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Project of a cogeneration system using biogas

Projeto de um sistema de cogeração usando biogás

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Abstract

Brazil has been among the countries with the cleanest energy matrix in the world. The country showed high growth rates on its economy during the first years of the 21st century, which brought a rapid demand for energy supply. Recently, the situation got worse with long dry seasons, resulting on the use of several thermoelectric plants, with high energy costs and increased GHG emissions. The discussed study involves the design of a biogas cogeneration system for the Federal University of São Carlos. The considered biomass originates from the campus itself and is composed of organic waste. The proposed system consists of a modified diesel engine, accoupled to an electric generator and three heat exchangers, which could archive a monthly production of electricity of 7.7 MWh with a power of 30 kW. The monthly production of thermal energy would be 9,8 MWh with a power of 37.6 kW. The costs are quoted adding up to R$ 211,237.00 for the complete system. The annual savings with the system is estimated at R$ 91,126.40, reaching an amortization time of two years and four months.

Keywords: Decentralized energy; biogas; methane; cogeneration.

Resumo

O Brasil está entre os países com a matriz energética mais limpa do mundo. O país apresentou altas taxas de crescimento da economia durante os primeiros anos do século 21, trazendo um rápido aumento na demanda de energia. Mais recentemente, a situação se agravou com as longas estações secas, que resultaram no comissionamento de várias usinas termoelétricas, sabidamente com custo da unidade de energia mais cara e com maiores emissões de GEE. O presente estudo discute o projeto de um sistema de cogeração à biogás para a Universidade Federal de São Carlos. A biomassa considerada é originária do próprio campus e é composta por resíduos orgânicos. O sistema proposto consiste em um motor a diesel modificado, que é acoplado a um gerador elétrico e três trocadores de calor. A produção mensal esperada de eletricidade é de 7,7 MWh com potência de 30 kW. A produção mensal esperada de energia térmica é de 9,8 MWh com potência de 37,6 kW. Os custos são cotados somando R$ 211,237.00 para o sistema completo. A economia anual com o sistema é estimada em R$ 91.126,40, com um prazo de amortização calculado em dois anos e quatro meses.

Palavras-chave: Energia descentralizada; biogás; metano; cogeração.

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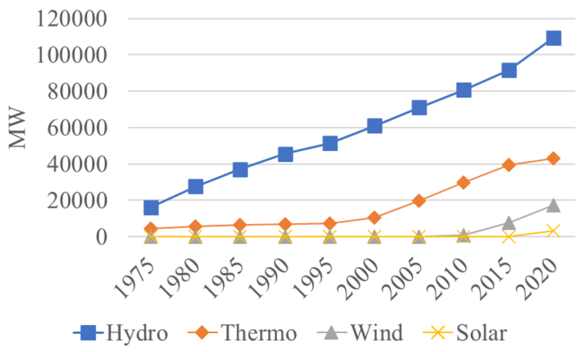
Introduction

Energy in Brazil

Since the beginning of the 20th century, Brazil has been a major producer of electricity from renewable sources due to the potential capacity of its hydrological basins. As a result of this mainly single energy source dependence, Brazil faced a severe energy crisis in the first years of the new century. The growth in generation capacity from hydroelectric sources is almost linear as shown in Figure 1.

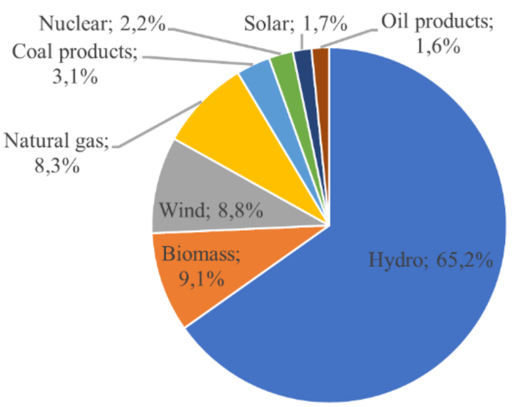
Figure 1 – Evolution of electricity generation in Brazil.



Source: Adapted from EPE (2021).

It is worth mentioning that, according to Mansor and Vichi (2009), between the ‘40s and ´90s the hydroelectric sources made up around 90% of the electricity generation in the country, a level that dropped to 64% in 2021, see in Figure 2.

Figure 2 – Sources of electricity generation in Brazil in 2021.



Source: Adapted from EPE (2021).

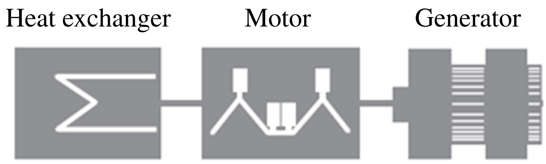
Another important issue to be considered, concerning the Brazilian energy system, is the size of this continental country. This is directly related to the challenges of transmission from generation sites to final users. The use of big hydroelectric plants is a clear example of centralized generation, that is, large amounts of electrical energy are generated at a certain point of the territory and sometimes must be transmitted too far to reach the final consumers.

