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TECHNICAL AND ECONOMIC ANALYSIS OF A COGENERATION PLANT FOR A BRAZILIAN SCENARIO

Eudes Müller D'Oliveira Santos

Marco Antônio Rosa do Nascimento

Federal University of Itajubá – Campus Professor José Rodrigues Seabra – Av. BPS, 1303, Pinheirinho, Itajubá - MG

eudesmdos@unifei.edu.br

marcoantonio@unifei.edu.br

Abstract. Cogeneration systems are among the most efficient methods to produce mechanical or electrical power as well as thermal energy for industrial and residential applications. An overview of the Brazilian cogeneration sector, highlighting its relevance and a bibliographical review of the literature was introduced. This work evaluated technically and economically the proposal of a thermal cycle representative of the Brazilian cogeneration sector. Since the methodology depends on the price of electricity and fuel, and these parameters vary according to the Brazilian state, this study allowed to identify the Brazilian state that presents better investment for a typical cogeneration plant. A sensitivity analysis was presented. It is intended that the tool that was presented in this work serve as guidance for studies and research in the cogeneration sector, at least in the first phase of a project.

Keywords: Cogeneration, technical analysis and economic analysis.

1. INTRODUCTION

The data presented below were extracted from the Generation Information Bank (BIG), consulted on August 10, 2017. Data refer to the installations that comply with the regulatory resolution N° 235 of November 14, 2006, in the case of cogeneration qualified. Brazil has 99 thermoelectric plants with qualified cogeneration, 94 in operation, 2 under construction and 3 with construction not started, according to Figure 1. In a new consultation in August 2018, of the 5 plants under construction or with construction not started, 1 plant was under construction.

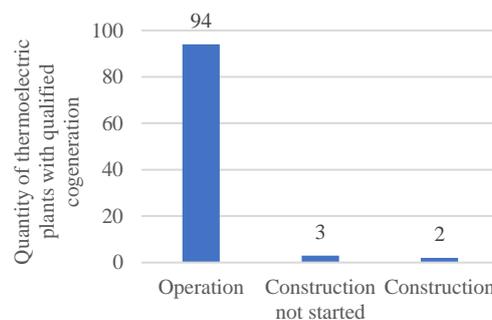


Figure 1. Number of thermoelectric plants with qualified cogeneration.

The power of the plants in operation was 4220556 kW (representing 99.583% of the total), of the plants under construction it was 8782 kW (representing 0.207% of the total) and plants with uninitiated construction it was 8900 kW (representing 0.210% of the total), totaling 4238238 kW (100%), according to Figure 2. In August 2018, with the completion of four plants, the power of the plants in operation was increased to 4236813 kW (representing 99.81% of the total) and of the plants under construction it was 7902 kW (representing 0.19% of the total), totaling 4244715 kW (100%).

The plants under construction are in the states of São Paulo and Rondônia, with a power of 7902 kW and 880 kW respectively. The fuel used in São Paulo will be natural gas and in Rondônia the diesel oil. In August 2018, the only plant under construction is the one from the state of São Paulo.

The plants with uninitiated construction will be in the states of Rio Grande do Sul, Santa Catarina and Rio de Janeiro, with a power of 4600 kW, 3000 kW and 1300 kW, respectively. Natural gas will be used in all three plants. In August of 2018, no plant found with uninitiated construction was found.

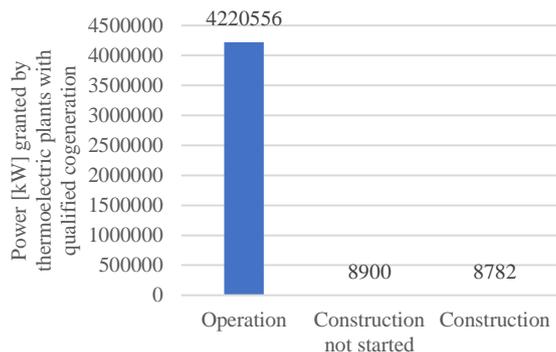


Figure 2. Power granted by thermoelectric plants with qualified cogeneration.

The first plant in operation was registered in 1954 and the last plant was put into operation in may 2018. Many plants were seen to be operational in 2002 and 2004. The evolution of the plants' can be verified in Figure 3.

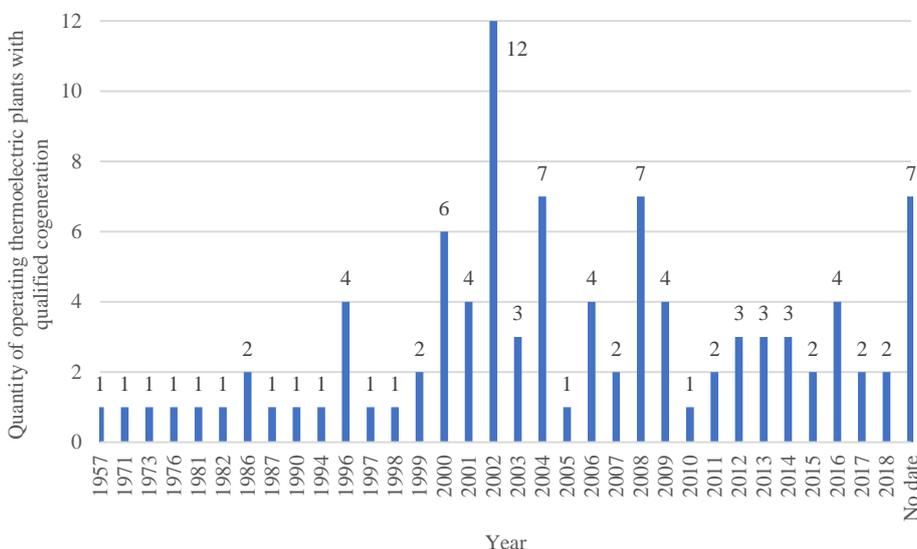


Figure 3. Quantity of operating thermoelectric plants with qualified cogeneration per year.

The plants in operation are distributed among 15 states of the national territory, being the largest concentration in the state of São Paulo, followed by Rio de Janeiro, Minas Gerais and Bahia. The distribution of plants by state can be verified in Figure 4. In August 2018, the states of Bahia, Rio de Janeiro, Rio Grande do Sul, Rondônia and Santa Catarina contained one more plant each. Thus, the plants in operation were distributed in 16 states. One less plant was registered in the state of Ceará.

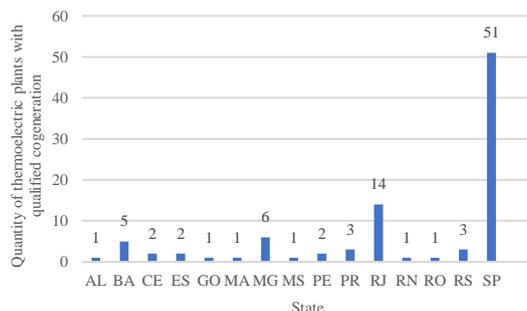


Figure 4. Quantity of thermoelectric plants with qualified cogeneration by state.

