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COGENERATION SYSTEMS FOR A DAIRY INDUSTRY. COMPARATIVE EXERGY AND THERMOECONOMIC EVALUATION.

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Abstract. *This paper presents a comparative thermoeconomic analysis of cogeneration systems, utilizing natural gas, designed for a dairy industry in Colombia. Steam, chilled water, compressed air, electricity, cooling tower water and potable water must be provided for the processes of the plant. These comparisons were developed for a scenario in which the utilities plant can generate a surplus of electricity to be exported. The cogeneration systems are a steam cycle with extraction/condensation steam turbine, a gas turbine based system and a gas engine based system. In the thermoeconomic analysis the equality and extraction cost partition methods were utilized in order to determine the production costs of the utilities for each process in the plant, in the original operating condition and for each one of the considered operating scenarios for the cogeneration plants. This comparison indicates the feasibility of the cogeneration systems for each production scenario.*

Keywords*. Exergy, Thermoeconomic, Cogeneration, Dairy Industry.*

Nomenclature

η	: efficiency
B	: exergy rate (kW)
C	: cost rate(US$/s)
c	: specific cost (US$/kJ)
GEEq	: gas engine with equality method
GTEq	: gas turbine with equality method
GTEx	: gas turbine with extraction method
I	: Investment cost rate(US$/h)
MMBtu	: 10^6 Btu
OOC	: original operating condition
STEq	: steam turbine with equality method
STEx	: steam turbine with extraction method
TCR	: Total Cost Rate (US$/h)

Subscripts

equip	: equipment
i	: inlet
o	: oulet

1. Introduction

The implementation of cogeneration in the Colombian industrial sector will be of great relevance in order to provide a rational utilisation of fossil fuels and reduction of electricity demand from the National Interconnected System (SIN). The use of cogeneration systems in the Colombian industrial sector will be important because this sector is the major consumer of natural gas, oil and coal and the second major consumer of electricity in the country.

In the industrial sector, food industry is the major energy consumer. It also has the greater cogeneration potential. Inside the food industry, the dairy industry is a very interesting one because it demands various utilities and has a great variety of products and processes.

Colombia has important natural gas reserves and the cogeneration systems could optimise its use. In addition to this fact, the substitution of the fuel oil used in the dairy industry by natural gas could bring environmental advantages.

The dairy industry, used as a model for the analysis in this work, produces milk, yogurt, cheese, oats, fats and desserts of different types. The whey, that is a by-product of the processes, is used in the production of some drinks and in the feeding of pigs that are sold alive.

The utilities demand curves of the whole plant were constructed based on the demands of the various equipment and on their hourly tendency. In order to do that, it was made a survey of the processes that take place in every section of the plant and an inventory of the equipment operation in each process. The utilities required by each equipment were identified and the thermal loads and mass flow rates were all calculated in an hourly basis (Loboguerrero, 2001).

2. Utilities Plant Description

This dairy industry demands electricity, steam, chilled water, compressed air and potable water (See Fig. (1) and Fig. (2)).

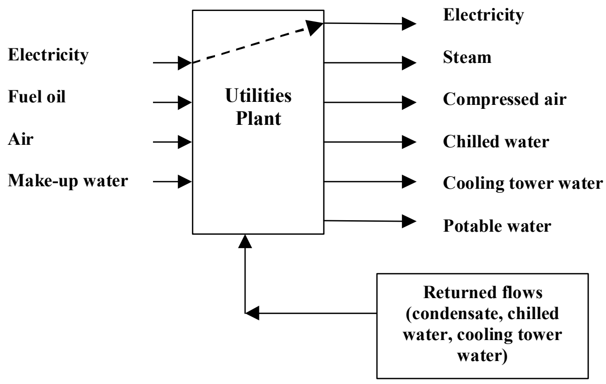

Figure 1. Scheme of the Utilities Plant.