Centralized generations have advantages and disadvantages over decentralized ones. As an advantage, there are improved efficiencies that can be achieved in large-scale processes than in small-scale ones. A disadvantage is the issue of losses during transmission of the generated energy.

Cogeneration

The term cogeneration is defined by ANEEL (2006), as “an operational process to obtain mechanical and thermal energy, which are generally converted totally or partially into electrical energy”. Figure 3 shows an option for cogeneration with an internal combustion motor, coupled to a generator and to heat exchangers. The potential energy used as input for the system is of chemical type and may be solid, liquid, and gaseous compounds such as biogas.

Figure 3 – Explanatory scheme for cogeneration.

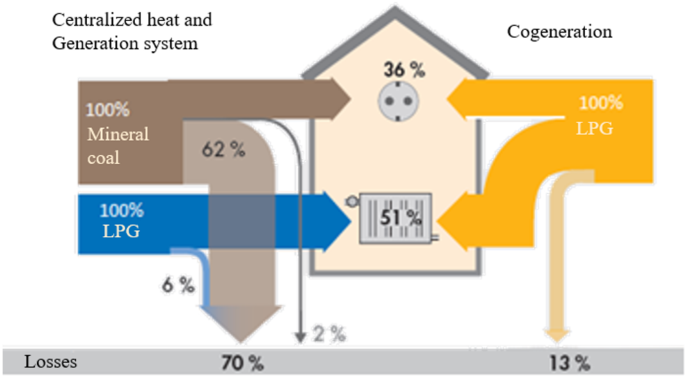


Source: Adapted from ASUE (2012).

Figure 4 compares cogeneration with Liquefied petroleum gas (LPG) to a common generation system by thermoelectric plant for electricity and usual house heating with LPG. In the traditional system, a loss of 70% of all energy supplied is expected, while in the cogeneration system these losses can be less than 15%.

In Brazil, cogeneration is a reality in sugar and ethanol plants powered by sugarcane bagasse. In this case, the fuel is a waste from the manufacturing process. The products of cogeneration, mechanical or electrical power, and steam, are used in the process itself. The burning of bagasse, which is considered a primary source of energy, generates steam that will be supplied to the turbines of mechanical drives, such as pumps, mills, shredders, among others, and electric power generators (FIOMARI, 2004).

Figure 4 – Comparison between common generation and cogeneration.



Source: Adapted from ASUE (2012).

In the south of the country, mainly in Paraná state, there are several examples of using animal waste for generating biogas, fueling internal combustion engines. However, most applications still use only the gain of the system with electrical energy, that is, the heat continues to be dissipated to the environment.

Biomass

Originally, biomass is used as an energy source by direct burning, leading to negative factors such as the high emission of pollutants composed of nitrogen and sulfur oxides (NO_x and SO_x) and low efficiency in burning systems.

In Brazil, the use of biomass is still mostly in the form of biofuels, which as mentioned, may be in form of solid, liquid, or gaseous (biogas). Biogas has advantages over direct biomass burning, such as being easily transported and stored.

Inspiration for the project

The inspiration for this study is a similar project already installed at the University of Triesdorf, in southern Germany. The Hochschule Weihenstephan-Triesdorf consists of about 50 buildings that are completely powered by renewable sources, the first university in Europe to achieve such a feat. The sources are biomass and photovoltaic panels. Biomass is used in two ways: with the direct incineration of wooden pallets and with the generation of biogas. The entire installation was done and is managed by an outsourced company that operates the site. According to the company's own data (HOCHSCHULE. . . , [2016]), the electric generator supplies 195 kW of power. Thermal gains generate sufficient heat based on the average annual campus consumption. In peak heating during the winter, the two incinerators together have a capacity of 2,150 kW to meet the demand. According to the company, the installation manages to save 700,000 m^3 of natural gas for thermal generation, preventing the release of 1,400 tons of carbon dioxide equivalent into the atmosphere. For the electric power generation, the installation prevents 1,000 tons of carbon dioxide (CO_2) from being released into the atmosphere.

Background review

Biogas

Biogas is formed naturally in the decomposition of organic compounds by anaerobic digestion by the action of bacteria.

In Brazil, studies and applications began in 1996 (MARQUES, 2012) and are mostly found in swine farming and landfills. The southernmost state of the country has several applications in operation, concentrated in electricity generation, and not on cogeneration.

