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ANALYSIS OF THE ENERGY USE OF BIOGAS IN THE EXISTING COGENERATION PLANT OF A FOOD INDUSTRY

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Abstract. *The concept of energy efficiency when applied in industries can result in significant economic and environmental gains. In most of these plants, there is the demand for thermal and electric energy, making cogeneration systems an adequate application, especially when it comes to food industries. In its processes, there is the generation of waste and effluents with high organic load that need adequate treatment, which is often biodigestion with the formation of biogas. However, for existing cogeneration, the insertion of biogas as a fuel is possible under different energy arrangements, requiring an evaluation of the model that provides the highest energy efficiency. Thus, the present work seeks to determine the most technically adequate energy system for the existing cogeneration of a food industry considering the insertion of biogas as fuel through simulations in GateCycle software. In addition, the most cost-effective energy arrangement was evaluated considering the costs of implementation and maintenance. As a result, all the proposed arrangements are technically viable. However, the one that brings the best financial return to the investor is the insertion of the biogas in the existing boiler, having its co-combustion with biomass.*

Keywords: *cogeneration, biogas, GateCycle, energy efficiency*

1. INTRODUCTION

Energy efficiency has gained greater attention because it contributes to solving problems such as energy consumption and pollutant emissions. Thus, efficiency, in different forms, can result in energy and, consequently, economic and environmental gains (Hieu and Denysova, 2014). Considering the steady increase in energy demand in the world and the existing matrixes, largely with finite sources of fuel, there are two ways to overcome this adversity: the implementation and enhancement of renewable energies and the improvement of existing conversion methods to make use of energy sources more efficiently, such as cogeneration systems (Çakir et al., 2012).

In recent years, the increase in energy consumption due to rapid industrial development has threatened the environmental balance. The generation of food waste can also result in pollutant emissions if it is not well managed. These residues have a high concentration of biodegradable organic components and can be digested anaerobically for the production of biogas, which is a type of bioenergy (Thi, 2017). One way to combine energy savings and the use of renewable sources is the combination of cogeneration systems and the use of biogas (Basrawi et al., 2011). Biomass residues generated in the food industry are well applied as raw material for anaerobic digestion. The products of this process are biogas and the digestate, which can be used as fertilizer. Thus, the biodigestion process circumvents the problem of waste treatment generated in the industrial food process, besides generating a renewable energy source that can increase the energy efficiency of the plant (Bozym et al., 2015).

The conversion of biogas into useful energy is mainly done through cogeneration. The criteria for choosing the most appropriate energy system vary according to location, efficiency, maintenance intervals and repair costs (Ministério das Cidades, 2015). Typically, four-stroke engines or diesel engines are used, but gas turbines are an alternative (Deublein and Steinhauser, 2008). In larger plants, biogas can be used as fuel in boilers and internal combustion engines to generate electricity (Hosseini et al., 2016).

This work presents a study on the energy use of biogas in an existing cogeneration system of a food industry, considering the technical characteristics of typical cogeneration systems and their different arrangements. Among the systems studied, seek one that presents the best cost benefit as the electrical efficiency through simulation in GateCycle and on the respective necessary investments through financial analysis.

2. CASE STUDY

The present study deals with commercial forms of biogas energy use in a cogeneration plant in the food industry Bem Brasil Alimentos S.A. (Bem Brasil), the largest manufacturer in Latin America of frozen pre-fried potatoes. In existing cogeneration, there is the burning of eucalyptus chips for the generation of steam for the industrial process of Bem Brasil and the generation of electric energy to meet part of the unit's energy demand. The power plant is 7.5 MW and the expected power generation is 54,000 MWh / year, serving more than 60 % of the plant demand. This energy is equivalent to the consumption of a city of 138 thousand inhabitants.

For the installed capacity of 7.5 MW, the main characteristics of the biomass are:

- LHV: 2,800 kcal/kg;
- Mass flow: 15,530 kg/h.

In the unit, there was the installation of treatment of liquid effluents and solid waste that generate biogas and the expectation is that its use promotes the reduction of 20 % in the consumption of biomass, which is burned in the boiler. From this treatment, it will be possible to reuse the water used in the plant's processes for irrigation in crops and to create organic compounds from the remains and bark of potatoes that can be applied in agriculture as fertilizers, closing a sustainability cycle.

According to laboratory analysis of the biogas performed by Bem Brasil, its Lower Heating Value – LHV – is 5,440 kcal/m³ and its composition is presented in Tab. 1.

