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ELECTRICITY GENERATION FROM BIOGAS PRODUCED IN SEWAGE TREATMENT PLANT

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Abstract. *Renewable energy and energy efficiency play a key role in ensuring the future supply of electricity, meeting new standards and environmental requirements. In addition to their essential sanitary and environmental functions, Sewage Treatment Plants (STP) are also sources of biogas which present a potential for energy recovery. The main component in biogas generated at STPs is methane gas, an alternative to decentralized electrical generation. The use of this gas allows for optimal use of energy resources which are underused in STPs. The main objective of this study is to perform an analysis of the different technologies used for energy recovery from biogas. The paper presents volumetric biogas monitoring, enabling an energy potential study of biogas as well as an exergy analysis. Use of alternative technologies in power conversion is proposed for recovering heat generated in the process, such as the Organic Rankine Cycle. From this analysis, an economic feasibility study of the use of STP biogas was carried out, in order to increase the efficiency of thermal systems at acceptable costs.*
Keywords: *Biogas; Power Generation; STPs*

1. INTRODUCTION

Sewage Treatment Plants (STP), aside from their crucial role in sanitation and environment protection, also serve as sources of biogas which can be used to produce energy. The main component generated from biogas is methane gas, which is an alternative for decentralized electrical energy generation. By making use of this gas, STPs becomes more efficient in terms of energy resource consumption.

The proportion of each gas in sewage material depends on a number of parameters, including the type of digester and the substrate (type of organic material to digest). However, overall, the mix is essentially composed of methane (CH_4), and its lower heating value potential is directly related to the quantity of methane in the gaseous mix. The formation of biogas basically involves three stages: Fermentation, Acetogenesis and Methanogenesis.

Energy production through the use of process byproducts is the most relevant economic factor for value aggregation when considering residuals; moreover, there are environmental questions in play, as these materials' final destination is the environment (CENBIO, 2013).

It is worth mentioning that the gains in energy efficiency in productive process in the industrial sector, as well as in sewage treatment, are associated with the reduction in environmental impacts generated through more effective utilization of energy resources, especially when the objective is to diminish atmospheric emissions.

One possible utilization of biogas is electrical energy generation. According to a survey of water and sewer services carried out in Brazil in 2007, electrical energy consumption in water sanitation corresponded to 2% of the entire volume of water consumed in the entire country (SNIS, 2009).

The search for incentives for using alternative energy sources could balance out and even make up for the costs involved in the implementation of energy efficiency projects (COSTA, 2006). According to CENBIO (2001), countries such as Germany, Italy, England, and Spain incentivize biogas energy generation through policies which stimulate sustainable development.

In order for biogas to become a commonly-used energy source, whether it be in generators, gas turbines or Organic Rankine Cycle micro turbines (ORC), the parameters which determine its real electrical energy generation, including chemical composition, lower heating value potential and flow rate measurement, need to be established.

Biogas pretreatment processes, such as removal of H_2S (hydrogen sulfate) and humidity, should also be studied in order to avoid damaging equipment and increasing its heat-generating power. Analysis of H_2S principles in chemical, biological and physical terms, should aim for efficiency and economic viability, thus enabling its use and optimization in electrical energy generation processes.

This article details the analysis of an STP located in Passos, Minas Gerais, Brazil. The plant has an Anaerobic Reactor with Ascending Flow (UASB).

The UASB reactor came about in the 1970s through research developed by Dr. Gatze Lettinga from the University of Agriculture at Wageningen in the Netherlands (FIELD and SIERRA, 2002). Investigation proved the reactor to be efficient in treatment of material with high concentrations of organic material and low solid content (POLPRASERT, 2007).

The station under analysis has a capacity to treat 16 million liters of sewage per day. However, currently, the maximum sewage per day reaches 600m^3/h, which represents 14.4 million liters/day, with a consumption of 20 million liters of treated water.

The plant's biogas volume is not constant throughout the year and depends directly on factors such as the volume of sewage and the quantity of organic material. When dealing with STPs which have rainwater, or surface water, networks which are not separated from sewage treatment, there is also certain seasonality due to rainy seasons. Heat and climate also affect the biogas formation, as periods of higher temperature tend to accelerate this process. In order to determine the volume of biogas generated at the Passos STP, the methods of DBO and DCO (SALOMON, 2007) were adopted. Results of the application of those methodologies are shown in Fig. 1, and the average used for this calculation is 96 m^3/h. The greatest volume variations in biogas production was due to the fact that the station was in its initial stages of use, and was not operating at full capacity.

