



Performance Study of a Microturbine System for Cogeneration Application Using Biogas from Manipueira

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Abstract

Cassava is a commodity that has great importance in food security in many developing countries. The main product in Brazil produced from cassava is the flour, representing approximately 60% of the cassava final destination. As a by-product of this process, we have a wastewater called manipueira. This effluent is highly toxic because it contains cyanidric acid. The manipueira has great potential for biogas production, adding values to the cassava production chain and, also, reducing the content of cyanidric during the methanation process. This study analyzes the energy and economic efficiency of the biogas production from the manipueira produced in a large power plant, using it as an energy source in the feeding of a cogeneration system composed of a gas microturbine and a heat recovery system, whose purpose is to generate electric and thermal energy. The use of the microturbine system instead of other conversion technology is based on the power it presents when it is used for cogeneration, increasing the system efficiency. The study showed that from the economic feasibility calculation, it was possible to determine the cost of producing electricity of US\$ 0.16/kWh and of thermal energy of US\$ 0.04/kWh with an amortization period of 1.3 years. The results obtained from these analyzes showed that the use of this biofuel is a good choice for energy generation.

Keywords Biogas · Manipueira · Cogeneration · Energy analysis · Economic analysis

Abbreviations

\dot{m}_{ar}	Air Mass Flow (kg/m ³)	CM_{STG}	Gas Microturbine System Maintenance Cost (US\$/kWh)
\dot{m}_{comb}	Fuel Mass Flow (kg/m ³)	$C_{p_{gas}}$	Specific Heat of gas (kJ/kg · K)
\dot{m}_{gas}	Gas Mass Flow (kg/m ³)	C_v	Annualized Cost of Steam production (US\$/kWh)
\dot{m}_v	Steam Mass Flow (kg/m ³)	E_{comb}	Fuel Power (kW)
$\dot{V}_{bioga's}$	Biogas Volume Flow (m ³ /s)	E_p	Electricity Power (kW)
\dot{W}_e	Electric Power (kW)	E_{rc}	Heat Power Recovery (kW)
C_{comb}	Fuel Cost (US\$/kWh)	E_v	Steam Power (kW)
C_{el}	Annualized Cost of Electricity production (US\$/kWh)	G_{pel}	Annual Gain due to electricity production (US\$/ano)
CM_{RC}	Heat Recovery Maintenance Cost (US\$/kWh)	G_{pv}	Annual Gain due to steam production (US\$/ano)
		h_2	Gas Enthalpy at T ₁ (kJ/kg)
		h_3	Gas Enthalpy at T ₂ (kJ/kg)
		h_6	Enthalpy of saturated steam at the heat recovery outlet temperature (kJ/kg)
		h_7	Enthalpy of saturated liquid at 90°C (kJ/kg)
		h_8	Enthalpy of compressed liquid at 95°C (kJ/kg)
		I_B	Biodigester Investment (US\$)
		I_{RC}	Heat Recovery Investment (US\$)
		I_{STG}	Gas Microturbine System Investment (US\$/kW)
		I_T	Total Investment (US\$)
		P_{el}	Electricity purchase cost (US\$/kWh)
		T_1	Compressor inlet temperature (°C)

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T_2	Air temperature after compressed ($^{\circ}\text{C}$)
T_3	Gas temperature leaving the Combustion Chamber ($^{\circ}\text{C}$)
T_4	Exhaust Gas Temperature ($^{\circ}\text{C}$)
T_{4m}	Average Temperature between T_4 and T_5 ($^{\circ}\text{C}$)
T_5	Heat Recovery output Temperature ($^{\circ}\text{C}$)
η_{cc}	Combustion Chamber Efficiency
η_e	Electric Generator Efficiency
η_G	Global Efficiency
η_{gc}	Heat Generation Efficiency
η_{ge}	Electric Generation Efficiency
η_{rc}	Heat Recovery Efficiency
η_t	Gas Turbine Efficiency
$\rho_{\text{bioga's}}$	Biogas Specific Mass (kg/m^3)
F	Annuity Factor (1/ano)
H	Equivalent Period of annual operation (h)
J	Annual Interest Rate
K	Amortization Period (year)
LHV	Lower Heating Value (kJ/kg)
Per	System Losses (kW)
Q	Capital Value (US\$)
R	Expected Annual Revenue (US\$)
Rest	Air/Fuel ratio

Introduction

According to data from the United Nations Food and Agriculture Organization (FAO) [1], cassava production (*Manihot esculenta Crantz*) is found in more than 100 countries, recording an average growth of 13.9% in the last 5 years and reached 242 million tons in 2017. Nigeria is the world's largest producer with 45 million tons per year, followed by Thailand, with 30.1 million tons per year, and Brazil, responsible for 26.6 million tons per year.

