circular economy by sharing substrate logistics, biomethane distribution networks, and CHP infrastructure [8, 9]. However, much of the techno-economic literature focuses on medium and large-scale plants (flow > 250 L/s or agricultural units > 500 kW_e), leaving significant gaps regarding the performance of compact plants [10, 11].

Among these gaps, the numerous WWTPs equipped with UASB reactors operating at flow rates below 30 L/s, typical of small and medium-sized communities in Latin America, Africa and South Asia, stand out. In these contexts, the predominant practice is to simply burn the biogas in flares, losing the calorific value and emitting methane, a gas whose global warming potential reaches 28 CO_2 equivalents in 100 years [12].

In contrast, case studies in Europe show that combined heat and power (CHP) can reduce energy costs for larger plants by an average of 60% and achieve a return on investment within 3 to 5 years [13, 14]. However, few authors have investigated whether similar benefits are maintained when production levels drop to a few dozen rather than hundreds of cubic meters of biogas per hour.

According to the Brazilian Institute of Geography and Statistics, IBGE (2024), only 3000 municipalities out of more than 5000 in Brazil properly dispose of their waste through collection networks to sewage treatment plants (STP), according to information published in the latest national survey on basic sanitation [15]. The lack of collection and treatment of a considerable part of the sewage generated, for example, can have an impact on the environment, on health, and, therefore, on the population's quality of life. It is estimated that in Brazil, 65% of hospital admissions of children under the age of 10 are due to the inefficiency or absence of sewage treatment and the lack of clean drinking water [16]. However, with the enactment of Law 11.445 of January 5, 2007, basic sanitation became a right guaranteed to all, and municipalities have invested in recent years in new treatment plants [17] in order to reverse this situation and provide access to clean water, sanitation and clean and affordable energy, which correspond, respectively, to goals 6 and 7 of the United Nations Sustainable Development Program [18].

The increase in the number of anaerobic STP in Brazil has led to an increase in the generation of biogas and sludge, which are the main by-products of the process [17, 19]. Unfortunately, the energetic use of biogas is still in its incipient stage, with most landfills and domestic sewage and industrial effluent treatment plants simply collecting and burning the biogas generated, without taking advantage of its energetic potential.

Two ways of using the main by-products generated in STP are decentralized electricity generation and heat production [20]. The National Electric Energy Agency (ANEEL) Normative Resolution No. 1.059 of February 7, 2023, the product of an action to minimize the intrinsic barriers to distributed generation in Brazil, established the general conditions for access to distributed micro and mini generation of electricity in the national territory, as well as defining the electricity tariff compensation system. For the purposes of this resolution, distributed microgeneration can be understood as an electricity generating plant with an installed capacity of less than or equal to 100 kW. Distributed mini generation, on the other hand, is a generating plant with an installed capacity of more than 100 kW and less than or equal to 5 MW [21].

This resolution benefits sanitation companies that have anaerobic STP. These systems, especially those based on *Upflow Anaerobic Sludge Blanket* (UASB) reactors, are widely used in Brazil due to the low cost of installation and operation compared to aerobic systems, which require aerators. UASB reactors produce biogas as a by-product of the degradation of organic matter, composed mainly of 60–80% methane CH_4, 10–25% nitrogen N_2, dissolved in the sewage, and 5–10% CO_2 [17, 20], which can be used as an energy input within the STP itself, which consumes significant amounts of electricity, especially in the aeration aerobic systems, which can account for 30–80% of the plant's electricity demand [22]. Taking advantage of the biogas generated to generate electricity provides a reliable supply and, at the same time, helps to mitigate greenhouse gas emissions [23]. On the other hand, when there is a surplus in generation, it can be redirected to reduce the energy bills of other projects run by the concessionaire, such as water treatment plants, administrative buildings, or other (STPs) that do not have the technology to collect biogas, by reinjecting this extra energy into the electricity grid of the local energy concessionaire, as provided for in ANEEL's resolution [21].

Various studies reported in the literature show the feasibility of using the biogas generated in STP for energy. Basrawi et al. [24] carried out an economic study of the behavior of a cogeneration system employing micro gas turbines (MTG) of different powers (30–200 kW) in a sewage treatment plant. They concluded that the best configuration results when the nominal fuel consumption of the MTG is approximately equal to the plant's biogas production. Mirmasoumi et al. [25] studied the effect of pre-treating the sludge and increasing the temperature in the biodigester at an anaerobic digestion sewage treatment plant in Tabriz, Iran, combined with a trigeneration energy system (cooling, heat, and power). The results showed an increase in biogas production with the use of pre-treatment and an increase in temperature in the biodigester of up to 180%, which consequently led to a decrease in the total cost rate and the levelized cost of energy of up to 41.29%. Lee et al. [26] integrated an anaerobic STP with a cogeneration system, investigating the effect of component efficiencies, temperature differences in the heat exchangers, and the ratio of pressures in the compressor and gas turbines. A multi-objective genetic algorithm was used to minimize environmental impacts and the total cost rate, achieving a reduction of 5.3% and 16.9%, respectively, and the energy generated could cover 47% of the plant's electrical demand, as well as 100% of the thermal demand. Mosayebnezhad et al. [13] investigated a hybrid system that employs MTG and solid-state fuel cells (SOFC) using biogas generated at a wastewater treatment plant (WWTP) in Italy. Two configurations were analyzed: SOFC-WWTP and SOFC-MTG-WWTP. The results showed an increase in electricity generation and a decrease in the levelized cost of electricity of 12% in the second configuration. Di Fraia et al. [27] used a cogeneration system composed of an Internal Combustion Engine (ICE) and a gasification system that uses the sludge generated in a WWTP as fuel. The gas produced in the gasifier is used to drive a dual fuel ICE that also uses waste vegetable oil altogether. The economic analysis showed a payback for the proposed installation of 6.8 years, 1 year longer than that calculated for an analogous conventional system, but the net present value was 30% higher. A study on two WWTP plants in Austria using biogas produced in CHP systems with heat pumps and co-digestion systems fed with organic waste and concentrated wastewater was conducted by Nowak et al. [28]. The results showed a 180% increase in energy generation compared to the plants' energy needs, making them self-sufficient. Helal et al. [29] studied the application of renewable energy sources in a WWTP plant in Toukk, Egypt, using HOME software to simulate and compare different hybrid systems composed of CHP units, fuel cells, wind turbines, and photovoltaic systems, concluding that the fuel cell and the microturbine variant maximize the power-heat ratio. Five WWTP plants located in Catalonia, Spain, which treat mixtures of domestic and industrial wastewater were studied by Silvestre et al. [30]. The results showed that depending on the configuration of the installation and its operation, between 39 and 76% of the electricity consumed could be supplied by the biogas produced in the process when burned in internal combustion engines coupled to electric generators with a payback period of between 2 and 3 years. In recent years, technological advances have also increased the attractiveness of substrates with lower productivity. Intracellular shock wave digestion processes have reduced the particle size of sludge and increased the specific methane yield by 18–30%, with an estimated investment of ≈ 110 USD/t of sludge [31]. Thermochemical treatments such as steam explosion and mild alkalization increased the biomethanation potential of rye straw by approximately 42% and that of hay by 35%, showing that pretreatments with low investment costs (< 15 USD/ton biomass) can make abundantly available lignocellulosic substrates profitable [32]. In addition, co-digestion strategies with horticultural waste have increased biodegradable volatile solids content and consequently biogas flow, all with a payback period of often less than 24 months, depending on the local electricity tariff and incentive framework [33, 34].

