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PERFORMANCE ASSESSMENT OF AN ELECTRICITY MICROGENERATION PLANT USING BIOGAS

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KEYWORDS

energy balance, biodigester, efficiency, microgenerator, biogas production.

ABSTRACT

The operating costs and investment in microgeneration plants are high, and the maximum efficiency of the process should be targeted such that farmers can obtain the best financial returns. In this study, the efficiency of a microbiogas plant was estimated using a methodological analysis that involved a biodigester mass balance and plant energy balance. The plant had two biodigesters and an engine generator. The biodigesters under study were considered low tech. The results showed 65% utilization of the volatile solids present in the substrate by the biodigesters, producing biogas with an average methane concentration of 57%. The equipment necessary for the operation of the system consumed 19.45% of the energy produced, and most of this energy was used for the transportation of substrates. The energy balance of the plant indicated an energy efficiency of 27.24% during the production process. The hydraulic retention time, pH, intermediate/partial alkalinity ratio, and organic loading rate indicate that reactor A is underutilized, has a low nutrient supply, and may result in low methane production. These indicators suggest that biogas production and quality can be improved by better distribution of substrates among the digesters.

INTRODUCTION

Globally, electricity systems around the world have been undergoing a transition from fossil fuels to low-carbon energy sources (Carvalho et al., 2020; Nieto et al., 2020; Axon et al., 2023). In Brazil, the electricity matrix is predominantly renewable; however, it is highly dependent on two sources: hydraulic and natural gas (Werner & Lazaro, 2023). Therefore, diversification of the matrix is necessary (Ferreira et al., 2018). In this context, biogas is an alternative to fossil fuels that can be used as a vehicular fuel and a substitute for natural gas (Nsair et al., 2019).

Biogas is produced from the anaerobic biodegradation of biomass in the absence of oxygen and the presence of anaerobic microorganisms (Souza et al., 2023; Karthikeyan et al., 2024). Furthermore, biogas can help reduce greenhouse gas emissions (Kodba et al., 2023; Chen et al., 2023).

In an agricultural environment, the production of biogas through anaerobic digestion of waste plays a significant role in mitigating environmental problems and reducing carbon emissions. The valuation of biogas as an economic activity through the production of electricity also provides local development (Freitas et al., 2019; Werncke et al., 2023).

Developing countries usually use simpler models of biodigesters, employing less technology and no heating or agitation capabilities (Bond & Templeton, 2011; Margallo et al., 2019). This is the case in Brazil, where the tropical climate and local characteristics allow the process to be performed using low-technology digesters (Freitas et al., 2019).

The models applied in Brazil can be considered low-technology, but the investment in a biogas plant is still very high compared to the income of rural producers. For example, Ricardo et al. (2018) estimated the return on investment for a biogas plant in pig farming in Brazil over

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seven years for the recovery of invested capital. On the other hand, Martins & Oliveira (2011) estimate the return over five years. In both studies, the investment income was electricity commercialization or the avoided expenses of electricity in the farm, considering the tariff by the local utility.

Biogas production involves a relatively high initial investment and high operational costs for energy production. According to Stürmer et al. (2021), biomass production and transportation expenses usually constitute the largest portion of biogas production costs, and these costs depend on characteristics such as plant size and biomass availability in the region.

To maintain competitive production and remain in operation for long periods, a biogas energy plant must find the ideal mechanization of the system. Additionally, it is necessary to improve the process efficiency, reduce costs, and increase plant production (Nsair et al., 2019). In this regard, monitoring and evaluation of the process allows the identification of problems to improve its efficiency.

There are different approaches for estimating the energy performance of biogas plants, including calculating the energy balance by identifying the energy flows that cross the plant boundary (Havukainen et al., 2014). Implicit in this balance is the energy requirement of the equipment, which varies depending on the plant arrangement and efficiency of the energy conversion systems (Maechtig et al., 2019). The energy supplied to the produced energy is useful for comparing the energy demands of different plants (Havukainen et al., 2014).

