

EXERGOECONOMIC ANALISYS AND EVALUATION OF DIFERENT COGENERATION SYSTEMS

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Abstract: *This paper presents an energetic and exergetic efficiency comparison of three different cogeneration systems, running with natural gas. Cogeneration products are electricity, hot water and steam. Exergetic costs and costs rates associated to all them are calculated. Systems work under the same site conditions and also the same cogeneration product demand. The first alternative consists of an Otto cycle engine that produces electric energy and heat, recovered in HRSG and also from its jackets. The second alternative is build by a gas turbine and the last one uses a supersaturated steam generator associated to a backpressure steam turbine. The simulations are made using IPSEpro software, running with a new library specially developed to solve mass and energy balances simultaneously to thermoeconomics equations. Alternative with the Otto cycle engine shows the better exergetic and energetic efficiency. The second better results is observed in the Brayton cycle gas turbine and the least attractive results belongs to the alternative with supersaturated steam generation.*

Keywords: *cogeneration, thermal systems, exergy, exergoeconomy, natural gas.*

1. Introduction

The possible finish of fossil fuel, the great variations of the petroleum prices and the environmental worryness about the gases emissions that causes greenhouse effect are important motivations to cogeneration studies and new technologies to electric energy productions. A specific tannery plant was chosen as a case study, and three cogeneration systems were proposed in order to analyze energetic and exergetic performances. Tannery uses wood as fuel to obtain thermic energy and buys electric energy (Schneider *et al*., 2003). Three configurations were proposed: 1) Otto cycle engine, 2) Brayton cycle gas turbine and 3) Superheated steam generation associated at a backpressure steam turbine. All them were simulated considering the same working load. Thermodynamics properties concerning all streams and associated costs were calculated. Exergetic efficiency of all equipments of the three proposed plants was also calculated.

Simulations were done using the software IPSEpro (SimTech, 2000). Libraries concerning mathematical modeling of the equipments and also thermodynamic properties of fluids were modified in order to calculate exergy values and to solve the resulting exergetic cost equation system. This system is solved together with the thermodynamic simulation, avoiding the need of a second code of post-processing.

2. Problem description

Tannery energetic demand is mainly concentrated in electric motors and in the production of saturated steam and hot water to process up to 90 ºC. An earlier study by Schneider *et al*. (2003) consolidated these energetic demands and Table 1 displays some average loads that were taken as design data.

Table 1. Tannery average loads.

Source	Power (kW)	Contribution (%)
1- Electricity	325.0	24.54
2- Hot water	283.1	25.73

3- Steam	492.1	44.73
2 + 3	775.2	70.45
1 + 2 + 3	1100.2	

Electric energy generation is about 30% of the total system demand. This situation indicates a good opportunity to employ cogeneration systems, once devices as turbines or engines convert about 35% of the input chemical energy into mechanical energy. The complementary amount of energy (65%) is rejected as heat, which can recover to generate steam or hot water.

3. Methodology

3.1 Exergy and exergetic efficiency

According to Bejan *et al*. (1996), the total exergy of a system (*Ex*) can be expressed as the summation of four components: physical exergy (Ex^{PH}) , kinetic exergy (Ex^{KN}) , potential exergy (Ex^{PT}) and chemical exergy (Ex^{CH}). Assuming that both velocity and height of the system are null ($Ex^{KN}=Ex^{PT}=0$), total exergy is the sum of physical and chemical exergies.

Physical exergy of a closed system is given the expression:

$$E^{PH} = \dot{m}\left[(h-h_o)-T_o(s-s_o)\right] \tag{1}$$

where $\dot{m}$ is the mass flow rate (kg/s), T_0 is the reference state temperature (K), *h* and *s* are specific enthalpy (kJ/kg) and entropy (kJ/kg K), respectively.

Chemical exergy is given by:

$$Ex^{CH} = \dot{m}\ (\ \sum x_K e_K^{CH} + RT_o \sum x_K \ln(x_K)\ ) \tag{2}$$

where x_K is the mole fraction of gas k, e_K^{CH} is the standard chemical exergy, *R* is the universal constant of gases.

