COMPUTATIONAL EXERGOECONOMIC ANALYSIS OF A COGENERATION FACILITY FOR A HOSPITAL

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Abstract. *The aim of this paper is to present the opportunities of energetic improvement that can be achieved in a cogeneration system by means of exergoeconomic analysis. The cogeneration plant, designed to simultaneously supply electricity and thermal energy to a hospital, is presented together with its main exergetic and exergoeconomic parameters. Calculation is performed with a commercial software for thermal system simulation (IPSEPro) with the help of an exergoeconomic library, developed by some of the authors of this paper. The exergetic efficiency of the plant rised up from 38.47% to 40.58%, meaning that an important amount of irreversibility can be avoided. The energetic efficiency, according to the first law, after the improvement process is 4.4% higher than the original design , reaching 70.82 %.*

Keywords: *exergoeconomic analysis, cogeneration, exergy, thermal system simulation, IPSEPro*

1. INTRODUCTION

The central point of this work is the search for efficient systems. The expectation of continuous economic growth for the emerging countries creates worries about an eminent crises in energy supply. Some well known technologies as cogeneration systems make their return as an attractive engineering option when the key word is energetic efficiency. The efficiency of cogeneration systems according to a first law analysis is quite high and can easily reach 70% and over, with significant savings in gas emissions to the atmosphere. Although these advantages seem to be sufficient to justify a cogeneration system, it must displace other conventional systems over a life cycle assessment, and sometimes it is hard to find economical viability for them. An avoided cost with fuels is the decision parameters in this case and that is one of the main reasons for the rising interest on cogeneration in Brazil nowadays.

Only first law analysis is not sufficient to improve thermal efficiency, and second law arrives as an important tool because it deals with the maximal useful work that can be reached by a system as a theoretical reference and searches for better performances for the actual system. The exergoeconomic analysis does not replace the classical economical or financial analysis, based on cash flow, where the main items that build the final cost of the system are made explicit and compared on present value basis. Exergoeconomics associates values for every stream of the system based on a second law analysis. The availability of streams of fuel, flue gases, power shafts and any other fluid stream are calculated after their exergy and the engineer have to evaluate their value. The system optimization based on that approach is performed by improving valuable output streams (products), mitigating useless rejections and reducing exergy destruction along the system. The methodology is described on this text on Item 2 and it is follows Bejan *et al*. (1996).

The present case study is the result of a research project carried on at a hospital in Porto Alegre (Brazil), The Hospital de Clinicas of Porto Alegre - HCPA, with expressive energy demands (Smith Schneider *et al*, 2006). During the year long project, the energy demands were identified by means of bill survey, experimental measurements and some rule of thumb estimation, ending up with a general mean view of the hospital, precise enough for a long term energy analysis. Two seasonal load profiles were identified, representing summer and winter situations. Several cogeneration systems were proposed, based on reciprocating engines, turbines and finally steam generators as main drivers, burning natural gas. Every plant was reproduced in a thermal system simulation software (IPSEPro, http://www.simtechnology.com) in order to quantify the product quantities, auxiliary needs and overall efficiency. A cash flow analysis pointed out the option based on a reciprocating internal combustion engine as the best architecture, and the present paper presents its improvement based on an exergoeconomic analysis.

The exergoeconomic analysis can became a fastidious task if performed manually, and that motivated Santos and Smith Schneider (2005) to develop a specific library to be run at IPSEPro, enabling to simultaneously simulate any thermal system, calculate its first law efficiency and perform a second law analysis for physical and chemical exergy streams, based on the exergoeconomic methodology.

2. EXERGOECONOMIC ANALYSIS

2. Exergy and exergetic efficiency

According to Szargut *et al* (1988), 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:

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

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:

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

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.

2.2. 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 (R$/h) as

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

where Ex is the exergy associated to a given stream (kW) and c is the average cost per unit of exergy (R$/GJ). There will be an exergetic cost for fuel cf, relative to the natural gas that feeds both engine and auxiliary burner, and for stream products cp.

The relative relation among the exergetic costs of products and fuel is given by r (%), and it is calculated for every equipment k as

$$r = \frac{cp - cf}{cf} \tag{5}$$

The Capital Investment and Operation and Maintenance rate Z_k for each one of the equipments k is defined as the ratio of two products: the product of A with PEC for the given equipment k to the product of τ with the summation of PEC's.