The plants in operation use 10 different types of fuel, the most common being natural gas, followed by sugarcane bagasse and diesel oil. The amount of plants in operation according to the type of fuel used can be seen in Figure 5. In August 2018, the number of plants supplied with natural gas increased to 55 and with diesel oil increased to 11.

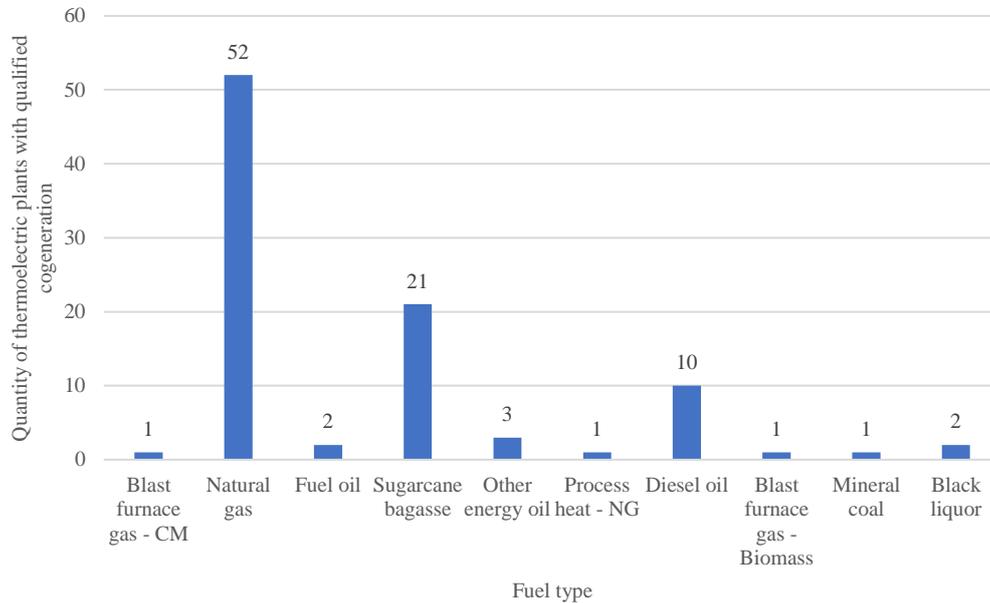


Figure 5. Quantity of thermoelectric plants with qualified cogeneration by type of fuel.

The column chart in Figure 6, obtained from the Association of the Energy Cogeneration Industry (COGEN), shows the evolution of the installed capacity of cogeneration in Brazil from 1980 to 2016 and the increase of capacity in each time interval analyzed. In December 2016, the installed capacity reached 16 MW, due to an increase of 6736 MW in the last 16 years, an increase of 72% compared to the values of 2010. The pie chart in Figure 6 shows the 16 MW portion according to the fuel used as source in the cogeneration plant. The three main fuels, representing 96% of the installed capacity, are bagasse of sugar cane, natural gas and black liquor.

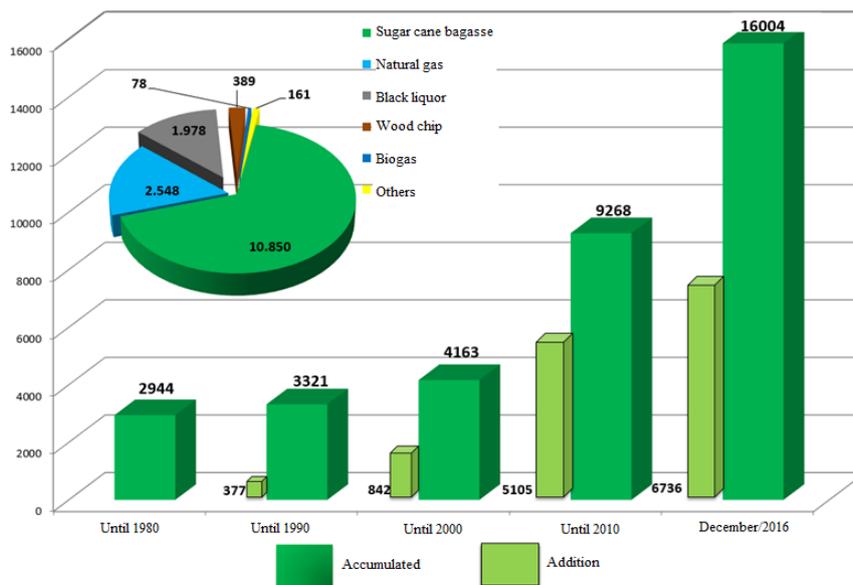


Figure 6. Evolution of cogeneration in Brazil.

In 2017 was celebrated the 30 years of biomass cogeneration in Brazil. The energy cogeneration from sugarcane biomass in the sugar and ethanol plants, with surplus distribution to the interconnected grid of the National Electric System

Operator (ONS), represents approximately 7% of the Brazilian matrix. Generally, biomass represents 9% of the installed capacity (14512 MW), according to the National Electric Energy Agency (Aneel). Cane bioelectricity has the potential to represent 24% of national consumption by 2024.

According to the Energy Research Company (EPE), 212 of the 378 sugarcane biomass operating plants in the country did not commercialize electricity in 2016. The modernization of these plants to take advantage of bagasse, sugar cane straw and biogas of the vinasse, could provide a bioelectricity generation of up to 6 times the current supply, from 21.2 TWh to 128.8 TWh.

Figure 7 shows the evolution of bioelectricity generation in the last 12 years. We can observe the constant growth in the analyzed period, highlighting the growth of 2007 in relation to 2006 and of 2010 in relation to 2009 as the largest in percentage in the analyzed period. There is a constant growth of 5% in 2015 and 2016.

The paragraphs above showed an overview of the Brazilian cogeneration sector, highlighting its relevance and justifying the commitment of research in the sector.



Figure 7. Evolution of the Brazilian bioelectricity generation.