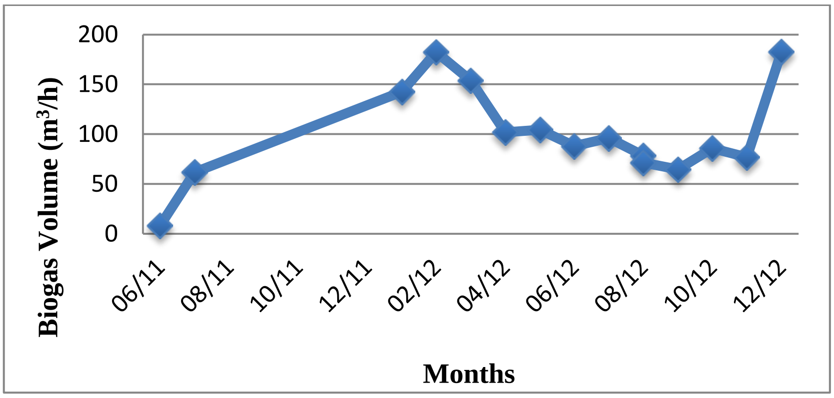

Figure 1 - Biogas Volume at Passos STP

With the aim of establishing potential biogas energy in STP, maximum flow measurement and chemical composition were analyzed to determine maximum thermal and exergetic efficiency and maximum electrical power produced through use of the studied technology

Table 1 shows biogas composition from the Passos STP, collected in the month of November by an outsourced company. Values were assumed for the calculation.

Table 1 – Analytical data collected from Passos STP.

	CO_2	CH_4	O_2
Concentration of components before burning [1] (% vol.)	19.1	78.7	0.4
Concentration of components after burning [2] (% vol.)	1.6	0.6	18.6

[1] 1.8% of other substances present in biogas. [2] 79.2% other products of reaction, which will be calculated.

2. BIOGAS ENERGY CONVERSION FOR DISTRIBUTED GENERATION

Currently in Brazil, roughly 80% of the nation's electrical energy supply comes from large hydroelectric dams which are distant from those who consume that energy. Small-scale generation provides an important and viable option to diversify the Brazilian energy network.

Great strides have been taken in this area in terms of alternative motors, steam turbines, and gas turbines, all forms of technology which have matured and are available on the market. Other technology which is available, such as

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Stirling motors and combustion cells with less maintenance costs, high performance with partial loads and high electrical efficiency, are more suitable for small-scale generation. However, this conversion technology still does not maintain a competitive operational cost and/or is not commercially available.

The destination of the electrical energy produced at the STP is also a fundamental question, as this information sheds light on revenue evaluations, economies and expenses. For the purposes of this study, the aim is to utilize electricity to supply the treatment facility, due to its distant location and relatively small production of biogas – two motives which make commercial energy production infeasible. In doing so, this would help avoid a current problem at the plant: the sporadic energy blackouts at the plant, which interrupt the city's sewer treatment system.

The energetic conversion of biogas into electrical energy can be carried out in a number of ways due to advances in technology. The most commonly utilized types of technology are gas-powered micro-turbines, medium-scale gas turbines and Spark Ignition Engine and Diesel Engine internal combustion generators. Recent studies have investigated the feasibility of implanting the Organic Rankine Cycle.

It is also worth mentioning other types of technology, such as the use of direct burning of biogas in boilers for co-generation and other remaining technologies and, while not commercially available, such as the fuel cell.

Gas turbines and internal combustion motors are the most commonly utilized types of technologies for this type of energetic conversion. Although motors, in general, have greater electrical energy conversion efficiency, gas turbines can also provide an increase in global conversion efficiency when operated in cogeneration systems (heat and electricity) (COSTA *et al.*, 2001).

The use of gas with low heat-generating potential in these technologies requires two considerations: First, the remodeling of the micro-turbine to handle the burning of poor gas, with special attention paid to the combustion chamber, and a gas cleansing process before burning, thus improving yields.

The corrosive effects of H_2S can be diminished through a number of techniques from physics, biology and chemistry. Firstly, however, a filter is used which is provided by the manufacturer, which serves to reduce the concentration of hydrogen sulfide gas and will retain eventual particles present in the biogas, thus preserving the generator (S. SILVA, 2009). In this study these techniques were not reported; however, for future studies, each removal technique will be evaluated to see which best for the STP in question.

Transportation of the biogas produced in the reactor and transferred to the generator can be done with a 1CV radial compressor.

2.1 Gas Turbines

This study analyzed medium-scale gas turbines in open, simple Brayton cycles. There are variations to this cycle, depending on its utilization. Its thermal yield is approximately 35%, but can reach up to 42% (PECORA, 2006).

Gas turbines (Brayton Cycle) work under high pressure, injecting air into a combustion chamber, thus providing the necessary oxygen for the burning process. The resulting gas drives a compressor and a generator. The greater the temperature and input pressure, and the lesser the exhaust temperature, the greater the process' efficiency will be.

2.2 Gas Micro-Turbines

This designation is given to the gas turbine which generates electrical potential in the range from 25 to 300 kW. This technology is characterized by a radial flow and varies in rotation speed from 90,000 to 120,000 rpm.