3.2 Exergoeconomic analysis

Defining the Purchase Equipment Costs (*PEC*) of a given equipment *k*, the Total Capital Investment (*TCI*) is defined in Bejan *et al*. (1996) as

$$TCI = 4.16 \sum PEC_k \tag{3}$$

Considering a stream of mater with rates of specific exergy e_x (kJ/kg), Tsatsaronis (1993) defines the cost rate *C* (\$/h) as

$$C = c\,Ex = c(\dot{m}\ e_x) \tag{4}$$

where *c* is the average cost per unit of exergy (\$/kJ) and *Ex* is the exergy associated to a given stream (kW).

Let *W* and *Q* be the power and the heat transfer, respectively, that crosses the control volume boundaries, the Capital Investment and Operation and Maintenance rate Z_k is defined as:

$$Z_k = \Sigma C_o - \Sigma C_i + \Sigma W - \Sigma C_Q \tag{5}$$

where indices *i* and *o* are related to incoming and outgoing streams. This last equation states a balance of cost rates by dividing the annual contribution of capital investment and the annual operating and maintenance costs (O&M), by the annual number of hours of system operation, proportional at the *PEC* of each equipment.

$$Z_k = \frac{A}{\tau \sum PEC_k} PEC_k \tag{6}$$

3.3 Thermoeconomic Evaluation

System evaluation is a methodology to mitigate energy and exergy inefficiencies, improving cost effectiveness. Local improvement of each one of the analyzed devices shall not be taken as an optimization procedure, in the sense of a mathematical method. Bejan *et al*. (1996) proposed the following list of steps:

1. Rank the components in descending order of cost importance using the sum $C_d + Z$. Design changes should be considered for equipment where this sum is high.

2. Components with a high relative cost value need special attention.

3. The major cost source can be identified using the exergoeconomic factor $f=Z/(C_d + Z)$:

3.a -If f is high, investigate whether its cost effective to reduce the capital investment for the component at the expense of the component efficiency.

3.b - If f is low, try to improve the component efficiency by increasing the capital investment.

4. Eliminate or reduce any steps or sub processes that increase the exergy destruction or exergy loss without contributing to the reduction of capital investment or fuel costs.

5. If a component has relatively low exergetic efficiency, or a relatively large value of exergy destruction, an increase in the exergetic efficiency might be cost effective.

4. Cogeneration alternatives

Three different alternatives of cogeneration systems are proposed in order to observe which one will display the best economic output. Their common parameters are: a) plant economic life: 20 years; b) average general inflation rate: 5 %/ year; c) natural gas raising cost rate: 6 %/ year; d) required annual return: 12.6%/ year; e) fuel cost: 0.135 $ /kg f) capacity factor: 7446 hours/year; and g) O&M: 5% of *TCI*. Environment is modeled as a simple compressing system, at uniform temperature *To* = 25ºC, and pressure *po* = 1,01325 bar.

Otto cycle engine - Figure 1 presents a schematic diagram of this first alternative, where an Otto cycle engine M1 produces electricity at G1. Heat from combustion gases GC3 is recovered in the steam generator TC5, while a hot stream of water from engine jackets is also recovered in TC2.

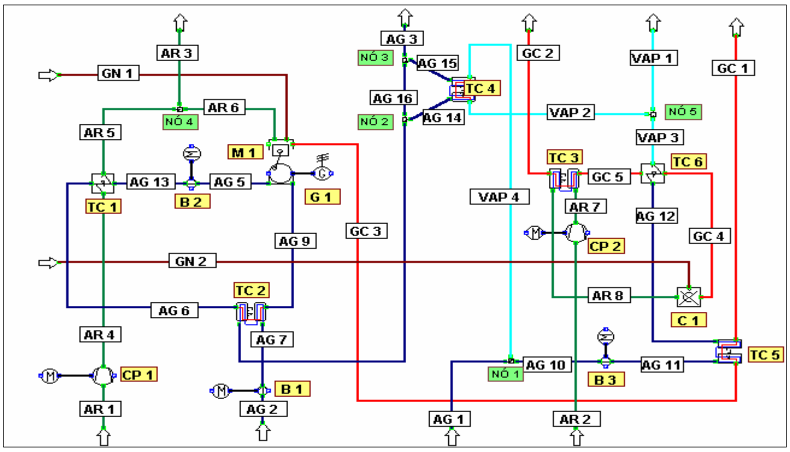

Figure 1 – Schematic diagram of the cogeneration system with Otto cycle engine (alternative 1).

