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Energetic, exergetic and economic analysis of a cogeneration system: Case for a sugarcane plant of São Paulo

Análisis energético, exergético y económico de un sistema de cogeneración: Caso para una planta azucarera de San Pablo

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Abstract

Due to many advantages that cogeneration systems present, they have become a widely used technology for energy generation. In these processes, the efficiency is relatively high and the emissions of greenhouse gases are low. In this paper a technical and economic study of a cogeneration system for a sugar plant in São Paulo is carried out. For this propose the 1st and 2nd laws of thermodynamics are applied for the technical analysis. The cost of the electrical energy and steam produced are determined in the economic analysis. In the sizing of the plant, four gas turbines are analyzed that are in thermal parity with the process. The results show that the plant has a production capacity of 148MW of electricity and 147MW of steam. On the one hand the energy analysis reveals that the efficiency of the plant is 67%, while the exergetic analysis shows that this efficiency is 56%. The results of the economic analysis indicate that the prices of electricity and steam produced are 0.105 and 0.068 US $ / kWh, respectively.

Keywords: Cogeneration, economic analysis, energetic analysis, exergetic analysis.

Resumen

Los sistemas de cogeneración, debido a las numerosas ventajas que presentan, se han convertido en una tecnología bastante utilizada para la generación de energía. En estos procesos, la eficiencia es relativamente alta y las emisiones de gases de efecto invernadero son bajas. En este trabajo se realiza un estudio técnico y económico de un sistema de cogeneración para una planta azucarera en San Pablo. La primera y segunda ley de la termodinámica son aplicadas para el análisis técnico. Los costos de producción de la energía eléctrica y vapor producido son determinados en el análisis económico. En el dimensionamiento se analizan cuatro turbinas de gas que están en paridad térmica con el proceso. Los resultados muestran que la planta tiene una capacidad para producir 148 MW de electricidad y 147 MW de vapor. Por un lado el análisis energético revela que la eficiencia de la planta es de 67 %, mientras que el análisis exergético muestra que esta eficiencia es de 56 %. Los resultados del análisis económico expresan que los precios de la electricidad y vapor producido son de 0,105 y 0,068 US$/kWh, respectivamente.

Palabras clave: Cogeneración, análisis económico, análisis energético, análisis exergético.

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1. Introduction

Cogeneration is the process of combined energy production from a single source of fuel. For example, the production of thermal and electrical energy from natural gas [1]. This term is not new; industrial plants used the concept of cogeneration in the early 1880s when steam was the main source of energy. However, at present, this type of processes still play an important role in the production of energy, since their low in-vestment, operation and maintenance costs, as well as their greater efficiency and lower environmental im-pact, make them more attractive [2–4].

The combined cycle (CC) is one of the most common cogeneration systems. This cycle works in two stages: the first one works at high temperature (gas turbine) and the second stage of the cycle at a lower temperature (it uses the thermal energy of the exhaust gases of the gas turbine to produce steam) [5]. CCs have received much recognition in the last decades. Therefore, several plants have been installed and some existing units have been reactivated [6]. This fact means that technical and economic analyzes are used more frequently in order to optimize the performance of these plants.

On the other hand, the first and second law of thermodynamics are important tools to improve the efficiency of this type of process and reduce irreversibility. In the same way, an economic analysis is also considered to be a powerful tool for the study and optimization of energy systems. This analysis is applicable in investment decisions [7]. According to Silvei-ra and Tuna [8], the goal of an economic analysis is to evaluate the cost of energy produced by the cogenera-tion system (electricity and steam). In these contexts, several studies have been reported in specialized literature. Kordlar and Mahmoudi [9] present an exergo economic analysis and the optimization of a new co-generation system that produces energy and cooling. On the other hand, Gambini and Vellini [10], as well as Gvozdenac et al. [11] show an analysis of high ef-ficiency cogeneration systems.

Kanbur et al. [12] present a thermodynamic evaluation of a microcogeneration system. The results show that exergy and energy efficiencies are between two and three times higher than in the case of conventional energy generation. In his work, Sun [13] determined energy efficiency and analyzed the economic viability of an engine driven cogeneration system. In this case, the system provided electricity and cooling/heating for buildings. Here, the results show that the primary energy savings of the cogeneration system is greater than 37% compared to the conventional system.

For their part, Abusoglu and Kanoglu [14] applied the first and second laws of thermodynamics to cogeneration systems with diesel engines. In this study, the results show that the overall thermal efficiency of the plant is 44.2% and the exergy efficiency is 40.7%.

As shown in the specialized literature, there are several studies for the technical and economic evaluation of cogeneration systems to date. The present work differs from the articles studied in the literature; An energy, exergy and economic analysis is made to a particular cogeneration system, with the purpose of applying it to a sugar mill in São Paulo. The thermal demand of the process (main parameter for sizing), the type of gas turbine and the methodology used for the analyzes make this an original work.

This article is structured as follows: Section 2 presents the case study. The methodology adopted for the energetic, exergetic and economic analysis is described step by step in Section 3. The results and discussions are shown in Section 4 and, finally, the conclusions are presented in Section 5.

2. Description of the system

2.1. Description of the sugar plant

In the sugar industry, the main cogeneration system uses steam turbines in three basic configurations: back pressure turbines, combination of backpressure tur-bines with condensation turbines, and extraction-condensation turbines [15]. The present work analyzes a plant that implements two of the configurations men-tioned above (counterpressure and condensation-extraction turbines), an existing plant in São Paulo, Brazil (see Figure 1).