Micro turbines may also be divided into two classes: with or without heat recovery. Micro turbines with heat recovery utilize their own exhaust gas to pre-heat the air admitted into the combustion chamber, thus improving the quality of the burn, which diminished the amount of fuel necessary and, in turn, increasing efficiency from 25% to 30%. In the case of micro turbines without heat recovery, efficiency is generally lower (around 18%); however, its implementation costs are also lower.

The utilization of micro turbines presents elevated costs and the useful lifespan of this equipment, when using biogas, is relatively short (SOUZA *et al*., 2004).

Advantages of utilizing micro turbines:

- Low number of moving parts;
- Compact size;
- Low weight/potential relation;
- Elevated efficiency in co-generation systems;
- Low emissions levels;
- Operates with residual fuels;
- Extended maintenance intervals.

Disadvantages:

- Low electrical efficiency;
- Loss of potential and efficiency in locations with high temperature and at high altitude.

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Most of these units use a heat exchanger with the goal of utilizing the heat from exhaust gases to heat the combustion air. Without a heat exchanger, global efficiency of the micro turbine remains between 15 and 17%, while utilizing the heat exchanger provides a heat-efficiency of (~85%), and efficiency can be doubled, reaching up to 33% (WILLIS; SCOTT, 2000).

2.3 Internal Combustion Generator Groups

Internal combustion generator groups represent the most developed and most commonly utilized distributed energy generation technology. Its range of use is varied and can fluctuate from 5 kW to 30 kW or more. Its efficiency varies from 25% to 45%. The costs associated to this technology are the lowest among different prime movers. Costs range for this type of motor, its capacity and the type of fuel used. Below are the advantages and disadvantages for these alternative motors:

Advantages:

- Low investment costs;
- Great electrical efficiency (up to 45%);
- Fast start-up;
- Fuel flexibility;
- High reliability;
- Low gas pressure required.

Disadvantages:

- Greater atmospheric emissions;
- Noise generation;
- Frequent maintenance.

Equipment available on the market for electrical energy generation utilizing biogas has been manufactured with the goal of making use of animal waste. For application in sewers, it is necessary to verify the quantity of methane in the biogas and then select the suitable potential, with the goal of obtaining greater generator efficiency (S. SANTOS, 2009). For the motor to run correctly, the biogas must contain at least 65% methane in its composition (S. SILVA, 2009).

For the Diesel Engines, biofuels were chosen for operation (40% diesel and 60% biogas). This percentage was chosen based on studies with reduced emission rates. Gas is introduced along with air in the admission phase; the initial burn is started by a small pilot injection of diesel to enable ignition through compression, thus starting gas combustion, admitted into the cylinder by the admission collector. One of the system's advantages is that there are no modifications to be made to the motor, as is the case with Spark ignition engines (PECORA, 2006).

Yet for internal combustion motors using the Spark Ignition Engines, there need to be small modifications in order for them to be used with biogas. However, these are the not the most suitable nor most commonly indicated for generation of electrical energy. The most suitable is the Diesel cycle motor due to its robust nature and lower cost for the same potential level when compared to the Spark Ignition Engines. The introduction of biogas in Diesel engines motors can be obtained through two technologies: the transform in Spark Ignition Engine and diesel/gas, (PEREIRA, 2005) which will be studied in this article.

2.4 Organic Rankine Cycles (ORC)

The conventional Rankine cycle is a practical approach to the Carnot cycle, in which heated water vapor is generated in a boiler to then be expanded in a turbine and generate electrical potential via a generator. The remaining vapor is condensed and recycled by the boiler, thus closing the cycle. However, due to the fact water is used as the working fluid, one disadvantage is that, by having to heat the water, the humidity level upon expansion can be too high and lead to corrosion and erosion of the turbine.

On the other hand, organic substances can be used as a working fluid at temperatures less than 400 ^{o}C, and it is not always necessary to carry out super-heating, in turn making the cycle more efficient. This is due to the fact that, in heat recovery systems, the level of super-heating generates more steam and, consequently, more energy can be recovered from the heat source. Small-scale Organic Rankine Cycles have been used commercially in the last two decades with efficiency measuring from 10-20% (GANAPATHY, 2003).

Currently ORC cycles represent the most commonly used thermal system to recover heat and is commercially available for systems between 200 – 4000 KW. The spread of these systems has been fast, seeing that in 1994 there were approximately 11 units installed in Austria, Switzerland, Italy and Germany and more than 13 units built (but not installed) in the same countries. Today, in Europe, there are between 300 and 400 ORC plants.

Considering the availability of fuel, it is clear that any prime mover can be utilized for small-scale cogeneration; each of these also has its respective advantages and disadvantages. For the purposes of this study, only technology which is available at the commercial stage will be evaluated.

Table 2 presents the main properties for each type of technology used in this article.

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Table 2 – Properties for each type of technology.