The energetic efficiency (η_{PLANT1}) and exergetic efficiency (ε_{PLANT1}) are calculated as:

$$\eta_{PLANT1} = \frac{(\dot{W}_{G1} - \dot{W}_{B1} - \dot{W}_{B2} - \dot{W}_{B3} - \dot{W}_{CP1} - \dot{W}_{CP2}) + \dot{m}_{VAP1}(h_{VAP1} - h_{AG1}) + \dot{m}_{AG3}(h_{AG3} - h_{AG1})}{(\dot{m}_{GN1} + \dot{m}_{GN2})\ LHV} \tag{7}$$

$$\varepsilon_{PLANT1} = \frac{(\dot{W}_{G1} - \dot{W}_{B1} - \dot{W}_{B2} - \dot{W}_{B3} - \dot{W}_{CP1} - \dot{W}_{CP2}) + (Ex_{VAP1} - Ex_{AG1}) + (Ex_{AG3} - Ex_{AG2})}{Ex_{GN1} + Ex_{AR1} + Ex_{GN2} + Ex_{AR2}} \tag{8}$$

$\dot{W}_{G1}$ is the electric power associated to the electric generator G1, pumps B1 to B3 and compressors CP1 and CP2, in kW; $\dot{m}_{VAP1}$ and $\dot{m}_{AG3}$ are the steam and hot water flows, $\dot{m}_{GN1}$ and $\dot{m}_{GN2}$ are the massic flows of natural gas, all in kg/s; *h* is the specific enthalpy in the indicated positions, in kJ/kg. *LHV* is the low heat value of the fuel. Energetic and exergetic efficiencies are of 79.28 % and 30.77 % respectively.

Simulation allows calculating the cogeneration product costs rate, by the following relations:

$$C_{WATER\_Q\_1} = C_{AG3} + 1/3\left(\sum_{PUMPS} C_{SHAFT\_B} + \sum_{COMPRESSORS} C_{SHAFT\_CP} + \sum_{COMB\_PRODUCTS} C_{GC} + C_{AR3} \right) \tag{9}$$

$$C_{STEAM\_1} = C_{VAP1} + 1/3\left(\sum_{PUMPS} C_{SHAFT\_B} + \sum_{COMPRESSORS} C_{SHAFT\_CP} + \sum_{COMB\_PRODUCTS} C_{GC} + C_{AR3} \right) \tag{10}$$

$$C_{EE\_1} = C_{SHAFT\_G1} + 1/3\left(\sum_{PUMPS} C_{SHAFT\_B} + \sum_{COMPRESSORS} C_{SHAFT\_CP} + \sum_{COMB\_PRODUCTS} C_{GC} + C_{AR3} \right) \tag{11}$$

The sum of the Purchase Cost Equipment is \$ 63,240.00, Total Cost Investment is \$ 263,078.40 and Annuity *A* is \$ 76,763.83. Values of PEC and the calculated values of Z_k are presented in Table 2.

Table 2 – Values of PEC_k and Z_k for the Otto cycle engine alternative.

EQUIPMENT	ENGINE (M1)	PUMP 2 (B2)	COMPRESSOR 1 (CP 1)	HEAT EXCHANGER 1 (TC 1)	PUMP 1 (B1)	PUMP 3 (B 3)	HEAT EXCHANGER 5 (TC 5)	HEAT EXCHANGER 2 (TC 2)	HEAT EXCHANGER 4 (TC 4)	HEAT EXCHANGER 3 (TC 3)	COMBUSTION CHAMBER (C 1)	COMPRESSOR 2 (CP 2)	EVAPORATOR (TC 6)
PEC (\$)	38.000.00	60.00	750.00	5.000.00	15.00	15.00	5.000.00	5.000.00	5.000.00	150.00	4.000.00	100.00	150.00
Z (\$/h)	6.19	0.01	0.12	0.82	0.00	0.00	0.82	0.82	0.82	0.02	0.65	0.02	0.02

Hot water cost rate $C_{WATER\_Q\_1}$ is 5.41\$/h, steam cost rate C_{STEAM_1} is 18.05 \$/h and electric energy cost rate C_{EE_1} is 16.69 \$/h. Total cost rate of cogeneration products is 40.15 \$/h. Table 3 shows the thermoeconomic variables for component evaluation ranked by $C_d + Z$. Decision variables before and after simulation are also displayed.