Table 1. Composition of biogas produced by Bem Brasil process.

Composition	Fraction (%)
Oxygen	0.590
Nitrogen	2.200
Carbon dioxide	30.000
Methane	67.000
Isopentane	0.196
Other hydrocarbons	0.014

After the implementation of cogeneration, the construction of biodigestors and anaerobic lagoons were started for the treatment of industrial waste and the generation of biogas, which will be used as complementary fuel in the existing cogeneration plant. In this way, the energy configurations that permit the energetic use of the biogas in the existing or combined system will be studied.

3. METHODOLOGY

GateCycle allows the simulation of energy systems and has a database referenced in commercial models. According to the arrangement, the software reports typical data of thermodynamic analysis of these systems, being between them, the value of electrical efficiency and net power of the cycle.

As an example, León (2016) cites the simulation of a plant in the commercial version of the GateCycle software and, as a result, a five year payback was found for the analyzed project. In another work cited, the gas turbine system was compared with a combined cycle and the payback reduced by 31 % and the NPV increased by 55 %. GateCycle was also used in the system-wide performance simulation by Kang et al. (2014). Co-combustion of natural gas and biogas was implemented in a gas turbine for a cogeneration system in order to analyze the reasons for each type of gas and the respective influence on the generation of heat and the cost of electricity, reaching financial ratios such as simple payback and net present value. In the study of Kalina (2012), several configurations of a cogeneration system based on different gasification and gas turbine technologies were proposed and analyzed theoretically. The gas cogeneration plant was modeled using GateCycle and the results were compared in terms of power generation efficiency, biomass energy utilization factor, CO_2 emission reduction and fossil fuel energy saving. It has been found that both the gasification technology and the plant configuration have significant influence on the results. Through GateCycle, Kim et al. (2018) compared and evaluated some technologies to increase the power and efficiency of a combined cycle plant using liquefied natural gas.

Thus, the suggested arrangements were implemented in GateCycle so that the electrical efficiency information of the cycles could support the decision of which arrangement would present the best performance.

The values reported by GateCycle are based on efficiency calculations according to thermodynamic equations, but the software does not accurately inform the equations used. In order to have a comparison with the values reported by GateCycle, some thermodynamic equations were implemented as shown in equations 1 to 7. The nominal thermal power is determined according to the energy flow being supplied by the fuel and calculated by means of Eq. 1 (Ministério das Cidades, 2010).

$$\dot{W}_{th} = \dot{Q} \times LHV \tag{1}$$

Where:

$\dot{W}_{th}$: rated thermal power [kW];
$\dot{Q}$: fuel flow [m³/h] or [ton/h];
LHV: Lower Heating Value [kWh/m³] or [kWh/ton].

One way of expressing the total efficiency of the cogeneration thermoelectric power plant cycle is to consider the useful energy as the sum of the electric power and the consumption of heat by the consumer, and can be calculated from Eq. 2 (Lora and Nascimento, 2004).

$$\eta_{cog} = \frac{\dot{W}_{el} + \dot{Q}_{sc}}{\dot{W}_{th}} \tag{2}$$

Where:

η_{cog}: cogeneration efficiency;
$\dot{W}_{el}$: generated electrical power [kW];
$\dot{Q}_{sc}$: heat consumed by steam consumer [kW]

When biogas is burned, its compression may be necessary, since this fuel has a lower calorific value. With part of the energy being devoted to the compressor drive, the net generated energy and the efficiency can be obtained as indicated by Eq. 3 and Eq. 4, respectively (Kang et al., 2012).

$$\dot{W}_{net} = \dot{W}_{el} - \dot{W}_{Comp} \tag{3}$$

$$\eta_{net} = \frac{\dot{W}_{net}}{\dot{W}_{th}} \tag{4}$$

Where:

$\dot{W}_{net}$: net electrical power [kW];
$\dot{W}_{Comp}$: power required to drive the compressor [kW];
η_{net}: net efficiency.

The power generated in the gas turbine cogeneration and in the Brayton and Rankine combined cycle are obtained, according to Eq. 5 and Eq. 6.

$$\dot{W}_{CHP} = \dot{W}_{GT} \tag{5}$$

$$\dot{W}_{CC} = \dot{W}_{GT} + \dot{W}_{ST} \tag{6}$$

Where:

$\dot{W}_{CHP}$: electric power generated in gas turbine cogeneration [kW];
$\dot{W}_{GT}$: electrical power generated by the gas turbine [kW];
$\dot{W}_{CC}$: power generated by the Brayton and Rankine combined cycle [kW];
$\dot{W}_{ST}$: power generated by the steam turbine [kW].