Technology	Potential	Thermal Yield	Emissions $(NO)_x$
Gas Turbine[1]	500 kW - 250 MW	20 - 30%	35 - 50 ppm
Micro Gas Turbine[1]	30 - 250 KW	24 - 28%	>9 ppm
Spark Ignition Engine [1]	30 kW - 20 MW	30 - 34%	> 3000 ppm
Diesel Engine[1]	500 kW - 150 MW	30 - 35%	27 ppm
ORC	2 MW	10 a 20%	ND

[1]PECORA, (2006)

3. THERMODYNAMIC ANALYSIS
3.1 Low Heating Power (LHV)

The determination of heat-generating power of the biogas at the STP was carried out using the annual average volume of gas generated, based on the data collected on site. The biogas' LHV depended mainly on the percentage of methane present, thus enabling estimation based on the percentage of methane, as shown in Figure 2 (LIMA, 2005).

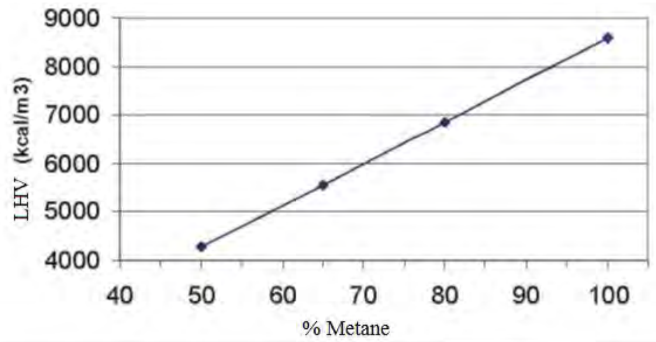

Figure 2 - Heat-Generated Potential in Relation to Methane Percentage.

3.2 Energetic Analysis

Energetic analysis will be done based on the first law of thermodynamics in order to then compare the analysis with exergetic efficiency.

Energetic efficiency of the technology types under analysis is obtained using Eq. (1).

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{W}_{net}}{(\dot{m}_d PCI_d) + (\dot{m}_g PCI_g)} \tag{1}$$

3.3 Exergy

The analysis of the second law is based on the concept of exergy; that is, the energy available, given that exergy, (and not energy) is the source of the value (GAGGIOLI, WEPFER, 1980).

Exergy serves as a valuable tool in determining the quality of energy and comparing its work potential to different forms and systems. Merely evaluating exergy is not sufficient for the study of engineering devices between two fixed states. This is due to the fact that, when exergy is evaluated, the final state is always assumed as being a dead state, which is rarely the case in real systems. Two quantities which are related with the initial and final process states and serve as valuable tools in evaluation of components and systems are reversible work and irreversibility (or destruction of exergy) (DA COSTA,2007).

Exergetic analysis is the confirmation of points throughout a process at which losses can happen and can be identified with a certain ease, seeing that it is precisely at these points in which the most exergetic destruction occurs. This destruction is the function of irreversibility of the process or degradation of the quality of the energetic resources (KOTAS, 1985).

This type of analysis enables energy conversion given that it provides a tool for guiding clear discussion on exergy losses to the environment and internal and external irreversibilities to the process (CAMPO,1990).

When exergy is balanced, the quantities of exergy which enter the system must be transformed, whenever possible, into exergy output. Theses outgoing flows represent the ends for which the system was defined.

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The differences between input and output exergies can be justified by the losses or irreversibilities in the process. Based on this difference, and due to the internal causes of the system, it is known as destroyed exergy and is taken out of the flows which do not represents, and rather, subtract from the ends for which the system was conceived. For this reason, these are known as exergy losses (KOTAS, 1985).

3.4 Biogas exergy

To calculate biogas exergy, measurement was conducted on the average volume and percentage, in volume, of each biogas component. Equation 2 demonstrates this calculation (MORAN SHAPIRO, 2000).

It is important to highlight that, for each chemical reaction, the exergy of the biogas changes due to the number of moles; therefore, for each technology type, there is a different biogas chemical exergy. As biogas is formed by a mixture of gases and calculated exergy for Eq. (2)

$$\dot{E}_{fuel} = E^{Ch} + E^{M} + E^{Th} = \dot{E}x^{ch}_{fuel} = \frac{\dot{m}_{fuel}}{\sum y_i MM_i} \sum y_i \left[\dot{E}x_i^{chp} + R\, T_0 \ln(y_i)\right] \tag{2}$$

The Exergy thermal and mechanical fuel, are zero because the input condition such that the combustion chamber is the same as the ambient condition.

For the Diesel Cycle, given that the combustion is done using a mixture of fuels, the exergy of diesel is represented by the Eq. (3). And the exergy the mix fuels are represented the Eq. (4).

$$ex^{ch}_{diesel} = \left[\bar{g}_{diesel} + a\bar{g}_{O_2} + 3{,}76\, a\, \bar{g}_{N_2} - (b+y)\bar{g}_{CO_2} - c\,\bar{g}_{H_2O} - d\,\bar{g}_{N_2} - (e+z)\bar{g}_{O_2}\right](T_0,P_0) + T_0\bar{R}\ln\left[\frac{(y^e_{O_2})^a}{(y^e_{CO_2})^{(b+y)}(y^e_{H_2O})^c}\right] \tag{3}$$

$$\dot{E}_{fuel} = E^{ch}_{biog} + E^{ch}_{Diesel} \tag{4}$$

For this calculation, the combustion reaction presented in Eq. (5) is needed to find the number of moles for each component. For calculate the exergy for biogas with diesel.

$$n_d(C_{12}H_{26})diesel + a\,(O_2 + 3.76N_2) \rightarrow bCO_2 + cH_2O + dN_2 + e\,O_2 \tag{5}$$

3.5 Exergetic Analysis

For each energy generation technology type, exergetic analysis was carried out for the cycle. Thus, the goal is to estimate which of these is more efficient according to this parameter.