Next, a review of the literature on analysis of cogeneration systems is presented. Coronado et al. (2007) presented an analysis of cogeneration systems applied to a pulp and paper industry. Showed some technical characteristics of the operation, as well as the technical-economical analysis of the proposed systems and the feasibility of the implementation comparing a system with two backpressure turbines and another with a condensing turbine, according to the sale price of surplus electricity. Arteaga (2010) evaluated a cogeneration system with an internal combustion engine with natural gas using the general demands of the Hospital of UNICAMP. Computer programs were used in the evaluation of the cogeneration system, with the definition of parameters and thermodynamic relationships for a given project and annual operating condition. The performance of the cogeneration system for a year of operation was analyzed through eight sets of demand profiles (weather seasons, weekdays and weekends). The energy analysis of the cogeneration system made it possible to visualize the energy savings using this technology, while the exergetic analysis identified in a qualitative and quantitative way the component that can be optimized to improve the performance of the cogeneration system. Andreos (2013) analyzed the technical and economic feasibility of small natural gas cogeneration plants in the tertiary sector of the state of São Paulo. The analyzes evaluated the energy utilization factor, initial investments, cash flow, return on investments, internal rate of return and net present value. Were evaluated the technologies of, internal combustion engine, microturbine, liquid cooler by absorption and electric liquid cooler. The results showed a reversal in the financial viability of cogeneration, mainly related to the cost of fuel. Balli et al. (2010) made thermodynamic and thermoeconomic analyzes of a trigeneration system with gas-diesel engine of power of 6.5 MW. Was applied the specific exergy costing method based on actual operational data. The specific unit exergetic cost of the net electrical power, heat energy 1, heat energy 2 and chilled water produced by the trigeneration system were 45.94 US\$/GJ, 29.98 US\$/GJ, 42.42 US\$/GJ and 167.52 US\$/GJ, respectively. Moussawi et al. (2017) revised the principles and benefits of cogeneration systems, in addition to their different classifications, and basics differences in various prime movers technologies. The authors suggested in order to make a choice regarding the installation of multi-generation systems depending on specific measures and case study conditions.

2. METHODOLOGY

The methodology applied in this work is adapted from Coronado et al. (2011). In the discipline Special Topics I Cogeneration - Fundamentals, technical and economic aspects of the Postgraduate Program in Mechanical Engineering of the Federal University of Itajubá, the methodology found in Coronado et al. (2007) was applied to carry out a technical and economic analysis of a typical plant of the pulp and paper sector. These two works evaluate a cogeneration plant,

each one with a type of technology. The principles adopted in the analyzes are similar, being the differences due to the characteristics of the technology adopted. From the study of these two works, the development of this article arose. Thus, the methodology adapted was applied to a representative configuration of the brazilian cogeneration sector to technically and economically analyze it.

The cogeneration plant selected for analysis, shown in Figure 8, was obtained in Santo and Gallo (2017). The trigeneration system is suitable for obtaining electricity, hot water and ice water (air conditioning). The cogeneration system is formed by one internal combustion engine, primary and secondary hot water circuits, one exhaust gas heat exchanger (EGHE), one hot water single stage absorption chiller, and auxiliary equipment (pumps, cooling towers and heat exchangers). The secondary circuit recovers energy from the engine oil radiator and intercoolers and uses it to warm water for sanitary purposes at heat exchanger 2 (HE₂). The primary circuit recovers energy from the engine jacket, the water is reheated at the EGHE utilizing the energy of the engine exhaust gases, after it is directed to the absorption chiller for chilled water production. Primary circuit energy that is not recovered in the absorption chiller is used to warm water for sanitary purposes at heat exchanger 1 (HE₁) after recovery at secondary circuit. The natural gas composition of 90% CH₄, 8% C₂H₆ and 2% C₃H₈, and LHV of 45462 kJ/kg it was assumed (Santo and Gallo, 2017). The fluid type, flow rate, temperature and pressure data from points 1 to 19 shown in Figure 8 are shown in Table 1. This work was selected because it presents a more representative cogeneration cycle of the last ten cogeneration plants registered as qualified cogeneration between 2015 and 2018. They are plants with a maximum power of 4000 kW, where the use of internal combustion engine is the most indicated.

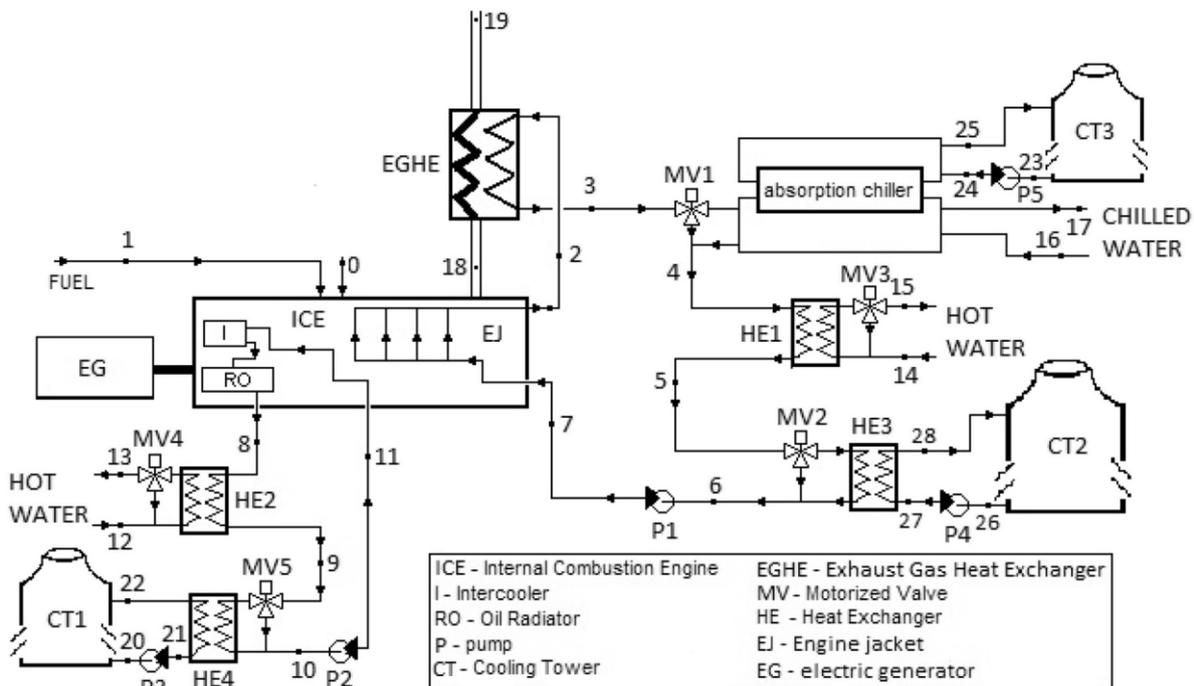


Figure 8. Cogeneration plant.