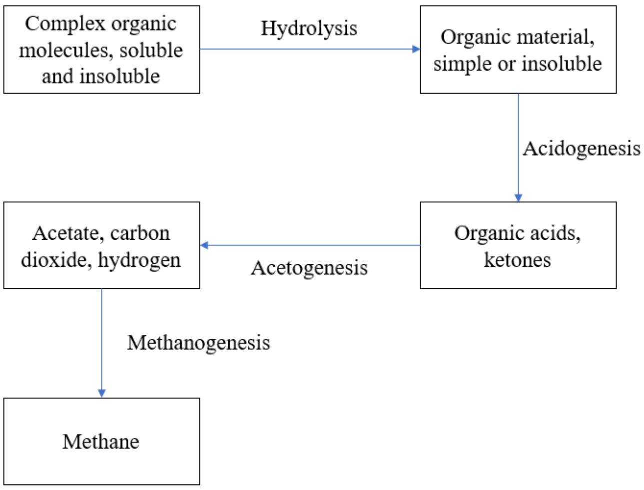
Anaerobic digestion

Anaerobic digestion is a biochemical reaction carried out by bacteria in a humid environment and absence of oxygen. Caron *et al.* (2009) summarizes the process in four phases: hydrolysis, acidogenesis, acetogenesis, and methanogenesis as follows, Figure 5.

Composition

Table 1 shows typical ranges of the elements in the biogas composition, most of which are comprised of methane and carbon dioxide. The concentrations of each element and the volume produced depend on several factors, such as temperature, the type of biodigester and the organic matter used.

Figure 5 – Metabolic steps of anaerobic digestion for biogas generation.



Source: Adapted from Marques (2012).

Table 1 – Composition ranges of the generated biogas.

Components in biogas	Concentration (%)
CH_4	40 – 75
CO_2	25 – 40
N_2	0.5 – 2.5
H_2S	0.1 – 0.5
H_2	1 – 3

Source: Castanon (2002).

Table 2 shows the low calorific value (LCV) of some of the most used gaseous fuels and the methane found in biogas.

Table 2 – Low Calorific Value of some gaseous fuels.

Gaseous fuel	LCV (kcal/m^3)
Methane	8,500
Propane	22,000
Butane	28,000
Coke oven gas	4,400
City gas	4,000
Natural gas	8,554

Source: Iannicelli (2008).

Biomass sources

The characteristics of biogas production vary according to the biomass used, being an essential factor in calculating the production potential. The material used in digestion is initially placed to dry, obtaining the amount of material in total dry matter and wet matter. The wet matter is unsuitable for fermentation and is therefore disregarded, as it is normally excluded in the drying process itself. The total dry matter has a volatile and a non-volatile portion. The volatile part is used in anaerobic digestion and the non-volatile part is decanted in the fermenters, requiring maintenance to exclude it from the system.

The properties of each type of biomass may be found on the literature (ARNOLD, 2006; FNR, 2013; HÖHN *et al.*, 2014; RAMESOHL; REINHOLD, 2005). This study uses the data from Archea Service (2016), containing values for different types of biomasses: dry percentage (TS); percentage of volatile solids (%TS); volume of biogas obtained; and percentage of methane in the generated biogas.

Biodigester

Anaerobic digestion requires an oxygen-free environment, in this case, an environment provided by the construction of a biodigester that must meet safety and performance specifications to achieve the various factors for satisfactory production of biogas. According to Kunz, Perdomo and Oliveira (2004), Brazil suffered a great delay in the dissemination of biodigesters due to the following factors:

- lack of technical knowledge about construction and operation;
- high installation and maintenance cost;
- lack of equipment for the purification of biogas;
- high availability of liquefied petroleum gas (LPG) and low cost of electricity.

In other places, such as Europe and China, biodigesters have been applied for decades, helping as an alternative for generating energy, using waste, and fighting sanitary diseases (MCGARRY; STAINFORTH, 1978).

There are different techniques in the construction of biodigesters. Initially, these are classified according to the supply of biomass in continuous or intermittent mode, where in the latter the supply occurs in certain periods (FONSECA; ARAÚJO; HENDGES, 2009).

Figure 6 describes the main components involved in the construction that are:

A - Inlet tank: the place where the initial mixture of biomass is deposited;

B - Loading tube: conduit through which the residue is introduced into the digester;

C - Digester: closed tank where the anaerobic digestion of organic matter takes place;

D - Septum: the wall that divides and directs the flow of waste inside the digester;

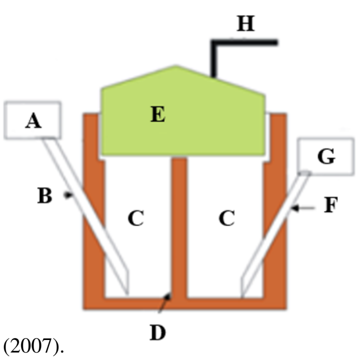
E - Gasometer: a chamber in which the biogas generated by anaerobic digestion accumulates;

F - Discharge tube: the conduit through which the liquid residue is expelled;

G - Drying bed: the tank where the liquid residue is collected, which, after the remove of excess water, becomes the biofertilizer;

H - Biogas outlet: a piping installed at the top of the gasometer to carry the biogas to the point of consumption.