Moreover, knowing that exergy is given by Eq. (6), the exergy provided by the system for Eq. (7) and the exergy destroyed in Eq. (8) can be determined.

$$\dot{E}x = \int \delta Q \left(1 - \frac{T_0}{T}\right) \tag{6}$$

$$\dot{E}x_{in} = \dot{m}_{fuel}\, ex_{fuel} \tag{7}$$

$$\frac{dE_{VC}}{dt} = Q\left(1 - \frac{T_0}{T}\right) - \left(W - p_0\frac{dV_{VC}}{dt}\right) + \sum \dot{m}_s e_{f_s} + \sum \dot{m}_e e_{f_e} - \dot{E}_d \tag{8}$$

Exergetic efficiency of a component is given by Eq. (9), and Exergetic efficiency cycle is presented in Eq. (10).

$$\eta_{II} = \frac{\dot{E}x_{out}}{\dot{E}x_{in}} = \frac{W_{net}}{\dot{E}x_{in}} = 1 - \frac{\dot{E}x_{dest}}{\dot{E}x_{in}} \tag{9}$$

$$_{II} = \frac{_{th}}{\left(1 - \frac{T_L}{T_H}\right)} \tag{10}$$

The methodology of exergy applied herein was adapted from Kanoglu, 2008, and Da Caso, 2007, among others.

3.6 Economic Viability

The overarching objective for the investment in biogas energy generation at the Passos STP is to make the installation more economically viable. Therefore, the project of a new thermal system will require an appropriate

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economic evaluation. Thus, investments, taxes, operational costs and maintenance must be established in order to obtain a thorough view of economic project viability.

According to Johansson *et al*. (1993), operational costs in biogas production in a UASB plant, of medium-scale, is between US$ 0.03 and US$ 0.05/ Nm^3. For large-scale operations, these costs can fall to around US$ 0.02/Nm^3.

For energy generation via biogas, the first economic factor to be analyzed is the use of a combustible gas at a low cost, given that biogas is a byproduct of anaerobic digestion and is normally wasted and is, at times, emitted directly into the atmosphere, in turn aggravating environmental impact through greenhouse gas emission. Sometimes this gas is burnt as a “flare” to minimize environmental damage (PECORA, 2006). This input could contribute to the diminishing of electrical energy consumption at STPs, thus optimizing its use of natural resources.

Purchasing costs for each piece of equipment (PEC) which makes up the cycle are estimated through non-linear mathematical correlations, generally in function to the area required for the evaporators, heat exchangers, condensers and electrical potential generated or consumed in the case of turbines and pumps. This can be observed in other studies, such as Lian *et al.* (2010); Maraver *et al.* (2011); Taljan *et al.* (2012); Campos *et al.* (2013). These values are demonstrated in Table 3 (WU , R.Z. WANG D.W., 2006).

Table 3 – Parameters and operational costs for each technology type.

Parameters	**Turbines**	**Micro Turbines**	**Spark Ignition Engines**	**Diesel Cycle**	**ORC**
Capacity	50 kW - 500MW	15 - 300 kW	3 kW - 6MW	5 kW - 20MW	5 kW – 4 MW
Electrical Efficiency (%)	70-20	15-30	25-43	35-45	8 - 20
Life span (years)	25-35	10	20	20	20
Cost of Installation (US$/kW)	100-200	900-1500	800-1600	340-100	3000
Operation and Maintenance Costs (US$/kWh)	0.004	0.01-0.02	0.0075-0.015	0.0075-0.015	0.003

The other costs of the thermal systems, the total direct costs are 50% of the PEC and the indirect total costs is 10% of TDC. It was assumed that average biogas cost would be 0.0025 US$/kWh for the calculations. Taxes were disregarded, as the energy will be used to supply the station, and therefore would not incur any taxation due to commercialization. Depreciation was utilized at 5% per year. The useful life span was considered as 20 years, operating at 60% capacity year-round (5,200 hours).

The main financial indicators considered in this analysis were Internal Rate of Return (IRR) and Net Present Value (NPV). NPV is presented in Eq. (11), and the target IRR figure adopted was 15%.

$$NPV = -I + \sum_{t=1}^{n} \frac{FC_t}{(1+i)^t} \quad (11)$$

3.6.1 Uncertainty Analysis

As described earlier, the economic analysis of a project demands the formulation of cash flows in which the data utilized are considered constant along its time line. This rarely occurs in practice since these data contain estimated values which, in reality, vary throughout all periods of the investment. Thus the NPV and IRR values are not exact.