A large part of this production, about 60%, is destined to produce flour. From this manufacture, we have the manipueira as residue [2–4]. Manipueira is the wastewater from the cassava pressing process that produces derivatives, with a high content of organic material. In this way, the manipueira needs treatment so that it can be discarded without causing damage [5–8].

The pollution generated by this effluent is directly linked to its high BOD (Biochemical Oxygen Demand) load and the presence of hydrocyanic acid in its composition. The presence of hydrocyanic acid in its composition differentiates the manipueira from other agro-industrial residues [9].

According to Fioretto [10], 3 kg of mass of grated and pressed cassava generate 1 l of manipueira and when dumped erroneously causes pollution equivalent to a population of 230 to 300 inhabitants.

As a solution to this problem, in recent years, the anaerobic treatment of agro-industrial effluents has increased, solving

the wastewater problem of cassava in a very comprehensive way. This process generates as biogas by-product, which can promote the energy optimization of the use of the manipueira from the generated biofuel, leading to an environmental sustainability in the sector [11–13].

To use the most of biogas energy potential, it can be applied in a cogeneration system. Cogeneration can be defined as an intelligent arrangement of the process of converting a fuel into mechanical energy which, by means of waste heat recovery processes, increases the overall efficiency of fuel processing, generating not one but two forms of energy. The most common forms of energy produced by cogeneration systems are thermal energy and mechanical energy, which is usually converted into electrical energy through a generator or alternator [14, 15].

There are several technologies for the energy conversion of biogas; among them, “Otto cycle” engines with internal combustion are the technologies most commonly found in the literature. In general, the motors have higher electrical conversion efficiency, although it also has severe restrictions on heat recovery from low temperature levels.

However the use of turbines gas in cogeneration provides an overall efficiency of approximately 75% which can be justified from of the total energy to the fuel used in combustion, about 30% is converted into mechanical energy, approximately 50% is contained in the exhaust gases (which are expelled from temperatures of the order of 500–600 $^{\circ}\text{C}$) [14–16].

In this way, this article aims to analyze the energy and economic efficiency of the biogas production from the manipueira produced in a large plant, using biogas as a source of energy in the feeding of a cogeneration system composed of a gas turbine and heat recovery system, where the purpose is to generate electric and thermal energy.

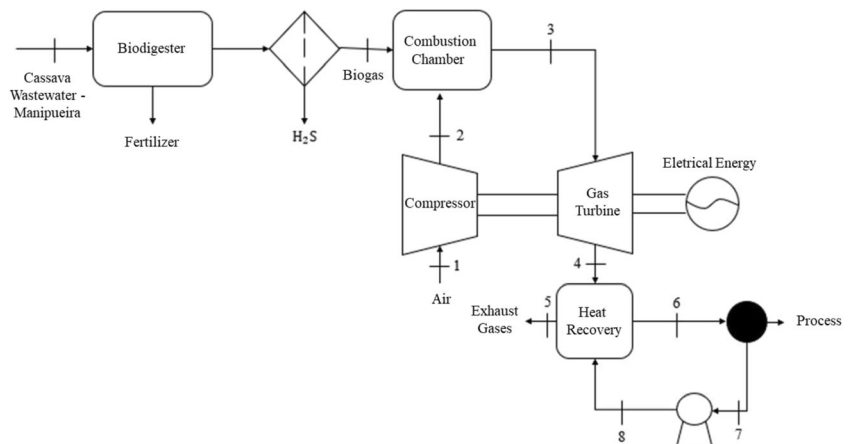
Methodology

The study of the energy and economic feasibility of this article was based on the EDUCOGEN (The European Association for the Promotion of Cogeneration) plant [17], where a biodigester was associated with the electric power generation process, as shown in Fig. 1.