Despite the environmental benefits, the reduction of fugitive methane, the replacement of fossil electricity, and the production of biofertilizer, sustainability is only consolidated if it is accompanied by profitability. Investment portfolio analyzes show that renewable energy projects in emerging markets need to exceed an internal rate of return of ≈ 12% per year to attract private capital, especially in scenarios with exchange rate fluctuations and regulatory uncertainty [35]. Therefore, studies that accurately quantify the cost of energy (LCOE), net present value (NPV) and sensitivity to electricity and substrate prices are essential to support decisions by wastewater treatment plant operators, regulators, and infrastructure funds.

Given this scenario, this investigation focuses on a representative case study: a sewage treatment plant in Angra dos Reis, Brazil, designed for 25 L/s and equipped with a UASB reactor with an average biogas flow rate of 9.7 m^3/h. The energy conversion was then modeled with a 25 kW_e engine generator with an efficiency of 30%, with a cost analysis based on offers from national suppliers. The research tests the following hypothesis: "A UASB wastewater treatment plant with a flow of less than 30 L/s can meet $\geq$ 45% of its own electricity demand with a simple CHP retrofit and minimal gas cleaning, amortize the initial investment of an estimated 380 to 420 USD/kW_e in $\leq$ 24 months." The urgency to test this hypothesis stems from the fact that there are ≈ 18,000 wastewater treatment plants of similar size in middle-income countries that still waste biogas, representing a theoretical potential of ≈ 2.2 TWh/year of electricity and ≈ 72 Mt CO_2-eq of emissions reduction.

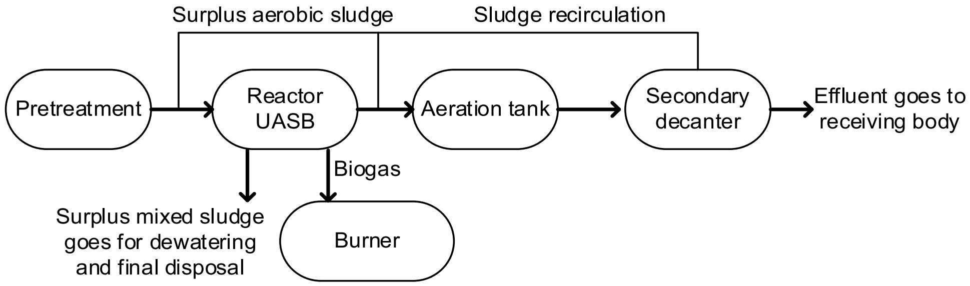
This research aims to provide fundamental insights to drive energy-positive sanitation policies, establish green financing criteria, and provide guidance to manufacturers on the sizing of equipment for decentralized markets.

Methodology

This work is based on a case study that will evaluate the possibility of implementing the use of internal combustion engines to use the biogas generated in an operational sewage treatment plant run by SAAE in Angra dos Reis, in the area known as Praia da Chácara, located in 23°00′11.2″S, 44°18′18.4″W. This plant is part of the sewage system in sub-basin G, which includes the neighborhoods of Balneário and Parque das Palmeiras. Designed to serve 10,000 people, it currently treats the sewage of 6600 inhabitants with a mean flow of 25 L/s proposed in the project developed by SANEVIX ENGENHARIA company. In the future, the idea is to expand the STP area of operation and include other neighborhoods such as Marinas and the hills closest to Parque das Palmeiras (Fig. 1).

The STP type UASB + BFMO + DS is pre-molded and built entirely in carbon and stainless steel to ensure greater durability due to its proximity to the sea. It uses an Ascending Flow Anaerobic Reactor followed by an Organic Matter Biofilter and a Secondary Decanter, with an inlet box system designed to retain the solids and dirt that are thrown into the network. This is followed by an anaerobic treatment process in which a colony of bacteria feeds on the organic loads. This is followed by an aerobic process which carries out the final treatment with new colonies of bacteria. This reduces the organic load by 96%. It also has a special system to prevent bad smells. Even though the reactor technology (UASB—Upflow Anaerobic Sludge Blanket) has been implemented, which increases the production of biogas and sludge, the project proposed by the company does not offer the option of using the biogas generated from anaerobic digesters and sludge storage tanks for energy, being burned directly in a flare without any energy use. A new plant configuration

Fig. 1 Actual configuration of the sludge treatment plant under study



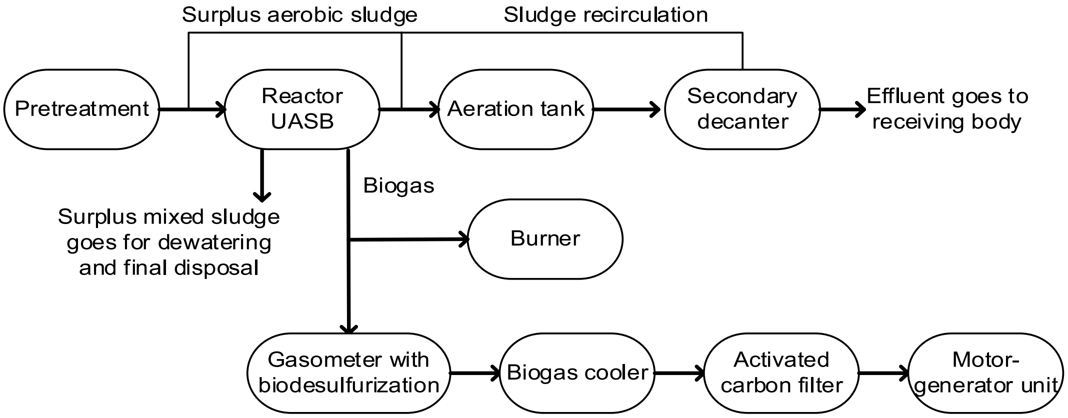


Fig. 2 Schematic representation of a modified plant as used in this study

scheme similar to the plant under study but using the biogas generated can be seen in Fig. 2.

Two scenarios will be analyzed: the first scenario would be considering the plant's current situation with an average flow of 25 L/s of effluent, being a flow from a small station that will only serve a small territory. The second scenario would be a hypothetical situation in a future expansion of the plant that would be able to meet the needs of the entire population of the city of Angra dos Reis, which amounts to approximately 167,434 inhabitants, of whom 85% have access to adequate sewage systems [36].

To evaluate the viability of biogas energetic use in an internal combustion engine, some project variables involved in the production of the same in sludge treatment plant must be calculated.