In the western region of Paraná, different plant configurations are observed during operation, but most use a set of low-technology biodigesters and an engine generator. Little data are available in the literature on the efficiency of these systems. Therefore, the objective of this study was to evaluate the efficiency of a biogas microelectric energy generator plant with local characteristics.

MATERIAL AND METHODS

The rural property analyzed is in the city of Toledo, Parana State, Brazil (latitude 24°35′33″ S, longitude 53°50'57″ W). This property has an electricity-generating plant for biogas with a nominal production capacity of 75 kW connected to the energy distribution network. The energy produced was used for this property. Thus, plants fall into the microgeneration category based on the local demand.

The plant under study was considered low tech. The plant has two biodigesters, denoted A and B, as illustrated in Figure 1, and is fed swine waste from finishing, dairy cattle manure, and swine waste from maternity. Digester A is called the complete mixture type, where the circular geometry allows organic matter to remain homogeneous with the help of mixers. Digester B is a rectangular tubular biodigester with a trapezoidal section that generates a piston flow.

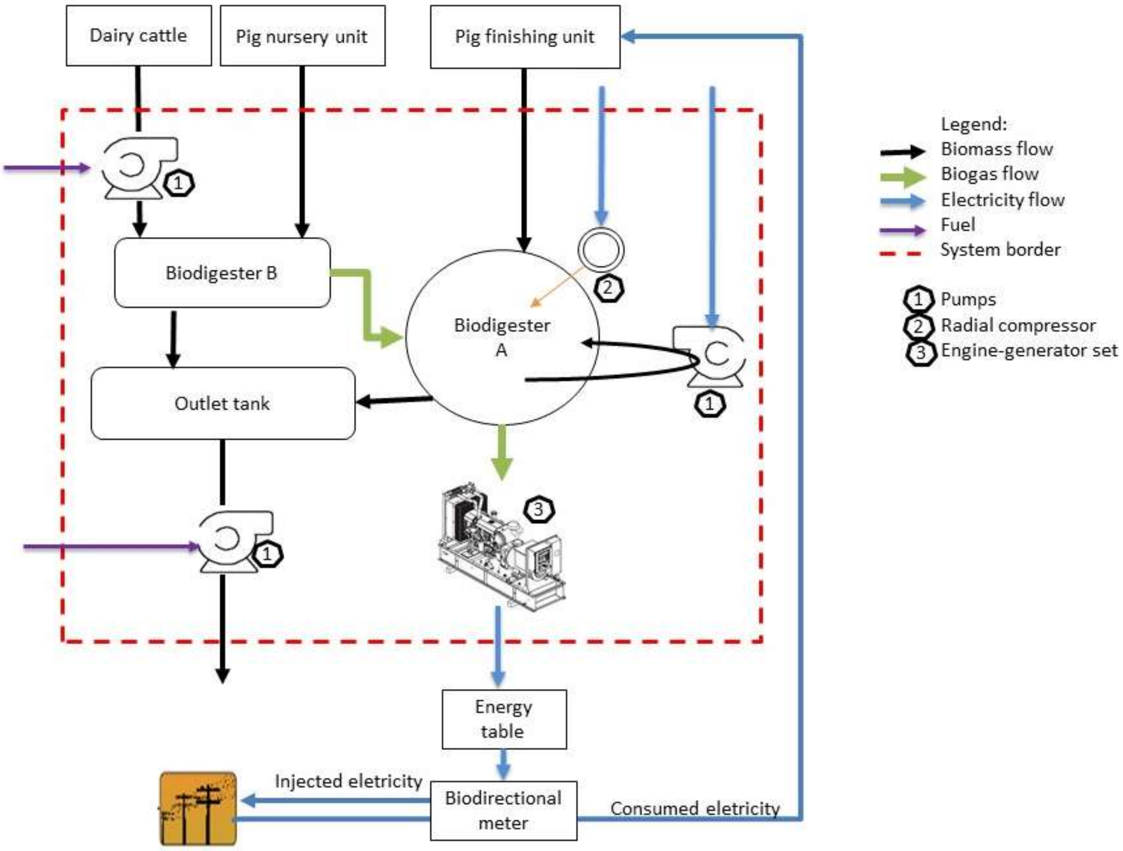

FIGURE 1. Diagram representing the equipment, flows and system boundary of the plant.