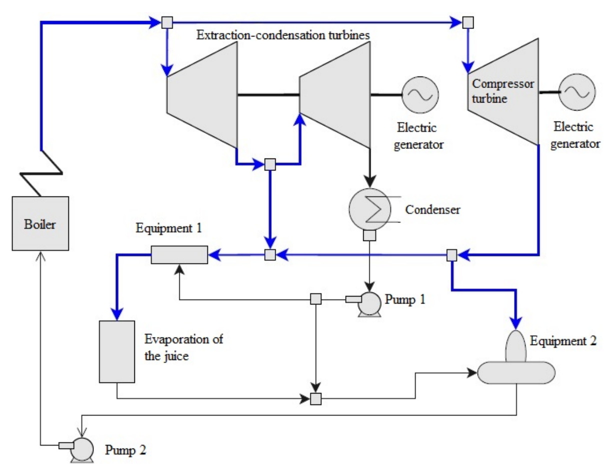

Figure 1. Existing sugar plant in São Paulo, Brazil.

The conventional boiler of this plant has a capacity to produce 160 t/h of steam at 68.6 bar, and 530 °C. 125 t/h of this steam is consumed by an extraction-condensation turbine coupled to a 32 MW generator. In this section, an extraction of 97 t/h of steam at a pressure of 2.45 bar is carried out for the cane juice evaporation process. The remaining steam (35 t/h) is directed to the backpressure turbine which is coupled to a 12 MW generator.

Additionally, the plant analyzed in this paper has the capacity to process 1 500 000 tons of sugarcane, corresponding to 240 harvest days. It mills 286 t/h of cane and generates 75.2 t/h of bagasse. The latter is used as fuel in conventional boilers to generate the necessary steam for the plant [15].

2.2. Description of the proposed system

The proposed cogeneration system has to satisfy the same thermal demands (160 t/h of steam) and generate at least 4 times more electrical energy. To accomplish this goal, the possibility of changing the conventional steam boiler (see Figure 1) for a gas turbine and a re-covery boiler is analyzed in this paper, as shown in Figure 2.

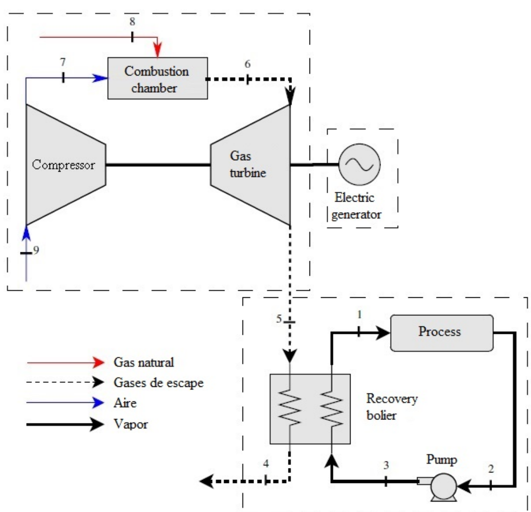

Figure 2. Scheme for the proposed cogeneration system.

As noted in Figure 2, the system is composed of a gas turbine, a combustion chamber (CC), a compressor, a recovery boiler (CR), a generator, a pump and the process. The latter includes almost all the equipment in the plant in Figure 1, the only element that remains outside is the conventional boiler.

We opted for a combined cycle system using natural gas in order to determine the feasibility of installing this process specifically in this sugar industry. If the installation of the CC is feasible, future studies will include the analysis of the gasification of the 75.2 t/h of cane bagasse generated by the plant to produce synthesis gas and substitute the use of natural gas.

3. Materials and methods

3.1. Selection of the gas turbine

The first stage in the design of this cogeneration process is the selection of the gas turbine. This turbine is selected in parity to the thermal demand of the pro-cess. Thus, the selection is made based on the temperature and the flow of the exhaust gases. The latter is determined by Equation 1 [16]:

$$\dot{m}_5 = \frac{\dot{m}_1(h_1 - h_3)}{\eta_{CR} Cp_G (T_5 - T_4)} \tag{1}$$

Where:

$\dot{m}_5$ = exhaust gas flow (kg/s)
$\dot{m}_1$ = vapor flow in the CR (kg/s)
h_3 = enthalpy of steam in CR (kJ/kg)
h_1 = enthalpy of water (kJ/kg)
η_{CR} =performance of the CR (-)
Cp_G = specific heat at constant pressure of the exhaust gases (kJ/kg·K)
T_5 = exhaust gas temperature in the CR (°C)
T_4 = exhaust gas temperature at the CR CR outlet (°C)

3.1.1. Calculation thereof Cp_G

To apply Equation 1, it is necessary to calculate Cp_G, which is determined by Equation 2 [17]:

$$Cp_G = \frac{\sum Cp_i \cdot n_i}{\sum \dot{m}_i} \tag{2}$$

For the calculation of Cp_i we have Equation 3.

$$Cp_i = a + bT + cT^2 + dT^3 \tag{3}$$

Where:

Cp_G = specific heat at constant pressure of the exhaust gases (kJ/kg·K)
Cp_i = specific heat at constant pressure of component i of exhaust gases (kJ/kg·K)
$\dot{m}_i$ = exhaust gas flow (kg/s)
$\dot{n}_i$ = molar flow of component i of the exhaust gases (kmol/s)

Parameters a, b, c, and d are obtained in Çengel and Boles [17] and are the factors to calculate the spe-cific heat at constant pressure of an ideal gas.

3.1.2. Calculation of the mass of exhaust gases

For this calculation, the composition of the natural gas (Table 1) that will be used is first defined.

Table 1. Chemical composition of natural gas [18]

Composite	Formula	% Vol	% Molar
Methane	CH_4	95	1
Ethane	C_2H_6	3,2	0,0337
Propane	C_3H_8	0,2	0,0021
Butane	C_4H_{10}	0,03	0,0003
Nitrogen	N_2	1	0,0105
Carbon dioxide	CO_2	0,55	0,0058
Oxygen	O_2	0,02	0,0002

With the composition of natural gas, Equation 4 is established:

$$\begin{aligned} CH_4 + 0,0337C_2H_6 + 0,0021C_3H_5 + 0,0003\dots \\ +0,0105N + 0,0058CO_2 + 0,0002O_2\dots \\ +(1+x)a_{th}(O_2 + 3,76N_2) \rightarrow aCO_2 + bH_2O\dots \\ +xa_{th}O_2 + dN_2 \end{aligned} \tag{4}$$

After the solution of Equation 4, the fuel mass and air mass are calculated.