Given the information above, one should apply a methodology which allows for the evaluation of alterations in results of the project, with the aim of verifying which parameters of the cash flow should be established as the most important criteria and which exercise the greatest impact over the project’s economic viability.

There are three alternatives for analysis under uncertainty:

1. Decision Matrices
2. Sensitivity Analysis
3. Simulation

According to Ross *et al*. (2000), sensitivity studies in financial analysis make it possible to evaluate the impact of a certain input variable over economic indicators. However, this methodology does not enable simultaneous analysis of input variables, thus making it impossible to analyze the application of more accurate uncertainty methods, in turn limiting the identification of the project’s most important variables.

For a more accurate quantification of risk, the most utilized tool is Monte Carlo simulation. Referring to the game of chance, this method involves the generation of observations along a probability distribution and the use of a sample obtained to approximate the function of interest.

According to Bruni *et al.* (1998), Monte Carlo is a method which utilizes artificial sampling, employed to work with complex, random numerical systems. Monte Carlo Simulation is a method based on simulation of random values to resolve problems which are divided into four phases:

1. Estimate the variation range possible for each variable which could influence the cash flow. Establish a probability distribution for each variable;
2. Choose the values for each variable according to the probabilities of occurrence and calculate the NPV or IRR;
3. Execute these operations repeatedly until arriving at a distribution of probabilities for return on investment;
4. Accumulate the probability distributions for return in order to obtain a general vision of the behavior curve, average and standard deviation.

4. RESULTS AND CONCLUSIONS

4.1 LHV

A concentration of 78.7% of methane in the biogas results in LHV of 6500 kcal/m^3 (37797.5 kJ/kg), using a biogas density of 0.72 kg/m^3. It should not be lost that the LHV and the biogas' density can be altered due to the concentration of CH_4, and a number of factors from generation in sewer treatment facilities.

4.2 Energetic Analysis

Table 4 presents the data for each Technology studied for this calculation, properties such as Turbine Work, Pump and Compressor Work. The software program HYSIS ® was utilized for Gas Turbines, Micro turbines and ORC. For the Spark Ignition Engines and Diesel Engines motors, the calculations were based on the literature (DA COSTA, 2007).

In the case of the ORC, multiple types of organic fluids were tested, such as R134, R600, R600$_a$, R290, R125$_a$, R1270, and R717. The fluid which presented the best energetic and exergetic efficiency was R600. Results are presented in Figure 3.

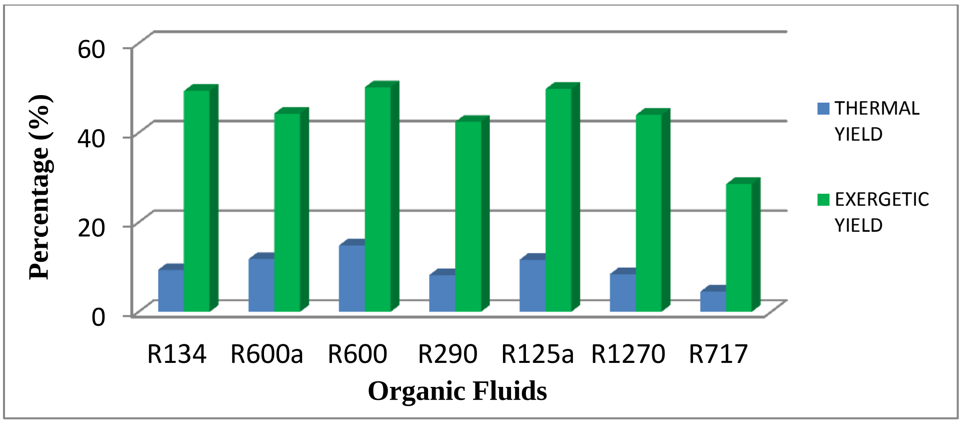

Figure 3 - Comparison of Energetic and Exergetic Efficiencies for each Organic Fluid in the ORC.

Table 4 – Thermal efficiency results.

Technology Type	Turbine Potential (W_t) (kW)	Compressor or Pump Potential ($W_{b,c}$) (kW)	Heat Flow (Q_e) (kW)	Motor Potential (kW)	Thermal Yield ($_{tl}$) (%)
Gas Turbine	1226	801.1	1426.11	--	29.84
Micro Turbine	250	144.1	419.72	--	25.23
Spark Ignition Engines	--	--	211.27	74	35.02
Diesel Engines	--	--	304.67	100	32.82
ORC	881.4	63.89	5516.67		14.82

The Heat Flow in this table is due to the fuel flow and its LHV, calculated for each type.

