EXEREGOCONOMIC ANALYSIS IN TWO COGENERATIONS PLANTS FOR A SHOPPING CENTER IN SALVADOR

Gean Claudio de Souza Santana
UEFS-Universidade Estadual de Feira de Santana, Av. Universitária, s/n - km 03 da BR 116, Campus Universitário, CEP: 44031-460, Feira de Santana – BA
UFBA/Escola Politécnica/DEQ/PPEQ/LEN/ Rua Aristides Novis, n°2, 3°andar, Federação/ Salvador-Bahia-Brasil UFBA – Universidade Federal da Bahia, Rua Aristides Novis, 1, CEP 4.000-000 Federação, Salvador-Ba
e-mail gclaudio@ufba.br

Ednildo Andrade Torres
UFBA/Escola Politécnica/DEQ/PPEQ/LEN/ Rua Aristides Novis, n°2, 3°andar, Federação/ Salvador-Bahia-Brasil UFBA – Universidade Federal da Bahia, Rua Aristides Novis, 1, CEP 4.000-000 Federação, Salvador-Ba
ednildo@ufba.br

Abstract. *Recent instability in the Brazilian electrical energy supply and the possibility of further instability in the future, together with the re-structuring of the power sector and government initiatives to increase natural gas participation in the system have led to discussion over the possibility of implementing cogeneration plants that utilize natural gas as an energy source in power generating for use in cooling and heating systems.*
Given this context, the use of cogeneration plants (using Otto Cycle or gas turbine) is an alternative for service sector companies (such as retail centers, universities, schools, and hospitals) that would like to implement with the goal of producing electricity and cooling for indoor environmental climate control.
The choice of the configuration (if turbine or engine, for example) for a specific type of energy demand for a company is one of the factors that determines the economic viability of plants.
This work provides a thermoeconomic or exergoconomic study in two configurations of plants cogeneration for a shopping center in Salvador, Bahia, as a complement to a previous study which performed analyses of the first and second laws of thermodynamics, showing which of the two configurations is more adequate..
Keywords*: Exergoeconomic Analyis,Cogeneration, Turbine, Motor.*

1. Introduction

Studies of the installation of cogenerative plants have, in the last two years, been the subject of debate for the alternatives for the diversification of Brazilian energy sources. In 2001 Brazil experienced an electrical energy generation crisis due to the lack of investment in the sector and consequently had electrical energy rationing, economic slowdown including the causing of unemployment, among other disruptions to the country. At that time solutions were eagerly sought to the electrical energy shortage and cogeneration presented itself as a viable solution, together with the availability of natural gas.

Currently the increase in the price of gas, together with its identification for the long term; the non-definition of an energy policy; the large reserve of water in reservoirs, among other factors have contributed to the lack of enthusiasm for investment in energy generation by cogeneration.

Investment in the generation and distribution of energy is necessary, as according to our own government, there will be a shortage of electrical energy in the near future if there is no investment in the sector. The problem is that many investors prefer to risk investment in projects that have a short term return and cogeneration offers a long term return.

The study of cogeneration has several aspects: technical, economic, political and institutional. Technically, the alternative technologies are evaluated for the installation of cogeneration units such as: if the generation will be by motor or gas turbine, if the centre will be designed to satisfy the thermal or electrical demand etc. Economically the existence of economic viability is studied and the most viable technical solution found; it can be that the most viable solution technically is not the most viable economically. From the institutional point of view a study is made of the possibility of installation of a cogeneration plant analysing the legal situation, the government's energy policy and the definition of the price of natural gas, when the fuel is natural gas.

This work studies cogeneration from the point of view of technical and economic considerations for a shopping center, installed in Salvador, considered as the second largest shopping center in the capital of Bahia.

Among the advantages of cogeneration the following can be cited:

- Diversification of Brazilian energy sources;
- Substitution of high cost generator units for cogeneration centres;
- Increase in the offer of energy available;
- Guarantee of the supply of energy;
- Primary energy economy.