Figure 1 begins with the entry of the manipueira into the biodigester. As a result of the anaerobic digestion process there is compost and biogas. Before use of the biogas produced, a cleaning process must be carried out, so a filter is introduced into the system, which removes traces of hydrogen sulfide (H_2S) present.

To continue the flow of the plant, air (point 1) is sucked in and compressed by compressor (point 2), then mixed with fuel and burned in the combustion chamber. The resulting gas (point 3) is expanded in the turbine blades, producing work.

Fig. 1 Plant to produce electric and thermal energy using biogas



The work produced gives rise to mechanical power, which is used to drive the generator, providing electricity.

The exhaust gases from the turbine (point 4) are directed to the heat recovery, where they will be used for steam generation (point 6). The steam produced is available as a form of thermal energy for use in the process. Once used, this heat flow returns to the system (point 7) and is pumped to the heat exchanger (point 8). Finally, the exhaust gases (point 5) released.

Energy Analysis

The most classical way of determining the thermal performance of cogeneration plants is through the use of the first law of thermodynamics. This analysis allows to define, from the point of view of energy, the performance of each equipment, as well as the overall performance of the system. [18–20].

In general, the first law is expressed by the Equation (1) shown below:

$$\dot{Q} - \dot{W} = \sum_{output} \dot{m}_s \left(h_s + \frac{v_s^2}{2} + gz_s \right) - \sum_{input} \dot{m}_e \left(h_e + \frac{v_e^2}{2} + gz_e \right) \tag{1}$$

Where:

\dot{Q} : the heat added to the control volume under analysis (kW)

\dot{W} : work done by the control volume (kW)

\dot{m} : the mass flow of fluid (kg/s)

h : the enthalpy of the fluid (kJ/kg)

v : the velocity of the fluid (m/s)

z : the portion of the control surface with fluid passage (m)

g : the acceleration of gravity (m/s²)

Since the studied plant was not considering kinetic and potential energy differences, the Equation (2) shows the first law of thermodynamics simplified:

$$\dot{Q} - \dot{W} = \sum_{output} \dot{m}_s h_s - \sum_{input} \dot{m}_e h_e \tag{2}$$

The data analyzed below were determined under conditions of ambient temperature of 25 ° C, sea level, and with 60% relative humidity.

Initial Considerations

According to Madeira et al. [9], a large industry processes about 22,000 tons/day cassava to produce dry flour, generating 6,600,000 liters per year of manipueira. This allows the formation of approximately 2160 kg per day of biogas.

The biogas composition produced from the cassava effluent, determined by gas chromatography, is given in 81% CH₄ and 19% CO₂, according to Lamaison [21] with LHV (lower heating value) of 25,000 kJ/kg.

Thus, the specific mass of biogas can be calculated according to Equation (3), proposed by Xavier [22]:

$$\rho_{biogas} = \rho_{CH_4} (\%CH_4) + \rho_{CO_2} (\%CO_2) \tag{3}$$

where the specific mass of CH₄ and CO₂ is 0.72 kg/m³ and 1.96 kg/m³ respectively

For energy analysis, the operating conditions of each stage of the system were studied, mainly analyzing the input and output temperatures and the efficiency of each equipment (Table 1).

Calculations of Air and Fuel Mass Flow

The mass flow of inlet fuel (biogas) at the combustion chamber is shown by the Equation (4):

$$\dot{m}_{comb} = 0.044435 \text{ kg/s} \tag{4}$$

According to Antunes [23], the mass flow of fuel (\dot{m}_{comb}) is given by the Equation (5):

Table 1 Description of the operating conditions of equipment in different stages of the plant