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

where A is the annual contribution of capital investment together with the operating and maintenance cost -O&M, PEC is Purchase Equipment Cost for a given equipment k, and τ is the annual number of hours of system operation.

The relative difference among costs can be either caused by high values of Z_k or high exergy destruction costs C_d. In order to reduce the ratio r of Equation (5), one can use the exergoeconomic factor f_k, given by

$$f_k = \frac{Z_k}{Z_k + C_d} \tag{7}$$

as an indication for future actions toward a better performance of the equipment.

2.3. 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 $f=Z/(C_d + Z)$:
   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.
   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.

3. CASE STUDY

The HCPA is a hospital run by the Educational Ministry and academically attached to the Federal University of Rio Grande do Sul (UFRGS). By the time this study was performed, it was equipped with 738 beds and employed almost 4000 regular collaborators, 267 professors (tutors) and 281 medical trainees (residents), throughout 60 different specialties. Its annual numbers (in 2005) included 520 thousand consultations, 32 thousand surgeries, 4.5 thousand births, 27 thousand admissions, over 2 million exams and 320 transplantations. It is estimated that around 20 thousand people crosses the Hospital during working days (Lippi et al, 2006).

Electricity is the more intense energetic, followed by natural gas, burned to produce saturated steam and provide thermal energy for showers, cooking and laundry. All data were compiled by Smith Schneider *et al* (2006), who also studied several architectures for cogeneration systems, using reciprocating engines, turbines and superheated steam generators. The best option, compromising energetic efficiency to costs was found for internal combustion reciprocating engines, chosen here to perform an exergoeconomic analysis. Surplus electricity is not a well paid product on the Brazilian market, and the only energy load scenario that could bring viability to this cogeneration plant was the one where the system runs in steady state regime only to generate the base electricity demand. Fig. 1 shows two daily load curves, with mean values for winter (left) and summer (right), respectively.

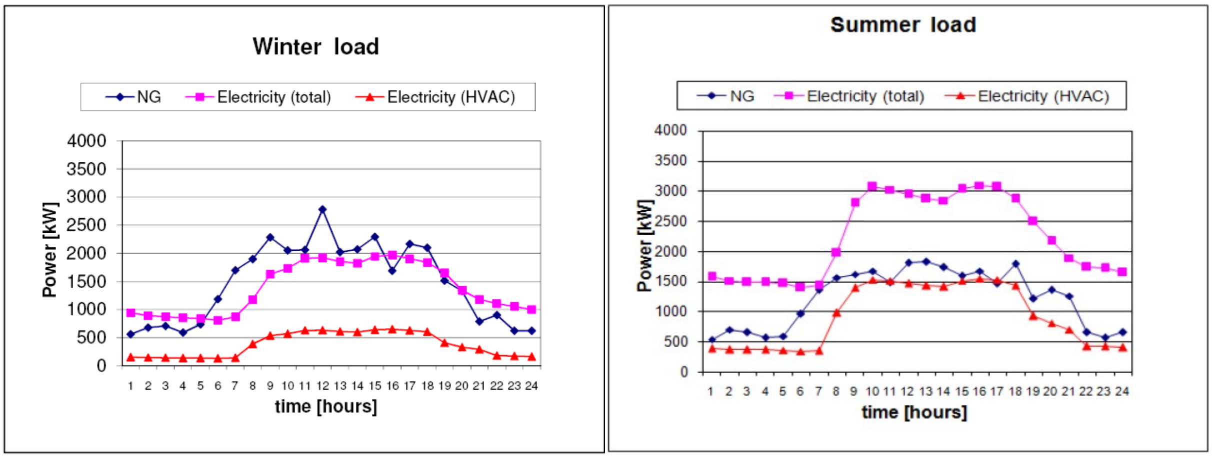

Figure 1- Daily profile of demand for an average winter (left) and summer (right) day for HCPA.

For both average daily sequences, the electric base load to be supplied by the cogeneration system is the minimum value of the electricity (total) curve. These base loads are 1 MW for winter days and 1.5 MW for summer days, and any increase on the electrical demand is designed to be supported by the local energy company. The cash flow analysis showed that this strategy was the only way to viabilize the cogeneration system. Electricity for heating and cooling (HVAC) is also displayed separately to explore the possibility of employing absorption machines for water cooling, and its value is a part of the electricity (total) data. The power demand for heat was supplied by a steam generator burning natural gas.