For the tertiary sector like shopping centers, universities and schools, residential condominiums, distribution centres for perishable foods, hospitals, among others, the installation of cogeneration can be used for illumination, environment acclimatization, food conservation (including fruit and similar in markets), sanitation, food roasting, among other applications.

The exergetic analysis evaluates the thermodynamic performance of an energetic system and the efficiency of the components by the quantifying of generation of entropy and its components. On the other hand, the exergoeconomic analysis estimates the unit cost of each product such as electricity and steam/hot water and quantifies the monetary losses due to irreversibilities (Kwak et. Alil., 2003). For complex energetic systems such as cogeneration plants and combined cycle plants, in which there is more than one product from the same input, it is important to determine the unit costs of the products, with this the exergoeconomic which contains concepts of exergy together with economic principles permit the unit cost of the products to be obtained (Kwon et al. 2001).

The shopping center under study currently consumes 3 MW of electrical energy, part of this being to supply the thermal demand of the center, about 1.5kW, the equivalent of 1500TR, according to estimates taking into account the characteristics of the equipment for the production of chilled water in the shopping center. In this situation, the power-heat ratio is 1 and for this situation a cogeneration plant will be analysed utilising a turbine and a natural gas motor.

2. Analysis of the Proposed Configurations

In the first configuration the natural gas is burned in two motors, one of 2216 kW and another 470 kW, which work with a generator to produce electrical energy. The thermal energy contained in the exhaust gases are used in the production of steam in the recovery furnace. The climate control of the shopping center is made by chilled water produced in absorption chillers which use the steam as a source of energy and produce around 362 TR's. The rest of the thermal demand is supplied by a compression chiller and is the equivalent of 1138TR's approximately.

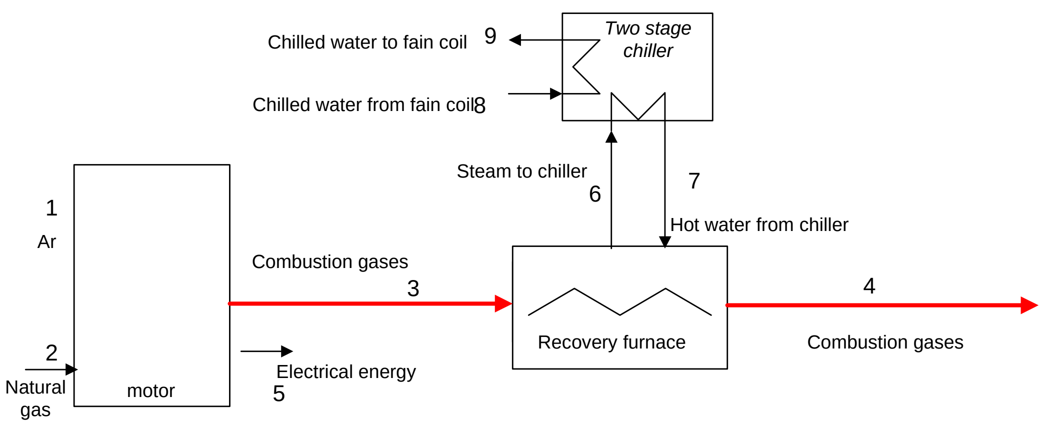

Figure 1 – Simplified diagram of the 1st configuration proposed for the shopping center under study.

The second configuration will comprise of a turbine with the capacity to produce 1663 kW of electrical energy. The residual energy of the exhaust gases will be utilized for steam production for use in the steam absorption chiller. The chiller has a capacity to supply 2000 TR's, that is 500 TR higher than predicted.