Equation 5 is used for fuel mass:

$$\begin{aligned} \dot{m}_{comb} = m_{molar}CH_4 + 0,0337m_{molar}C_2H_6\dots \\ +0,0021m_{molar}C_3H_5 + 0,0003m_{molar}C_4H_{10}\dots \\ +0,0105m_{molar}N_2 + 0,0058m_{molar}CO_2\dots \\ +0,0002m_{molar}O_2 \end{aligned} \tag{5}$$

Equation 6 is used for air mass:

$$\dot{m}_{ar} = (1+x)a_{th}(m_{molar}O_2 + 3,76m_{molar}N_2) \tag{6}$$

Equation 7 is used to calculate the combustible air ratio:

$$AC = \frac{\dot{m}_{ar}}{\dot{m}_{comb}} \tag{7}$$

Where:

$\dot{m}_{ar}$ = air flow (kg/s)

$\dot{m}_{comb}$ = fuel flow (kg/s)

Thus the compensated equation of the reaction is ob-tained and represented in 8:

$$\begin{aligned} CH_4 + 0,0337C_2H_6 + 0,0021C_3H_5 + 0,0003\dots \\ C_4H_{10} + 0,0105N + 0,0058CO_2 + 0,0002O_2\dots \\ +(1+x)a_{th}(O_2 + 3,76N_2) \rightarrow 1,0807CO_2\dots \\ +2,1111H_2O + 4,3220O_2 + 24,2710N_2 \end{aligned} \tag{8}$$

From Equation 8 we obtain the mass of the exhaust gases, which is calculated with Equation 9:

$$\begin{aligned} \dot{m}_{escape} = 1,0807m_{molar}CO_2 + 2,1111m_{molar}\dots \\ H_2O + 4,3220m_{molar}O_2 + 24,2710m_{molar}N_2 \end{aligned} \tag{9}$$

Now, equations 2 and 3 can be applied to obtain Cp_G. Figure 3 shows Cp_G obtained for a range of temperatures.

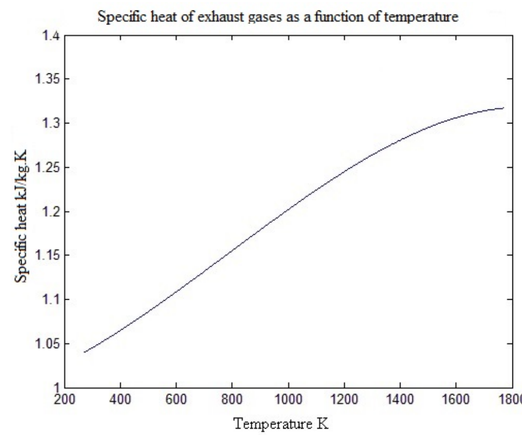

Figure 3. Specific heat of the exhaust gases as a function of temperature.

Finally, with the Cp_G Equation 1 can be applied. Table 2 shows the turbines selected and Figure 4 shows the location of each turbine according to the flow of exhaust gases.

Table 2. Selected turbines [19]

Code	Power (MW)	Efficiency	Exhaust gases (kg/s)	Gas temperature (°C)
V94.2	157	34,4	514,54	540
PG7241	171	36,5	455,9	599,44
SGT6	208	38,1	508,18	577,77
7EA	184	38,1	451,36	604,44

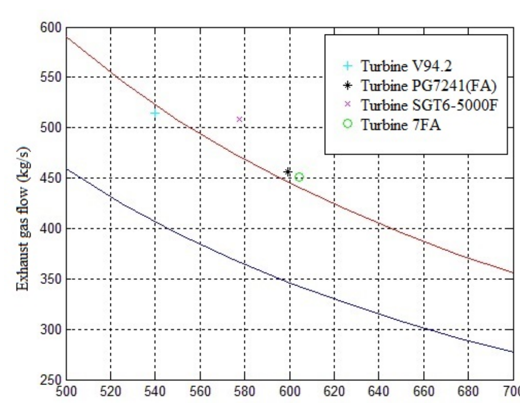

Figure 4. Turbines selected according to the temperature and flow of exhaust gases.

As can be seen in Figure 4, the V94.2 turbine is discarded because it does not meet the plant's thermal needs. The SGT6 turbine is discarded because it has an excess of exhaust gas flow. Turbines PG7241 and 7FA are the ones in thermal parity with the process. So, with the consideration that this system must generate at least 4 times more energy than the conventional sugar plant, the PG7241 turbine is finally selected.

The PG7241 turbine data is presented in Table 2 in the following conditions (Ambient Temperature =15 °C and altitude of 0 m). Therefore, turbine data must be corrected for the local conditions of the plant (Ambi-ent Temperature = 25 °C altitude of 530 m), this step is important to carry out since the environ-mental condi-tions directly influence the performance of the turbine.

3.1.3. Calculation of Pinch-Point

The temperature of the exhaust gases at the outlet of the recovery boiler must be corrected with the Pinch-Point method according to the criteria presented in Figure 5. This shows that in order to avoid a thermodynamic impropriety, one must have a minimum temperature difference for the cooling profile. According to Sue and Chuang, [20] this value can be between 10 °C and 30 °C.