The technical analysis consisted in applying the energy balance for the evaluated cycle. First was calculated the power of the fuel (E_{Fuel}), the power of the hot water 1 and 2 (E_{HW1} and E_{HW2}) and the power of the cold water (E_{CW}), respectively by Eqs. (1) - (4).

$$E_{Fuel} = m_1 \cdot LHV_{Fuel} \quad (1)$$

$$E_{HW1} = m_{14} \cdot C_{P,Water} \cdot (T_{15} - T_{14}) \quad (2)$$

$$E_{HW2} = m_{12} \cdot C_{P,Water} \cdot (T_{13} - T_{12}) \quad (3)$$

$$E_{CW} = m_{16} \cdot C_{P,Water} \cdot (T_{16} - T_{17}) \quad (4)$$

Where m is the mass flow rate, LHV_{Fuel} is the lower heating value of the fuel, $C_{P,Water}$ is the specific heat at constant pressure of the water and T is the temperature. The subscripts 1, 12, 13, 14, 15, 16 and 17 indicate the point of the cogeneration system. The value used for the specific heat at constant pressure of the water was 4.1860 kJ/(kg.K).

Table 1. Thermodynamic properties.

Point	Fluid type	Flow rate [kg/s]	Temperature [°C]	Pressure [kPa]
0	Air	1.544	25.00	100
1	Fuel	0.05977	25.00	100
2	Primary circuit water	5.704	90.00	525
3	Primary circuit water	5.704	114.89	450
4	Primary circuit water	5.704	76.30	400
5	Primary circuit water	5.704	74.96	350
6	Primary circuit water	5.704	74.96	350
7	Primary circuit water	5.704	75.00	600
8	Secondary circuit water	4.035	55.00	250
9	Secondary circuit water	4.035	34.94	200
10	Secondary circuit water	4.035	34.94	200
11	Secondary circuit water	4.035	35.00	400
12	Hot water	3.186	22.20	310
13	Hot water	3.186	47.60	260
14	Hot water	3.186	47.60	260
15	Hot water	3.186	50.00	210
16	Chilled water	31,50000	12,70	300
17	Chilled water	31,50000	7,20	250
18	Exhaust gases	1,60400	487,00	102
19	Exhaust gases	1,60400	113,70	100

After calculating the power, the efficiencies for generation of electricity (η_{GE}), hot water 1 and 2 (η_{GHW}), cold water (η_{GCW}) and global efficiency (η_{Global}) were calculated, respectively by Eqs. (5) - (8).

$$\eta_{GE} = \frac{E_P}{E_{Fuel}} \quad (5)$$

Where E_P is the power produced by the engine. Its value is 1028.2 kW.

$$\eta_{GHW} = \frac{E_{HW1} + E_{HW2}}{E_{Fuel}} \quad (6)$$

$$\eta_{GCW} = \frac{E_{CW}}{E_{Fuel}} \quad (7)$$

$$\eta_{Global} = \frac{E_P + E_{HW1} + E_{HW2} + E_{CW}}{E_{Fuel}} \quad (8)$$

To calculate the efficiency of the absorption chiller (η_{AC}) it is necessary to calculate the energy of the exhaust gases (E_{EG}) and the energy of the water of the jacket (E_{WJack}) by Eqs. (9) and (10). Subtracting from the sum of these two parts the value of the power of the hot water 1, it is obtained the energy of the water supplied to the absorption chiller (E_{WAC}). Finally, the efficiency of the absorption chiller is calculated by Eq. (11).

$$E_{EG} = m_{18} \cdot C_{P,EG} \cdot (T_{18} - T_{19}) \quad (9)$$

$$E_{WJack} = m_2 \cdot C_{P,Water} \cdot (T_2 - T_7) \quad (10)$$

$$\eta_{AC} = \frac{E_{CW}}{E_{WAC}} \quad (11)$$

Where, $C_{P,EG}$ is the specific heat at constant pressure of the exhaust gases. The values used for the specific heat at constant pressure of the exhaust gases at the temperatures T_{18} and T_{19} , respectively, was 1.0227 kJ/(kg.K) and 1,0517 kJ/(kg.K). The subscripts 2, 7, 18 and 19 indicate the point of the cogeneration system.

For the economic analysis, the technique found in Boehm (1987) was used. According to Eq. (12), from a known investment value (I_{ref}), for a given capacity (S_{ref}), it is possible to determine the investment value (I) for the desired capacity (S). The cost of reference investment, reference power and incidence factor (m) are shown in Table 2.

$$I = I_{ref} \cdot \left(\frac{S}{S_{ref}} \right)^m \quad (12)$$

Table 2. Data to apply the Boehm technique.

Reference engine investment cost	$I_{Engine(ref)}$	US\$1200000.00
Reference exhaust gases heat exchanger investment cost	$I_{HEGE(ref)}$	US\$950.00
Reference heat exchanger 1	$I_{HE1(ref)}$	US\$3000.00
Reference heat exchanger 2	$I_{HE2(ref)}$	US\$950.00
Reference absorption chiller investment cost	$I_{AC(ref)}$	US\$160000.00
Reference engine power	$S_{Engine(ref)}$	4038 kW
Reference exhaust gases heat exchanger power	$S_{HEGE(ref)}$	1 kW
Reference heat exchanger 1 power	$S_{HE1(ref)}$	10 kW
Reference heat exchanger 2 power	$S_{HE2(ref)}$	1 kW
Reference absorption chiller	$S_{AC(ref)}$	500 TR
Engine incidence factor	m_{Engine}	0.83
Exhaust gases heat exchanger incidence factor	m_{HEGE}	0.45
Heat exchanger 1 incidence factor	m_{HE1}	0.55
Heat exchanger 2 incidence factor	m_{HE2}	0.45
Absorption chiller incidence factor	m_{AC}	0.66

Once the price of the investment to purchase the equipment that make up the plant is determined, the costs to generate the electricity (C_{El}), hot water (C_{HW1} and C_{HW2}) and cold water (C_{CW}) are calculated by the Eqs. (13) - (16).

$$C_{El} = \frac{I_{Engine} \cdot f}{H \cdot E_P} + \frac{C_{Fuel} \cdot FP_E}{E_P} + CM_{Engine} \quad (13)$$

$$C_{HW1} = \frac{I_{HE1} \cdot f}{H \cdot E_{HW1}} + \frac{C_{Fuel} \cdot FP_{HW1}}{E_{HW1}} + CM_{HE1} \quad (14)$$

$$C_{HW2} = \frac{I_{HE2} \cdot f}{H \cdot E_{HW2}} + \frac{C_{Fuel} \cdot FP_{HW2}}{E_{HW2}} + CM_{HE2} \quad (15)$$

$$C_{CW} = \frac{I_{AC} \cdot f}{H \cdot E_{CW}} + \frac{C_{Fuel} \cdot FP_{CW}}{E_{CW}} + CM_{AC} \quad (16)$$

Where f is the annuity factor, determined by Eq. (17); H is the number of hours of operation per year; C_{Fuel} is the fuel price; FP_E , FP_{HW1} , FP_{HW2} and FP_{CW} are the weighting factor of energy produced, hot water 1 and 2 and cold water, respectively determined by Eqs. (19) - (22); and CM is the maintenance cost.