Biodigesters have a simple construction. They were dug out of the ground and covered with High-Density Polystyrene (HDPE) blankets according to their geometry. The cover, which served as a gasometer, was also made of an HDPE blanket.

The plant uses an engine-generator (Cummins 6-cylinder) set for the production of electricity, which consists of a diesel engine transformed into an Otto cycle for the utilization of biogas coupled to the axle of a generator with 75 kW of power.

The plant uses substrates from neighboring properties, and pumps are required for transportation. It uses a 3-inch pump powered by an engine running on Liquefied Petroleum Gas (LPG) and a 4-inch pump powered by an engine running on diesel oil.

The plant also uses an electric motor-driven pump that performs the function of mixing the substrate on Digester A by recirculating it.

The volume of the biogas produced by the plant was measured using a thermal mass flow transmitter, Magnetrol brand, model TA2. The device was installed in a gas line near the engine intake to measure the engine flow rate during operation. The device measured the instantaneous flow rate and had an accumulator. At the end of each engine operating period, the accumulator value was manually recorded.

The power generation system connected to the distribution network has a microprocessor controller (model GC600), which is part of the control panel of the generator set. The controller supervised and protected the electric power generation system. It has an accumulator and, at the end of each generator set operation period, the value is manually registered on the control sheets.

The volume of biomass fed into the biodigesters was estimated by measuring the biomass levels in the accumulator tanks using a ruler.

The total solids (TS), volatile solids (VS), fixed solids (FS), pH, and intermediate/partial alkalinity (IA/PA) concentrations were determined. The biogas properties were analyzed using a portable gas extraction monitor (Landtec Model GEM 5000). The equipment identified the concentrations of CH_4, CO_2, O_2, and H_2S in the biogas. The system boundaries for this study were determined to encompass all the equipment and processes involved in the production of biogas and its conversion into electrical energy, as illustrated in Figure 1.

After analysis of the inflow and effluent solids, [eq. (1)] is used to calculate the performance of the biodigester (*Pb*) as a function of the reduction of solids, that is, the proportion of energy of the substrate taken advantage of in %, where VS_e are the volatile solids at the entrance of the biodigester and VS_{ex} are the volatile solids at the exit of the biodigester, both expressed in g L^{-1}.

$$Pb = \frac{(VS_e - VS_{ex})}{VS_e} * 100 \quad (1)$$

Plant efficiency is determined through energy balances that account for the available energy and energy demand in a given system (Havukainen et al., 2014). Energy that crosses the system boundary comes in different forms, such as fuel from pumps and biomass. All energy flows were converted to the same unit of measurement in kWh; therefore, it was possible to balance the energy crossing the system boundary.

For the fuels, the energy was represented by the lower heating value (LHV) of each fuel in kWh kg^{-1} or kWh L^{-1}, and the demand for each piece of equipment was determined in the field.

The biomass that feeds the biodigesters contains energy in the form of nutrients, which feed the microorganisms present in the biodigester responsible for methane production. The energy was estimated using [eq. (2)], according to (Mito et al., 2018), where the mass flow rate of VS ($\dot{m}_{VS}$) is expressed in kg VS d^{-1} and the potential methane production (B_0) is expressed in m^{-3} CH_4 kg VS^{-1}.

$$E_{bm} = \sum_{n=1}^{N} (\dot{m}_{VS} * B_0 * LHV_{CH4} * \rho_{CH4}) \quad (2)$$

After measuring all the energy flows and converting them to the same unit of measurement, the plant performance was determined through two different considerations:

- Approach 1: The input energy of the system is considered the sum of all energy forms crossing the system boundary, including the energy contained in the biomass (E_{bm}) and the energy demand of the equipment (E_{equip}) in the form of fuel and electricity. Equation 3 relates the output energy of the system in the form of electricity (E_E) to the input energy to express the energy conversion efficiency of the plant.

$$\eta = \frac{\sum Exits}{\sum Entrances} = \frac{E_E}{E_{bm} + E_{equ}} \quad (3)$$

- Approach 2: Relate the energy demand of the equipment (E_{equip}) to the energy produced in the form of electricity (E_E), demonstrating the portion of the energy produced that is required by the production process of the system itself through [eq. (4)]:

$$\eta 2 = \frac{E_{equip}}{E_E} \quad (4)$$

The monitoring of the plant started on September 8, 2020, and concluded on October 15, 2020, at an interval of 80 days. During this period, data on biogas and electric energy production were collected daily, and there were two production stops, resulting in three days without electric energy production. Therefore, 77 samples were collected during this period. Throughout this period, organic material was collected for physicochemical characterization and biogas composition readings.

The energy contained in the biomass was estimated after characterization of the VS and the daily flow rate of each substrate based on weekly averages. Data from the local literature were used to determine the maximum methane potential of each. For bovine waste, 0.395 m^3 CH_4 kg VS^{-1} (Matinc et al., 2017) was used; for swine waste, 0.303 m^3 CH_4 kg VS^{-1} (Amaral et al., 2016) and for piglet waste 0.642 CH_4 kg VS^{-1} (Amaral et al., 2016).

RESULTS AND DISCUSSION

Biodigester B had a hydraulic retention time (HRT) of 21 days (Table 1). In contrast, biodigester A, at the beginning of the swine housing from finishing, operated with an HRT of 93 days and 37 days at the end of the housing, owing to the increase in the production of manure by the pigs throughout their growth (Table 1). The optimal HRT depends on the characteristics of the biodigester and solid concentration. D'Aquino et al. (2019) observed in trials of a complete-mix reactor that a 30-day HRT was better in terms of treatment efficiency; however, for energy purposes, a 20-day HRT better absorbed organic load variations that naturally occur during the process. Souza et al. (2008) reported that a lower HRT resulted in higher volumetric methane production.

TABLE 1. Parameters of the anaerobic digestion process.

	Biodigester A		Biodigester B	
Parameter	Entrance	Exit (%)	Entrance	Exit (%)
HRT (d^{-1})	93 to 37	—	21	—
pH	—	8.03 ± 0.14	—	7.82 ± 0.03
IA/PA	—	0.29 ± 0.05	—	0.31 ± 0.05
Flow (m^3 d^{-1})	7.5 to 18.5	—	20.2	—
TS (g L^{-1})	40.08 ± 11.72	17.00 ± 4.01	24.68 ± 3.18	11.41 ± 2.75
VS (g L^{-1})	27.99 ± 8.8	9.2 ± 3.43	17.67 ± 3.22	5.82 ± 2.11
OLR (kgVS m^{-3} d^{-1})	0.66 ± 0.20	—	0.89 ± 0.17	—
Reduction of TS (%)	—	56.57 ± 7.98	—	53.95 ± 8.79
Reduction of VS (%)	—	65.44 ± 9.67	—	67.44 ± 9.39

HRT: Hydraulic retention time. IA/PA: intermediate/partial alkalinity. TS: total solids. VS: volatile solids. OLR: Organic loading rate.

Digester A had an average pH of 8.0, which is above the recommended pH for biodigesters, and biodigester B had an average of 7.8 (Table 1). Both values are above the ideal value, implying lower methane production. pH is extremely important in biogas production, and the operating range for biodigesters is 6.0 to 8.0, with the ideal point being pH 7.0, which usually occurs when the reactor is working well (Quadros et al., 2010).