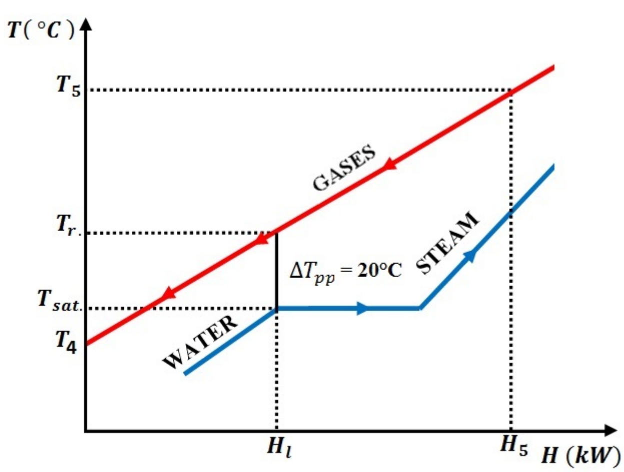

Figure 5. Pinch-Point.

The temperature at the dew point is determined with Equation 10:

$$T_r = T_{sat} + \Delta pp \tag{10}$$

For the temperature of the exhaust gases at the CR outlet, the following equations are used:

$$T_4 = T_5 - \left[\frac{T_5 - T_r}{H_5 - H_i} \cdot H_5\right] \tag{11}$$

$$H_5 = \dot{m}_5 \cdot Cp_G(T_5) \cdot T_5 \tag{12}$$

$$H_l = \dot{m}_1 \cdot h_l \tag{13}$$

Where:

h_l = enthalpy of the saturated liquid at the recovery boiler's operating pressure (kJ/kg)

3.2. Thermodynamic analysis

The technical analyses carried out in the cogeneration system are based on the 1st and 2nd law of thermodynamics, that is, energy and exergy analysis, respective-ly.

3.2.1. Energy analysis

Brayton cycle volume control

To calculate the flow of natural gas, we have Equation 14:

$$Heat\ rate \cdot P_{generador} = PCI_{gas\ natural} \cdot \dot{m}_8 \tag{14}$$

The LHV of natural gas is 48 300 (kJ/kg) [21].

The air flow at the compressor inlet is calculated with the following equations:

$$\dot{m}_9 = \dot{m}_5 - \dot{m}_8 \tag{15}$$

$$\dot{m}_9 = \dot{m}_7 \tag{16}$$

Compressor control volume

The pressure at the compressor outlet depends on the inlet pressure and the pressure ratio. This pressure is calculated with Equation 17:

$$Rp = \frac{P_7}{P_9} \tag{17}$$

The relative pressure at point 7 is calculated with Equation 18:

$$Pr_7 = Pr_9\frac{P_7}{P_9} \tag{18}$$

The enthalpy of point 7 is calculated with Equation 19:

$$h_7 = \frac{h_{7s} - h_9}{\eta_{comp}} + h_9 \tag{19}$$

By the law of conservation of energy, we have:

$$\dot{m}_6 \cdot h_6 = \dot{m}_7 \cdot h_7 + PCI_{gas\ natural} \cdot \dot{m}_8 \tag{20}$$

Control volume of the gas turbine

The following equations are used to analyze the gas turbine:

$$Pr_5 = Pr_6\left(\frac{P_5}{P_6}\right) \tag{21}$$

$$\eta_{isentrópica} = \frac{h_6 - h_5}{h_6 - h_{5s}} \quad (22)$$

Energy efficiency

For the calculation of the efficiency of the gas turbine we have Equation 23:

$$\eta_{turbina} = \frac{P_{turbina}}{PCI_{gas\ natural} \cdot \dot{m}_8} \quad (23)$$

Where:

$\dot{m}_8$ = natural gas flow (kg/s)
$PCI_{gas\ natural}$ = lower heating value of natural gas (kJ/kg)
$P_{turbina}$ = power in the turbine (kW)
$\eta_{turbina}$ = turbine efficiency (-)

To calculate the total efficiency of the cogeneration system, we have Equation 24:

$$\eta_{sistema} = \frac{P_{turbina} + [(h_1 - h_3) \cdot \dot{m}_1] - P_{bomba}}{PCI_{gas\ natural} \cdot \dot{m}_8} \quad (24)$$

Where:

h_1 = enthalpy in point 1 (kJ/kg)
h_3 = enthalpy in point 3 (kJ/kg)
$\dot{m}_1$ = flujo de vapor (kg/s)
P_{bomba} = power consumed in the pump (kW)
$P_{turbina}$ = power in the turbine (kW)
$\eta_{sistema}$ = system efficiency (-)

3.2.2. Exergetic analysis

The exergy analysis consists of the qualitative evaluation of the losses through the concept of exergy via the application of the second law of thermodynamics. A basic procedure to perform this analysis is to deter-mine the input and output values of exergy for all the components of the system and the reason for its varia-tion in the entirety of the process [16].

Compressor control volume

In the compressor, point 9 is air at ambient temperature and pressure, and point 7 is compressed air (see Figure 2).

Equation 25 is applied to find the entropy difference between the compressor's input and output:

$$(s_7 - s_9) = (s_7^0 - s_9^0) - Rln\left(\frac{P_7}{P_9}\right) \quad (25)$$

Where:

s = entropy in the different points of the process (kJ/kg K)
P = pressure in the different points of the process (kPa)

The exergy difference in the compressor is calculated with Equation 26:

$$\Delta\psi_{compressor} = (h_7 - h_9) - T_0(s_7 - s_9) \quad (26)$$

Exergy at the compressor output is obtained by apply-ing Equation 27:

$$ex_7 = \Delta\psi_{compressor} \cdot \dot{m}_9 \quad (27)$$

Donde:

ex_7 : exergy in point 7 (kW)

Irreversibility is calculated with Equation 28:

$$I_7 = \frac{(h_7 - h_9) \cdot \dot{m}_7}{\eta_{compressor}} - ex_7 \quad (28)$$

The efficiency of the second law of thermodynamics in the compressor is calculated with Equation 29:

$$\eta_{IIcompressor} = \frac{\Delta\psi_{compressor}}{\frac{h_7 - h_9}{\eta_{compressor}}} \quad (29)$$

Control volume of the CC

In the CC, point 7 is compressed air, point 8 is natural gas and point 6 are exhaust gases (see Figure 2).