Stage	Conditions	References
1	$T_1 = 25\text{ }^\circ\text{C}$	[18, 23]
2	$T_2 = 300\text{ }^\circ\text{C}$ $\eta_{cc} = 95\%$	[17, 18]
3	$T_3 = 1100\text{ }^\circ\text{C}$	[17]
4	$T_4 = 700\text{ }^\circ\text{C}$ $\eta_t = 33\%$	[18, 22, 23]
5	$T_5 = 150\text{ }^\circ\text{C}$ $\eta_e = 95\%$	[18, 23]
6	$T_6 = 150\text{ }^\circ\text{C}$ $\eta_{rc} = 75\%$	[18, 23]
7	$T_7 = 90\text{ }^\circ\text{C}$	[23, 30]
8	$T_8 = 95\text{ }^\circ\text{C}$	[23, 30]

$$\dot{m}_{comb} = \frac{\dot{m}_{gas} \times (h_3 - h_2)}{PCI \times \eta_{cc} - h_3} \quad (5)$$

where:

$$h_2 = Cp_{gas}(T_2) \times (T_2 - T_1) \quad (6)$$

$$h_3 = Cp_{gas}(T_3) \times (T_3 - T_1) \quad (7)$$

According to Xavier [22], the specific heat of gases from the combustion of biogas as a function of temperature (Cp_{gas}), can be found by the Equation (8):

$$Cp_{gas}(T) = 1.044 - \frac{4.490 \times T}{10^5} + \frac{5.332 \times T^2}{10^7} - \frac{2.616 \times T^3}{10^{10}} \quad (8)$$

where:

$$\dot{m}_{gas} = 0.9074 \frac{kg}{s} \quad (9)$$

The mass air flow (\dot{m}_{ar}) is given by Equation (10):

$$\dot{m}_{ar} = \dot{m}_{gas} - \dot{m}_{comb} \quad (10)$$

where:

$$\dot{m}_{ar} = 0.8630 \frac{kg}{s} \quad (11)$$

The stoichiometric ratio (rest) is given by Equation (12):

$$rest = \frac{\dot{m}_{ar}}{\dot{m}_{comb}} = 19.4 \quad (12)$$

Calculation of the Generated Electric Power

According to Xavier [22], the power supplied by the fuel (E_{comb}) is given through the fuel mass flow (\dot{m}_{comb}) and LHV (lower heating value) as shown in Equation (13):

$$E_{comb} = \dot{m}_{comb} \times LHV \quad (13)$$

Parallel to this study, Pérez [18] says that the power supplied by the fuel (E_{comb}) can also be found by Equation (14):

$$E_{comb} = \frac{E_p}{\eta_t} \quad (14)$$

In this way, the electric power (W_e) can be defined as shown in Equation (15):

$$E_p = W_e \times \eta_e \quad (15)$$

where E_p is equivalent to the electrical power produced by the system. The efficiency of electric power generation (η_{ge}) is given by Equation (16):

$$\eta_{ge} = \eta_t \times \eta_e \quad (16)$$

Calculation of Recovered Thermal Power

The thermal power recovered from the exhaust gases, E_{rc} , can be found by Equation (17) [18]:

$$E_{rc} = \dot{m}_{gas} \times Cp_{gas}(T_{4m}) \times (T_4 - T_5) \quad (17)$$

where, according to Pérez [18], T_{4m} is the average temperature between the exhaust gas temperature when exiting the turbine (T_4) and the outlet temperature of the heat recuperator (T_5).

The energy balance operated in the heat recovery system can be obtained by Equation (18) [18]:

$$\eta_{rc} = \frac{E_v}{E_{rc}} \quad (18)$$

where, the power of heat provided in the form of steam, E_v , is given by Equation (19):

$$E_v = \dot{m}_v \times (h_6 - h_8) \quad (19)$$

According to Antunes [23], m_v is defined as the mass flow rate of steam generated (h_6), with a saturated vapor enthalpy at the outlet temperature of the heat recovery system unit (T_5) and h_8 as the enthalpy of compressed liquid at T_8 which is the temperature of the flow that returns to the process.

The heat generation yield (η_{gc}) is determined by Equation (20):

$$\eta_{gc} = \frac{m_v \times (h_6 - h_7)}{E_{comb}} \quad (20)$$

where, according to Antunes [23], h_7 can be determined by the enthalpy of the temperature T_7 .