$$f = \frac{q^k \cdot (q - 1)}{(q^k - 1)} \quad (17)$$

Where q is determined by Eq. (18) and k is the amortization period time, analyzed from 1 to 20 years.

$$q = 1 + \frac{r}{100} \quad (18)$$

Where r is the annual interest rate. The analyzes were made for annual interest rates of 6%, 8%, 10%, 12% and 14%.

$$FP_E = \frac{E_P}{E_P + E_{HW1} + E_{HW2} + E_{CW}} \quad (19)$$

$$FP_{HW1} = \frac{E_{HW1}}{E_P + E_{HW1} + E_{HW2} + E_{CW}} \quad (20)$$

$$FP_{HW2} = \frac{E_{HW2}}{E_P + E_{HW1} + E_{HW2} + E_{CW}} \quad (21)$$

$$FP_{CW} = \frac{E_{CW}}{E_P + E_{HW1} + E_{HW2} + E_{CW}} \quad (22)$$

In the cost of hot water 1, the contribution of the exhaust gas heat exchanger to the generation of hot water 1 was calculated and 3.36% of the value of exhaust gases heat exchanger investment and maintenance cost was added to the heat exchanger 1 investment and maintenance cost. The same analysis was made for the cost of cold water and 96.64% was the contribution of the exhaust gas heat exchanger.

The value of the cost of maintenance of the engine, heat exchangers and absorption chiller are respectively, 0,010 \$/kWh, 0,003 \$/kWh and 0,008 \$/kWh (Coronado, 2011).

The maximum number of hours operation in the year (H_{Max}) is 8640 h/year. Three operating scenarios were analyzed, 25%, 50% and 75% of the maximum time, respectively 2160, 4320 and 6480 h/year.

As the state of São Paulo has the most qualified cogeneration facilities, the price of fuel marketed by a company in the state was adopted. For an operation of 25% of the maximum time, the gas consumption falls within a range different from that to 50% and 75%, resulting in a different value for the fuel. For operation of 2160 h/year, the fuel price is 0.039060 US\$/kWh and for operation of 4320 and 6480 h/year, the fuel price is 0.036560 US\$/kWh (COMGAS). Four scenarios for the price of fuel were considered, 15% and 30%, more expensive and cheaper. The values can be observed in Table 3.

Table 3. Fuel price.

	2160 h/year	4320 and 6480h/year
30% cheaper	0.027342US\$/kWh	0.025592 US\$/kWh
15% cheaper	0.033201 US\$/kWh	0.031076 US\$/kWh
Reference price	0.039060 US\$/kWh	0.036560 US\$/kWh
15% more expensive	0.044919 US\$/kWh	0.042043 US\$/kWh
30% more expensive	0.050778 US\$/kWh	0.047527 US\$/kWh

3. RESULTS

The results of the powers and the generation efficiencies are shown in the Table 4 and it is in agreement with Gallo (2017).

Table 4. Results of the powers and the generation efficiencies.

Power of the fuel	E_{Fuel}	2717.2637 kW	Generation efficiency of electricity	η_{GE}	37.8396%
Power of the hot water 1	E_{HW1}	32.0078 kW	Generation efficiency of hot water	η_{GHW}	13.6445%
Power of the hot water 2	E_{HW2}	338.7495 kW	Generation efficiency of cold water	η_{GCW}	26.6895%
Power of the cold water	E_{CW}	725.2245 kW	Global efficiency	η_{Global}	78.1736%

The results of the energy to analyze the absorption chiller are shown in the Table 5.

Table 5. Results of the energy to analyze the absorption chiller.

Energy of the exhaust gases	E_{EG}	594.3080 kW
Energy of the water of the jacket	E_{WJack}	358.1542 kW
Energy of the water supplied to the chiller of absorption	E_{WAC}	920.4543 kW
Efficiency of absorption chiller	η_{AC}	0.7879

The costs of investments are shown in Table 6.

Table 6. Results of the cost of investment.

Engine investment cost	I_{Engine}	US\$385556.13
Exhaust gases heat exchanger investment cost	I_{EGHE}	US\$16827.86
Heat exchanger 1 investment cost	I_{HE1}	US\$5688.69
Heat exchanger 2 investment cost	I_{HE2}	US\$13066.79
Absorption chiller investment cost	I_{AC}	US\$164195.78

The products of the cogeneration system are electricity, hot water 1 and 2 and cold water. The highest cost is that of electricity, followed by cold water, hot water 1 and 2. A variation in the price of fuel will cause a greater variation in the cost of hot water 2, followed by hot water 1, cold water and electricity. This trend is observed regardless of the amortization period, interest rate, operating time, fuel cost and electricity price. Table 7 shows the cost values at an analyzed point where this behavior can be verified.

Table 7. Cost of products for operation of 4320 h/year, 1 year amortization period and 6% interest rate.

	Fuel at a reference price	Fuel 15% more expensive	Variation
Cost of electricity	0.148777 US\$/kWh	0.155792 US\$/kWh	4.7152%
Cost of hot water 1	0.097812 US\$/kWh	0.104827 US\$/kWh	7.1720%
Cost of hot water 2	0.059232 US\$/kWh	0.066247 US\$/kWh	11.8434%
Cost of cold water	0.118722 US\$/kWh	0.125737 US\$/kWh	5.9088%

For an operation of 2160 hours per year, the 30% variation in fuel price results in the total cost a minimum variation of 8.8230% for a 1 year amortization period and 14% interest rate, from 0.679581 US\$/kWh to 0.619621 US\$/kWh for a cheaper fuel and to 0.739540 US\$/kWh for a more expensive fuel. A maximum variation of 22.9301% for amortization period of 20 years and 6% interest rate is resulted, from 0.261487 US\$/kWh to 0.201527 US\$/kWh for a cheaper fuel and for 0.321446 US\$/kWh for a more expensive fuel. The 15% variation in fuel price results in the total cost a minimum variation of 4.4115% for a 1 year amortization period and 14% interest rate, from 0.679581 US\$/kWh to 0.649601 US\$/kWh for a cheaper fuel and to 0.709560 US\$/kWh for a more expensive fuel. A maximum variation of 11.4651% for amortization period of 20 years and 6% interest rate, from 0.261487 US\$/kWh to 0.231507 US\$/kWh for a cheaper fuel and for 0.291466 US\$/kWh for a more expensive fuel.