In the same way as in the compressor, the entropy difference between the input and output of the CC, the exergy change, the exergy in point 6 and the efficiency of the second law of thermodynamics are calculated in the CC. The calculations are done with equations:

$$(s_6 - s_7) = (s_6^0 - s_7^0) - Rln\left(\frac{P_6}{P_7}\right) \quad (30)$$

$$\Delta\psi_{cam.comb.} = (h_6 - h_7) - T_0(s_6 - s_7) \quad (31)$$

$$\Delta ex = \Delta\psi_{cam.comb.}\dot{m}_9 \quad (32)$$

$$ex_6 = \Delta ex + ex_7 \quad (33)$$

$$\eta_{IIcam-comb.} = \frac{ex_6}{ex_7 + ex_8} \quad (34)$$

Turbine control volume

In the turbine, point 6 is the inlet of the exhaust gases to the turbine and point 5 is the outlet (see Figure 2).

In the same way as in the compressor and the CC, the following equations are applied to the gas turbine.

$$(s_6 - s_5) = (s_6^0 - s_5^0) - Rln\left(\frac{P_6}{P_5}\right) \quad (35)$$

$$\Delta\psi_{turbina} = (h_6 - h_5) - T_0(s_6 - s_5) \quad (36)$$

$$\Delta ex = \Delta\psi_{turbina} \cdot \dot{m}_9 \quad (37)$$

$$ex_5 = ex_6 - \Delta ex \quad (38)$$

$$\eta_{IIturbina} = \frac{W_{total}}{\Delta_{ex}} \quad (39)$$

Control volume in the CR

In the CR, point 5 is the entry of exhaust gases and point 4 is the outlet of exhaust gases to the environment. On the other side of the CR, point 3 is water and point 1 is superheated steam (see Figure 2).

The exergy of the exhaust gases is calculated with Equation 40:

$$ex_4 = \left[c_p(T_4 - T_0) - T_0\left(c_p ln\frac{T_4}{T_0} - Rln\frac{P_4}{P_0}\right)\right]\dot{m}_4 \quad (40)$$

The entropy at point 4 is determined with Equation 41:

$$s_4 - s_0 = c_p ln\frac{T_4}{T_0} - Rln\frac{P_4}{P_0} \quad (41)$$

The exergy change between points 4 and 5 is calculat-ed with equations:

$$\Delta ex_{4-5} = \lfloor c_p(T_4 - T_5) - T_0(s_4 - s_5)\rfloor \cdot \dot{m}_5 \quad (42)$$

$$s_4 - s_5 = c_p ln\frac{T_4}{T_5} - Rln\frac{P_4}{P_5} \quad (43)$$

The exergy change between points 1 and 3 is calculat-ed with equations:

$$\Delta\psi_{1-3} = (h_1 - h_3) - T_0(s_1 - s_3) \quad (44)$$

$$\Delta ex_{1-3} = \Delta\psi_{1-3} \cdot \dot{m}_1 \quad (45)$$

The efficiency of the second law in the CR is calculat-ed with Equation 46:

$$\eta_{IICR} = \frac{\Delta ex_{1-3}}{-\Delta ex_{4-5}} \quad (46)$$

Pump control volume

In the pump, points 2 and 3 are water. In this case point 3 shows a pressure greater than point 2 (see Figure 2).

For the exergy in point 3 we have Equation 47:

$$ex_3 = \dot{m}_3 \cdot [(h_3 - h_2) - T_0 \cdot (s_3 - s_2)] \quad (47)$$

For the irreversibility in point 3 we have Equation 48:

$$I_3 = ((h_3 - h_2) \cdot \dot{m}_3) - ex_3 \quad (48)$$

To calculate the efficiency of the second law in the pump, we have Equation 49:

$$\eta_{IIbomba} = \frac{ex_3}{P_{bomba}} \quad (49)$$

Exergy system efficiency

The total efficiency of the second law of thermodynamics is calculated with Equation 50:

$$\eta_{IIbomba} = \frac{P_{turbine} + \Delta ex_{1-3} - P_{pump}}{PCI_{natural\ gas} \cdot \dot{m}_8} \quad (50)$$

3.3. Economic analysis

The economic analysis determines the cost of electricity and steam produced by the cogeneration system. For this analysis, we considered the value of the equipment, maintenance value, the plant's operational costs, tax rates, time of return of the investment, and the cost of the natural gas.

3.3.1. Cost of equipment

According to Castro [16] and Silveira [22] the following equations are applicable to calculate the value of the equipment:

Investment in the gas turbine:

$$I_{TG} = \left(\frac{US\$}{kW} \cdot E_{PTG}\right) \quad (51)$$

Where:
$\frac{\text{US\$}}{\text{kW}} = 234\ \frac{\text{US\$}}{\text{kW}}$ [19]
E_{PTG} = power produced by the turbine (kW)

Investment in the recovery boiler:

$$I_{CR} = 4745 \cdot \left(\frac{h_1}{log(T_5 - T_1)}\right) + 11820 \cdot \dot{m}_1 + 658 \cdot \dot{m}_5 \quad (52)$$

Cost of electric power and steam

To calculate the cost of electricity and steam produced, equations 53 and 54 are used respectively:

$$C_{elec} = \frac{I_{TG} \cdot f}{H \cdot E_{PTG}} + \frac{C_{comb}\left(E_{comb} - E_c - \frac{P_{er}}{2}\right)}{E_p} \cdots + Cm + Co \quad (53)$$

$$C_v = \frac{I_{CR} \cdot f}{H \cdot Q_p} + \frac{C_{comb}\left(E_{comb} - E_c - \frac{P_{er}}{2}\right)}{E_v} \cdots + Cm_{CR} + Co \quad (54)$$

Donde:

C_{comb} = fuel cost $\frac{US\$}{kWh}$
C_{elec} = electricity cost $\frac{US\$}{kWh}$
Cm = maintenance cost of GT $\frac{US\$}{kWh}$
Cm_{CR} = maintenance cost of CR $\frac{US\$}{kWh}$
C_v = Steam production cost $\frac{US\$}{kWh}$
Co = cost of operation staff $\frac{US\$}{kWh}$
E_{comb} = fuel power (kW)
E_p = electricity produced (kWh) $\frac{US\$}{kWh}$
E_v = steam produced (kWh) $\frac{US\$}{kWh}$

For the annuity factor we have Equation 55 and for the value of capital Equation 56:

$$f = \frac{q^k \times (q-1)}{q^k - 1} \tag{55}$$

$$q = 1 + \frac{r}{100} \tag{56}$$

Where:

k = amortization period (years)
r = tipo de interés anual annual interest rate (%)

4. Results and discussion

4.1. Results of thermodynamic analysis

The results of the thermodynamic analysis are shown in Tables 3 and 4. Table 3 shows the energetic and exergetic efficiencies.

Table 3. Energy and exergy efficiencies

Equipment	Energy Efficiency	Exergy Efficiency
Compressor	-	86%
Combustion chamber	-	76%
Gas turbine	39%	79%
Recovery boiler	-	59%
Pump	-	47%
Total efficiency	67%	56%

From Table 3 we can see how the total efficiency of the system (energy) is almost two times higher than the efficiency of the turbine. This is due to the fact that exhaust gases from the gas turbine are used to generate steam (cogeneration).

The works of Castro [16] and Paula Santos et al. [23] show similar technical studies in CC systems where efficiencies greater than 50% were obtained, which corroborates the results of this work.

On the other hand, Table 4 presents the thermodynamic parameters for each point of the co-generation system.

Table 4. Summary of the energy and exergy analysis

#	m kg/s	P kPa	T °C	h kJ/kg	s kJ/kg·K	ex kW
1	50	6860	530	3484	6,9	67871,5
2	50	245	126,8	532,5	2,27	0
3	50	7860	128,1	543,4	1,6	254,44
4	419	94,3	227,9	503	2,31	25020
5	419	94,3	634,6	941,6	2,92	112071
6	419	1462	1208	1612	2,73	417112
7	408	1462	407,5	692,5	1,75	153508
8	8,1	94,3	25	-	-	393611
9	408	94,3	25	298,6	1,69	0

For a better representation of the results in terms of energy, a Sankey diagram is presented in Figure 6. This diagram represents the energy flows from the system input to the system output, as well as the losses of each component.

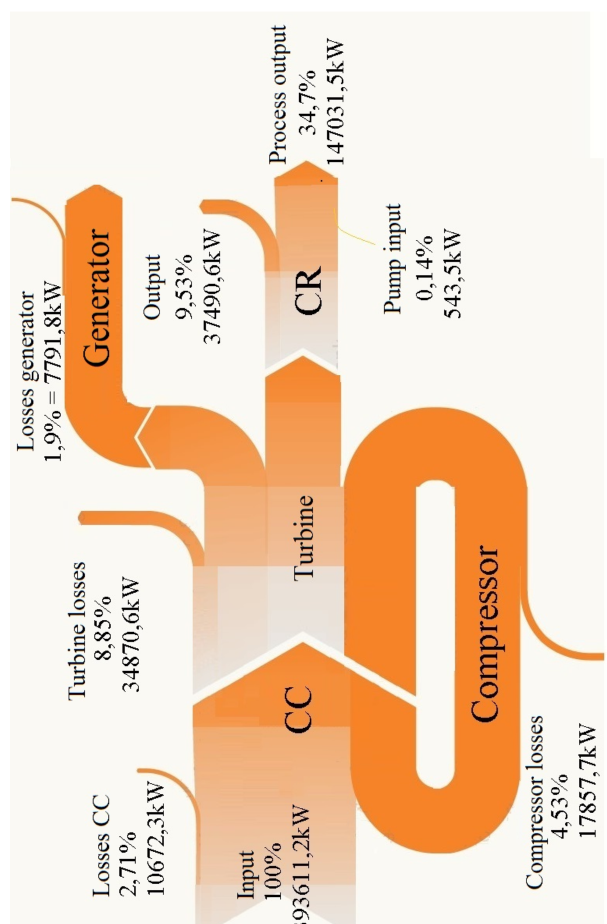

Figure 6. Sankey diagram

In the same way, for the exergy analysis the Grassman diagram is presented in Figure 7.