The electric efficiency of the combined cycle can be calculated according to Eq. 7 (Kang et al., 2014):

$$\eta_{el,CC} = \frac{\dot{W}_{CC}}{\dot{W}_{th}} \tag{7}$$

Where:

$\eta_{el,CC}$: electric efficiency of Brayton and Rankine combined cycle.

In order to validate the models to be implemented in GateCycle, a simulation of the existing plant without any proposed modification was made so that the data of generation, flow and temperature are compared with those measured by the technical team of the industrial unit. The actual operating conditions for the average generation of 7.5 MW were considered and other process conditions required for the GateCycle simulation were inferred by the software itself based on the imputed premises.

In this simulation, the mass flow of steam in the turbine was 54.915 ton/h at a pressure of 7.000 kPa and a temperature of 495 °C and, therefore, the temperature and pressure data are exactly in agreement with the existing operating conditions. The mass flow rate is 0.15 % lower than projected (55 ton/h). The power generation cycle was 7.67 MW, with a deviation of 2.3 % of expected power of 7.5 MW, demonstrating that the simulation and the results obtained are close to expected, validating the software for the analysis of proposed arrangements.

According to a bibliographical survey, it was verified that there are five possibilities of insertion of the biogas in the existing cogeneration of a food industry or combined with this, considering technologies consolidated in Brazil:

- Arrangement 1: The co-combustion of biogas and wood biomass in the existing boiler, adapting it with a burner to receive the biogas, according to its physico-chemical characteristics;
- Arrangement 2: The combustion of biogas in a gas turbine for electrical energy generation;
- Arrangement 3: The combustion of biogas in a gas turbine for electrical energy generation and the utilization of the residual heat present in the exhaust gases for the preheating of the water to be inserted in the boiler;
- Arrangement 4: The combustion of biogas in an internal combustion engine for electrical energy generation;
- Arrangement 5: The combustion of biogas in an internal combustion engine for electrical energy generation and the utilization of the residual heat present in the exhaust gases for the preheating of the water to be inserted in the boiler.

The proposed arrangements can be observed integrated to the flow diagram of the cogeneration in Fig.1.

The arrangements suggested were implemented in GateCycle. For this, the simulation of the existing cogeneration, which can be observed in Fig. 2, was used as base and the other changes were made according to the expected biogas flow and with adaptations to the commercial equipment models present in the software database.