For an operation of 4320 hours per year, the 30% variation in fuel price results in the total cost a minimum variation of 12.7423% for a 1 year amortization period and 14% interest rate, from 0.440427 US\$/kWh to 0.384306 US\$/kWh for a cheaper fuel and to 0.496548 US\$/kWh for a more expensive fuel. A maximum variation of 24.2547% for amortization period of 20 years and 6% interest rate, from 0.231380 US\$/kWh to 0.175259 US\$/kWh for a cheaper fuel and for 0.287501 US\$/kWh for a more expensive fuel. The 15% variation in fuel price results in the total cost a minimum variation of 6.3712% for a 1 year amortization period and 14% interest rate, from 0.440427 US\$/kWh to 0.412367 US\$/kWh for a cheaper fuel and to 0.468487 US\$/kWh for a more expensive fuel. A maximum variation of 12.1274% for amortization period of 20 years and 6% interest rate, from 0.231380 US\$/kWh to 0.203320 US\$/kWh for a cheaper fuel and for 0.259440 US\$/kWh for a more expensive fuel.

For an operation of 6480 hours per year, the 30% variation in fuel price results in the total cost a minimum variation of 15.3766% for a 1 year amortization period and 14% interest rate, from 0.364974 US\$/kWh to 0.308854 US\$/kWh for a cheaper fuel and to 0.421095 US\$/kWh for a more expensive fuel. A maximum variation of 24.8751% for amortization period of 20 years and 6% interest rate, from 0.225610 US\$/kWh to 0.169489 US\$/kWh for a cheaper fuel and for 0.281730 US\$/kWh for a more expensive fuel. The 15% variation in fuel price results in the total cost a minimum variation of 7.6883% for a 1 year amortization period and 14% interest rate, from 0.364974 US\$/kWh to 0.336914 US\$/kWh for a cheaper fuel and to 0.393035 US\$/kWh for a more expensive fuel. A maximum variation of 12.4375% for amortization period of 20 years and 6% interest rate, from 0.225610 US\$/kWh to 0.197549 US\$/kWh for a cheaper fuel and for 0.253670 US\$/kWh for a more expensive fuel.

As many results were generated and qualitatively the behavior is the same, the operating time of 6480 h/year was selected in 1, 5, 10, 15 and 20 years amortization periods to show comparisons of product cost values. Figure 9 shows the comparison of the cost of electricity for fuel in the reference price and 30% cheaper. Figure 10 shows the comparison of the cost of hot water for fuel in the reference price and 15% more expensive. Figure 11 shows the comparison of the cost of cold water for fuel in the reference price and 30% more expensive. It is worth mentioning that significant reductions in cost in relation to the previous period occur approximately until the fifth year, as can be observed in Figure 9 - Figure 11, where the difference from the fifth to the twentieth year is much smaller in relation to the difference of the first to the fifth year.

Analyzing the influence of operating time in the total cost, when it changes from 2160 to 4320 hours per year, a maximum variation of 37.9772% (32.8572%) is obtained for a 1 year amortization period and a 14% interest rate, of 0.619621 US\$/kWh (0.739540 US\$/kWh) to 0.384306 US\$/kWh (0.496548 US\$/kWh) for 30% cheaper fuel (30% more expensive). A minimum variation of 13.0345% (10.5602%) is obtained for a 20-year amortization period and a 6% interest rate, of 0.201527 US\$/kWh (0.321446 US\$/kWh) to 0.175259 US\$/kWh (0.287501 US\$/kWh). For a 15% cheaper fuel (15% more expensive), the maximum variation obtained is 36.5200% (33.9750%) for a 1 year amortization period and a 14% interest rate, from 0.649601 US\$/kWh (0.709560 US\$/kWh) to 0.412367 US\$/kWh (0.468487 US\$/kWh). The minimum variation obtained is 12.1756% (10.9879%) for a 20-year amortization period and a 6% interest rate, from 0.231507 US\$/kWh (0.291466 US\$/kWh) to 0.203320 US\$/kWh (0.259440 US\$/kWh). For the reference price, the maximum variation was 35.1914% for a 1 year amortization period and a 14% interest rate, from 0.679581 US\$/kWh to

0.440427 US\$/kWh, and the minimum variation was 11.5136% for a 20-year amortization period and a interest of 6%, from 0.261487 US\$/kWh to 0.231380 US\$/kWh.

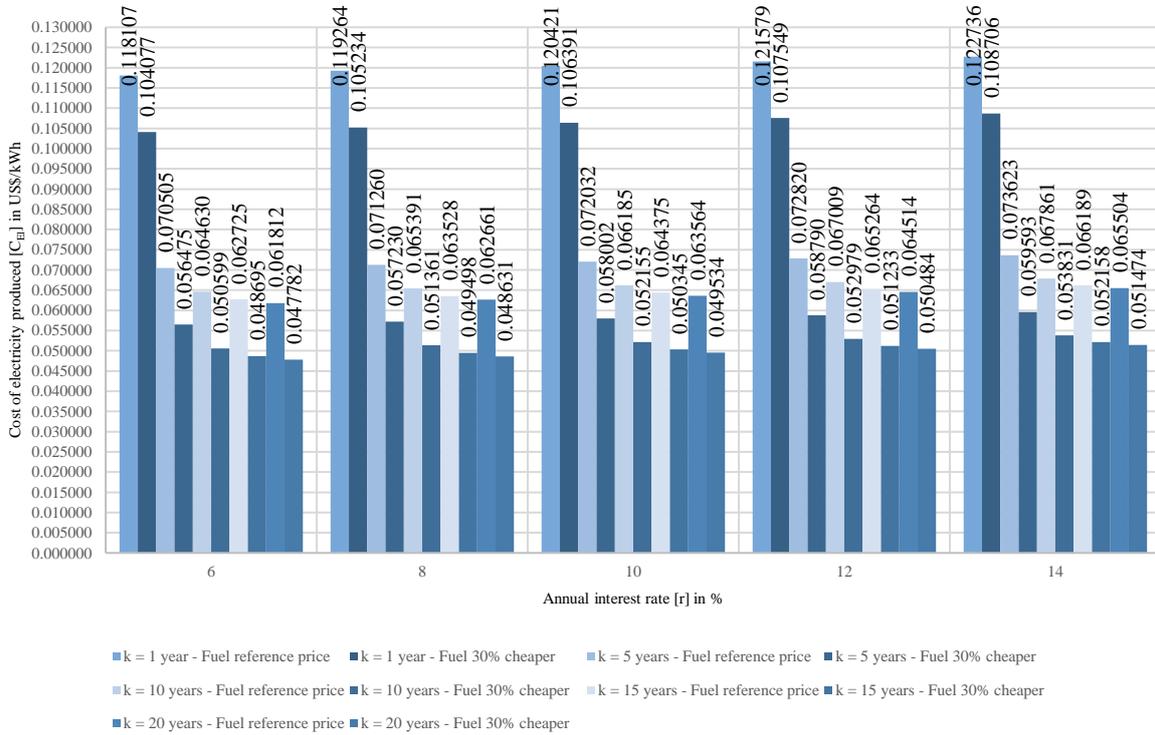


Figure 9. Comparison of the cost of electricity.