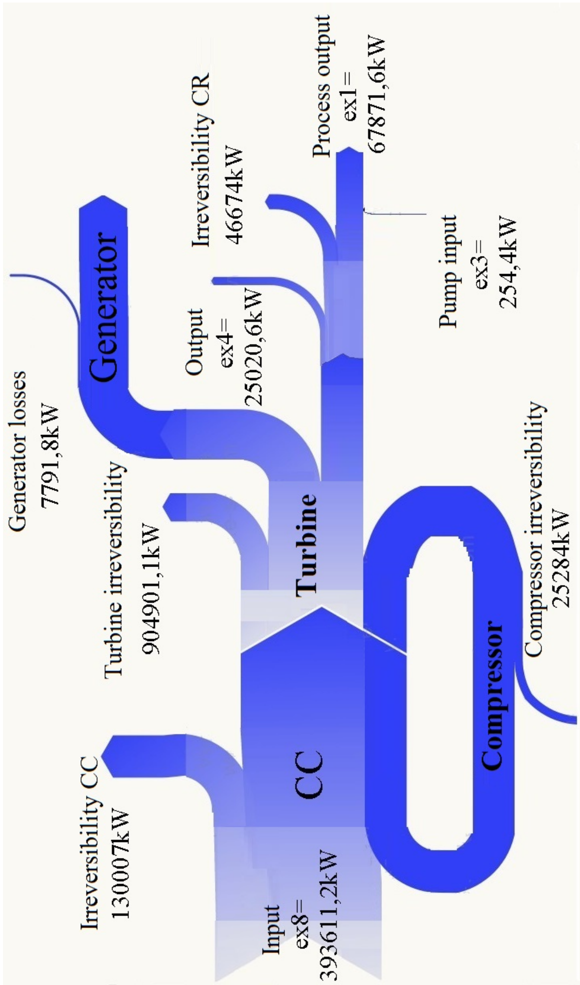

Figure 7. Grassman diagram

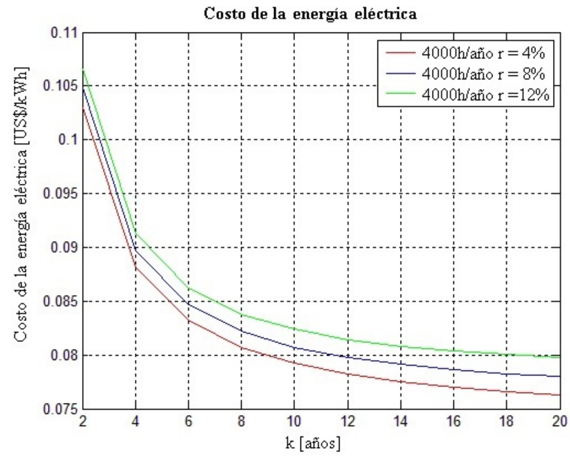

Figure 8. Cost of the electric power produced

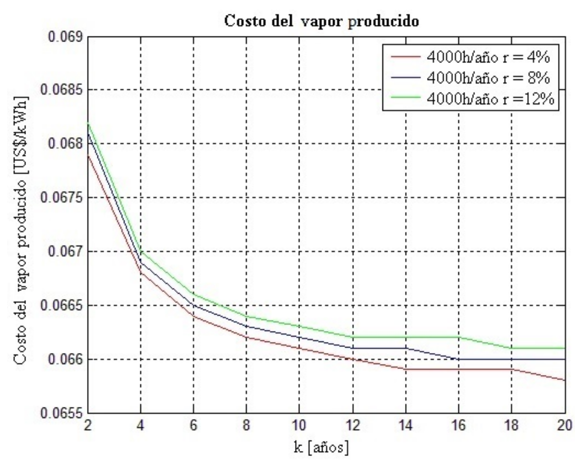

Figure 9. Cost of steam produced

The results of this analysis are the costs of electricity and steam produced by the plant considering a tax rate of 4, 8 and 12% and a repayment period of up to 20 years. It also takes into account that the plant works only 4000 hours, as the intent is to conduct the analy-sis in the most drastic conditions.

On the one hand, Figure 8 presents the cost of the electricity produced.

As can be seen in Figure 8, the highest value (price) of the electricity produced is 0.108 US$/kWh (r = 12%) while the lowest value is 0.103 US$/kWh (r = 4%), which applies when the plant is newly installed.

After 20 years this value is reduced by approximately 30%.

Finally, Figure 9 presents the cost of the steam produced by the process.

In the same way, as observed in Figure 9, the highest price of steam produced is 0.068 2US$/kWh (r = 12%) and the cheapest is 0.0678 US$/kWh (r = 4%) when the plant is newly installed. These values are reduced by approximately 5% after 20 years.

4.2. Discussion of economic analysis

According to the National Electric Energy Agency in Brazil, the sale price of electric energy in 2015 was 191,11 R$/MWh. Considering the exchange rate of dollars to reais in the first quarter of that same year (1 US$ = 2 R$), the price of energy is 0.095 US$/kWh. Thus, the implementation of this system can be considered acceptable since, in addition to producing electricity, steam is being produced. Additionally, this price can be considerably improved if the plant works 7200 h/year and if the bagasse is gasified to produce synthesis gas and replace the use of natural gas. These last two hypotheses are being studied and results will be presented in future publications.

5. Conclusions

In this work, a technical study was carried out based on the first and second law of thermodynamics and the economic study of a cogeneration system. On the one hand, the energy analysis shows that the plant has an output capacity of 148.045 MW and a thermal capacity of 147.031 MW. In addition, this analysis shows that the total efficiency of the system is approx-imately twice as high (67%) as the efficiency of the turbine. This is due to the fact that the turbid exhaust gases are used to generate steam.

On the other hand, the exergy analysis shows that the capacity of electric energy is the same, while the thermal capacity decreases to 67 MW due to irreversibilities. In this case, the total efficiency of the system is 56%. The economic analysis shows that the prices of electricity and steam produced are 0.105 and 0.068 (US$/kWh) when the plant is initially installed; this cost is reduced by 30% in the case of electric energy and 5% in the case of steam after 20 years.

Finally, the dimensioning section leads to conclude that the flow of exhaust gases of the selected turbine at thermal parity revealed to be sufficient to supply the electrical and thermal needs of the cogeneration sys-tem without the need for additional fuel burning.

Continuing with this study, we intend to carry out the thermodynamic analysis of the gasification process of cane bagasse to produce synthesis gas with the objective of replacing the use of natural gas and reducing the cost of energy production.