Affluent Sewage Volumetric Flow

The amount of sewage that feeds the sewage treatment plant is currently stipulated in the project at 25 L/s, which will be the average flow for scenario 1. For scenario 2, an estimated effluent flow will be considered based on the population that will be served by the hypothetical plant, which, according to IBGE data for the municipality in question, would amount to 142,319 inhabitants. Using the example from Eq. 1, it determines that:

$$Q = \frac{QPC \times C_r \times Pop}{1000} \tag{1}$$

Where:

Q is the influent sewage flow in the STP (m^3/d).

Q_{Hab} is the per capita contribution flow (l/inhab.d).

C_r is the coefficient of recycle of sewage/water per capita.

Pop is the population (inhab).

In Brazil, according to the last census carried out by the IBGE, an individual's per capita use of water, called quota per capita (QPC), was 116 L per day. Among the major regions, the Southeast has the highest per capita use, with 143 L, while the lowest use is recorded in the Northeast, with 83 L per inhabitant. The domestic sewage flow was calculated based on the project population and the value assigned to the average daily water consumption (assumed to be equal to 116 l/inhab.day) [15], with a correspondence between sewage production and water consumption. The return coefficient (C_r) was adopted as 0.8 inhabitant/day, the recommended value when there are no local research data available [37].

Volume of biogas produced in UASB reactors

According to Von Sperling [38] and Lobato et al. [39], it is acceptable to use 300 mg/l for biological oxygen demand (BOD) and 600 mg/l of chemical oxygen demand (COD), respectively, due to the physical chemistry characteristics of domestic and sanitary sewage influents into wastewater plants. These values of BOD and COD are the same as the ones proposed in the project and are consistent with the COD values obtained with diluted domestic wastewater in tropical conditions, COD < 1000 mg/l and T > 20 °C [40].

Chernicharo [41] stated that biogas production is directly proportional to the total removal of organic loads in the reactor. The COD from the effluent depends on the efficiency of the reactor is shown in Eq. 2.

$$E_{COD} = 1 - 0{,}68 \times HRT^{-0.35} \tag{2}$$

In which:

E_{COD} is the efficiency of COD removal in the UASB reactor (%).

HRT is the hydraulic retention time (h), adopted in this study 8 h [40].

The removed organic load in the reactor can be obtained by Eq. 3.

$$COD_{CH4} = \left[Q \times \left(S_0 - S\right)\right] - \left(Y_{obs} \times S_0 \times Q\right) \tag{3}$$

Where:

COD_{CH4} is the organic load converted to methane (kgCOD$_{CH4}$/d).

Q is the mean influent flow (m^3/d).

S_0 is the influent COD to UASB reactor, adopted 0.60 kgCOD/m^3) [26, 27].

S is the effluent COD filtered into UASB reactor (kgCOD$_{fil}$/m^3).

Y_{obs} is the coefficient of total suspended solid production (kgCOD$_{TVS}$/kgCODapplied).

The effluent COD load (S) can be determined when the removal efficiency of the USAB reactor is known as follows:

$$S = S_0 \times (1 - E_{COD}) \tag{4}$$

Van Haandel and Lettinga [42] determined that the value of coefficient of total suspended solid production in UASB reactors (Y_{obs}) may vary between 0.1 and 0.2. In this study, the value of 0.2 was used. The higher limit was selected because the more sludge generated, the lower the methane production, which would be the worst-case scenario in a sewage plant.

Chernicharo also states that the methane flow can be calculated once the correction factor of the reactor temperature is known, as shown in Eq. 4.

$$K_{(T)} = \frac{P \times K}{R \times (273 + T)} \tag{5}$$

Where:

$K_{(T)}$ is the correction factor to the operational temperature in the reactor (gCOD$_{CH4}$/l).

P is the atmospheric pressure (atm).

K is the COD corresponding to 1 mol of CH_4 (64gCOD/mol).

R is the gas constant (0.08206 atm.l/mol.K).

T is the operational temperature in the reactor (25 °C).

The methane flow produced in m^3/d is the ratio between the organic load converted to COD_{CH4} by the correction factor to an operational temperature $K_{(T)}$, as shown in Eq. 5.

$$Q_{CH4} = \frac{COD_{CH4}}{K_{(T)}} \tag{6}$$

The biogas from domestic sewage has a typical concentration of 60 to 80% of methane depending on the organic load [17, 20], considering the mean methane concentration experimentally determined in Brazilian STP using UASB reactors is higher than 70% [17]. We will consider the worst-case scenario, which would be a biogas production with 60% CH_4 in its composition. Another estimate made is referring to the losses of methane to the theoretical production, which are in the order of around 20 to 50% [43]. In this case, full-scale sewage plant measurements in Brazil were considered, where losses were estimated between 36 and 40% of the produced methane, which leaves the reactor dissolved in the effluent. Other losses considered in the order of 5% can also occur through the surface of the settler compartment and leaks in the system. For these reasons, the total loss value assumed was 40% of the methane flow produced [40]. Thus, the worst operating conditions of the plant were considered.

The real mass flow of biogas produced can then be determined as follows:

$$Q_{\text{biogas}} = \frac{Q_{CH4}}{\%CH_4} \tag{7}$$

Volume of biogas produced in UASB reactors

Potential of energy generation in STP

The annual electricity produced from biogas can be estimated by Eq. 8.

$$P_{\text{generation } EE} = \frac{(Q_{\text{biogas}} \times 365)}{1000} \times \frac{LHV \times \eta_{\text{engine}} \times \eta_{\text{generator}} \times C_s}{C_{kw}} \tag{8}$$

In which:

$P_{\text{generation EE}}$ is the potential of electricity generation (MWh/yr).

LHV is the lower heating value of biogas with 60% of methane from reference [19] assumed as 5500 kcal/Nm^3.

η_{engine} is the engine efficiency (%).

η_{gerador} is the generator efficiency (%).

C_s is the coefficient that adjusts the plant operation throughout the year (considering an operation of 8000 h during a year, which corresponds to an availability factor of more than 90% [44]).

C_{kw} is the factor of conversion kcal to kWh (860.42 kcal/kWh).

The thermal efficiency of biogas engines varies between 30 and 40% according to Perez et al. [45] and [46]. The electric generator has an efficiency between 90 and 97%; to be on the safe side and considering the worst case, the lowest values will be used for both cases..

Economic Viability

The economic viability will be assessed by an extensive analysis of all costs involved in the implementation of the plant as well as the annual revenue. Economic decision-making indicators will be determined, such as payback and net present value. Any investment project has an initial period of expenses that is followed by a net revenue period. Payback is the period in which all expenses are covered by revenues. This period can be considered with or without an updated cash flow.

In the NPV model, the aim is to find the value of the investment by discounting the cash flow at a rate that reflects the associated risk. Initially, the internal rate of return (IRR) is calculated to verify the investment profitability. This rate shows the equivalence between the incoming and outgoing cash flows, that is, when the NPV is zero. When compared to the minimum attractive rate of return (MARR), this rate must be higher for the investment to be advantageous. The MARR indicates the minimum value for profitability of a project for it to be a viable implementation. These indicators are used as decision-making criteria for financial investment in cogeneration plants [47].