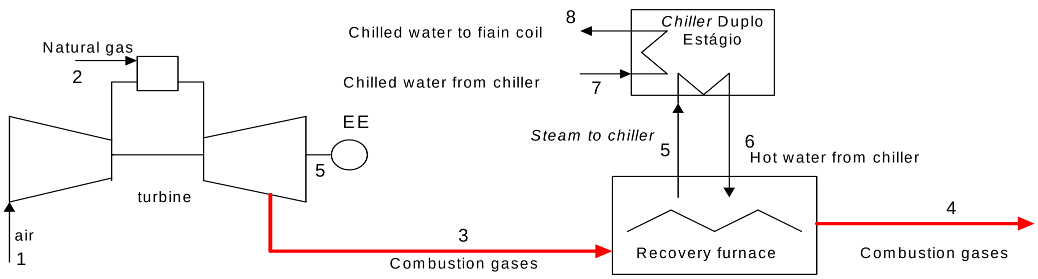

Figure 2 – Simplified diagram of the second configuration proposed for the shopping center under study.

Table 1 – Thermodynamic properties of the flows necessary for the thermodynamic analysis for the 1st configuration.

Points	Description	Temp(°C)	$\dot{m}$ (kg/s)	h – (kJ/kg)	s-(kJ/kg)	ex –(kJ/kg)
2	Fuel	25.0	0.125	48,528	-	50,954.4
3	Gas Fuel	359.0	4.99	352.7	0.7903	117.1
4	Gas Fuel	160.0	4.99	134.4	0.3738	22.94
6	Sat steam	175.2	0.4357	398	1.25	29.93
7	Sat liq	95.0	0.4357	2773.0	6.624	803.2
8	Sat liq	12.0	59.21	50.38	0.18	1.22
9	Sat Liq	7.0	59.21	29.41	0.106	2.37

Reference conditions: T_0 = 25°C, P_0 = 101,3kPa, relative humidity = 62.47 %, absolute humidity = 0,018804 kg water/kg of dry air. Sat = saturated

Table 2 – Thermodynamic properties of the flows necessary for the thermodynamic analysis of the 2nd configuration.

Points	Description	Temp(°C)	$\dot{m}$ (kg/s)	h – (kJ/kg)	s-(kJ/kg)	ex –(kJ/kg)
2	Fuel	25.0	0.223	48,528	-	50,954.4
3	Gas fuel	359.0	13.77	571.8	1.085	248.4
4	Gas fuel	160.0	13.77	132.2	0.3677	22.57
6	Sat steam	175.2	2.421	398	1.,25	29.93
7	Sat liq	95.0	2.421	2773.0	6.624	803.2
8	Sat liq	12.0	239.87	50.38	0.18	1.22
9	Sat liq	7.0	239.87	29.41	0.106	2.37

Reference conditions: T_0 = 25°C, P_0 = 101,3kPa, relative humidity = 62.47 %, absolute humidity = 0,018804 kg water/kg of dry air. Sat = saturated

The exergy of water and the exhaust gases was calculated from the following expression:

$$ex = (h - h_0) - T_0\ (s - s_0) \tag{1}$$

For the exhaust gases

$$\Delta h = \int c_p dT\ ,\ \Delta s = \int \frac{c_p}{T} dT\ \text{ e }\ c_p = \sum_j x_i c_{pi} \tag{2}$$

Where $c_{pi} = A_i + B_i T + C_i T^2$ (CALLEN, 1960) and represents the calorific capacity of the compound i present in the exhaust gases, calculated from the composition of natural gas, mass of air and fuel. The average price of natural gas for the exergoeconomic calculations was R$0.50 per m^3.

2.1 Definition of Fuels, Products and losses (F-P-L) for each subsystem

Tables 3 and 4 show for each control volume in each configuration the initial investment, the fuels, the products and the losses.

Table 3. Definition of F-P-L in the 1st configuration.

Equipment	Z_i (R$)	$\dot{Z}_i$ (R$/h)	Fuels (kW_{ex})		Products(kW_{ex})		Losses(kW_{ex})	
Motors	2,500,250	66.92	Ex_1+Ex_2	6,887.15	Ex_3-Ex_4+ Ex_5	3,270.32	Ex_4	
Recov. Furn.	132,000	3.53	Ex_3-Ex_4	584.32	Ex_6-Ex_7	336.91	-	-
Chiller	500,000	13.38	Ex_6-Ex_7	336.91	Ex_9-Ex_8	68.05	-	-

Table 4. Definition of F-P-L for the 2nd configuration.