Figure 6 – Main components in building a biodigester.



Source: Beck (2007).

Purification of generated biogas

In cogeneration, the biogas is generated and stored in the biodigester and, subsequently, burned in the internal combustion engine. Other applications may involve storage in tanks and flow through pipelines. The storage of biogas can cause several problems to the combustion system due to the corrosive components present in the composition of the gas.

Carbon dioxide (CO_2) and the water itself must be extracted from the biogas to increase its calorific value. Hydrogen sulfide (H_2S) is removed due to its corrosive characteristic and odor (OLIVEIRA, 1993).

Biofertilizer

Anaerobic digestion results in three products at the end of the process: biogas, liquid effluents, and solid material. The solid material is used as a biofertilizer for crops. Liquid effluents can feed algae in tanks that are later used as food for fish in ponds (MARQUES, 2012).

Cogeneration system

The usual components in a cogeneration system with biogas are engines/turbines, heat exchangers, and electrical generators. These must be dimensioned to meet the necessary demand or to supply the production of biogas. The complete system must be housed in a safe, dry place with good ventilation and at temperatures not exceeding 40 °C (MARQUES, 2012).

Motor

According to Marques (2012), the engines that can be used with biogas are the Otto or Diesel cycle engines. The technology for converting the use of conventional liquid fuel to gas is already used in applications with natural gas.

Due to its high-octane number, around 130 (SOUZA, 2006), biogas is more suitable for engines with high compression ratios, that is, Diesel cycle engines. However, the temperature reached inside the ignition chamber in the Diesel cycle is close to 553 K, much lower than the autoignition temperature of 1087 K of the biogas (BHASKOR; UJJWAL, 2015). This calls for an addition of diesel to the process for ignition to take place. The addition is known as pilot flame and should not be less than 5% of the total gas inserted, with an average value of 20% (LASTRES, 1988). There are already other studies looking for a pilot flame that is composed of fuels from renewable sources, for example, the study by Bhaskor and Ujjwal (2015).

Engines that use a mandatory mixture of fuels are known as Dual Fuel engines.

For the diesel engine to start operating in dual mode, a biogas mixer must be installed in the air inlet. The reduction of diesel consumption occurs automatically by the speed regulator, but care must be taken to ensure that the injection pump or injection units are always in good working order (CONCEIÇÃO, 2006). The dual-fuel engine ends up working more silently and more stable than the Diesel one, since the air/biogas mixture is more homogeneous than the one related to the use of diesel oil alone (LASTRES, 1988).

If one wants to operate the engine with 100% biogas, one option is to convert the engine from Diesel to the Otto cycle (OBERT, 1999). This conversion is not so simple, as it involves the introduction of a spark ignition system, removal of the injection pump, installation of a mixer for the insertion of biogas, and reduction of the compression ratio.

Cogeneration systems are usually designed as stationary systems, where environmental, space and operating conditions are favorable. The wear on the engine is drastically reduced if the maintenance is correctly done and planned. Maintenance and operation should run side by side.

The use of biogas also has the advantage of having a lower soot release. This keeps the engine in a cleaner condition when compared to those using fossil fuels. This also represents lower wear rates, as the lubricating oil is less exposed to impurities and has fewer dilution problems (LASTRES, 1988).

Electric generator

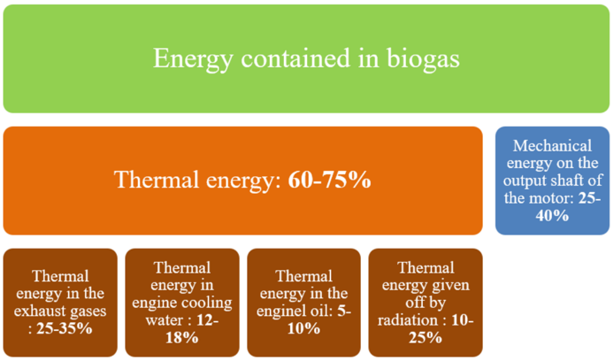
The connection between the engine and the electric generator can be performed with an elastic coupling, avoiding alignment problems between the axes and vibration of the combustion machine. Attention should also be paid to the frequency, voltage, power factor, and number of phases and poles desired (MARQUES, 2012).

Heat exchangers

The heat exchangers involved are the great differential of cogeneration for allowing the use of energy that would be wasted in the traditional system. It is through them that much greater use of the fuel is obtained, making the process advantageous.

Figure 7 shows the ranges of energy values contained in biogas and the possible ways of using it in cogeneration systems.

Figure 7 – Distribution of energy contained in biogas in the use of internal combustion engines.



Source: Beck (2007).

Figure 7 shows the possible application of heat exchangers in the exhaust gas exhaust, in the water cooling of the engine housing, and in the engine lubricating oil.

An advantage of the stationary system is to operate with constant loads, which allows a better dimensioning of the heat exchangers and, consequently, better efficiencies and maintenance of the system.