System assessment was done by numerical simulation with IPSEpro software (http://www.simtechnology.com/), a mass and energy balance equation solver with an object oriented library of several thermal devices and equipments. The choice of this software relays on its open source library code (MDK), that allowed introducing physical and chemical exergy relations to every stream of fluid and fuel, and all exergoeconomic equations for the plant's equipments. This new library was validated by Santos and Smith Schneider (2005) against the well known CGAM problem (Valero et al, 1993), a cogeneration plant proposed as a case study. Figure 2 is a flow sheet diagram of the simulation environment PSE of IPSE, and it gives a functional view of the studied plant.

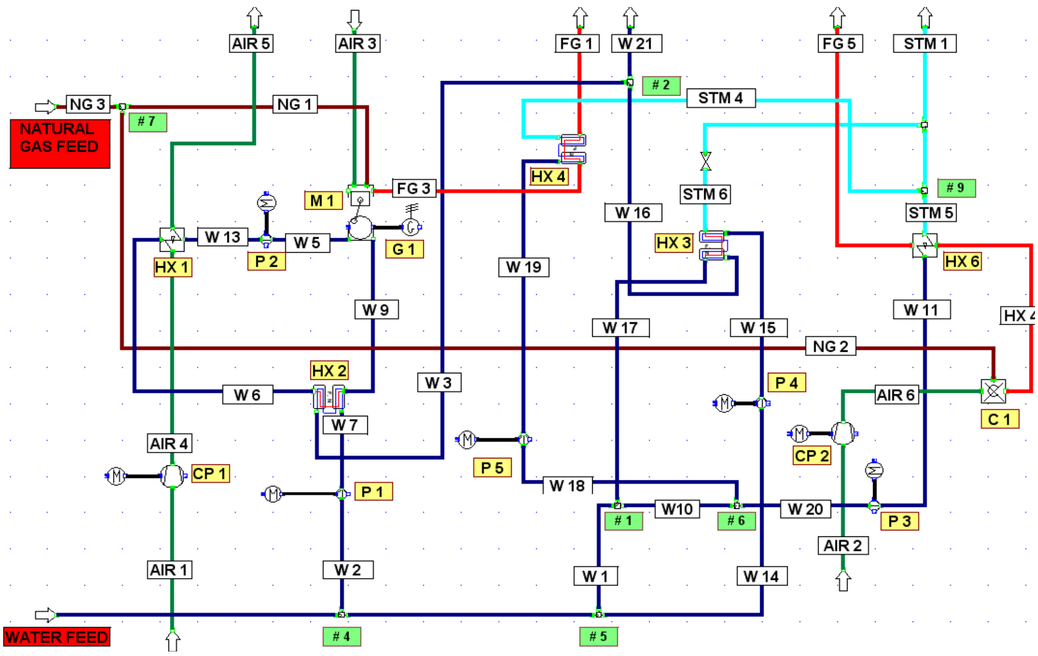

Figure 2- IPSE's worksheet diagram of the proposed cogeneration system.

The driver device (M1) is a reciprocating engine operating under an Otto cycle with natural gas (NG1) and coupled to an electric generator (G1), working at steady revolution. Simultaneous heat recovery is achieved by both the outputs of flue gas from the engine and its water cooling circuit. The rejected heat from each one of them is pretty similar in quantity, although their availability or exergy is quite different. Temperature level of the flue gas stream (FG3) enables to generate saturated steam in a heat recovery steam generator (HX5 and HX6), equipped with an auxiliary natural gas burner (C1), whenever additional heat load is required. The water cooling circuit rejects heat at HX2 to a stream of liquid water (W16). The engine original cooling water system (HX1 and P2) is kept in standby mode, for security reasons. Simulation was performed following the input data set presented on Tab. 1.

Table 1- Input data for the base load scenario for the cogeneration system at constant electricity generation (1.2 MWe) and its auxiliary heating system (combustor C1 in Fig. 2), in MW

Power demands	Without auxiliary heating	Relative weight	With auxiliary heating	Relative weight
Electricity	1.200	41.9 %	1.200	40.7 %
Hot water	1.466	51.3 %	1.548	52.5 %
Steam	0.194	6.8 %	0.200	6.8 %
Thermal	1.661	58.1 %	1.748	59.3 %
Thermal + electricity	2.860		2.948	

The output from the electrical generator (1.2 MW_e) was a main prescribed value and all heat recovery depend on it. As heat demands of the hospital could sometimes overpass the recovery achieved by the system, some extra heat was added to it by burning natural gas at C1 to generate steam at HX6. Internal combustion engines display a conversion efficiency of around 30% to 40% , and the cogeneration viability relies on the capability of recovering the complementary value of energy, rejected as heat to the environment. In the present case, thermal demand represents around 60% of the total energetic needs and points out to a favorable feasibility of cogeneration.