Equipment	Z_i (R$)	$\dot{Z}_i$ (R$/h)	Fuels (kW_{ex})		Products(kW_{ex})		Losses(kW_{ex})	
Turbine	1,164,100	31.16	Ex_1+Ex_2	11,362.83	Ex_3-Ex_4+ Ex_5	4,772.21	Ex_4	310.79
Recov. Furn.	397,800	10.65	Ex_3-Ex_4	3,109.21	Ex_6-Ex_7	1,872.09	-	-
Chiller	1,622,477	43.42	Ex_6-Ex_7	1,872.09	Ex_9-Ex_8	275.85		

Where Z_i is the total cost of investment and $\dot{Z}_i$ is the cost of economic amortization per hour:

$$\dot{Z}_i = \varphi Z_i \tag{3}$$

Factor φ is defined as:

$$\varphi = \frac{f_{O\&M}}{\tau}\left[\frac{r(1+r)^t}{(1+r)^t - 1}\right] \tag{4}$$

where $f_{O\&M}$=1,05 is the factor of operation and maintenance; τ=5760 h/year, is the average annual time for operation of the plant, r=12% per year is the discount rate of cash flow, and t=15 years is the projected useful life of the plant.

Considering the control volumes in figures 1 and 2, the matrix for the exergetic and exergoeconomic costs are (Lozano et. al., 1993; Lozano and Muñoz, 1986):

$$\left[A\right]\cdot\left(\dot{E}x^*\right) = \left(\dot{Y}\right) \tag{5}$$

and

$$\left[A\right]\cdot\left(\dot{D}\right) = \left(\dot{Z}\right) \tag{6}$$

Where [A] is inspired by the incidence matrix of Leontieff, $\left(\dot{E}x^*\right)$ and $\left(\dot{D}\right)$ are respectively the custom exergetic vector and custom exergoeconomic vector – related to the flows, and $\left(\dot{Y}\right)$ and $\left(\dot{Z}\right)$ are respectively the cost of exergetic amortization vector and the cost of economic amortization vector – related to the contributions external to the system.

The exergetic cost is a conservative property, that is the sum of all exergetic costs which enter the control volume is equal to the sum of all exergetic costs which leave the control volume. With this proposition applied to the three control volumes for each configuration, three equations result. Nevertheless, the system presents 9 unknowns, which suggests the adoption of the following propositions (Lozano et. al., 1993; Lozano and Muñoz, 1986):

1) The flows of the external losses must be attributed to nil exergetic costs, in this way the exhaust gases leaving the chimney will have an exergetic cost;
2) The natural gas and air have an exergetic cost equal to exergy, $\dot{E}x_1^* = \dot{E}x_1$ e $\dot{E}x_2^* = \dot{E}x_2$
3) For a system that has products formed by various flows, the unit exergetic cost will be the same for each of them (rule of products) therefore it can be concluded that the unit exergetic cost of the products of the motor/turbine are equal ($k_i = \dot{E}x_i^* / \dot{E}x_i$), $k_3 = k_5$
4) Another consideration is to consider that $k_7 = k_6$ and $k_9 = k_8$

The matrices obtained for the exergetic and exergoeconomic analysis were resolved using the Gauss method implemented in Fortran.

3. Results and Conclusions

This work made an exergetic and thermo-economic study in two configurations of plant for cogeneration to attend the thermal and electrical demand of a shopping center. To determine the plant costs, a comparative analysis was made of the energy and exergy data of the various flows in the system, taking into account the point of view of the 1st and 2nd laws of thermodynamics.

The method of exergetic cost by Valero et al. (1986) was chosen to determine the internal costs of the system. The first stage was to select the control volumes with their fuels and products. For these selected control volumes, shown in figures 1 and 2, a balance of exergetic cost was made. We can see that the flows 1 and 4 for both configurations are zero.

Table 5 – Exergetic and Exergoeconomic Costs of the Two Configurations.