Calculation of Overall System Efficiency

As the cogeneration system involves the production of more than one form of energy, the global efficiency of the system (η_G) must be defined accounting for the electric and thermal power produced, as shown in Equation (21) adapted from Coronado [24]:

$$\eta_G = \frac{E_p + E_v}{E_{comb}} \quad (21)$$

In this way, it is possible to determine how close the system is to achieving the maximum energy utilization that is available by the fuel, being an essential parameter for the analysis of a cogeneration system.

Results of the Energy Analysis

The results found during the energy analysis are presented in Table 2, as well as the parameters calculated during the development of the applied methodology.

Analyzing the results obtained, it is possible to evaluate the energy distribution of the system that is composed by the percentage of energy produced by the microturbine, its conversion in to electric energy, and the heat flow that can be recovered, in view of the performance of the proposed plant using biogas as biofuel, as shown in Fig. 2.

Thus, only 31.5% of the available energy is converted into electrical energy, and about 41.3% is recovered through the cogeneration system. Of this total recovered, 75% was converted into thermal energy in the form of steam.

The losses represent 16% of the available fuel energy, encompassing natural convection, conduction, and radiation heat losses as well as turbine output losses and compressor losses (the most critical point in the system).

According to Silva [25], the overall efficiency of a cogeneration system using gas turbine ranges from 60–85%, while

the yield of electric power production ranges from 15–35% and the thermal efficiency ranges from 40–59%.

In addition to the data previously described, two relationships can be defined between thermal energy production and electric energy, as shown in Table 3.

The ratio $\frac{m_v}{E_p}$ represents how much steam is capable of being produced for each kW of electrical energy generated by the system and can be used as a parameter for future system design.

The ratio $\frac{E_v}{E_p}$ shows that for every 1 kW of electrical energy that is produced, about 1.21 kW of thermal energy is recovered and converted to useful heat in the form of steam. According to Silva [24], the heat/electricity ratio of a generic cogeneration system using a gas turbine ranges from 1.2 to 2.

The biogas energy conversion technology usually used in cogeneration systems is the Otto cycle internal combustion engines, such as the configuration suggested by Xavier [22], with an overall efficiency of about 57% and $\frac{E_v}{E_p}$ ratio equal to 0.6144. When comparing these results with those obtained in this study, overall yield of 72.65% and $\frac{E_v}{E_p}$ ratio equal to 1.2083, it can be concluded that the use of microturbines to gas has been shown to be more efficient, guaranteeing a significant improvement in of the fuel.

In this way, the use of gas microturbines is considered a technological innovation when compared to Otto cycle engines, guaranteeing energy advantages.

Economic Analysis

The methodology adopted follows the procedures described by Antunes [23], considering suggestions from Xavier [22] and Silveira [26] and the particularities of the studied plant.

This methodology contains the calculation of the production costs of the system based on the investment value, fuel cost, and maintenance cost. Subsequently, the values of annual revenue related to the installation of the system are calculated in substitution of the conventional systems of production of electric and thermal energy.

Investment Costs

The investment cost of the plant under study is defined as the cost of purchasing equipment and its cost of installation. Thus, it is necessary to determine the costs of the gas turbine system (involving compressor, combustion chamber, gas turbine, generator electrical and other accessories), the heat recovery system, and the biodigester used.

Thus, the Equation (22) defines the total investment cost of the plant (I_T), which will be given in US\$ [18]:

Table 2 Energy analysis parameters

2.1.2 Calculations of air and fuel mass flow	
$Cp_{gas}(T_2)$	1,14412 $\frac{kJ}{kg \cdot K}$
$Cp_{gas}(T_3)$	1,31041 $\frac{kJ}{kg \cdot K}$
h_2	314.63 $\frac{kJ}{kg}$
h_3	1408.68 $\frac{kJ}{kg}$
2.1.3. Calculation of the generated electric power	
E_{comb}	1110.88 kW
E_p	366.59 kW
η_{ge}	31.35%
2.1.4. Calculation of recovered thermal power	
$Cp_{gas}(T_{Am})$	1.18347 $\frac{kJ}{kg \cdot K}$
h_4	650.91 $\frac{kJ}{kg}$
E_{rc}	590.64 kW
E_v	442.98 kW
h_6	2733.99 $\frac{kJ}{kg}$
h_7	376.92 $\frac{kJ}{kg}$
η_{gc}	41.3%
2.1.5. Calculation of overall system efficiency	
η_G	72.63%

$$I_T = 1.3 \times (I_{STG} + I_{RC} + I_B) \tag{22}$$

Being the multiplicative factor 1.3 referring to the equipment installation costs considered as 30% of the initial investment.