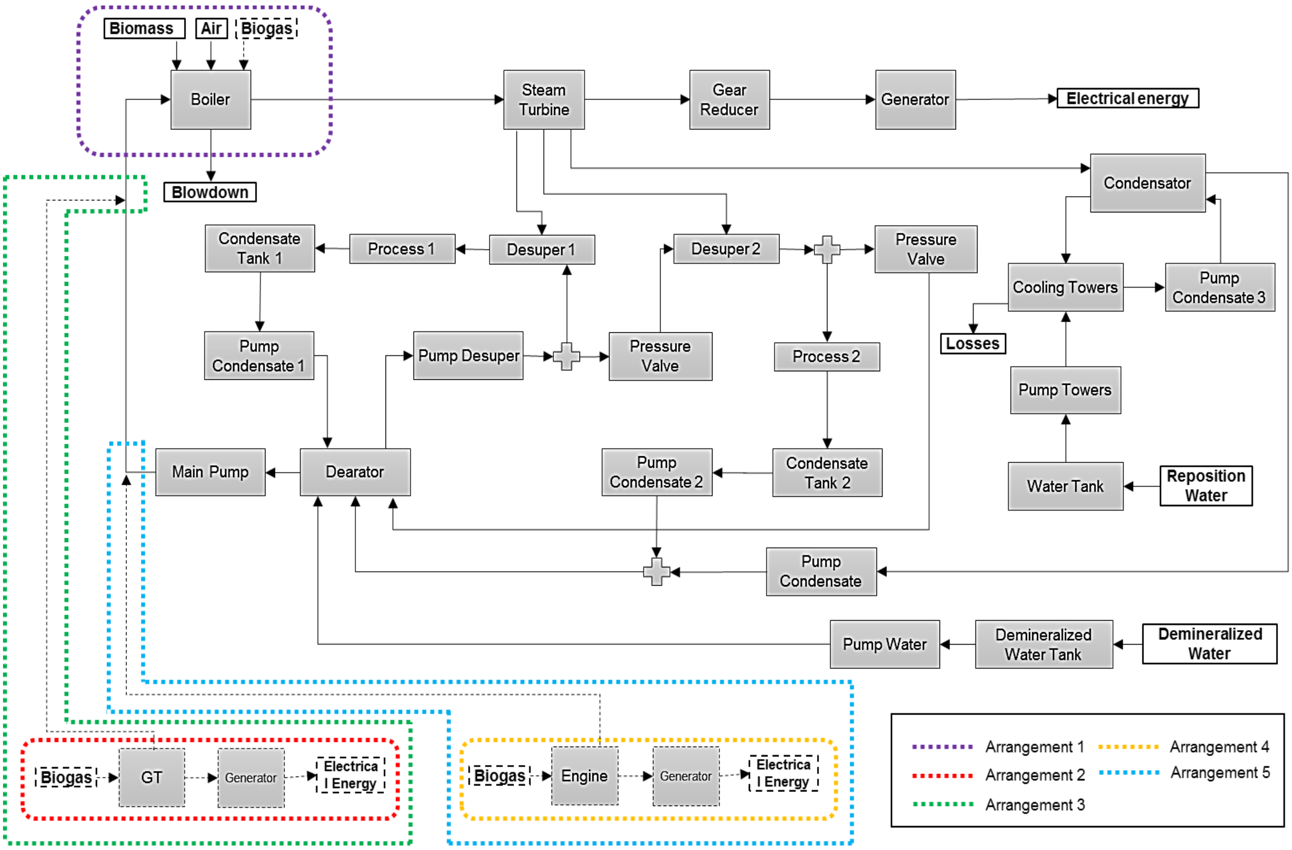

Figure 1. Arrangements 1 to 5 implemented to existing cogeneration.