To determine these parameters (Table 4), certain boundary conditions were adopted for each work cycle, following the operation conditions for each piece of equipment, such as the turbine input temperature, compression relation, and compressor input air flow (DIAS, 2011; RODRIGUES, 2009).

In the ORC simulation, saturation pressure was limited to 80% of critical pressure for each working fluid. The condenser operates with water at room temperature.

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4.3 Exergy analysis

Table 5 presents the results for fuel chemical exergy in order to complete the calculation of exergetic efficiency. Those results are shown in Table 6.

Table 5 – Results of biogas chemical exergy for each technology.

	Gas Turbine	Micro-Turbine	Spark Ignition Engines	Diesel Engines	ORC
$ex^{ch}_{biog.}$ **(kW)**	1134.32	333.95	168.25	136.52	4396.47
ex^{ch}_{Diesel} **(kW)**	--	--	--	143.17	--
$ex^{ch}_{Diesel+Biog.}$ **(kW)**	--	--	--	279.69	--

The chemical exergy of biogas for Spark Ignition Engines and Diesel Engines was low because the flow rate mass amount of fuel it's used a specific consumption for engines 200 gr/cv h.

Table 6 – Results of Cycle Exergetic Efficiency.

Technology	Thermal Yield ($_{tI}$)	Cold Source Temperature (T_0) (K)	Hot Source Temperature (T_H)(K)	Work (kW)	Chemical Exergy (kW)	Exergetic Yield ($_{II}$) (%)
Gas Turbine	0.29	298.15	1188.15	424.9	2064.09	40.05
Micro Turbine	0.25	298.15	1188.15	105.9	178.90	33.67
Spark Ignition Engines	0.35	--	--	74.0	417.33	17.73
Diesel Cycle	0.33	--	--	100.0	220.98	45.25
ORC	0.15	298.15	423.15	516.7	31032.46	50.16

Figure 4 compares the efficiencies in order to obtain an analysis of each studied technology.

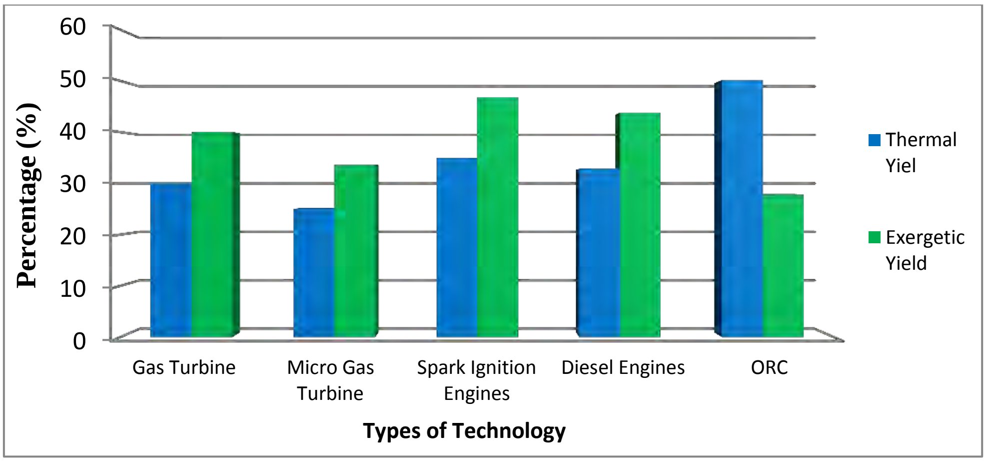

Figure 4 - Comparison of Energy Efficiencies and Exergetic each technology.

It can be concluded by analyzing the figure that, in terms of Exergetic Yield, Spark Ignition Engines presented the greatest results. This implicates that there is more energy available to be used, or converted, into electrical energy through this cycle. The lowest Exergetic Yields were presented by the Spark Ignition Engines motors. Yet the greatest thermal efficiency came from the Spark Ignition Engines motors as well; on the other side of the analysis, the micro turbines presented the lowest efficiency.

4.4 Economic analysis

Amid the different technologies analyzed there is a considerable difference in the time to evaluate the feasibility of the project, obtaining NPV values between -258.000 and 228.000 dollars, this grid variation is a result of changes in

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income and changes in project implementation costs, values associated exclusively capacity and power generation technology used respectively listed in Table 7.

Table 7 – Results of the economic analysis

Technology	NPV ($)	IRR (%)
Gas Turbine	-258600.0	12.2
Micro Gas Turbine	-250500.0	6.5
Spark Ignition Engines	228072.0	29.0
Engines Diesel	213081.9	34.1
ORC	170965.7	16.1

According to the results it can be seen that the use of gas turbines and micro-turbines is not attractive from the economic point of view, even if a technology of generating greater capacity when compared to internal combustion engines.

Spark Ignition Engines operating at present as the best option from an economic standpoint, however, this technology is the one with the lowest capacity to produce energy, for which a risk analysis is used as the final criterion for selection

For this developed a *Monte Carlo* simulation with the purpose to assess the impact of possible changes on the economic and technical viability of the project.