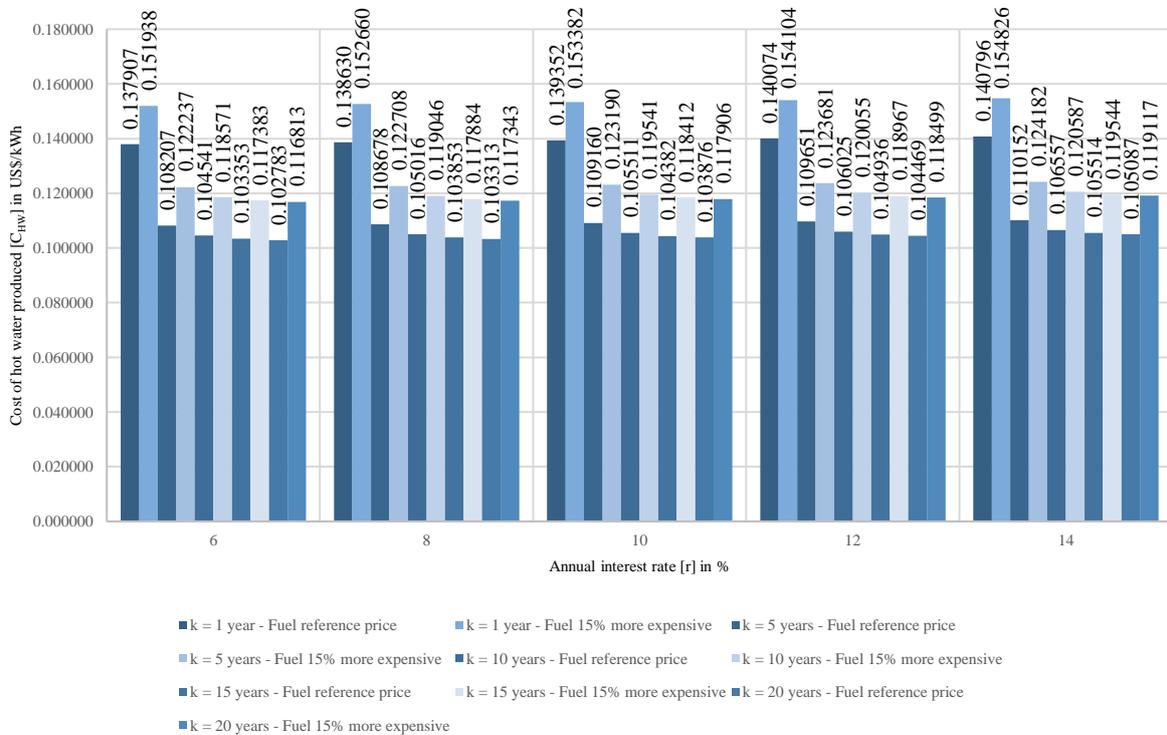


Figure 10. Comparison of the cost of hot water.

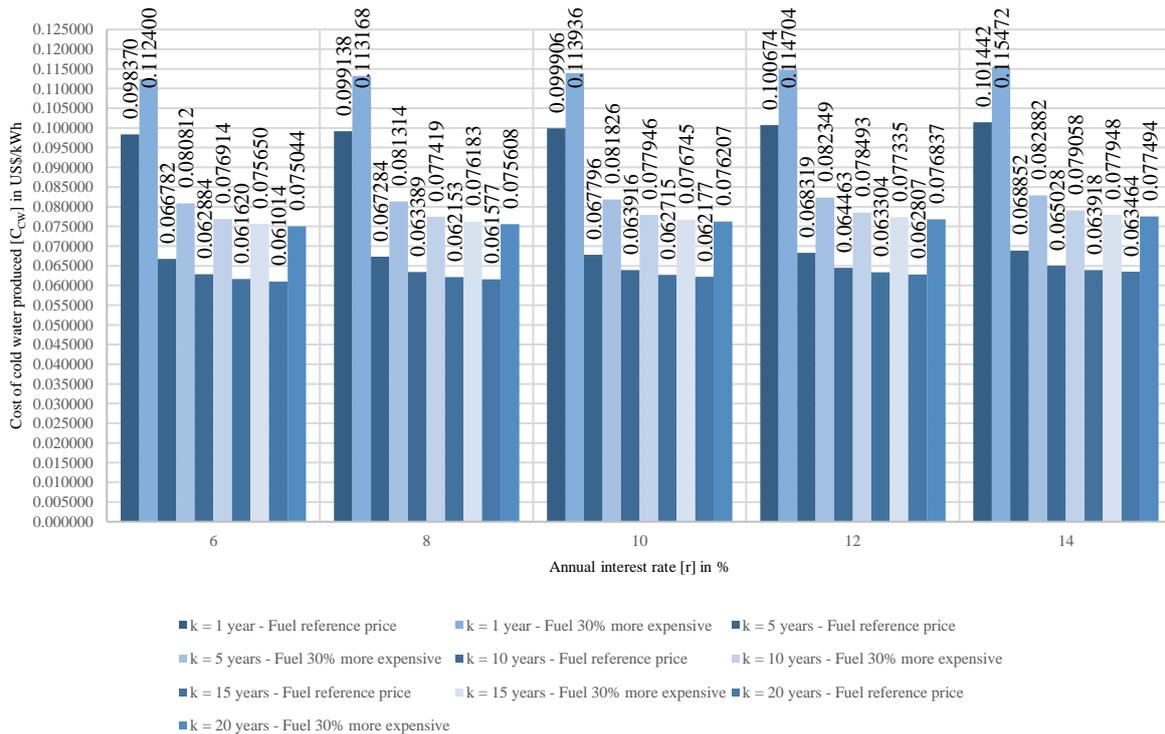


Figure 11. Comparison of the cost of cold water.

When we analyze the operation in 6480 compared to 2160 hours per year, a maximum variation in the total cost of 50.1545% (43.0599%) is obtained for a 1 year amortization period and a 14% interest rate, of 0.619621 US\$/kWh (0.739540 US\$/kWh) to 0.308854 US\$/kWh (0.421095 US\$/kWh). A minimum variation of 15.8978% (12.3553%) is obtained for a 20-year amortization period and a 6% interest rate, of 0.201527 US\$/kWh (0.321446 US\$/kWh) to 0.169489 US\$/kWh (0.281730 US\$/kWh), for 30% cheaper fuel (30% more expensive). For a 15% cheaper fuel (15% more expensive), the maximum variation obtained is 48.1353% (44.6087%) for a 1 year amortization period and a 14% interest rate, from 0.649601 US\$/kWh (0.709560 US\$/kWh) to 0.336914 US\$/kWh (0.393035 US\$/kWh). The minimum variation obtained is 14.6681% (12.9677%) for a 20-year amortization period and a 6% interest rate, from 0.231507 US\$/kWh (0.291466 US\$/kWh) to 0.199491 US\$/kWh (0.253670 US\$/kWh). For the reference price, the maximum variation was 46.2942% for a 1 year amortization period and a 14% interest rate, from 0.679581 US\$/kWh to 0.364974 US\$/kWh, and the minimum variation was 13.7204% for a 20-year amortization period and a interest of 6%, from 0.261487 US\$/kWh to 0.225610 US\$/kWh.