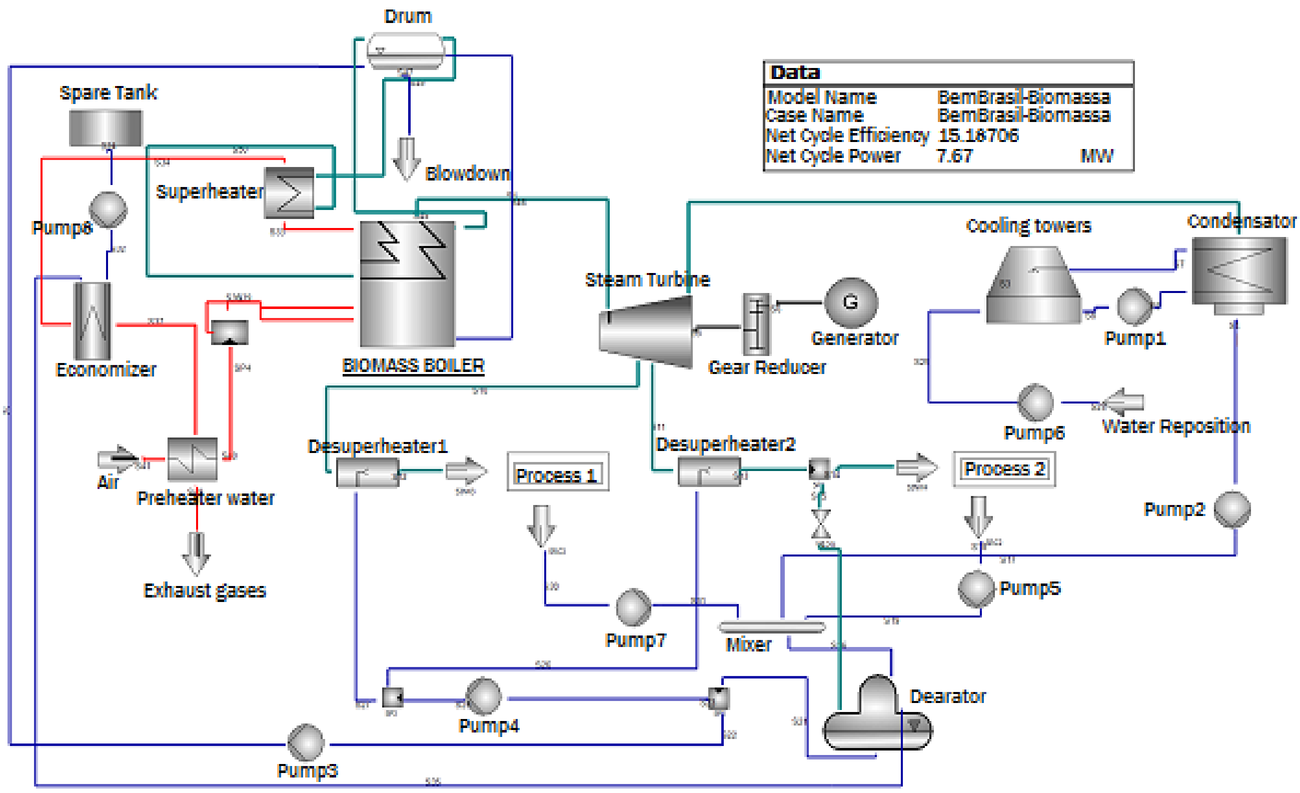

Figure 2. Diagram of existing power plant simulation.

4. COSTING

In order to evaluate the economic viability of a cogeneration unit, the costs of deployment and operation and maintenance - O&M - should be considered. O&M costs include the following items: fuel used, cost of electricity and equipment maintenance (Konstantakos et al., 2012). According to the identified arrangements, a search of these costs was carried out with national suppliers considering each energy arrangement so that the one with the best cost-benefit ratio to the food industry is indicated considering the existing cogeneration plant. In addition to the costs associated with the proposed arrangements, there was also a survey of the costs of the electric energy and wood chip inputs to the food industry in order to value the economy with the implementation of these systems.

5. RETURN ON INVESTMENT CALCULATION

Among the feasibility criteria, the most used are the Net Present Value (NPV), Internal Rate of Return (IRR) and the Payback Period (PP) (Biezma and Cristóbal, 2006). Eq. 8 demonstrates the calculation of NPV (Ozonoh et al., 2018).

$$NPV = -\beta \frac{\varphi_1}{(1+R)^1} + \frac{\varphi_2}{(1+R)^2} + \frac{\varphi_3}{(1+R)^3} + \cdots \frac{\varphi_T}{(1+R)^T} \quad (8)$$

Where β is the initial investment [R$]; φ is the cash flow [R$/year]; R is the rate of return or discount rate [%]; and T is the period of analysis of the evaluated model [year].

One project is more attractive than another if it presents a larger IRR and its calculation can be observed in Eq. 9.

$$VPL = -\beta \sum_{T=1}^{N} \frac{\varphi_T}{(1+TIR)^T} = 0 \quad (9)$$

A project with short payback is more attractive than the one with longer payback and its calculation is indicated in Eq. 10.

$$PP = p + \frac{(CF_p)}{CF_p - CF_{p+1}} \quad (10)$$

Where p is the period just before the cumulative cash flow is positive [year]; CF_p is the accumulated cash flow for period p [R$]; and $CF_{(p+1)}$ is the cumulative cash flow for period p + 1 [R$].

Both VPL and TIR are mathematical functions present in Microsoft Excel and this software was used for the feasibility calculations foreseen in this study.

6. RESULTS

All proposed arrangements in this study were viable technically by GateCycle, achieving the net power generation indicated in Tab. 3.

Table 3. Results of power generation from simulation of the proposed arrangements.

Arrangements	Net Power Generation [MW]
Arrangement 1	7.67
Arrangement 2	8.45
Arrangement 3	9.05
Arrangement 4	8.87
Arrangement 5	8.88

Applying the Eq. 1 to 7, the results found were close to those of the simulation as shown in Fig. 3. The same is observed for the electrical efficiency of the arrangements as indicated in Fig. 4.