4. EXERGETIC ASSESSMENT FOR PLANT IMPROVEMENT

A year long project (Smith Schneider *et al*, 2006) ended up with several economic values for different plan architectures. For the specific plant showed in Fig. 1, the Purchase Equipment Costs (*PEC*) was estimated, leading to a Total Capital Investment (*TCI*) of R$ 14.337.852,00; an Annual Cost Investment (ACI) of 3.214.546,40 R$/year and an Annual Operational and Maintenance Cost (O&M) of 576.280,11 R$/year.

Based on these values, the Capital Investment and Operation and Maintenance rate Z_k was calculated for every single equipment of the plant, used straight after as input data to the simulation. Running IPSE with the exergoeconomic library led to the calculation of a set of relevant parameters, showed in Tab. 2. The only additional information to perform the simulation was the definition of some cost rates *C*, considered by the software as auxiliary equations to the problem.

Table 2- Results of the exergoeconomic simulation with IPSE for the cogeneration plant from Figure 1.

Equipment	symbol	Power (kW)	Z (R$/h)	η_{ex} (%)	Ex_d (kW/h)	cf (R$/GJ)	cp (R$/GJ)	Cd (R$/h)	r (%)	f (%)	Cd + Z (R$/h))
Moto generator	M1 + G1	1200.0	276.20	50.80	2043.40	8.53	53.20	62.70	524.00	81.50	338.95
Heater 3	HX3	595.2	20.49	21.75	134.56	140.10	796.33	67.87	468.40	23.19	88.36
Heater 1	HX1	623.6	37.60	22.20	106.90	53.36	584.40	20.54	995.10	64.7	58.21
Heater 4	HX4	884.3	25.55	67.33	144.51	53.36	103.08	27.76	93.17	47.92	53.31
Heater 2	HX2	582.3	27.84	28.28	92.77	53.36	400.02	17.82	649.56	60.96	45.66
Evaporator	HX6	194.4	15.37	45.21	79.35	48.95	173.47	13.98	254.35	52.35	29.35
Combustor 1	C1	196.1	15.37	72.45	61.15	16.28	48.95	3.58	200.63	81.08	18.95
Valve 1	V1	0	0.01	85.42	33.49	119.67	140.10	14.43	17.07	0.07	14.44
Compressor 1	CP1	59.2	9.00	81.20	10.00	53.36	123.34	1.92	131.20	82.4	10.92
Compressor 2	CP2	15.7	3.85	85.75	2.02	53.36	150.48	0.39	181.97	90.87	4.25
Pump 2	P2	19.1	0.60	82.40	3.00	53.36	76.35	0.58	43.00	50.00	1.17
Pump 4	P4	3.4	0.31	80.57	0.60	53.36	100.31	0.12	87.99	72.55	0.42
Pump 1	P1	3.4	0.30	80.60	0.60	53.36	101.07	0.11	89.40	73.03	0.42
Pump 5	P5	0.4	0.08	83.75	0.06	53.36	129.97	0.01	143.55	86.50	0.09
Pump 3	P3	0.1	0.08	83.70	0.01	53.36	365.00	0.03	583.10	96.70	0.08

Z_k → capital investment and operation and maintenance rate; η_{ex} → exergetic efficiency; Ex_d → destroyed exergy; cf → exergetic cost of fuel; cp → exergetic cost of products; C_d → destroyed exergy cost; r → relative difference of products and costs; f → exergoeconomic factor

Improvements on the plant performance starts by modifying the engine operational setup. Looking at its incoming and shortcoming streams in Fig. 1, one can identify that the increase of the temperature difference among streams W9 and W13 leads to a decrease on the engine cooling water flow rate, and therefore its exergy destruction. Although this change makes HX2 efficiency to decrease, this heat exchanger holds a 6th position on a ranking list of equipments, where the engine keeps been the priority one, as indicated by the $(Cd + Z)_k$ column. In order to obtain a higher difference among these streams, W13 stream temperature is lower down from 98.5 ºC to 90.0 ºC, followed by the rising up of W9 stream temperature from 101.0 ºC to 117.0 ºC. As a result, water flow rate is reduced on the circuit, as well as pump power at P2, that can be replaced by a smaller and cheaper element. The ensemble of changes also made HX1 exergetic efficiency to increase.