Table 3. Thermoeconomic variables for component evaluation (left) and its decision variables before and after evaluation system (right) - alternative 1.

EQUIPMENT	EXERGETIC EFFICVIENCY (%)	EXERGY DESTRUCTION (Ed) (kW)	FUEL COST (cf) (\$/GJ)	PRODUT COST (cp) (\$/GJ)	EXERGY DESTRUCTION COST RATE (Cd) (\$/h)	RELATIVE COST DIFERENCE (r) (%)	EXERGO ECONOMIC FACTOR (f) (%)	Cd + Z (\$/h)	Yd (%)
ENGINE (M1)	48.39	621.11	4.27	11.78	9.54	175.92	39.36	15.738	33.279
EVAPORATOR (TC 6)	43.02	259.54	6.52	15.20	6.10	132.99	0.40	6.120	13.906
COMBUSTION CHAMBER (C 1)	71.47	196.55	4.40	6.52	3.11	48.27	17.32	3.766	10.531
HEAT EXCHANGER 5 (TC 5)	44.86	66.09	11.78	30.48	2.80	158.67	22.53	3.618	3.541
HEAT EXCHANGER 2 (TC 2)	42.14	32.12	11.78	37.63	1.36	219.43	37.43	2.178	1.721
HEAT EXCHANGER (TC 1)	4.36	23.65	11.78	480.72	1.00	3.980.14	44.83	1.818	1.267
COMPRESSOR 1 (CP 1)	80.91	2.49	11.78	17.78	0.11	50.90	53.63	0.228	0.134
HEAT EXCHANGER 3 (TC 3)	71.89	7.12	6.52	9.45	0.17	44.83	12.78	0.192	0.381
COMPRESSOR 2 (CP 2)	81.68	1.33	11.78	15.19	0.06	28.90	22.38	0.073	0.071
PUMP 2 (B2)	94.93	0.05	11.78	15.14	0.00	28.46	81.02	0.012	0.003
PUMP 3 (B 3)	81.62	0.05	11.78	17.65	0.00	49.83	54.65	0.004	0.003
PUMP 1 (B1)	81.85	0.04	11.78	18.57	0.00	57.58	61.16	0.004	0.002

VARIABLE		BEFORE CHANGES	AFTER CHANGES
PRESSURE (bar)	GC1	1.05	1.05
TEMPERATURE (C)	GC1	100	50
TEMPERATURE (C)	GC5	285	170
TEMPERATURE (C)	GC2	100	80
TEMPERATURE (C)	AG13	94	85
TEMPERATURE (C)	AG9	99	180
PRESSURE (bar)	AG5	3	10
TEMPERATURE (C)	AG10	26	26
TEMPERATURE (C)	AR3	80	175
FUEL -AIR RATIO	C1	1.4	1.05

After applying the thermoeconomic evaluation methodology, changes in the decision variables improved the cost effectiveness of the system, as well as the exergetic efficiency. Hot water cost rate was increased from 5.41 \$/h to 6.25 \$/h, an increase of 15.53%. This undesirable result is compensated by the decrease in the steam cost rate, from 18.05 \$/h to 16.51 \$/h (8.53 %), and also by decreasing electric energy cost rate, from 16,69 \$/h to 14.92 \$/h (10.61%). Total cost rate of cogeneration products was decreased from 40.15 \$/h to 37.68 4/h. The exergetic efficiency of these system changes from 30.77 % to 33.01 %, what means an increase of 7.28 %.

Brayton cycle engine - This second alternative is built by a gas turbine T1 connected at an electric generator G1. A heat recovery steam generator TC2 produces saturated steam that satisfies steam and hot water demands (Figure 2).