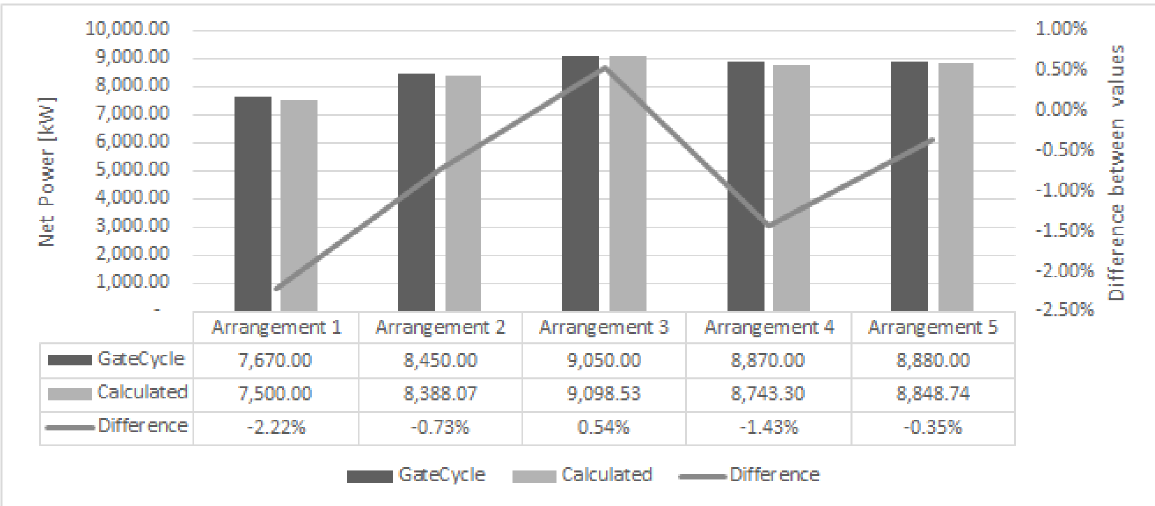

Figure 3. Power of proposed arrangements by GateCycle and equations.

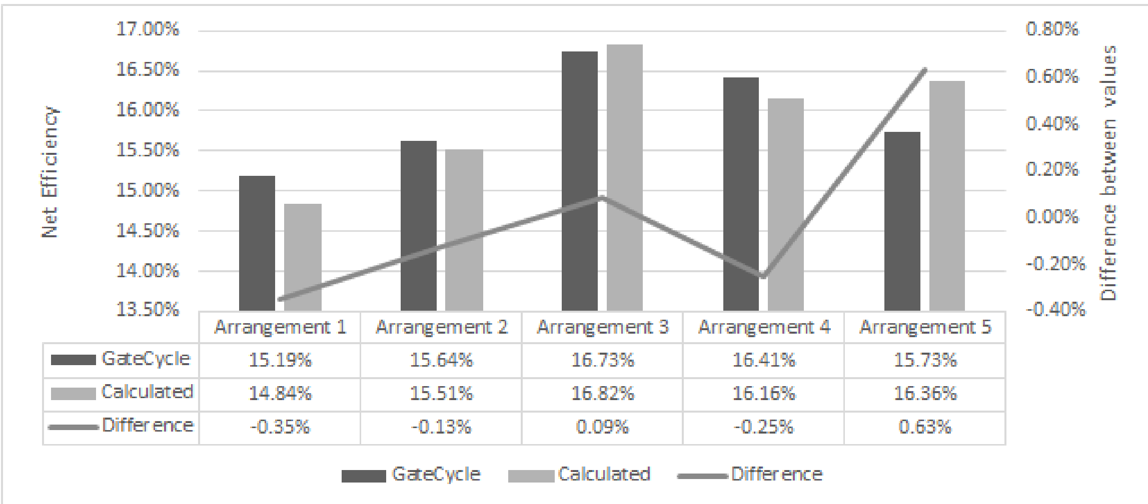

Figure 4. Electrical efficiency of proposed arrangements by GateCycle and equations.

The current costs of food industry inputs point to the acquisition of biomass at R$ 130.00/ton and the electric power supplied by the local utility of R$ 180.00/MWh.

Through a search of prices with the market of national suppliers, the prices of implantation, operation and retrofit for the gas turbine and internal combustion engine using biogas were collected. The cost of O&M and retrofit for the engine, as well as the cost of installing the integrated burner to the boiler, were not possible to obtain through market research.

The cost of acquiring and installing the burner was informed by the technical team of the food industry through a quotation made by them at the market, being R$ 250,000.00. Also according that technical team, this option does not apply for additional cost of O&M, since it already has the team itself and spare parts in order to meet the maintenance planned for the burner to be integrated into the boiler.