The investment cost of the gas turbine system (I_{STG}), given in US\$, is determined by the Equation (23) [18]:

$$I_{STG} = 0.00002 \times W_e^2 - 0.2078 \times W_e + 982.65 \tag{23}$$

The Equation (24) shows the investment cost of the heat recovery system (I_{RC}), given in US\$, is considered as [22]:

$$I_{RC} = 6996 + (211.5 \times m_v) \tag{24}$$

To determine the initial investment cost of the biodigester (I_B), it is necessary to size it. According the methodology of Ghiandelli [27], the required parameters are the HRT (hydraulic retention times), equal to 45 days, and the availability of feedstock, 6.600.000 $\frac{l}{year}$ of manipueira. Once that the biodigester volume is calculated, it is necessary to evaluate the required gasholder size. The proportion between total biodigester volume and gasholder is equal to 3:1.

Finally, the capacity required for the biodigester is approximately 1125 m³, and the investment cost is approximately 16,724.00 US\$ (see Table 4) [28]. So, the total investment cost (I_T) is 396,183.40 US\$.

Maintenance Cost

According to Silveira [26] and Antunes [23], the maintenance cost of the gas microturbine system (CM_{STG}) and the cost of maintaining the heat recovery system (CM_{RC}) are obtained by Equation (25) and (26):

$$CM_{STG} = 0.015 US_{\frac{kWh}{h}} \tag{25}$$

$$CM_{RC} = 0.008 US_{\frac{kWh}{h}} \tag{26}$$

The annual maintenance cost of the digesters was estimated at 2.5% of the initial value [29], so the CM_B is approximately 0.00017 $US_{\frac{kWh}{h}}$.

Annualized Cost of Production

In order to determine the annualized costs of electricity (C_{el}) and annualized costs for steam production (C_v), in US\$/kWh, of the plant studied, the Equations (27) and (28) proposed by Antunes are used [23]:

$$C_{el} = \frac{(I_T - I_{RC}) \times f}{H \times E_p} + \frac{C_{comb} \times (E_{comb} - E_{rc} - Per/2)}{E_p} + CM_{STG} + CM_B \tag{27}$$

$$C_v = \frac{I_{RC} \times f}{H \times E_v} + \frac{C_{comb} \times (E_{rc} + Per/2)}{E_v} + CM_{RC} + CM_B \tag{28}$$

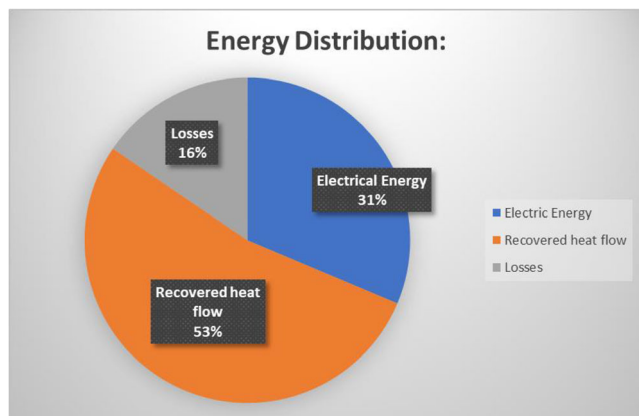


Fig. 2 Distribution of microturbine energy production

Table 3 Relationship between the production of thermal and electrical energy

Steam mass flow (\dot{m}_v) [kg/s]	Ratio $\left(\frac{\dot{m}_v}{E_p}\right)$ [(kg/s) vapor/kW]	Ratio $\left(\frac{E_v}{E_p}\right)$
0.1945	0.000531	1.208366

Thus, the annuity factor (f), in 1/year, given by the Equation (29) [23]:

$$f = \frac{q^k \times (q-1)}{q^k - 1} \tag{29}$$

where:

$$q = 1 + \frac{j}{100} \tag{30}$$

where “k” is the amortization period, given in years and “j” is the annual interest rate, set at 12% for this present study [18, 22, 25].