The AI/PA ratio in biodigester A (0.29) was below the recommended level, which demonstrated underloading in the biodigester, indicating a lack of nutrients. The AI/PA ratio of biodigester B (0.31) was within the recommended range (Table 1). Values between 0.3 to 0.4 are considered optimal, values above 0.4 indicate an overloaded reactor, and values below 0.03 indicate an underloaded reactor (Kunz et al., 2019). The alkalinity of a system represents its ability to neutralize acids. High alkalinity indicates a high concentration of alkali radicals and, as a result, has high buffering power (Sabeeh et al., 2020).

For the swine manure, which feeds biodigester A, the average obtained for TS was 40.0 g L^{-1} and 27.9 g L^{-1} for VS. Under similar management conditions, Oliveira & Higarashi (2006) identified 75.1 g L^{-1} of TS and 56.3 g L^{-1} of VS. The low concentration of solids in this manure corroborates the low nutrient availability indicated by the AI/PA ratio of this biodigester.

Biodigester B contained a mixture of swine waste from maternity and dairy cattle manure in proportions of 70% and 30%, respectively. As a result, biodigester B had 24.6 g L^{-1} of TS and 17.7 g L^{-1} of VS were obtained (Table 1). The concentration of solids was low. This is because of the management of the manure, which remains stored inside the facilities for long periods until it is destined for use as a biodigester. Consequently, certain solids were transformed and released into the environment.

The organic loading rate (OLR) in biodigester A (0.66 kgVS m^{-3} d^{-1}) was lower than that in biodigester B (0.89 kgVS m^{-3} d^{-1}) (Table 1). The lower OLR in biodigester A might have affected the production of volatile acids, leading to a lower AI/PA ratio. This may compromise the stability of the system because a lower alkaline reserve may make it more sensitive to pH variations (Ferreira et al., 2021).

Digester A, which is fed daily with swine manure, obtained an average efficiency of 57% for the reduction of TS and 65% for VS. Biodigester B does not have a continuous flow; it receives cattle manure daily and piglet manure once a week. This biodigester showed an average efficiency of 54% in the reduction of TS and 68% in the reduction of VS. The results were considered good for these low-tech biodigester models. Silva et al. (2015) achieved a VS reduction of 61% under similar conditions.

The produced biogas had an average methane concentration of 57% (Figure 2A). This mean value was within the range reported in other studies. In a case study in Sweden, Ahlberg-Eliasson et al. (2017) found methane concentrations between 54% and 65%. However, to improve the efficiency of the system, the methane concentration in biogas must be increased. The maximum concentration of H2S (3000 ppm) was observed around the fifth week when the biogas production volume exceeded 700 m^3 h^{-1} (Figure 2A). This indicates that the capacity of the biological desulfurization system does not meet the needs of the plant.