Energetic efficiency (η_{PLANT2}) and exergetic efficiency (ε_{PLANT2}) are calculated as:

$$\eta_{PLANTA2} = \frac{(\dot{W}_{G1} - \dot{W}_{B1} - \dot{W}_{B2} - \dot{W}_{CP1}) + \dot{m}_{VAP1}(h_{VAP1} - h_{AG1}) + \dot{m}_{AG3}(h_{AG3} - h_{AG1})}{(\dot{m}_{GN1} + \dot{m}_{GN2})\ PCI} \qquad (12)$$

$$\varepsilon_{PLANTA2} = \frac{(\dot{W}_{G1} - \dot{W}_{B1} - \dot{W}_{B2} - \dot{W}_{CP1}) + (Ex_{VAP1} - Ex_{AG1}) + (Ex_{AG3} - Ex_{AG2})}{Ex_{GN1} + Ex_{AR1} + Ex_{GN2} + Ex_{AR2}} \qquad (13)$$

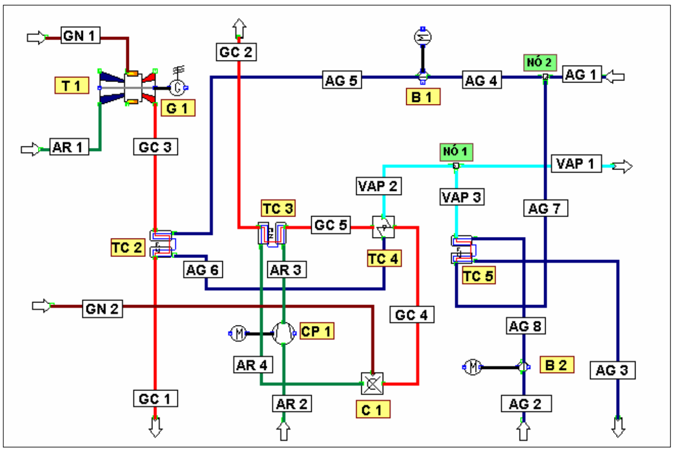

Figure 2 – Schematic diagram of the cogeneration system with Brayton cycle turbine (alternative 2).

Cogeneration products costs rate are calculated using the following equations:

$$C_{WATER\_Q\_2} = C_{AG3} + 1/3\left(\sum_{PUMPS} C_{SHAFT\_B} + C_{SHAFT\_CP1} + \sum_{COMB\_PRODUTS} C_{GC}\right) \qquad (14)$$

$$C_{STEAM\_2} = C_{VAP1} + 1/3\left(\sum_{PUMPS} C_{SHAFT\_B} + C_{SHAFT\_CP1} + \sum_{COMB\_PRODUTS} C_{GC}\right) \qquad (15)$$

$$C_{EE\_2} = C_{SHAFT\_G1} + 1/3\left(\sum_{PUMPS} C_{SHAFT\_B} + C_{SHAFT\_CP1} + \sum_{COMB\_PRODUTS} C_{GC}\right) \qquad (16)$$

Table 4 shows the Purchase Equipment Costs and Investment and O&M cost rates

Table 4 – PEC_k and Z_k for alternative 2.

EQUIPMENT	PEC ($)	Z ($/h)
STEAM TURBINE (T1)	55.000.00	8.97
HEAT EXCHANGER 2 (TC2)	10.000.00	1.63
HEAT EXCHANGER (TC 5)	5.000.00	0.82
PUMP 1	15.00	0.00
PUMP 2	15.00	0.00
HEAT EXCHANGER 3 (TC 3)	150.00	0.02
COMBUSTION CHAMBER (C 1)	4.000.00	0.65
COMPRESSOR 2 (CP 2)	100.00	0.02
EVAPORATOR (TC 4)	150.00	0.02

Economics results are: $\sum PEC_K$ is \$74,430.00 , TCI is \$ 309,628.80 and A is \$ 90,346.80. Energetic and exergetic efficiencies are 71.99 % and 28.28 % respectively. Thermoeconomic variables used for component evaluation are in Table 5, and decision variables before and after simulation are also displayed.

Hot water cost rate $C_{WATER\_Q\_2}$ is 7.54 \$/h, steam cost rate C_{STEAM_2} is 17.46 \$/h and electric energy cost rate C_{EE_2} is 19.30 \$/h. Cogeneration products costs rate after the changes are: $C_{WATER\_Q\_2} =$ 7.01 \$/h, $C_{STEAM\_2} = 18.01$ \$/h and $C_{EE\_2} = 18.25$ \$/h. The exergetic efficiency of the system increases 5.5 %, changing from 28.28% to 29.82%, and the total cogeneration total products costs rate was modified from 44.30 \$/h to 43.27 \$/h.

Table 5- Thermoeconomic variables for component evaluation (left) and its decision variables before and after evaluation system (right) - alternative 2.