Methodology

Project scope

The goal of the project was designing cogeneration system aiming to meet the demands of the current university restaurant (UR) of the UFSCar.

Chosen available raw materials

Biogas is generated from organic materials, which should be available close to the site. It would not be logical to seek these materials from a distant source, and so spend liters of fossil fuels for its transport. Thus, it focused on possible sources within the UFSCar campus.

The first source chosen was leftover food from the university restaurant. A study has already been carried out by the Dean of Community and Student Affairs (ProACE) involving the university restaurant on the campus, resulting on an average waste of 140 g of food per person for each meal made in the UR.

Of course, a decrease in the waste of meals in the UR is desirable, but for this study, this was considered an available and high-impact source for biogas generation.

The second source chosen was the use of organic household waste. In this case, the student's accommodation on the São Carlos campus was chosen as the source of this waste. A campaign to separate organic waste from the rest would be necessary, further helping to spread the project among students on campus.

According to Lopes (2006), 55% of household waste is composed of organic matter. The amount of household waste per capita varies according to the size of the city, as shown in Table 3 as a reference.

Table 3 – Household waste per capita by population in Brazil.

Population (inhabitants)	Household waste per capita (kg/(person.day))
To 9,999	0.46
from 10,000 to 19,999	0.42
from 20,000 to 49,999	0.48
from 50,000 to 99,999	0.56
from 100,000 to 199,999	0.69
from 200,000 to 499,999	0.78
from 500,000 to 999,999	1.29
over 1,000,000	1.16

Source: Adapted from IBGE (2000).

System to be supplied

The staff of the restaurant informed they use heat to directly prepare meals or to heat water used for different purposes. The water is heated by a vessel, hot water generator, as shown in Figure 8.

Figure 8 – Vessel currently used in the UR.

Source: The authors.

The vessel is fed by steam generated in a boiler, Figure 9, that is in an adjacent room.

The boiler is fed with LPG and is responsible for generating steam supplied to the other boiler. According to the technician responsible for its operation, the current boiler cannot meet the restaurant's peak periods of steam usage. Still, this is an essential equipment, as in the event of a breakdown, the entire restaurant operations are interrupted.

Figure 9 – Boiler used for steam generation in the UR.

Source: The authors.

Analyzing the parameters of the boiler, printed on its external surface, and according to the technician who operates it, we concluded that the cogeneration system would help the thermal supply limited by the current boiler. Table 4 shows the boiler data used in the project.

Table 4 – Currently installed boiler data.

Technical specification	value
Thermal power	321,000 kcal/h
Production of steam with water at 20 °C	500 kg/h
Production of steam with water at 80 °C	550 kg/h
Fuel	LPG
Consumption	32.5 kg/h

Source: The authors.

Calculation of biogas production potential

With the estimation of the daily supply of biomass, it is possible to calculate the approximate daily production of biogas from the biodigester.

The values used for the calculation are: percentage of dry mass (TS - *Trockensubstanz*); volatile mass percentage (oTS – *organisches* TS); volume of biogas per volatile mass ($Vol_{CH_4/kgoTS}$ – *spezifischer Gasertrag*) and the percentage of methane in the generated biogas ($R_{CH_4/Biogas}$ – *Methananteil*).

The calculation starts with equation (1):

$$M_{volatil} = M_{organic} \cdot TS \cdot oTS, \quad (1)$$

where $M_{volatil}$ is the mass of volatile solids responsible for the formation of biogas and $M_{organic}$ is the daily mass of organic material inserted into the biodigester.

With the mass of volatile solids determined, equation (1), the daily production of methane can be obtained by equation (2) and, then, the volume of biogas by equation (3)

$$Vol_{CH_4} = M_{volatil} \cdot Vol_{CH_4/kgoTS}, \quad (2)$$

$$Vol_{biogas} = \frac{Vol_{CH_4}}{R_{CH_4/Biogas}}. \quad (3)$$

Power generation

From the volume of biogas, equation (3), the daily power available in the fuel can be calculated, equation (4)

$$Pot_{biogas} = \frac{Vol_{biogas} \cdot PCI_{biogas}}{t_{operation}}. \quad (4)$$

This is due to the calorific value of biogas, Table 2, and the time that the engine will be in operation on a typical day.

Internal combustion engines have limited efficiency in transforming chemical energy present in the fuel into mechanical energy at the output of the shaft. With cogeneration systems, part of the losses is used in the form of thermal energy, making the system profitable.