Cost with Implementation of the Energy Generation Unit

We will evaluate the cost of implementation of the unit that meets the demands of the project and the size of the STP already in operation at Praia da Chácara with an influent mean flow of 25 L/s, as well as the hypothetical situation in a future expansion of the plant that would be able to meet the needs of the entire population of Angra dos Reis city.

Experimental tests carried out at the STP run by SABESP in Barueri/SP compared the performance of a microturbine system unit and an internal combustion engine unit (otto cycle) working in parallel to burn the biogas produced at the plant. The results showed that the cost/benefit of the genset system was much higher than that of the microturbine, mainly due to its low investment and operating costs in relation to the installed power and the energy produced when compared to other commonly used technologies such as gas turbines and microturbines [48].

However, to use the biogas generated in the STP in a gas engine, it needs to go through a purification process to remove the main impurities such as moisture, siloxanes, sulfur, halogenated compounds, and other contaminants [20], mainly CO_2 and H_2S, which affect the combustion process and increase heat losses in the engine [49]. The efficiency of removing these contaminants depends on the technological alternative used [40]. Therefore, the following economic feasibility assessment will be studied based on a unit that operates 24 h a day, consisting of a basic system with a dehumidifier, purifier with Fe_2O_3 bed and cooling tank, gasometer, and generator set (internal combustion engine + electrical generator).

All components have their respective functions in the process aiming to improve biogas conditions. The generator group, or internal combustion engine, will be chosen according to the estimate of biogas flow produced in the STP. The cost of purchasing the equipment used in the current plant (first scenario) was estimated through direct price surveys with international equipment suppliers. For the second scenario, the total capital investment in each of the subsystems was calculated using the factorial estimation method reported by Aguilera et al. [44] (Table 1). In this method, the costs of the main components of the plant for a known size are obtained as a reference, and an appropriate scaling factor is applied to calculate the cost for a desired equipment size using the following equation:

$$C = C_r \left(\frac{S}{S_r} \right)^m \tag{9}$$

Where:

C is the equipment cost with a certain capacity of interest S.

C_r is the equipment cost for the reference capacity S_r.

m is the incidence factor for economy scale (assumed to be equal to 0.6 [44]).

The values of the purchase costs obtained from suppliers show a certain lag with respect to current values today, so the chemical engineering plant cost index (CEPCI) was used, which accounts for inflation and changes in equipment costs over the years and is used to update all data to the current year.

$$C_{2023} = C_{\text{year ref}} \bullet \frac{\text{CEPCI}_{2023}}{\text{CEPCI}_{\text{year ref}}} \tag{10}$$

The CEPCI values used for the year 2019 were 607.5, and the average value of 797.9 from the current year's CEPCI for 2023 was used.

Besides investment equipment costs, the cost of operation and maintenance must be estimated as well. The cost of the operation and maintenance represents annually about 2 to 4% of the total investment of the unit [24, 50]. The estimated cost with operation and maintenance is calculated in Eq. 11.

$$C_{o\&m} = \left(C_d + C_p + C_{\text{gas}} + C_{\text{gg}} + \alpha \right) \times 0.04 \tag{11}$$

In which:

$C_{\text{o\&m}}$ is the cost with operation and maintenance (US$/yr).

C_d is the cost of investment with dehumidifier (US$).

C_p is the cost of investment with purifier (US$).

C_{gas} is the cost of investment with gasometer (US$).

C_{gg} is the cost of investment with generator group (US$).

α is the diverse cost with flowmeters, pipelines, valves and connections, peripheral, and structure (estimated from data given by Hengeveld et al. [50] and Basrawi et al. [24].

It is important to consider the depreciation of the equipment. The annual depreciation of the equipment is assumed to be linear for a 10-year period and was calculated by considering an average lifespan of the plant of 20 years, according to the estimates of lifespan for STP reported by [44] and [46], varying between 15 and 30 years.

$$W = \frac{100\% \times C}{U_l} \tag{12}$$

In which:

W is the depreciation of equipment (US$).

C is the total cost of equipment (US$).

U_l is the useful life (years).

The results of the investments will be evaluated according to the distribution of electricity produced in the network and the gain, through the generation of credit with the local energy distributor. This work did not evaluate bureaucratic terms such as environmental licensing, risk analysis, and the resistance of the existing market with regards to the

Table 1 General investment costs of the energy generation unit in US$*

Equipment/operation	Actual plant (9.7 m^3/h)	Future expansion plant (70.7 m^3/h)
Purifier	1957.6	10,285.1
Gasometer	548.13	8952.3
Engine generator	9035.2	53,414.9
Flow meter	1152.1	6390.8
Diverse	7347.6	23,251.6
Civil work	5464.9	17,991.2
Equipment depreciation	1246.3	6014.3
Operation and maintenance	1028.9	4811.4
Total (US$)	27,809.7	131,111.7

*An average dollar exchange of 5.13 BRL$ for the year 2023, defined by the central bank, was used to convert the values acceptance of sustainable projects. Therefore, a more thorough and complete analysis may be a topic addressed in another study.

The BDI (benefits and indirect expenses) is the element of a budget whose purpose is to measure the portions of the price of the civil work that indirectly affect the execution of the object. The BDI is made up of: central administration costs; financial costs of the civil work; systematic (non-diversifiable) risk costs applied to the project; municipal, state, and federal taxes; insurance and guarantees; and profit margin. Added to the direct cost of a civil work or service, the BDI defines the total cost of the project. In this study, a BDI of 24% was adopted for civil works and services and 14% for equipment, in accordance with Ruling 2622/2013 of the Federal Court of Auditors.

The company Shandong Tiger Machinery Technology Co., Ltd provides equipment quotations for actual plants, including 25 kW biogas STG25-BG genset with a configuration of 3 phase, 60 Hz, 127 V/220 V, PF = 0.8, with 30 kW gas engine (with gas engine control system), 25 kW alternator, base frame and shock absorbers, with control cabinet, free maintenance battery, wood case packing, heat recover system, silent canopy, and an auto-parallel for gas genset, which was operated at 90 ± 5% load. Declared electrical efficiency is 30% (ISO 3046); measured gross efficiency 29.4 ± 0.9%. Generator efficiency is 90% at unity PF. Exhaust heat was not recovered. A double-membrane gasometer of PVC material, 1.2 mm thickness, with gas inlet and outlet (size 3 cm), DM-100 (Holly Enterprise, CN, S/N DM-23–07) stores 2 h of production at low pressure 4–6 mbar (g), was selected. The purifier used has filters with molecular sieves to remove CO_2 and a column with iron oxide to remove sulfide, and it consists of four tanks, supplied by the Chinese company Holly Enterprise ElecMech Equip. Co., Ltd. The dual-stage purifier contains 45 kg of 3 Å sieve (bed height 0.50 m, SV ≈ 600 h^{-1}, ≥ 99%, Zeochem AG, CH, Lot #MS3A23-07), followed by 38 kg of iron-oxide pellets ($Fe_2O_3 \geq 92\%$, Sigma-Aldrich, Cat. No. 544884–1 kg, Lot #MKCF0496, bed height 0.42 m). Breakthrough is defined as $H_2S > 50$ ppm v/v at the outlet, typically after 1100 ± 120 h. Moisture is removed in a shell-and-tube condenser (TR2-04, Reftec, MX) held at 5 °C. Flow is logged every 2 s with a vortex meter KFG-1009 fitted with a CVT-TEM remote indicator (Kaifeng Chongqing, CN, S/N KFG-23–0415)—factory-calibrated to ± 0.5% FS.