EQUIPMENT	EXERGETIC EFFICVIENCY (%)	EXERGY DESTRUCTION (Ed) (kW)	FUEL COST (cf) (\$/GJ)	PRODUT COST (cp) (\$/GJ)	EXERGY DESTRUCTION COST RATE (Cd) (\$/h)	RELATIVE COST DIFERENCE (r) (%)	EXERGO ECONOMIC FACTOR (f) (%)	Cd + Z (\$/h)	Yd (%)
GAS TURBINE (T1)	43.51	669.85	4.17	14.40	10.04	245.751	47.164	19.010	32.283
EVAPORATOR (TC4)	43.01	346.90	6.46	15.04	8.07	132.902	0.303	8.091	16.719
HEAT EXCHANGER (TC5)	25.89	67.06	18.67	81.78	4.51	338.046	15.316	5.322	3.232
COMBUSTION CHAMBER (	71.47	262.68	4.42	6.46	4.18	46.142	13.496	4.832	12.660
HEAT EXCHANGER (TC2)	70.68	40.00	14.40	25.07	2.07	74.075	44.010	3.704	1.928
HEAT EXCHANGER (TC3)	71.89	9.51	6.46	9.26	0.22	43.430	9.974	0.246	0.458
COMPRESSOR (CP1)	81.64	1.78	14.40	18.21	0.09	26.446	14.976	0.109	0.086
PUMP 1 (B1)	83.55	0.06	14.40	19.30	0.00	34.048	0.002	0.006	0.003
PUMP 2 (B2)	72.25	0.05	14.40	25.37	0.00	76.134	49.561	0.005	0.002

VARIABLE		BEFORE CHANGES	AFTER CHANGES
PRESSURE (bar)	GC1	1.05	1.05
TEMPERATURE (C)	GC1	100	35
TEMPERATURE (C)	GC5	285	170
TEMPERATURE (C)	GC2	100	75
TEMPERATURE (C)	AG4	98	25.79
FUEL - AIR RATIO	T1	2.63	2.63
FUEL - AIR RATIO	C1	1.4	1.05

Supersaturated steam generation and backpressure steam turbine – Superheated steam is expanded in a backpressure turbine to generate electricity. The outgoing steam, at 8 bar approximately, is condensed in a heat exchanger (Figure 3)

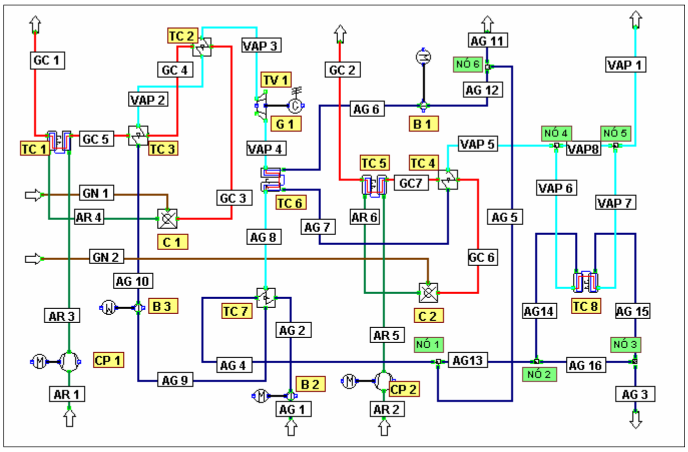

Figure 3 – Cogeneration system with supersaturated steam generation and steam turbine (alternative 3).

The energetic and exergetic efficiency are:

$$\eta_{PLANTA3} = \frac{(\dot W_{G1} - \dot W_{B1} - \dot W_{B2} - \dot W_{B3} - \dot W_{CP1} - \dot W_{CP2} - \dot W_{CP3}) + \dot m_{VAP1}(h_{VAP1} - \dot h_{AG1}) + \dot m_{AG3}(h_{AG3} - h_{AG1})}{(\dot m_{GN1} + \dot m_{GN2})\ PCI} \quad (17)$$

$$\varepsilon_{PLANTA3} = \frac{(\dot W_{G1} - \dot W_{B1} - \dot W_{B2} - \dot W_{B3} - \dot W_{CP1} - \dot W_{CP2} - \dot W_{CP3}) + (Ex_{VAP1} - Ex_{AG1}) + (Ex_{AG3} - Ex_{AG2})}{Ex_{GN1} + Ex_{AR1} + Ex_{GN2} + Ex_{AR2}} \quad (18)$$

The energetic efficiency is 42.05 % and the exergetic efficiency is 14,56 %. Table 6 shows the Purchase Equipment Costs and the Investment and O&M cost rate.