The O&M cost for the engine was based on the work of Gehring (2014), with a forecast of R$ 0.025/kWh. For an operation of 8,000 hours per year, this expenditure is at R$ 240,000.00 per year. For the retrofit cost of the engine, the work of Valente (2015) was used as reference, in which it considers the value of 120.00 €/kW. As it was pointed out the power of 1,200 kW motor for the simulation and considering the price of R$ 4.40/€ on 03/29/2019 (UOL, 2019), this expenditure would be R$ 633,600.00 in year 5 of operation.

For Arrangement 1, the food industry staff reported that there would be no additional cost of O&M compared to the current cogeneration plant, since it already has its own equipment and spare pieces in order to meet the planned maintenance for the burner to be integrated into the boiler.

The compilation of the costs considered for the three systems is shown in Tab. 4.

Table 4. Costs of evaluated systems.

Costs	Co-combustion	Gas Turbine	Engine
Deployment	R$ 250,000.00	R$ 4,970,000.00	R$ 2,296,124.77
Operation by year	-	R$ 114,000.00	R$ 240,000.00
Retrofit in year 5	-	R$ 1,800,000.00	R$ 633,600.00

Considering Arrangement 1, the installed power capacity remains the same and a biomass saving of 10.1 % is foreseen, according to simulation results. The wood chip mass flow rate of the cogeneration unit is 15.53 ton/h. Therefore, a reduction of 1.56853 ton/h is expected at a cost of R$ 130.00/ton or R$ 1,631,271.20/year, for 8,000 hours of operation.

For the financial analysis of Arrangements 2 to 5, the consumption of biomass is not changed and there is an increase of electric power generation due to the gas turbine and internal combustion engine drives. Given the above, the reductions with the electric energy cost for each arrangement were calculated considering the annual operation, as can be observed in Tab. 5.

Table 5. Electrical energy savings provided for Arrangements 2 to 5.

Item	Arrangement 2	Arrangement 3	Arrangement 4	Arrangement 5
Power capacity	8.45	9.05	8.87	8.88
Added power	0.78	1.38	1.2	1.21
Annual operational hours	8,000	8,000	8,000	8,000
Electric energy cost	180.00	180.00	180.00	180.00
Electrical energy saving	R$ 1,123,200.00	R$ 1,987,200,00	R$ 1,728,000.00	R$ 1,742,400.00

Through a 10-year cash flow, the respective financial results were calculated by NPV, IRR and Payback, as can be seen in Tab. 6.

Table 6. Financial results from proposed arrangements.

Arrangement	NPV	IRR	Payback
Arrangement 1	R$ 11,476,931.70	653 %	0.15
Arrangement 2	R$ 971,181.96	11 %	4.92
Arrangement 3	R$ 6,184,428.86	32 %	2.65
Arrangement 4	R$ 11,389,040.61	84 %	1.17
Arrangement 5	R$ 11,492,559.77	85 %	1.16

7. CONCLUSIONS

Increased efficiency in energy systems can also result in economic and environmental gains, and a possible action is based on the improvement of existing conversion methods. In addition, considering the constant increase in energy demand in the world and the existing matrixes, the ideal is that the energy systems make use of renewable energies with the use of residues generated in industrial processes, among them biogas.

A study was presented on the energy use of biogas in an existing cogeneration system of a food industry, considering the technical peculiarities of typical cogeneration systems and their different arrangements. These include the co-combustion of biomass and biogas in the existing boiler, the use of a gas turbine and an internal combustion engine, which may operate in parallel with the cogeneration or associated with it.

The analysis of the proposed energy systems were based on simulations in GateCycle software, a commercial tool that allows to evaluate both the configuration and the performance of thermoelectric plants, whether existing or still to be built. In addition, electrical efficiency calculations were implemented to compare with the results generated by GateCycle. The results obtained by the software and the calculations showed proximity and pointed out that all the Arrangements evaluated are technically feasible. Among them, Arrangement 3, which considers the use of combined gas turbine to the existing cogeneration cycle, is the one that provides greater electrical efficiency and installed capacity of the system as a whole.

In order to consider the economic and financial viability of the Arrangements studied, their implementation and maintenance costs were searched considering a ten-year term associated to the benefits of saving energy inputs. As a result, all the Arrangements are economically feasible and Arrangement 1, which provides for the co-combustion of biomass and biogas in the existing boiler of the cogeneration plant, is the one that presents the best cost-benefit relation with the return on investment over a period of 0.15 years and a IRR of 653 %. Thus, it is indicated that Arrangement 1 is the configuration adopted by the food industry to take advantage of the biogas generated in its installation.

8. ACKNOWLEDGEMENTS

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