First Configuration					**Second Configuration**				
i	Exergetic		Exergoeconomic		i	Exergetic		Exergoeconomic	
	$\dot{E}x_i^*$ (kW)	k_i^*	$\dot{D}_i$ (R$/h)	c_i^{Ex} (R$/GJ)		$\dot{E}x_i^*$ (kW)	k_i^*	$\dot{D}_i$ (R$/h)	c_i^{Ex} (R$/GJ)
1	0	0	0	0	1	0	0	0	0
2	6887.15	1	354.78	14.31	2	11,362.83	1.0	547.20	13.38
3	1230.58	2.106	75.34	17.00	3	7,645.61	2.235	389.14	14.14
4	0	0	0	0	4	0	0	0	0
5	5656.72	2.106	346.33	17.00	5	3,717.22	2.235	189.20	14.14
6	1278.02	3.652	81.92	17.79	6	7,941.53	4.084	415.24	14.52
7	47.62	3.652	3.05	17.79	7	295.93	4.084	15.47	14.52
8	1305.12	18.069	97.85	20.83	8	8,110.97	27.717	470.15	16.10
9	2535.62	18.069	190.09	20.83	9	15,756.58	27.717	913.33	16.10

In a previous work, Santana et al. (2004) made an energetic and exergetic analysis for the same systems proposed here and concluded that the first configuration presented an efficiency of 1st and 2nd laws greater than the second configuration. The efficiency of the 1st and 2nd laws was 77.7% and 51.9% for the first configuration and 66.9% and 30.4% for the second configuration respectively. The superior efficiency of the 1st configuration can be proven by the lower exergetic unit costs in relation to the 2nd configuration which are available in Table 5. However, the exergoeconomic analysis showed that the exergoeconomic unit costs for the 2nd configuration were less than the 1st configuration, which is influenced by the installation costs. In other words, the penalty for a greater inefficiency in the 2nd configuration was compensated in the installation costs.

Another fact to be taken into consideration is the operation of the turbine for partial loads. Perhaps an analysis of these configurations for the partial loads would find another conclusion.

3. Acknowledgements

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4. References

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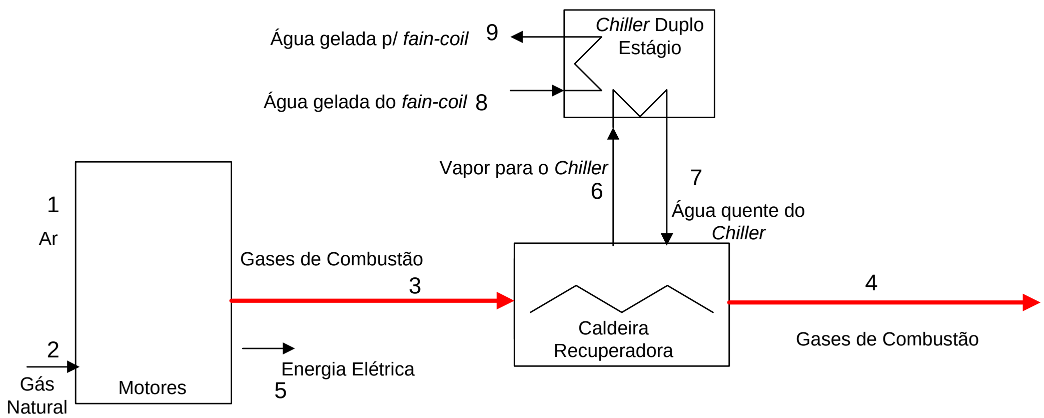

Figure 1 vocabulary (couldn't open graphic to type translation)

Ar = air
Gas natural = Natural gas
Motores = motors
Gases de Combustão = combution gases
Energia electrica = electrical energy
Caldeira Recuperadora = recovery furnace
Vapor para chiller = steam to chiller
Água gelada do fain coil = chilled water from fan coil
Agua gelada p/fain coil = chilled water to fan coil
Chiller duplo estagio = two stage chiller
Agua quente da chiller = hot water from chiller

Figure 2
As above and…
Turbine = turbine