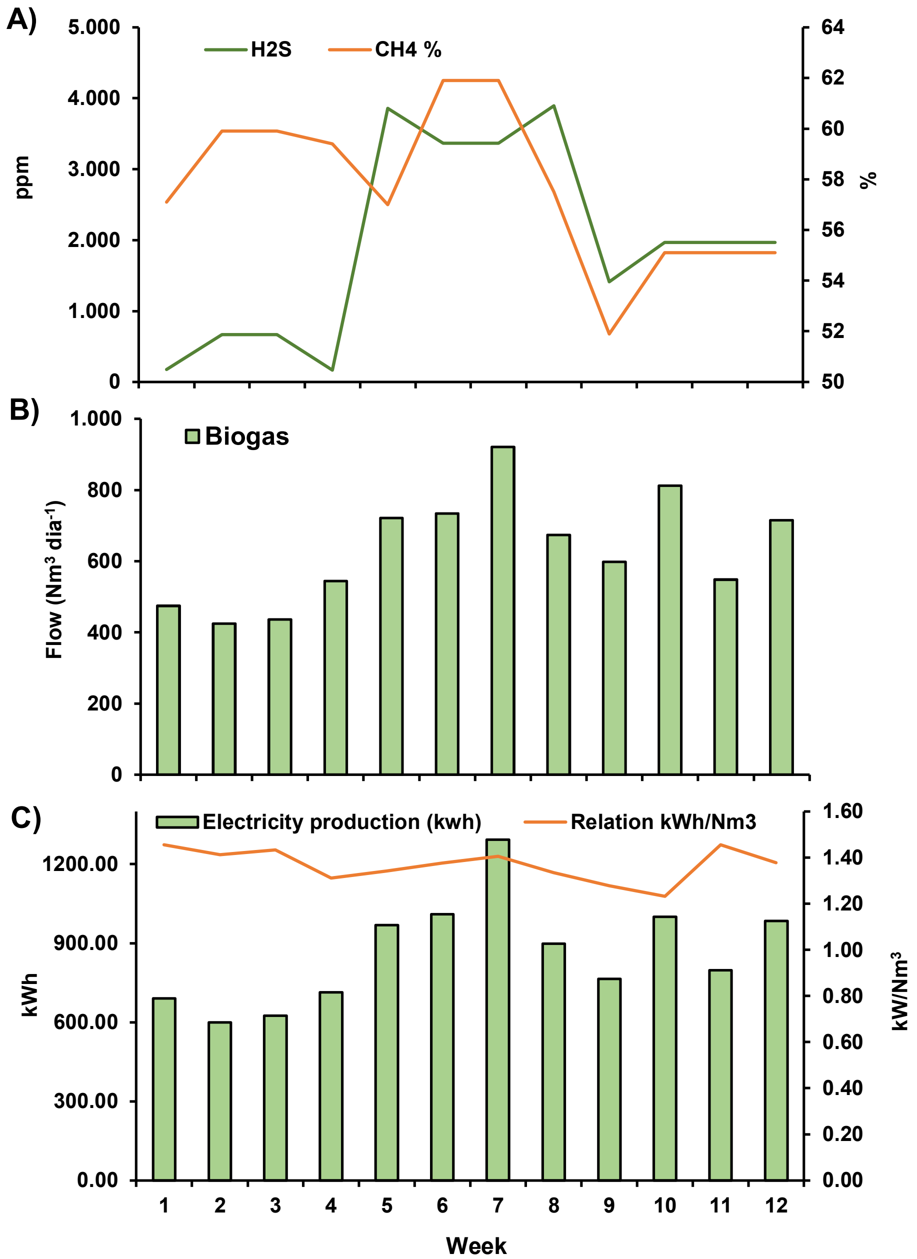

FIGURE 2. Biogas characterization (A), biogas production (B), and production of electric energy (C) in the generator set over twelve weeks.

The daily biogas production was 626 Nm^3 d^{-1}. The minimum value of 424 Nm^3 d^{-1} occurred at the beginning of the observation period, and the maximum of 920 Nm^3 d^{-1} occurred in the seventh week (Figure 2B). As observed by Souza et al. (2008), a reduction in HRT provides higher volumetric methane production owing to the higher volumetric organic load. Biogas production tended to increase throughout the observation period, which coincided with the beginning and end of the pig housing cycle. With the growth and fattening of pigs, the volume of waste increased, and the HRT in biodigester A decreased, thus increasing the volumetric production of biogas (Figure 2B). Drought and high temperatures were observed during the monitoring period from August to October 2020. According to Kunz et al. (2019), significant temperature fluctuations can compromise biogas production. The authors stated that temperature had a drastic impact on anaerobic activity, influencing the growth rate and metabolism of microorganisms and consequently affecting population dynamics within a biodigester.

The electrical energy produced by the generator was 851 kWh d^{-1}. The ratio of energy produced per m^3 of biogas averaged 1.37 kWh m^{-3} and showed little oscillation, indicating stability of the engine–generator set (Figure 2C).