Cost of Electricity Generation

According to the methodology of Pérez et al. [45], the cost is calculated by Eq. 13. In this method, the cost is estimated by the ratio between the initial investment of the project and the potential of electricity generation amortized according to a rate of interest added to the cost of operation and maintenance.

$$C_{el} = \frac{\left(Inv_{\text{plant}}\right) \times f + C_{o\&m}}{P_{\text{generation}EE} \times 1000} \tag{13}$$

In which the annuity factor is defined by:

$$f = \frac{q^k \times (q-1)}{q^k - 1} \tag{14}$$

With:

$$q = 1 + \frac{i}{100} \tag{15}$$

In which:

C_{el} is the cost with electricity production (US$/kWh).

Inv_{plant} is the total investment with the unit ($C_d + C_p + C_{gas} + C_{gg} + \alpha$ in US$).

$P_{\text{generationEE}}$ is the potential of electricity generation (MWh/yr).

f is the annuity factor (1/year).

$C_{\text{o\&m}}$ is the cost with operation and maintenance (US$/kWh).

k is the service life of the system (20 years) or payback.

i is the interest rate (8%, 12%, and 15%).

Revenue from Electricity Added to the Distribution Network

Through the compensation system mechanism from ANEEL Normative Resolution No. 1.059 [21], consumers can inject the energy generated in their consumer unit directly into the distribution network and receive a return in the form of energy credits, i.e., at the end of the month, the amount injected into the network is deducted from the amount consumed. To calculate the revenue generated by the generation of electricity, a tariff weight average is used (Eq. 16), composed of the tariff of electric energy (TE) and the tariff for use of the distribution system (TUSD), a value determined by ANEEL, in R$/MWh, used for the monthly billing of consumers and other users of the monthly billing of the electricity distribution system by the use of the system, considering the value of the peak hours and off-peak hours tariffs. Peak hours are considered the period between 6 pm and 8:59 pm, not applicable on Saturdays, Sundays, and public holidays. During daylight saving time, peak hours are between 19:00 pm and 21:59 pm.

$$T_{\text{end}} = \frac{\left[\left(TE_p + TUSD_p\right) \times H_p\right] + \left[\left(TE_{op} + TUSD_{op}\right) \times H_{op}\right]}{24} \tag{16}$$

The electricity generated by hydroelectric plants represents the largest share of Brazil's electricity matrix [51].

During months with little rainfall, energy production from this source is reduced due to low water flow. This means that other, more expensive sources of energy come into play, such as thermal power stations. With the need to use more expensive sources, the cost to energy distributors increases. In 2015, ANEEL implemented a system of tariff flags that reflect an increase in electricity tariffs for residential consumers due to unfavorable hydrological conditions. This feature is unique and relevant in the context of tariffs, focusing on seasonal fluctuations in water availability. The system is made up of three tariff flags: green, yellow, red level 1, and red level 2. The green flag corresponds to the scenario of tranquility for the consumer, as it represents favorable hydrological conditions, and the final tariff is not increased. The yellow flag is already a warning sign for less favorable generational conditions. Following the warning logic, the red flag level 1 corresponds to more costly generation conditions. Finally, the red flag level 2 represents the worst hydro scenario [52]. The additional cost of the electricity tariff as a result of the flag color is defined by ANEEL annually.

In the case of STP, considering it a mini-generation plant, included in the Electricity Compensation System (SCEE), ANEEL consumers group them into group B: a group made up of consumer units with a voltage connection of less than 2.3 kV and subdivided into subgroup B3. The tariffs for this group are listed in Table 2 [53]. In addition to the final tariff value, the federal, state, and municipal governments add tax PIS/COFINS, ICMS, and the Contribution for Public Lighting, which are not included, as they change from state to state. However, this final value serves as a benchmark for everyone.

Then, the revenue is given by Eq. 17.

$$\text{Revenue} = P_{\text{generation}EE} \times (R_{final} - C_{el}) \times 1000 \tag{17}$$

Payback

Payback is the most common method in the analysis of investments. It consists of quantifying, by means of cash flow, the period required to cover the initial investment. This method analyzes the moment at which the net profit accumulated is equal to the initial investment. The period can be found by the analysis of cash flow as well as the ratio between investment cost and expected profit [54]. Three variations of interest rate are used in Payback, amortized throughout the unit period, of 15%, 12%, and 8%.

Table 2 Composition of the final electricity tariff (BRL/MWh)

	Peak hours tariff		Off-peak hours Tariffs		
Distributor	TUSD	TE	TUSD	TE	Final Tarrif
ENEL-RJ	1494.72	62.57	469.10	62.57	659.87

Net Present Value

This is used to assess the profitability of an investment. The calculation is done by Eq. (18), decreasing the cash flow of the project that is being evaluated to a determined interest rate from the investor. This rate, called the discount rate, is the minimum return that must be expected for the project to be accepted. If the discount rate is higher than or equal to zero, the project is viable [54]. One of the advantages of the process is the inclusion of the capital cost of the company and the possibility of applying it to any cash flow. However, it is usually a complex method because it requires several parameters to be calculated. The adopted minimum rate of attractiveness will be 15%. This figure was devised taking into account the average of the most profitable yield at present, plus inflation and an investment risk rate related to market uncertainties stipulated at 2.25%.

$$NPV = -C_0 + \sum_{i=1}^{n} \frac{C_i}{(1+r)^n} \tag{18}$$

In which:

C_0 is the initial cost.

C_i is the cash flow year by year.

i is the years.

N is the total time of the project.

r is the risk rate to be discounted.

The final value of NPV must be positive for profit. In case it is zero, there is no profit or loss; that is, the investor will not have guarantees with such an investment.

Results and Discussion

The main objective of this study is to improve the self-sufficiency of the wastewater treatment plant by using biogas to generate electricity, as the internal energy demand is high. This approach ensures a direct reduction in operating costs and promotes the sustainable use of resources.