The energy losses (Per), in kW, can be calculated by Equation (31) [23]:

$$Per = E_{comb} - E_p - E_{rc} \tag{31}$$

The produced electricity (E_p), the residual heat of the gases (E_{rc}), the heat recovered in vapor form (E_v), and the power supplied by the fuel (E_{comb}) refer to the data obtained from the energy analysis.

The annual operating period (H) equals 7608 h, considering that the analyzed plant is of large scale, it operates in 3 shifts, operating 24 h a day from Monday to Saturday, excluding Sundays for equipment maintenance and rest of employees.

According to Xavier [22], the cost of fuel (C_{comb}), biogas, is estimated to be 0.019 US\$/kWh.

The amortization period (k) is determined according to the variables mentioned above, through an iterative procedure.

Table 4 Budget of biodigester with a volume of 1125 m³ [28]

Descrição	Valor (US\$)
Earthmoving and excavation	1,711.00
Civil construction and Hidraulic pump	3,340.00
Pipes and mechanical connections	425.00
Upper and lower blanket – PVC	8,617.00
Fastening accessories	1,504.00
Manpower	1,127.00
Total	16,724.00

Table 5 Economic analysis parameters

2.2.1. Investment costs	
I_{STG}	349,397.3US\$
I_{RC}	7,037.16US\$
I_B	16,724.00 US\$
I_T	465,106.00 US\$
2.2.2. Maintenance cost	
CM_{STG}	0.015 US $\frac{\$}{kWh}$
CM_{RC}	0.008 US $\frac{\$}{kWh}$
CM_B	0.00017 US $\frac{\$}{kWh}$
2.2.3. Annualized cost of production	
C_{el}	0.1534 US $\frac{\$}{kWh}$
C_v	0.0382 US $\frac{\$}{kWh}$
Per	0.154 kW
k	1.5 years
2.2.4. Annual revenue	
G_{pel}	1,829.01 US $\frac{\$}{year}$
G_{pv}	41,865.51 US $\frac{\$}{year}$
R	43,694.62 US $\frac{\$}{year}$

Annual Revenue

The annual revenue from the installation of the cogeneration system is determined by the sum of the gains associated with the production of electricity and useful heat [26].

The annual gain due to the production of electricity (G_{pel}), in US\$/year, is given by Equation (32):

$$G_{pel} = E_p \times H \times (P_{el} - C_{el}) \tag{32}$$

The value of the purchase price of the electric energy (P_{el}) used was US\$ 0.154/kWh [22].

Similarly, the annual gain due to steam production (G_{pv}), in US\$/year, can be determined by the Equation (33):