The energy required by all equipment necessary for the production of the system was 162.12 kWh d^{-1} (Table 2). The largest portion of this total (137.04 kWh d^{-1}) was required for the transportation of the digestate to its final storage, which was performed by a pump powered by a diesel engine. The pump demand was 60.26 kWh h^{-1}, and the flow rate was 13.5 m^3 h^{-1}. Dennehy et al. (2017) also noted in their study that the cost of transporting digestate, particularly for codigestion plants, is the largest factor affecting plant operating expenses. The transportation distance for both the organic material and digestate plays an important role in the energy and environmental performance of a biogas plant and may be related to the specific methane production of the biomass in question (Esteves et al., 2019).

TABLE 2. Energy demand (kWh d^{-1}) in the plant.

Equipment	Energy Demand (kWh h^{-1})	Flow (m^3 h^{-1})	Hours	Energy demand (kWh d^{-1})
Pump 1	64.87	48.37	0.13	8.45
Pump 2	60.26	13.50	2.27	137.04
Pump 3	2.60	—	3	7.80
Air compressor	0.38	—	24	8.83
Total				162.12

The estimated energy contained in the biomass for this period was 2961 kWh d^{-1} (Table 3). The sum of the contained energy of different biomasses, as performed in this study, does not consider the effect of codigestion, which, according to Matinc et al. (2017), increases biogas production and methane concentration compared with the mono-digestion of these biomasses.

TABLE 3. Energy contained in the biomass (kWh d^{-1}) fed into the biodigester.

Week	Bovine	Piglet	Swine	Total
1	183	2076	665	2924
2	183	2076	887	3146
3	183	2076	1117	3377
4	0	2076	1206	3282
5	0	1926	1330	3257
6	0	2076	1995	4071
7	183	0.00	2110	2293
8	183	0.00	2188	2371
9	183	0.00	2381	2564
10	162	1598	1469	3231.
11	162	1325	1176	2665
12	497	816	1042	2356
Average				2961

The average values obtained during the monitoring period were used to calculate the energy balance of the plants. The system inputs were the energy contained in the biomass and the energy supplied to the equipment. The output of the system consists of electrical energy produced and injected into the distribution network.

The ratio of output energy to input energy across the system boundary, as per Approach 1, indicates a 27.24% efficiency in the plant's energy use and conversion. Approach 2 relates the energy demand of the equipment to the energy produced, obtaining a value of 0.1946, indicating that 19.45% of the energy produced by the plant is required by the equipment necessary for plant operation.

Combustion engines usually dissipate much of their energy in the form of heat, which is typically not utilized (Hakawati et al., 2017). The simultaneous generation of electricity and thermal energy improves the energy efficiency of systems such as CHP plants. These systems require less fuel, promote high profitability, and have high conversion efficiencies, usually above 75% and up to 90% (Yin et al., 2019).

Plants with a higher technological level tend to disfavor this ratio, as more equipment demands more energy, as reported by Havukainen et al. (2014) for a plant in Finland, where this ratio was 38%. In a study conducted by Piñas et al. (2018), the electrical energy required by the system for equipment, such as mixing, pumps, silage transport, and desulfurization, depended on the volume of biomass added to the biodigester. The electricity demand was 9.4% to 10.7% for monodigestion systems and from 5.5% to 6.8% and from 5.7% to 6.6% for codigestion systems.

Through the energy balance from the biogas life cycle perspective for plants under Swedish conditions, Berglund & Borjesson (2006) showed results that the energy input in biogas systems corresponds to 20 to 40% of the energy contained in the biogas produced. They also pointed out that the system becomes unfeasible from an energy point of view when the transport of animal waste substrates exceeds 200 km.

CONCLUSIONS

Biogas production varies greatly, and the quality of biogas in terms of methane concentration is below the desired level. The energy balance of the plant indicated an energy efficiency of 27.24% during the production process. These indicators suggest that biogas production and quality can be improved by better distribution of substrates among the biodigesters. The plant requires little equipment for the production of biogas and electric energy; however, it consumes 19.45% of the energy produced.

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