Electric power generation

The electrical energy in a cogeneration system is obtained by coupling an electric generator to the output shaft of the combustion engine. The generated power is based on the efficiency of the transformations involved in the engine (η_{motor}) and the generator ($\eta_{generator}$), equation (5):

$$Pot_E = Pot_{biogas} \cdot \eta_{motor} \cdot \eta_{generator}. \quad (5)$$

Thermal power generation

As already illustrated in Figure 7, the thermal energy involved in cogeneration can be used from three sources in the engine: the lubricating oil, the cooling fluid, and the exhaust gases. The powers of these sources were determined by the energy balance following equation (6):

$$Q = \dot{m} \cdot c_p \cdot (T_{in} - T_{out}), \quad (6)$$

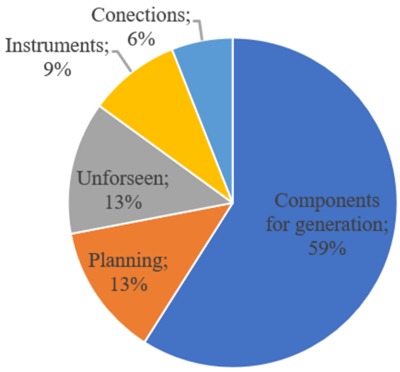
where $\dot{m}$ is the mass flow rate of the analyzed fluid, c_p is the specific heat of the fluid at constant pressure, T_{in} is the inlet temperature of the fluid in the heat exchanger and T_{out} is the outlet temperature of the fluid in the heat exchanger.

Expected costs

The cogeneration system is composed of the digester, engine, electric generator, and heat exchangers. Their costs are added to the variable $C_{components}$. The motor, C_{motor}, the electric generator, $C_{generator}$, and the heat exchangers, $C_{heat\ ex.}$. Prati (2010) presents biodigester costs, C_{biod/m^3}, according to its volume, Vol_{biod}, and a constant value for infrastructure spending, $C_{biod_{infr}}$.

ASUE (2012) presents the following graph, Figure 10, that estimates other marginal costs to the system.

Figure 10 – Marginal costs of the cogeneration system.



Source: Adapted from ASUE (2012).

Equations (7) and (8) show the calculation of the costs

$$C_{components} = C_{biod/m^3} \cdot Vol_{biod} + C_{biod_{infr}} + C_{motor} + C_{generator} + C_{heat\ ex.}, \quad (7)$$

$$C_{tot} = C_{components} + C_{plan} + C_{unfor} + C_{inst} + C_{conec}, \quad (8)$$

which, according to Figure 10:

$$C_{plan} = \frac{0.13}{0.59} \cdot C_{components};$$

$$C_{unfor} = \frac{0.13}{0.59} \cdot C_{components};$$

$$C_{instr} = \frac{0.06}{0.59} \cdot C_{components};$$

$$C_{conec} = \frac{0.09}{0.59} \cdot C_{components}.$$

Development and results

Biogas daily production

According to ProACE, UFSCar's internal housing has 574 residents. São Carlos had 241,389 inhabitants in 2015 (IBGE, 2015). Referring to Table 3, an average household waste of 0.78 kg/(person.day) results. Using the percentage of 55% that Lopes (2006) presented, there is a daily collection of 246.25 kg of organic matter in the house. Correcting this value for a collection from Monday to Friday (five days), 344.74 kg of organic matter can be removed per day from the house.

According to the management of the university restaurant, Table 5 shows the average number of meals served in the first three months of 2016.

Table 5 – Average meals in the UR during the first three months of 2016.

Time course	Number of meals
Lunch Monday to Friday	3.300
Dinner Monday to Friday	2.000
Lunch on saturdays	900

Source: The authors.

Considering an average waste per meal of 140 g per person, and distributing the weekly meals from Monday to Friday, it is possible to obtain a mean value of generated waste per working day of 767.2 kg. Adding the amount of waste obtained in the analysis for the student's accommodation, there is a daily insertion of 1.1 tons of organic matter in the biodigester.

Using the equations (1)-(3) and the data in Annex I for residential organic waste, *Bioabfall* - Biowaste, there is a daily production of biogas of 228 m^3. Considering that the system will only operate from Monday to Friday, there must be a biodigester capable of storing the biogas that is generated daily, including the volume produced on Saturdays and Sundays. Thus, there is a corrected final value of 455 m^3 in the daily production of biogas, resulting in the need for a biodigester with a capacity of 500 m^3.

Using the calorific value of biogas with 60% methane, Table 2 data from Archea Service GmbH, the daily energy available in biogas is obtained (ARCHEA SERVICE, 2016). This energy is spent in the engine in the form of heat and mechanical work. By equation (4), it is estimated 108 kW of available power in the generated biogas.

Selected motor

To select the motor, its operating hours must be specified, since the energy available to it is transformed at these hours, implying availability of the required power. In an interview with the operator of the boiler in the UR, it was informed that the restaurant starts operations at 06:30, ending at 19:00. So, in the project, it is considered to couple the operation of the cogeneration system with the boiler, setting for 12.5 daily operating hours.

Considering 30% of engine efficiency, estimated from ASUE (2012) according to the size of the motor, and 12.5 hours of operation, it was concluded that the engine should work with a power of 33 kW. This power was increased by 23% so that the engine does not run at full load and still has a certain safety margin for production peaks, which culminated in the selection of an engine of about 40.8 kW of power.