Economics results are: $\sum PEC_K$ is \$93,325.00, TCI is \$ 396,552.00 and A is \$ 115,710.18. Thermoeconomic variables for evaluation are in Table 7.

Cogeneration product cost rates are calculated using the equations bellow:

$$C_{WATER\_Q\_3} = C_{AG3} + 1/3\left(\sum_{PUMPS} C_{SHAFT\_B} + \sum_{COMPRESSORS} C_{SHAFT\_CP} + \sum_{COMB\_PRODUCTS} C_{GC} + C_{AG11}\right) \quad (19)$$

$$C_{STEAM\_3} = C_{VAP1} + 1/3\left(\sum_{PUMPS} C_{SHAFT\_B} + \sum_{COMPRESSORS} C_{SHAFT\_CP} + \sum_{COMB\_PRODUCTS} C_{GC} + C_{AG11}\right) \quad (20)$$

$$C_{EE\_3} = C_{SHAFT\_G1} + 1/3\left(\sum_{PUMPS} C_{SHAFT\_B} + \sum_{COMPRESSORS} C_{SHAFT\_CP} + \sum_{COMB\_PRODUCTS} C_{GC} + C_{AG11}\right) \quad (21)$$

Table 6 – PEC_k and Z_k for alternative 3.

EQUIPMENT	PEC ($)	Z ($/h)
COMBUSTION CHAMBER (C1)	20.000.00	3.26
EVAPORATOR (TC3)	15.000.00	2.45
HEAT EXCHANGER (TC1)	3.000.00	0.49
COMPRESSOR (CP1)	850.00	0.14
HEAT EXCHANGER (TC2)	10.000.00	1.63
STEAM TURBINE (T1)	18.000.00	2.93
HEAT EXCHANGER (TC6)	3.000.00	0.49
HEAT EXCHANGER (TC7)	15.000.00	2.45
PUMP (B3)	1.000.00	0.16
PUMP (B2)	60.00	0.01
PUMP (B1)	15.00	0.00
HEAT EXCHANGER (TC8)	5.000.00	0.82
COMPRESSOR (CP2)	100.00	0.02
HEAT EXCHANGER (TC5)	150.00	0.02
EVAPORATOR (TC4)	150.00	0.02
COMBUSTION CHAMBER (C2)	4.000.00	0.65

Table 7. Thermoeconomic variables for component evaluation – alternative 3.

Equipment	Eficiência Exergética (%)	Exergia Destruída (Ed) (kW)	Custo de Combustível (cf) ($/GJ)	Custo de Produto (cp) ($/GJ)	Taxa de Custo de Exergia Destruída (Cd) ($/h)	Diferença Relativa de Custo (r) (%)	Fator Exergo econômico (f) (%)	Cd + Z ($/h)	Yd (%)
HEAT EXCHANGER (TC7)	28.73	366.48	16.11	60.68	21.26	276.608	10.317	23.701	10.520
EVAPORATOR (TC3)	57.36	612.66	6.94	12.93	15.31	86.212	13.771	17.757	17.587
COMBUSTION CHAMBER (C1)	68.78	867.17	4.45	6.94	13.89	56.045	19.013	17.149	24.893
STEAM TURBINE (T1)	70.98	147.24	9.83	16.11	5.21	63.915	36.031	8.144	4.227
EVAPORATOR (TC4)	44.53	278.51	6.73	15.16	6.75	125.042	0.362	6.777	7.995
HEAT EXCHANGER (TC2)	60.50	150.97	6.94	13.43	3.77	93.490	30.171	5.403	4.334
COMBUSTION CHAMBER (C2)	68.78	240.07	4.40	6.73	3.80	53.179	14.648	4.452	6.891
HEAT EXCHANGER (TC1)	51.66	23.93	6.94	18.75	0.60	170.058	44.986	1.087	0.687
HEAT EXCHANGER (TC8)	69.72	2.51	17.11	63.77	0.15	272.634	84.073	0.970	0.072
HEAT EXCHANGER(TC6)	80.03	7.43	16.11	24.69	0.43	53.254	53.153	0.920	0.213
COMPRESSOR (CP1)	81.68	5.47	16.11	21.30	0.32	32.229	30.415	0.456	0.157
PUMP (B3)	83.15	0.69	16.11	32.72	0.04	103.062	80.344	0.203	0.020
HEAT EXCHANGER (TC5)	51.93	6.56	6.73	13.93	0.16	106.832	13.359	0.183	0.188
COMPRESSOR (CP2)	81.68	1.51	16.11	20.40	0.09	26.591	15.660	0.104	0.043
PUMP (B2)	85.61	0.17	16.11	21.51	0.01	33.505	49.914	0.020	0.005
PUMP (B1)	84.15	0.03	16.11	22.90	0.00	42.159	55.580	0.004	0.001