References

[1] D. Tomofuji, Y. Morimoto, E. Sugiura, T. Ishii, and A. Akisawa, "The prospects of the expanded diffusion of cogeneration to 2030 - Study on new value in cogeneration," *Applied Thermal Engineering*, vol. 114, Supplement C, pp. 1403–1413, 2017. [Online]. Available: https://doi.org/10.1016/j.applthermaleng.2016.09.071

[2] N. M. Isa, C. W. Tan, and A. Yatim, "A comprehensive review of cogeneration system in a microgrid: A perspective from architecture and operating system," *Renewable and Sustainable Energy Reviews*, vol. 81, Part 2, pp. 2236–2263, 2018. [Online]. Available: https://doi.org/10.1016/j.rser.2017.06.034

[3] R. Carapellucci and A. Milazzo, "Repowering combined cycle power plants by a modified STIG configuration," *Energy Conversion and Management*, vol. 48, no. 5, pp. 15 901–1600, 2007. [Online]. Available: https://doi.org/10.1016/j.enconman.2006.11.024

[4] A. Rovira, C. Sánchez, M. Muñoz, M. Valdés, and M. Durán, "Thermoeconomic optimisation of heat recovery steam generators of combined cycle gas turbine power plants considering off-design operation," *Energy Conversion and Management*, vol. 52, no. 4, pp. 1840–1849, 2011. [Online]. Available: https://doi.org/10.1016/j.enconman.2010.11.016

[5] D. Mahto and S. Pal, "Thermodynamics and thermo-economic analysis of simple combined cycle with inlet fogging," *Applied Thermal Engineering*, vol. 51, no. 1, pp. 413–424, 2013. [Online]. Available: https://doi.org/10.1016/j.applthermaleng.2012.09.003

[6] G. Heyen and B. Kalitventzeff, "A comparison of advanced thermal cycles suitable for upgrading existing power plant," *Applied Thermal Engineering*, vol. 19, no. 3, pp. 227–237, 1999. [Online]. Available: https://doi.org/10.1016/S1359-4311(98)00044-1

[7] J. Silveira and C. Tuna, "Thermoeconomic analysis method for optimization of combined heat and power systems. Part I," *Progress in Energy and Combustion Science*, vol. 29, no. 6, pp. 479–485, 2003. [Online]. Available: https://doi.org/10.1016/S0360-1285(03)00041-8

[8] ——, "Thermoeconomic analysis method for optimization of combined heat and power systems–Part II," *Progress in Energy and Combustion Science*, vol. 30, no. 6, pp. 673–678, 2004. [Online]. Available: https://doi.org/10.1016/j.pecs.2003.06.001

[9] M. A. Kordlar and S. Mahmoudi, "Exergeoconomic analysis and optimization of a novel cogeneration system producing power and refrigeration," *Energy Conversion and Management*, vol. 134, Supplement C, pp. 208–220, 2017. [Online]. Available: https://doi.org/10.1016/j.enconman.2016.12.007

[10] M. Gambini and M. Vellini, "High efficiency cogeneration: Electricity from cogeneration in CHP plants," *Energy Procedia*, vol. 81, Supplement C, pp. 430–439, 2015, 69th Conference of the Italian Thermal Engineering Association, ATI 2014. [Online]. Available: https://doi.org/10.1016/j.egypro.2015.12.117

[11] D. Gvozdenac, B. G. Urošević, C. Menke, D. Urošević, and A. Bangviwat, "High efficiency cogeneration: CHP and non-CHP energy," *Energy*, vol. 135, Supplement C, pp. 269–278, 2017. [Online]. Available: https://doi.org/10.1016/j.energy.2017.06.143

[12] B. B. Kanbur, L. Xiang, S. Dubey, F. H. Choo, and F. Duan, "Thermoeconomic assessment of a micro cogeneration system with

LNG cold utilization," *Energy*, vol. 129, Supplement C, pp. 171–184, 2017. [Online]. Available: https://doi.org/10.1016/j.energy.2017.04.071

[13] Z.-G. Sun, "Energy efficiency and economic feasibility analysis of cogeneration system driven by gas engine," *Energy and Buildings*, vol. 40, no. 2, pp. 126–130, 2008. [Online]. Available: https://doi.org/10.1016/j.enbuild.2007.01.013

[14] A. Abusoglu and M. Kanoglu, "Exergetic and thermoeconomic analyses of diesel engine powered cogeneration: Part 1 – Formulations," *Applied Thermal Engineering*, vol. 29, no. 2, pp. 234–241, 2009. [Online]. Available: https://doi.org/10.1016/j.applthermaleng.2008.02.025

[15] R. Passolongo, "Avaliação termodinâmica, termoeconômica e econômica da integração de sistemas de gaseificação da biomassa em uma usina sucroalcooleira," Master's thesis, Universidade Estadual Paulista, Faculdade de Engenharia de Ilha Solteira, 2011. [Online]. Available: https://goo.gl/uj3k4s

[16] I. A. de Castro Villela, "Combined fault detection and classification of internal combustion engine using neural network," Ph.D. dissertation, Universidade Estadual Paulista, Facultade de Engenharia de Guaratinguetá, 2007. [Online]. Available: https://goo.gl/w4hmYA

[17] Y. Çengel and M. Boles, *Termodinámica (8a. ed.):*. McGraw Hill, 2015. [Online]. Available: https://goo.gl/YoY7HE

[18] Uniongas. (2017) Chemical composition of natural gas. [Online]. Available: https://goo.gl/1ME1zf

[19] GTW. (2012) Gasturbine world handbook. Pequet. [Online]. Available: https://goo.gl/SNsJv1

[20] D.-C. Sue and C.-C. Chuang, "Engineering design and exergy analyses for combustion gas turbine based power generation system," *Energy*, vol. 29, no. 8, pp. 1183–1205, 2004. [Online]. Available: https://doi.org/10.1016/j.energy.2004.02.027

[21] Unitrove. (2017) Natural gas calorific value calculator. [Online]. Available: https://goo.gl/rU6Uir

[22] J. L. Silveira, "Cogeração disseminada para pequenos usuarios : estudo de casos para o setor terciario," Ph.D. dissertation, Universidade Estadual de Campinas, Facultade de Engenharia Mecânica, 1994. [Online]. Available: https://goo.gl/oBjSeK

[23] C. F. de Paula Santos, R. F. Silva Paulino, C. E. Tuna, and J. L. Silveira, "Thermodynamics analysis and ecological efficiency of a combined cycle power plant," *Engenharia Térmica*, vol. 13, no. 2, pp. 3–8, 2014. [Online]. Available: https://goo.gl/9Ei1Se