The selected engine corresponds to a Yanmar TNV series product (YANMAR, 2016). Table 6 shows the most important parameters selected from the supplier's catalog.

Table 6 – Technical properties of the selected motor.

Model	4TNV98
Type	Diesel motor, 4 strokes, water cooled
Number of cylinders	4
Engine capacity (liters)	3.319
Nominal power @ 1800 RPM (kW)	40.8

Source: Yanmar (2016).

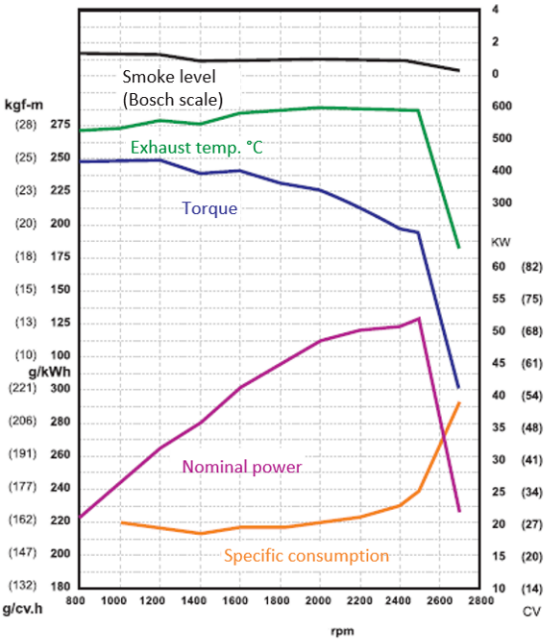
In Figure 11, the characteristic curves of the selected motor are shown. From them it is possible to calculate the mass flow in the exhaust manifold and its outlet temperature.

Selected electric generator

Considering an engine efficiency of 30% in the burning of biogas, plus efficiency in the electric generator of 90% (MARQUES, 2012), the electric energy generated daily in the generator is 367 kWh, equation (5).

Using the operating hours established for the cogeneration system, an electrical generator of almost 30 kW is obtained. Considering a power factor of 0.8, a 37 kVA generator is selected.

Figure 11 – Characteristic curves of the selected engine.



Source: Yanmar (2016).

Potential in thermal generation - parameters of heat exchangers

The thermal gain of the system is obtained with the heat exchangers that will capture the thermal energy dissipated from the engine and take it to preheat the boiler water. Table 4 shows how steam production increases in the boiler if the initial water temperature is increased, which can be accomplished using heat exchangers. Different possible arrangements for the heat exchanger system were evaluated.

Equation (6) obtains the thermal power of each heat exchanger. The temperatures and flows involved in the engine oil and in the cooling water were established according to the examples shown by Incropera (2008) and ASUE (2012). The closed-circuit mass flow rate was set at 0.5 kg/s.

The exhaust gases have an inlet temperature of 550 ºC in the exchanger established by the engine supplier catalog (YANMAR, 2016). The exhaust gas flow of 0.04 kg/s is calculated based on the engine displacement and operating speed for a given working power, data also obtained from the catalog. The exhaust gas outlet temperature of 100 ºC of the exchanger was established following ASUE (2012).

Figure 12 shows the final arrangement evaluated with three heat exchangers.

Economic viability

A brief study was carried out on the viability of the system, evaluating expected costs and gains based on not using the electricity from the grid and the LPG economy in the boiler.

Expected costs

Prati (2010) presents a value of R$ 150.00/m^3 for the tarpaulin to the biodigester, plus R$ 15,000.00 for its infrastructure. Considering the Brazilian inflation from 2010 to 2016 as 53,73% (IBGE, 2022), the previous mentioned values arise to R$ 230,60/m^3 and R$ 23,060.00, respectively.

Electric motor and generator were quoted by values found on internet purchase sites in May 2016 (GENSETEC GERADORES, [2016]; RPW, 2016). The company Alfa Engenharia budgeted three of the four possible heat exchangers to be applied. This budget served to reinforce the final decision to eliminate the heat exchanger with the engine oil, which was budgeted at R$ 2,770.00. A quote was not obtained for the heat exchanger with the exhaust gases.

Table 7 presents the final costs estimated through equations (7) and (8).