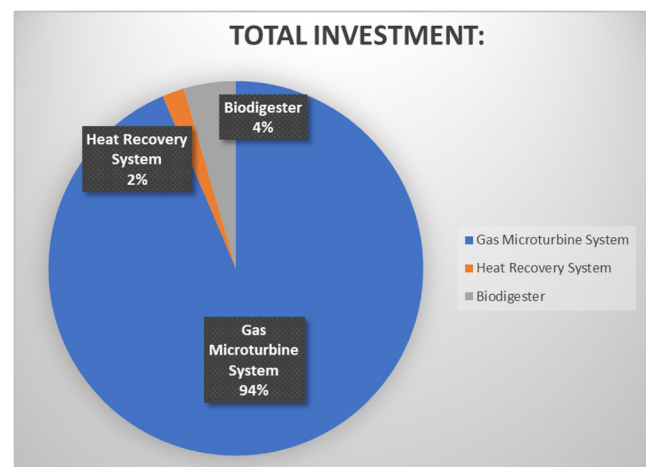


Fig. 3 Distribution of costs with the initial investment

COST OF ELECTRICITY PRODUCTION

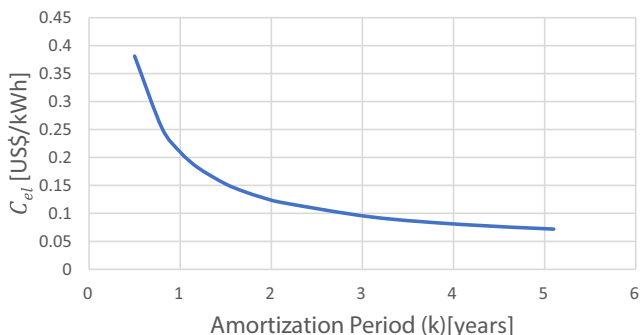


Fig. 4 Cost of electricity production (UU\$/kWh) in a cogeneration system

$$G_{pv} = E_v \times H \times (C_v) \tag{33}$$

The expected annual revenue (R), in US\$/year, is given by the sum of the gains due to the production of electricity and due to the production of steam by the cogeneration system, as shown in Equation (34):

$$R = G_{pel} + G_{pv} \tag{34}$$

The value of the amortization period (k) is determined when a revenue value greater than or equal to zero is obtained [26].

Economic Analysis Results

The results found during the economic analysis are presented in Table 5, as well as the parameters calculated during the development of the applied methodology.

The first parameter to be analyzed is the total investment cost of the plant, being equal to approximately US\$

COST OF PRODUCING STEAM THERMAL ENERGY

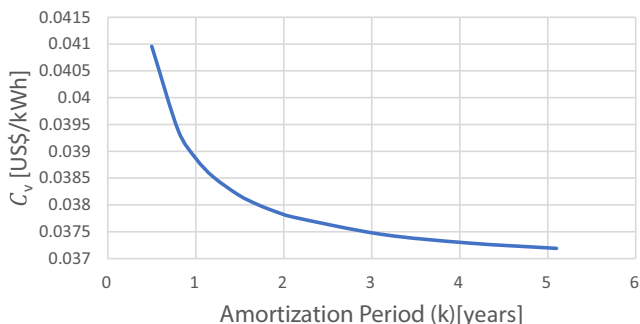


Fig. 5 Cost of production of thermal energy (UU\$/kWh) in the form of steam in a cogeneration system

465,106.00 that is 1322.3 US\$/kW of electricity produced. Figure 3 shows that the distribution of the value according to the investments made, showing that most of the initial cost, is related to the gas turbine system.

Other parameters to be analyzed are the costs of production of electric and thermal energy, where the values of 0.1534 US\$/kW and 0.0382 US\$/kW, respectively, were considered, considering the plant already amortized.

The graphs in Fig. 4 and Fig. 5 show the cost of energy production, in US\$/kW, as a function of the amortization period in years.

The production costs, both for electricity and for thermal energy, decrease over the years because, although fuel costs are adopted as constant values, the cost related to the initial investment in the plant decreases with time according to the amortization. This behavior is also related to the annuity factor, which is dependent on the annual interest rate considered (12%).

Another factor that influences the distribution of production cost curves is the annual plant operation period (H), considered in this study as a fixed value of 7806 hours per year.

Finally, the annual revenue behavior will be according to the damping period. The amortization period found is approximately 1.5 years. For a cogeneration plant using an internal combustion engine of the Otto Cycle fueled by biogas, Xavier [22] says that the damping period is around 2 years and when fed with another fuel such as natural gas, it is between 3 and 4 years.

The improved performance of biogas can be explained by its low cost, resulting in greater annual savings in plant installation and rapid return on investment.

Conclusion

The technologies of anaerobic digestion and the use of biogas are effective in the treatment and valorization of the manure, reducing the environmental impact caused by the undue disposal of this effluent. In addition, the results obtained during the economic and energy analysis guarantee the potential for biofuel.

From the use of cogeneration, there is an increase in the overall efficiency of the system, making the fuel has its energy potential better utilized. In addition, the proposed plant obtained significant results when compared to another configuration, where the ratio between heat/electricity and amortization period were more satisfactory using the gas turbine. Thus, the results obtained during the energy analysis ensure that the proposed configuration is capable of being implemented.

Another important conclusion is the short amortization period due to the use of a low-cost fuel and high-energy potential, ensuring the proposed economic viability configuration.

Finally, it is expected that, in the future, industrial effluents with a high-energy potential such as the one studied, instead of being discarded, will play a relevant role in world energy production, aiming increasingly for sustainability.

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