To estimate the theoretical production of methane at the current plant in operation, considering the design flow of 25 L/s, the volume of sewage considered was 2.160 m^3/d, corresponding to the maximum number of inhabitants served by the plant, who contribute an average flow of domestic sewage of 116 L/inhab.day. Considering the second scenario, in which a future expansion of the station is expected to be able to serve the entire population of the municipality of Angra dos Reis with access to the sewage network, the volume of affluent determined was 13,207.2 m^3/d; this value being considered the real potential of the region if all the domestic sewage generated were treated properly.

The potential for biogas production and electricity generation in the plant currently in operation is considerable. Considering the design flow rate of 25 L/s and the sewage volume of 2,160 m^3/d, we can estimate the theoretical production of methane. This corresponds to the maximum number of inhabitants served by the plant and contributing an average domestic sewage flow of 116 L/inhabitants/day. In the second scenario, it is assumed that a future expansion of the station will supply the entire population of the municipality of Angra dos Reis with access to the sewage network. The calculated inflow volume was 13,207 m^3/d, which corresponds to the actual potential of the region if all domestic sewage were treated appropriately.

Considering the average affluent flow rate and a COD concentration of 0.6 kg/m^3 with a hydraulic retention time of 8 h, a COD removal efficiency of 0.67 was determined, which is within the expected range for this type of technology using UASB reactors [40]. Based on the methodology mentioned above, the COD concentration in the effluent (removed) was 0.198 kgCOD/m^3. Using a total solids production coefficient of 0.2, the theoretical biogas throughput was 387.48 m^3/d for scenario 1 and 2826.7 m^3/d for scenario 2, assuming a biogas composition of 60% CH_4. It is expected that a considerable part of the CH_4 produced will be lost in the hydraulic structures at the reactor outlet, dissolved in the effluent or emitted into the atmosphere. Taking into account these losses of about 40% of the theoretical biogas stream [40], the actual production is estimated to be 232.5 m^3/d (9.7m^3/h) and 1696 m^3/d (70.7m^3/h) of biogas for scenarios 1 and 2, respectively.

Applying the appropriate considerations (30% engine efficiency and 90% generator efficiency), Eq. (8) gives an energy potential of 125 MWh/yr of biogas produced for electricity generation for the current sewage treatment plant. If the capacity of the entire region is considered, i.e., the sewage production for the entire population, the energy potential increases to 913 MWh per year.

Generating electricity from the biogas produced in the UASB reactors represents a significant opportunity to reduce greenhouse gas emissions. This decentralized mini generation promotes the sustainability and profitability of the wastewater treatment plant and contributes to mitigating global warming and climate change. The electricity generation capacity of 125 MWh/yr achieved by burning biogas in combustion engines is sufficient for the size of the current STP when compared with other studies results in a STP with an inflow of domestic sewage three times greater [17]. It should be noted that this study does not consider the thermal energy contained in the engine exhaust gases, which could be reused in the sludge dewatering process, nor the potential of the sludge itself to generate CH_4 during pre-treatment, which would further favor the implementation of this technology.

Considering a typical STP composed of UASB + BFMO + DS that demands approximately 0.34 kWh/m^3 of treated sewage affluent [23], it is possible to determine an annual electricity demand for the scenario 1 plant of approximately 264.4 MWh/yr, so the current proposal would be able to meet 47.4% of the plant's needs. When scenario 2 is analyzed, this percentage rises to 56.5%, a figure very similar to that reported by Rosa et al. in a plant using the same technology and capacity [17].

For a typical STP consisting of UASB + BFMO + DS and requiring approximately 0.34 kWh/m^3 of treated sewage [23], the annual electricity demand for the plant in scenario 1 is approximately 264 MWh/yr; the current proposal would therefore cover 47% of the plant's demand. When analyzing scenario 2, this percentage increases to 57%, a value that corresponds for a plant with the same technology and capacity [17].

Figure 3 shows the costs of electricity generation. The cash flow is amortized over the useful life with the annuity factor resulting for interest rates of 15%, 12%, and 8%, as shown in Fig. 2.

The cost of electricity production decreases over time for different depreciation rates (15%, 12%, and 8%) for both scenarios. This trend underlines the cost-effectiveness of using biogas for electricity generation. Looking at the final electricity tariff, which is made up of the tariffs charged at peak and off-peak times for the generation units included in ANEEL's electricity balancing system, the cost of electricity generation in scenario 1 is equal to the utility sales tariff in about 2 years. From the second year onwards, generation costs fall below this tariff, reaching minimum values of 0.023 US$/kWh and 0.017 US$/kWh in the tenth year, at discount rates of 15% and 8%, respectively. These results correspond to about half of the electricity generation costs

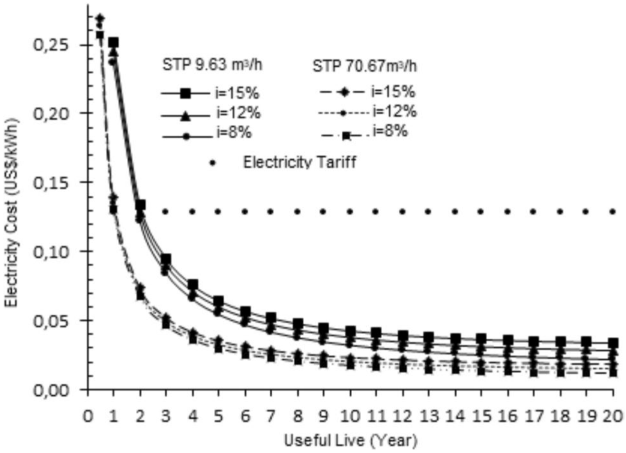


Fig. 3 Cost of electricity generated throughout the useful life of units

that Arslan and Yılmaz [55] state for a biogas-fired CHP plant (gas turbine, combined heat, power, and cooling).

If we consider the cost of electricity generation in the current plant, it varies from 0.080 US$/kWh in the third year and stabilizes around the tenth year at 0.031 US$/kWh for the lowest rate considered. These results confirm that internal combustion engine technology is one of the most economical options for biogas reuse in sewage or wastewater treatment plants, as it has relatively low CAPEX, OPEX, and maintenance costs compared to gas turbine or hybrid systems [13].

For scenario 2 (expanded STP capacity), unit electricity costs are even lower, confirming a positive economy of scale. Depending on the interest rate, parity with the electricity tariff is achieved in around one year. Overall, the levelized generation costs shown here are lower than those of other thermoelectric processes such as Rankine cycles ≈ 50–60 US$/MWh) [56].

Figure 4 shows the payback curve derived from the annual cash flow analysis, where the revenue is the difference between the local weighted electricity tariff and the cost of on-site electricity generation over a 20-year lifetime. For the plant producing 9.7 m^3/h of biogas, the payback period is 2 years; for the larger plant (70.7 m^3/h), the investment is amortized in 13 months. This rapid amortization underscores the profitability of the project: biogas that would otherwise be flared is upgraded to a cost-effective fuel for the genset.

A final factor influencing the payback is the cost of the initial equipment. All the lower-capacity machinery in the plant is imported, but even after deducting import duties and freight costs, the price is competitive with domestic alternatives. This indicates that domestic investment in small-scale biogas technologies is limited, which hinders the availability of lower-cost domestic equipment.