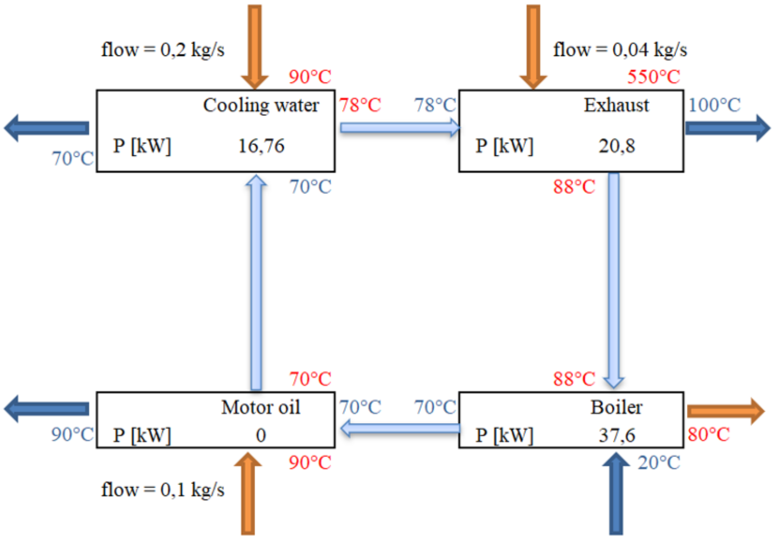
Savings

The cogeneration system generates alternatives for electricity and LPG that are consumed in the university restaurant. The system gain is calculated with the savings generated, that is, with the amounts of electricity and LPG saved.

The electrical energy saved corresponds to the value produced by the electrical generator. This amount is obtained with the calculated power on the generator (37 kW) together with the system's operating hours: 12.5 hours on weekdays. According to the Administration of the campus, in May 2016, the university paid an average amount of R$ 571.97/MWh.

The amount of LPG saved is obtained by the thermal power that the heat exchangers offer to the boiler by increasing the temperature of the inlet water. The LPG savings are calculated thanks to the consumption and production values of steam, established by the boiler supplier, Table 4. In this case, 37.6 kW in thermal power is capable of saving 40.88 kg of LPG per day. According to the Restaurant's administration, in 2015, around R$ 5.20/kg of LPG was paid.

Figure 12 – Temperatures and powers involved in the three heat exchangers in the final circuit established.



Source: The authors.

Table 7 – Estimated costs for the cogeneration system.

Cost group	BRL	Source
Biodigestor (500 m^3)	115,300.00	Prati (2010)
Biodigester infrastructure	23,060.00	Prati (2010)
Motor Yanmar 4TNV98	30,250.00	Gensetec Geradores [2016]
Electric generator Bambozzi 40 kVA	10,000.00	Rpw (2016)
Heat exchanger with cooling water	1,777.00	Alfa Engenharia
Final heat exchanger with boiler inlet water	970.00	Alfa Engenharia
Planning	9,474.00	ASUE (2012)
Unforseen	9,474.00	ASUE (2012)
Connections	6,559.00	ASUE (2012)
Instruments	4,373.00	ASUE (2012)
Total	211,237.00	

Source: The authors.

An average of 21 working days per month is used, which was the representative number in 2015, and the following values are obtained in Table 8. An annual reduction of costs of R$ 106,530.75 is estimated by electricity and LPG savings.

Table 8 – Gains from the cogeneration system.

	Electricity savings	LPG savings
	Values in BRL (R$)	
Savings per		
hour	16.81	17.00
day	210.15	212.59
month	4,413.12	4,464.44
year	52,957.41	53,573.34

Source: The authors.

There are operational specific costs as while the pilot flame is used in the combustion of 20% of diesel oil. Accordingly, the characteristic curve of engine consumption is used, Figure 11, fuel density according to ANP (2016), and the average cost of gas stations in São Carlos (R$ 2.90 per liter of diesel in May 2016). Discounting these expenses from the savings initially calculated, Table 8, an adjusted annual saving of R$ 91,126.40 is estimated, with a payback time of two years and four months.

Conclusion

For comparison, the average monthly electrical consumption of the restaurant, according to the campus administration, was obtained. The consumption was 26 MWh between January 2014 and August 2015.

Considering a monthly average of working days of 21 days for the same period, the cogeneration system has an average monthly production of electricity of 7.7 MWh, that is, the system can supply almost 30% of the restaurant's electrical demand.

With the total power of 37.6 kW of the heat exchangers, considering the data from the boiler (Table 4), a production of 41 kg of steam per hour, starting with water at 20ºC, would be obtained. This results in a reduction of 8.2% related to the consumption of the boiler.

The value of the amortization time of less than two years is something around 33% lower than the average found in similar studies (COLDEBELLA, 2006; FLORES, 2014; MARQUES, 2012; OLIVEIRA, 2009; PRATI, 2010). A value very close to this percentage reappears when comparing the thermal power calculated in the exchangers (37.6 kW) with that present in the fuel (108 kW). Contrarily, the studies targeting the isolated use of biogas for the generation of electricity, had an estimated payback of five years.

The simulation of economic viability has been greatly simplified, since many factors can vary during the years of operation, such as the price of electricity, LPG, and diesel oil. The value referring to the consumption of water, at the time of mixing it with the organic matter, was also disregarded. Values for system maintenance and operation were disregarded since no references were found for them.

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