In *Monte Carlo* simulation, used the Crystal Ball® software, in which the chosen variables and their distributions considered are presented in Table 8. The possible energy prices were symmetrically based on data provided by the National Agency of Electric Energy (ANEEL). The fuel is biogas produced in the STP by associating the cost thereof exclusively to cleaning treatment and storage. The operation time and the amount of electricity produced were selected through a customized distribution based on percentages of operating hours per year and load equipment

Table 8 - Distribution for each variable in the *Monte Carlo* simulation.

Variable	Distribution	Minimum	Probably	Maximum
Electricity Cost (US$/kWh)	Triangular	0.10	0.12	0.14
***Fuel Cost (US$/kWh)**	Triangular	0.0025	0.0025	0.01
Operation Time (h/ano)	Custom	4368	5241	6115
Load Operation (%)	Custom	60	70	100

* The value of fuel for the operation of diesel engines should take into account the mixture of biogas with diesel increased the value of this for U.S. $ 0.015 / kWh.

The results of the different scenarios are presented in Tab. 9 in which the probability of negative NPV determine the risk of each design point assessed and sensitivity analysis determines the factors that influence the viability of the project. In Monte Carlo simulation were 10000 simulations performed for each scenario evaluated in this study.

Table 9 – Results the *Monte Carlo* simulation and analyses sensibility.

Technology	Risk (%)	Time Operation (%)	Cost Electricity (%)	Fuel Cost (%)	Electricity Production (%)
Spark Ignition Engines	7.25	8	70.1	-18	4.3
Engines Diesel	44.7	0.5	48.9	-46.8	3.7
ORC	70.9	11.4	48.2	-40.2	1

According to the results, it can be seen that implementation of a system based on the ORC cycle has higher probability of less than zero NPV (70%), and fuel cost and electric energy production are the most influential factors in viability of the project.

Thus a comparative analysis between s Spark Ignition Engine and Diesel Engine shows that even with an NPV Similarly, the probability of obtaining NPV less than zero for the Spark Ignition Engine is around 7%. Therefore, from the economic point of view the best solution will be the use of this technology as a technological option of the energy use of the biogas produced in STP. The Figure 5 and Figure 6 diagram the frequency sensitivity and NPV for the selected technology.

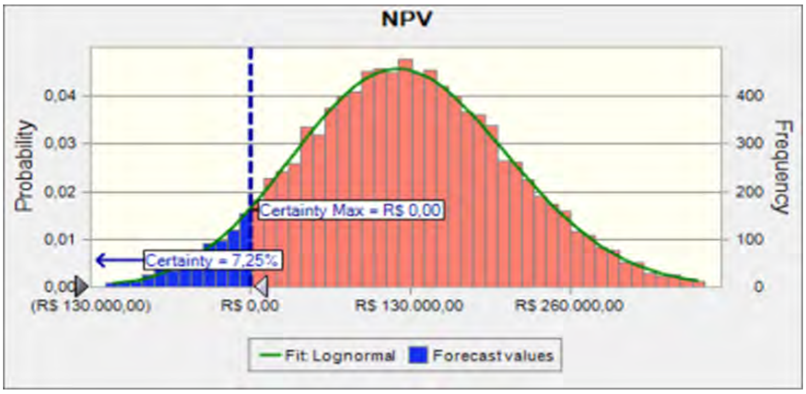

Figure 5 - Frequency diagram for the NPV of the design point.

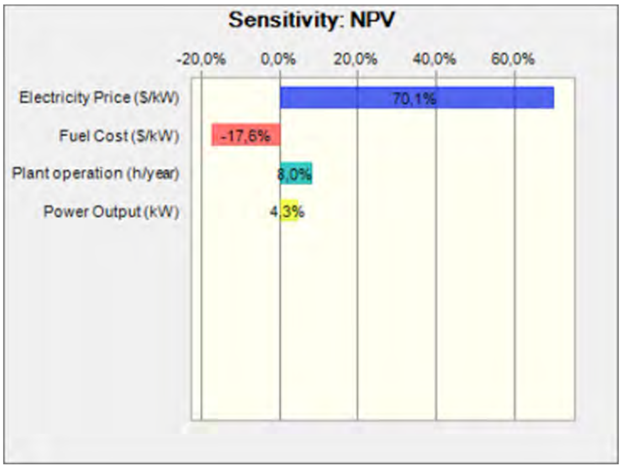

Figure 6 - Sensitivity analysis for NPV.

Aside from the economic benefits, the implantation of a project for sustainable electrical energy will bring about the increased use of cleaner, renewable fuel alternatives which are environmentally acceptable.

This research demonstrated that sewers constitute a great energetic potential, thus, for future research it is recommend that the following questions be studied:

- Study of project implementation in other STP’s;
- Investment of project revenue in process optimization for supply and treatment, seeking to minimize the physical losses and energetic losses;
- The rationing of water consumption;
- The reuse and confirmation of clean water for STP purposes.

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