When comparing the payback results obtained with other studies such as that of Buller et al. [23], which simulates various scenarios in an STP using the HOMER software, we find good agreement. For a medium-sized plant configured as an off-grid hybrid system with solar panels and a combustion engine (scenario 4) [23], a payback period of 3.35 years was determined. If the same hybrid configuration was connected to the electricity grid (scenario 6), the payback period fell to 1.38 years. These discrepancies reflect the differences in the system architecture and the underlying economic assumptions (discount rate, lifetime of the system, tariff structure). Compared to other technologies such as SOFC fuel cells or microturbines, internal combustion engines (ICEs) still have the lowest specific CAPEX and OPEX per unit of installed capacity and generated energy [13].

The net present value (NPV) analysis includes a minimum attractive rate of return (MARR), which must exceed the return of the most profitable alternative investment, considering inflation and market uncertainty. The Brazilian Selic base rate is currently 10.5% per year. An investment yielding 115% of the CDI (Interbank Deposit Certificate, assumed ≈ Selic), therefore, yields 7.47% per year in real terms. Adding the latest inflation rate (4.62%) and a market risk premium of 2.25% results in a MARR of 15%. The cash flow projections, which are discounted at 15%, 12%, and 8% (see Fig. 5), cover the entire 20-year operating horizon of the units.

The criterion when the NPV is used to make decisions such as "accept" or "reject" the project is as follows: if the NPV is greater than or equal to zero, the project should be accepted, as the company will obtain a return equal to or greater than the cost of capital invested and the project will preserve or increase its assets; otherwise, if the NPV is less than zero, the project should be rejected. It can be seen that

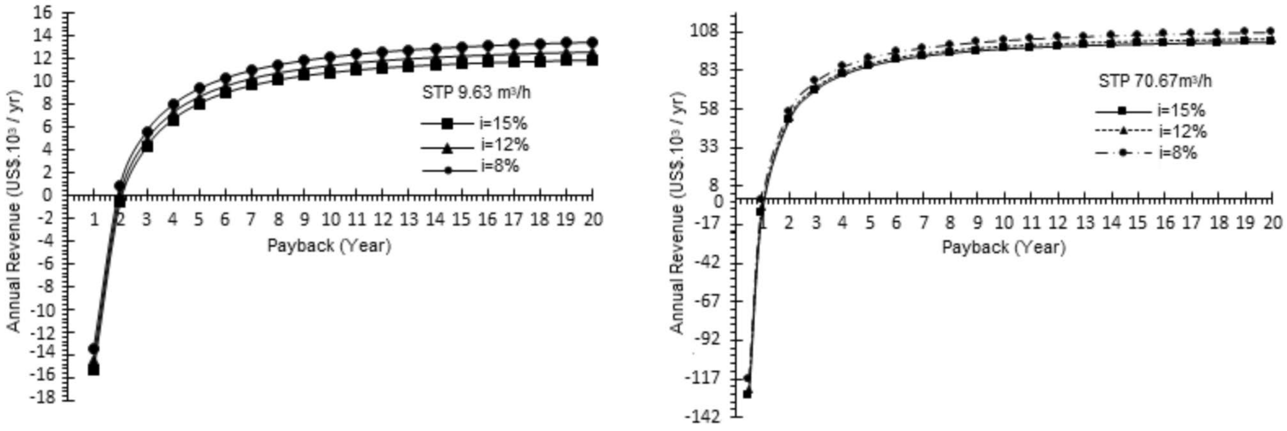


Fig. 4 Annual revenue from electricity produced to both units

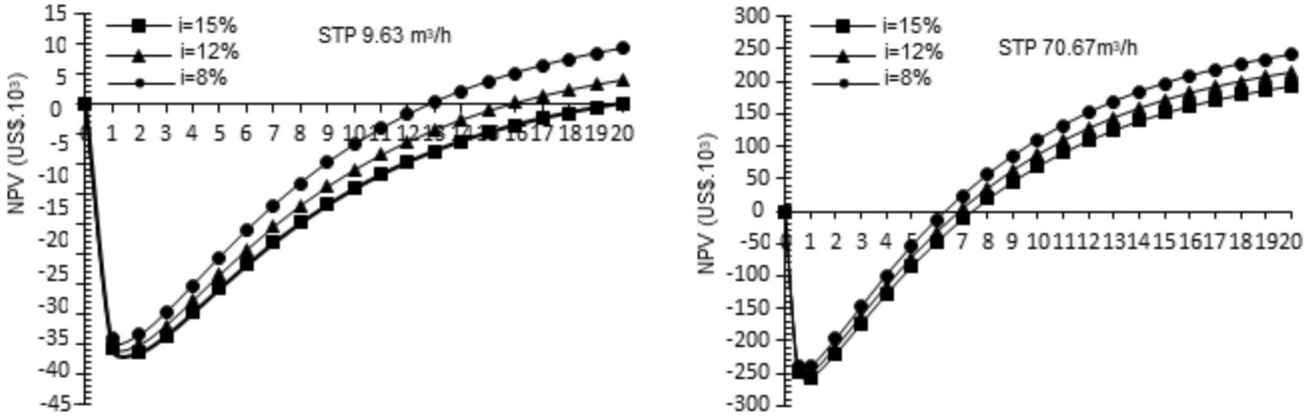


Fig. 5 NPV throughout the useful life produced by both STP units

for the two proposals evaluated, the NPV is positive over a given period of time. Considering the useful life of the plant, the NPV indicates that the investment is viable and that it is very attractive, observing the moment when the IRR (rate of return on investment) exceeds the MARR (minimum attractive rate), i.e., NPV equal to zero.

The decision rule for the NPV is simple: NPV $\geq 0 \Rightarrow$ accept, NPV $< 0 \Rightarrow$ reject. In both scenarios examined, the NPV becomes positive within the lifetime of the plant, confirming economic viability. Furthermore, the point at which the internal rate of return (IRR) exceeds the MARR (i.e., at which the NPV exceeds zero) occurs well before mid-life, which underlines the attractiveness of the investment.

Figure 5 shows that the investment in scenario 1 does not offer high NPV values; nevertheless, it remains a profitable investment at the three discount rates considered. A discount rate of 8% results in a NPV of ≈ US$ 9300 over a project life of 20 years, while the proposed expansion in scenario 2 results in a NPV of US$ 235,000.

The sensitivity analysis shows that the installation of combustion engines in small sewage treatment plants (≤ 10 000 inhabitants) becomes economically viable, with payback periods of less than 2 years, if the local electricity price is at least BRL 600/MWh (≈ US$ 117/MWh); below this threshold, the projects lose their feasibility. For medium and large sewage treatment plants (> 100,000 inhabitants), the break-even tariff falls to BRL 520/MWh (≈ US$ 101/MWh). With a discount rate of 8%, 12%, and 15%, the investment remains attractive and economically feasible.