W21 stream temperature was increased from 60.0 ºC to 70.0 ºC, rising up HX3 exergetic efficiency. The efficiency of HX1 was increased by changing its surface - heat transfer product *UA* from 20.0 kW/K to 24.0 kW/K, what reduced AR5 product cost, a rejected stream. Following the same procedure, HX4's *UA* was raised from 8.0 kW/K to 11.0 kW/K, reducing CG1 product cost, again a rejected stream. Stream temperature of W3 was raised from 60.0 ºC to 68.0 ºC, leading to a better exergetic performance of HX2. Stream temperature at GC5 was lowered down from 187.0 ºC to 145.0 ºC, order to achieve a better exergetic efficiency of the steam generator (HX6 + C1). Air ratio at combustor C1 dropped down from 1.12 (12%) to 1.05 (5%), closer to a stoichiometric ratio, on the seek of a better exergetic efficiency once again. All these changes allowed changing compressor CP1 to a smaller and less expensive model, as its power was also reduced. All decision variables are listed in Tab. 2, allowing a better overview of all proposed changes.

Table 2- decision variables for the system improvement

Stream temperature at W13	98.5 ºC	Stream temperature at FG5	187.0 ºC
Stream temperature at W9	101.0 ºC	*UA* coefficient at HX1	20.0 kW/K
Stream temperature at W21	60.0 ºC	*UA* coefficient at HX4	8.0 kW/K
Stream temperature at W3	60.0 ºC	Air excess at C1	12 %

Table 3 is quite similar to Tab. 1, as it displays the same variables after all proposed changes.

Table 3- Results of the improvement after simulation with IPSE with the exergoeconomic library.

Equipment	symbol	Power (kW)	Z (R$/h)	η_{ex} (%)	Ex_d (kW/h)	cf (R$/GJ)	cp (R$/GJ)	Cd (R$/h)	r (%)	f (%)	Cd + Z (R$/h))
Moto generator	M1 + G1	1200.0	276.22	51.02	2033.05	8.53	52.95	62.40	520.97	81.57	338.63
Heater 3	HX3	623.3	20.50	31.21	109.98	153.62	606.27	60.82	294.64	25.20	81.31
Heater 4	HX4	906.48	25.55	68.24	142.12	52.96	100.86	27.10	90.43	48.53	52.64
Heater 1	HX1	549.3	37.66	32.15	77.11	52.96	450.94	14.70	751.38	71.92	52.36
Heater 2	HX2	641.5	27.84	31.62	102.93	52.96	329.94	19.62	522.94	58.65	47.46
Evaporator	HX6	200.3	15.37	46.61	80.46	48.39	169.35	14.02	249.94	52.30	29.40
Valve 1	V1	0.0	0.01	76.58	56.13	117.64	153.62	23.77	30.59	0.04	23.78
Combustor 1	C1	196.1	15.37	73.08	59.63	16.10	48.39	3.45	200.56	81.64	18.82
Compressor 1	CP1	46.0	3.86	81.14	7.83	52.96	97.10	1.49	83.31	72.10	5.35
Compressor 2	CP2	14.71	3.86	85.75	1.89	52.96	155.89	0.36	194.32	91.45	4.21
Pump 1	P1	3.1	0.31	80.57	0.54	52.96	103.69	0.10	95.76	74.82	0.41
Pump 4	P4	2.7	0.31	80.57	0.48	52.96	108.26	0.01	104.40	76.91	0.40
Pump 2	P2	1.52	0.08	85.70	0.19	52.96	79.99	0.04	51.02	67.24	0.11
Pump 5	P5	0.4	0.08	83.76	0.06	52.96	127.85	0.01	141.38	86.29	0.09
Pump 3	P3	0.1	0.08	83.76	0.01	52.96	355.58	0.003	571.34	96.61	0.08

Z_k → capital investment and operation and maintenance rate; η_{ex} → exergetic efficiency; Ex_d → destroyed exergy; cf → exergetic cost of fuel; cp → exergetic cost of products; C_d → destroyed exergy cost; r → relative difference of products and costs; f → exergoeconomic factor

The aim of all this effort was to run the cogeneration plant with lower costs and at higher efficiencies. Data at Fig. 2 compare product costs of electrical energy, steam and hot water before and after those proposed changes. There was a 2.93% reduction on the electrical energy cost, 7.80 % on steam, 0.50% on hot water and a final 2.93% for the overall cogeneration cost of products.