When we analyze the operation in 6480 compared to 4320 hours per year, a maximum variation in the total cost of 19.6335% (15.1955%) is obtained for a 1 year amortization period and a 14% interest rate, of 0.384306 US\$/kWh (0.496548 US\$/kWh) to 0.308854 US\$/kWh (0.421095 US\$/kWh). A minimum variation of 3.2925% (2.0071%) is obtained for a 20-year amortization period and a 6% interest rate, of 0.175259 US\$/kWh (0.287501 US\$/kWh) to 0.169489 US\$/kWh (0.281730 US\$/kWh), for 30% cheaper fuel (30% more expensive). For a 15% cheaper fuel (15% more expensive), the maximum variation obtained is 18.2975% (16.1056%) for a 1 year amortization period and a 14% interest rate, from 0.412367 US\$/kWh (0.468487 US\$/kWh) to 0.336914 US\$/kWh (0.393035 US\$/kWh). The minimum variation obtained is 2.8381% (2.2242%) for a 20-year amortization period and a 6% interest rate, from 0.203320 US\$/kWh (0.259440 US\$/kWh) to 0.197549 US\$/kWh (0.253670 US\$/kWh). For the reference price, the maximum variation was 17.1317% for a 1 year amortization period and a 14% interest rate, from 0.440427 US\$/kWh to 0.364974 US\$/kWh, and the minimum variation was 2.4939% for a 20-year amortization period and a interest of 6%, from 0.231380 US\$/kWh to 0.225610 US\$/kWh.

To analyze the annual investment revenue, it would be necessary to know the installation for which the system was designed, since the peculiarities of an installation and its consumption profile are primordial for the efficient design of a cogeneration system. Thus, annual revenue has not been evaluated. However, it is possible to compare the cost of generating electricity in the cogeneration system with the price of electricity sold by the concessionaires. The price of electricity marketed in the 5 regions of the country was analyzed. Their values can be cheked in Table 8 (Aneel, 2018).

Table 8. Electricity price.

Central-west	0.116224US\$/kWh
Northeast	0.106139 US\$/kWh
North	0.132139 US\$/kWh
Southeast	0.112333 US\$/kWh
South	0.109811 US\$/kWh

All the scenarios presented in a given year in the useful life interval of the plant cost of generation of electricity inferior to the commercialized by the concessionaire. As the north region has the highest selling price of electricity, in this region the cost of electricity from cogeneration reaches a lower value than the concessionaire in a shorter time. The northeast is the region where the cost of electricity from cogeneration reaches a lower value than that of the concessionaire in the longest time, since it is in this region the lowest price of electricity sold by the concessionaire. The year in which the cost of electricity generated in the cogeneration system is lower than that marketed by the concessionaire can be verified in Table 9.

Table 9. Year in which the cost of electricity generated in the cogeneration system is lower than that marketed by the concessionaire.

C_{Fuel}	r	Central-west			Northeast			North			Southeast			South		
		H _{25%}	H _{50%}	H _{75%}	H _{25%}	H _{50%}	H _{75%}	H _{25%}	H _{50%}	H _{75%}	H _{25%}	H _{50%}	H _{75%}	H _{25%}	H _{50%}	H _{75%}
-30%	6%	3	2	1	4	2	1	3	2	1	3	2	1	4	2	1
	8%	3	2	1	4	2	1	3	2	1	4	2	1	4	2	1
	10%	3	2	1	4	2	1	3	2	1	4	2	1	4	2	1
	12%	4	2	1	4	2	1	3	2	1	4	2	1	4	2	1
	14%	4	2	1	4	2	2	3	2	1	4	2	1	4	2	1
-15%	6%	4	2	1	4	2	2	3	2	1	4	2	1	4	2	2
	8%	4	2	1	4	2	2	3	2	1	4	2	1	4	2	2
	10%	4	2	1	5	2	2	3	2	1	4	2	2	4	2	2
	12%	4	2	1	5	2	2	3	2	1	4	2	2	4	2	2
	14%	4	2	1	5	2	2	3	2	1	4	2	2	5	2	2
Reference price	6%	4	2	2	5	2	2	3	2	1	4	2	2	5	2	2
	8%	4	2	2	5	2	2	3	2	1	5	2	2	5	2	2
	10%	4	2	2	5	3	2	3	2	1	5	2	2	5	2	2
	12%	5	2	2	6	3	2	4	2	1	5	2	2	5	2	2
	14%	5	2	2	6	3	2	4	2	1	5	2	2	6	2	2
+15%	6%	5	2	2	6	3	2	4	2	1	5	2	2	5	3	2
	8%	5	2	2	6	3	2	4	2	1	5	3	2	6	3	2
	10%	5	2	2	7	3	2	4	2	1	6	3	2	6	3	2
	12%	5	2	2	7	3	2	4	2	1	6	3	2	6	3	2
	14%	6	3	2	8	3	2	4	2	1	6	3	2	7	3	2
+30%	6%	6	3	2	7	2	2	4	2	2	6	2	2	7	2	2
	8%	6	3	2	8	2	2	4	2	2	7	2	2	7	2	2
	10%	6	3	2	9	2	2	4	2	2	7	2	2	8	2	2
	12%	7	3	2	10	3	2	4	2	2	8	2	2	9	2	2
	14%	7	3	2	12	3	2	5	2	2	9	2	2	10	2	2

4. CONCLUSIONS

In this work, a method found in the literature is evaluated by analyzing a generic cogeneration plant representative of the last 10 installations registered with cogeneration in Brazil. They are facilities for electricity, heat and cold generation and maximum power of 4000 kW with use of internal combustion engine with natural gas. The applied methodology allowed the accomplishment of a technical analysis of the plant, and the results presented consistency when compared with the literature. Analyzing economically, the proposed method allows determining the costs to generate each cogeneration product. Costs are dependent on the value of the investment to purchase the equipment, operating time, generated power, fuel cost and maintenance cost. The increase in operating time resulted in lower costs in cogeneration products. The variation in the price of the fuel had an impact on the costs of the products, proving to be a crucial parameter for the feasibility of a cogeneration system. It should be emphasized that the evaluated method and its application present good qualitative results. However, quantitatively, we must analyze with caution, since projects of cogeneration systems depend on many specific variables of the studied application.

5. ACKNOWLEDGEMENTS

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