An additional source of revenue that was not analyzed here, but can further shorten the payback period, would be the implementation of cogeneration systems that allow the use of engine exhaust gases for the treatment of the digestate or processing through fast pyrolysis could increase the NPV of the project by a further 22%, while the sale of biochar captures additional biogenic carbon and opens markets for soil health [57]. Also, if Brazil introduces a carbon credit mechanism comparable to the EU Emissions Trading Scheme, monetizing the approximately 450 t CO_2-eq avoided each year per plant would halve the already short payback period [22].

Risk Assessment and Restrictions

This study demonstrates the potential of using biogas produced in wastewater treatment plants to generate electricity. However, several risks and limitations need to be considered in order to obtain a balanced perspective on the feasibility and implementation of this approach.

One of the main risks lies in the variability of the composition and quality of the biogas. The properties of the biogas produced in UASB reactors are influenced by factors such as the type of influent wastewater, operating conditions, and ambient temperature. Contaminants such as hydrogen sulfide (H_2S) and moisture can reduce the efficiency of combustion engines and lead to increased maintenance costs. Overcoming these challenges requires robust cleaning and storage systems, which are not always feasible for smaller plants due to the associated costs.

Economic viability is another important aspect. The financial success of the project is highly dependent on external factors such as fluctuations in interest rates, energy tariffs, and exchange rates. These variables can affect the payback period and the net present value (NPV) and thus change the economic attractiveness of the investment. In addition, unforeseen increases in operating or maintenance costs could have a negative impact on profitability.

Regulatory and political challenges are also potential obstacles. While Brazil has made progress in supporting decentralized power generation through regulatory frameworks such as ANEEL's Normative Resolution No. 1.059, bureaucratic delays in obtaining permits and connecting to the grid could hinder the implementation of projects. Furthermore, uncertainties regarding future energy policy and the regulation of carbon credits create additional complexity, especially for long-term projects.

From a technical perspective, the limitations of the existing infrastructure represent an obstacle. The sewage treatment plant under review does not have advanced gas cleaning and gas storage systems, which are critical to optimizing energy production. Upgrading these systems would require significant capital investment, which is not always feasible, especially in municipalities with tight budgets. In addition, the study does not consider the potential benefits of recovering thermal energy from combustion engine exhaust, which could improve overall energy efficiency.

Finally, the study has several inherent limitations. While the results were extrapolated to a larger plant serving the entire population of Angra dos Reis, logistical and technical barriers to real-world implementation were not fully considered. In addition, due to Brazil's underdeveloped carbon credit trading market, the analysis does not take into account the potential revenue from these credits, although this could significantly improve the economic viability of the project. These limitations emphasize the need for further research to investigate additional technical and economic factors as well as the broader implications of integrating biogas energy systems into wastewater treatment plants.

Future Prospects

The integration of biogas energy systems into wastewater treatment plants offers significant opportunities to improve sustainability and energy efficiency in urban and rural areas. Various avenues can be explored to maximize the potential of biogas utilization.

One promising avenue is the use of biogas for applications beyond electricity generation, such as upgrading to biomethane. This purified biogas could serve as a renewable substitute for natural gas, making it suitable for injection into existing gas grids or for use as a transportation fuel. Developing the infrastructure to support this transition could open up new markets and revenue streams for local authorities and private operators.

Another future prospect lies in the integration of combined heat and power (CHP) systems with advanced energy recovery technologies. By using the thermal energy from biogas incineration, sewage treatment plants can optimize sludge drying and thus reduce disposal costs and improve the overall efficiency of the plant. In addition, hybrid systems that combine biogas systems with solar or wind energy could offer greater energy stability and reduce dependence on fossil fuels, as well as systems with advanced pretreatments such as pressure shock waves or steam explosion for co-digestion of agricultural residues [58]. The use of generative AI digital can quickly explore thousands of CAPEX, OPEX, and policy scenarios, allowing utilities and investors to develop optimal deployment strategies much more quickly [59].

The potential of biogas systems to contribute to carbon markets also deserves attention. With an appropriate regulatory framework, the reduction of methane emissions through the capture and use of biogas could generate carbon credits, providing an additional financial incentive for the deployment of biogas plants. This is in line with global climate targets and could attract international investment.

Finally, scaling up biogas projects on a regional or national level could bring economies of scale, reducing unit costs and increasing energy production. Partnerships with industries such as food processing or agriculture could create opportunities for co-digestion, utilizing multiple waste streams to increase biogas yield and energy production.

Investment in research and development will be crucial to realize these prospects. Advances in anaerobic digestion, gas purification, and system integration technologies could overcome current limitations and make biogas systems more efficient, cost-effective, and environmentally friendly. With the right planning and support, biogas systems can evolve from complementary energy solutions to cornerstones in achieving sustainable development goals.

Conclusions

This study shows that even very small sewage treatment plants equipped with UASB reactors can go beyond energy neutrality and become net electricity generators, with a payback period of well under 2 years. The conversion of 9.7 m^3/h of biogas with a CH_4 content of 60% in a 25 kW_e spark ignition unit supplied 47% of the sewage treatment plant's own demand at a levelized cost between 0.017 and 0.023 US$/kWh; the simple payback period was 1.7 years, and the net present value, discounted at 8% per year, reached about 9300 US$. If the same concept is extended to the full urban load ($\approx$ 70 m^3/h), the payback period decreases to 13 months, and the net present value increases to about US$ 235,000. The measured electrical efficiency of 29% already reaches 90% of the theoretical limit defined by the free Gibbs energy of CH_4 combustion. This shows that further improvements must be achieved primarily through the integrated system design and not through the engine hardware.

Extrapolating these results reveals a much greater opportunity. About 18,000 wastewater treatment plants of comparable size in Latin America, Africa, and Asia are still flaring their biogas. If just a quarter of them were retrofitted with the low-CAPEX configuration described here, an additional 2.2 TWh of electricity could be generated from renewables and around 18 million tons of CO_2 equivalent could be saved each year, the same as taking 3.5 million cars off the road. The economic viability is robust: for plants supplying up to

10,000 inhabitants, the project remains attractive if the local tariff is at least BRL 600/MWh (≈ USD 117/MWh), while plants with more than 100,000 inhabitants cover their costs at BRL 520/MWh.

From a policy perspective, combining net metering with verified methane mitigation credits would create a dual revenue stream that lowers risk and accelerates private participation. Research should now focus on engine and purification packages that are tolerant of gas streams with less than 60% CH_4, hybridization of UASB systems with advanced pretreatments, and implementation of the use of AI to assist with multi-modal synthetic data fusion and analysis, simulation and modeling technologies. In summary, on-site biogas power generation in small sewage treatment plants is one of the fastest and most cost-effective climate change mitigation levers available to the wastewater sector worldwide. It combines immediate economic benefits with significant progress towards achieving Sustainable Development Goals 6, 7, and 13.

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Declarations

Ethics statement for the use of human and animal subjects Not applicable.

Consent for Publication Not applicable.

Competing Interests The authors declare no competing interests.

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