The results are: $C_{WATER\_Q\_3} =$ 15.88 $/h , $C_{STEAM\_3} =$ 25.76 $/h and $C_{EE\_3} =$ 31.16 $/h.

The decision variables before and after apply the methodology are shown in Table 8.

Cogeneration products costs rate after the changes are: $C_{WATER\_Q\_3} =$ 13.25 $/h, $C_{STEAM\_3} =$ 22.93 $/h and $C_{EE\_3} =$ 27.79 $/h. The exergetic efficiency of the system increases 21,77%, changing from 14.56% to 17.73%, and the total cogeneration total products costs rate was modified from 72.80 $/h to 63.97 $/h. After performing the evaluation methodology, some good results were achieved (Figure 4), with better results to alternative 3. Nevertheless, it doesn't mean that this alternative is the best one in regard to energetic and exergetic efficiency. The methodology delivered the worst results in alternative 2 probably because of its little number of decision variables.

Table 8. Decision variables before and after evaluation system – alternative 3.

VARIABLE		BEFORE CHANGES	AFTER CHANGES
TEMPERATURE (C)	GC1	100	33
TEMPERATURE (C)	GC5	200	136
TEMPERATURE (C)	GC2	100	73
TEMPERATURE (C)	GC7	200	167
TEMPERATURE (C)	AG9	90	117
PRESSURE (bar)	AG9	3	2.9
TEMPERATURE (C)	AG7	165	165.53
TEMPERATURE (C)	VAP2	250	257.51
TEMPERATURE (C)	VAP3	450	485
PRESSURE (bar)	VAP3	40	45
FUEL - AIR RATIO	C1	1.4	1.05
FUEL - AIR RATIO	C2	1.4	1.1

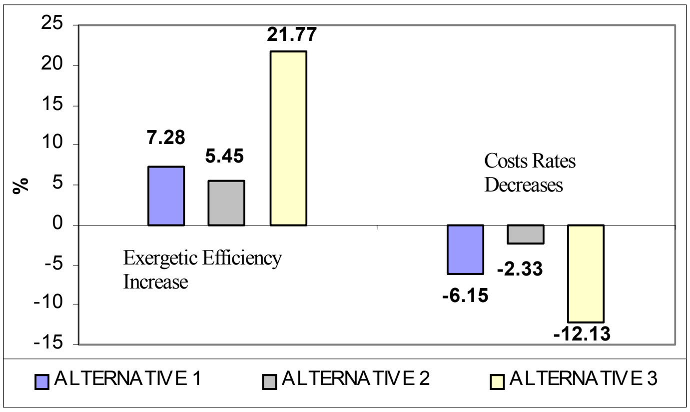

Figure 4. – Results of the evaluation methodology applied at the three plants.

5. Conclusions

The development of a new library to IPSEpro software allowed calculating mass and energy balances simultaneously to thermoeconomic analysis. This new tool gives an interesting reduction of time and effort to the simulation process. Three different alternatives of cogeneration plants were studied and an evaluation based on thermoeconomics was also performed. The product costs of each alternative were calculated to each proposed alternative. The best result was found to alternative 1, with an Otto cycle engine, followed by the Brayton cycle alternative, and finally by third alternative, composed by a supersaturated steam generator and a backpressure steam turbine. The same order was found to the exergetic efficiency. Alternative 1 has steam as its major cost, while electricity showed to be the major cost to plants 2 and 3, because of the high purchase costs of its energy drivers (gas turbine and the supersaturated steam generator).

6. References

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7. Responsibility notice

The authors are the only responsible for the printed material included in this paper.