Figure 3 shows the improvements on efficiencies, and one can identify that the gains in exergetic efficiency lead to a better energetic performance. The rise of 3% on the energetic efficiency projects a net gain of 1.5 million of reais for a 10 years period, and gives more viability to the economic project.

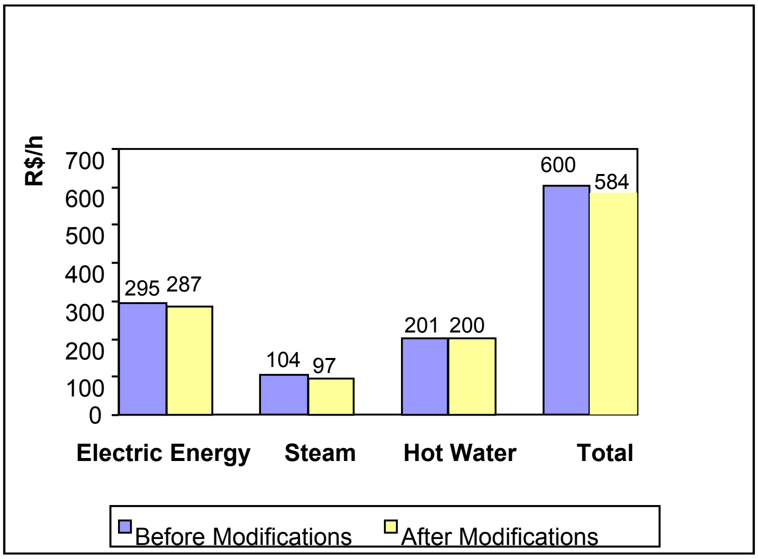

Figure 2 – Comparative between the rates of costs of cogeneration products.

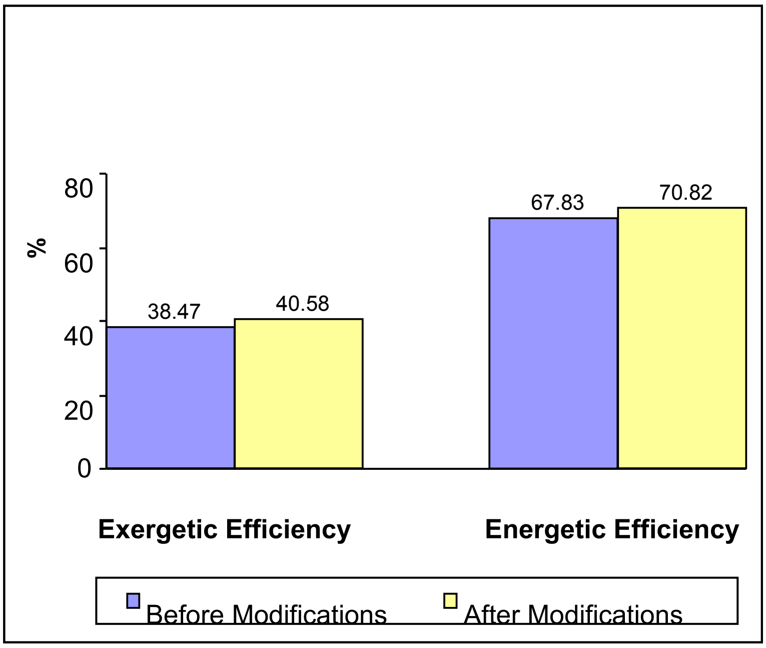

Figure 3 – Comparative between exergetic and energetic efficiency of plant.

5. CONCLUSIONS

Exergetic analysis is a powerful tool for system optimization. All economic gains give more feasibility to the project and have a positive impact on fuel consumption. The energetic simulation of the cogeneration plant was performed with a commercial software (IPSE) by using its standard library, and the exergoeconomic assessment was done with a new library, developed after the standard one, with all features for exergy and economic analysis. System improvement do not impose important engineering interventions, as the procedure identified changes to be performed on operational set points, and some downsizing in equipments, like pumps and heat exchangers.

6. ACKNOWLEDGEMENTS

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