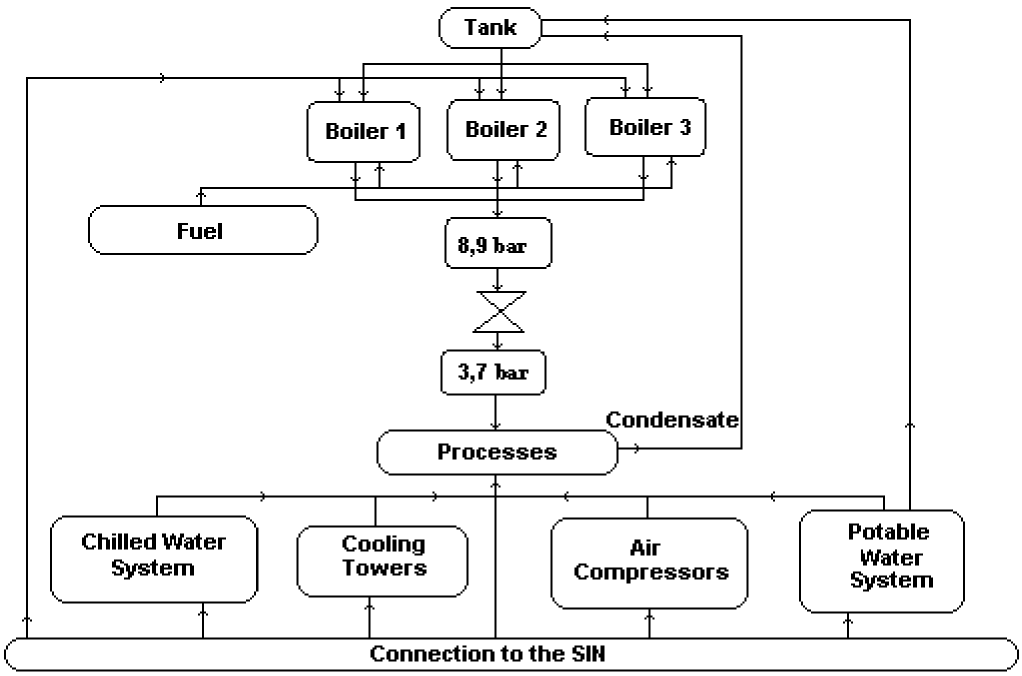

Figure 2. Facilities Distribution Lines.

The energy consumption/ demand conditions and the means of production of the utilities for this plant are as follows:

- The plant uses electricity to operate pumps, stirring rods, beaters, mills, slicing machines, packing machines, heating systems, fans and compressors, among others. The average power demand is 2.89 MW with a peak power demand of 3.16 MW (See Fig. (3)). The electricity, which is bought to an energy retailer, is obtained from the National Interconnected System (SIN) at 34.5 kV and transformed to 220 V and 440 V. The electricity tariff is negotiated. On October/2000, the plant paid 60.56 US$/MWh.

- Steam is used to pasteurize, to sterilize, to heat water and air and for cleaning purposes. It is also used in packing machines and industrial pots, among others. The majority of the applications use the steam enthalpy of condensation at 369.92 kPa and 414.15 K. The average energy demand of steam is 3.42 MW with a peak demand of 5.18 MW (See Fig. (3)). This represents an average demand of 1.81 kg/s, with a peak demand of 2.42 kg/s. The plant has three boilers (one in stand-by) that can produce 2.49 kg/s, 2.15 kg/s and 1.36 kg/s of steam at 889.80 kPa and 448.15 K, giving a total steam rate of 6 kg/s.

- Chilled water is employed in pasteurizing machines, cooling machines, production tanks, packing machines, cooling rooms and in the salt water in which cheese is submersed during manufacture, among others. The average energy demand of chilled water is 893.45 kW with a peak demand of 1705.14 kW (See Fig. (3)). For the production of chilled water, the plant has an ammonia system composed of three compressors (one of them in stand-by), two evaporative condensers, six expansion valves and 8 km of pipes. The pipes are submersed in six reservoirs in which water is cooled from 284.18 K to 274.15 K, in average. The system has a refrigerating capacity of 1825 kW.

- Cooling tower water is used in pasteurizing machines and production tanks, among others. It satisfies the cooling needs in processes where the use of chilled water is not required. In other processes, cooling tower water is employed in series with chilled water. The average energy demand of cooling tower water is 389.71 kW with a peak demand of 903.00 kW (See Fig. (3)). The cooling tower water is produced in a system composed of five cooling towers, which cools water from 308.15 K to 296.15 K, in average.

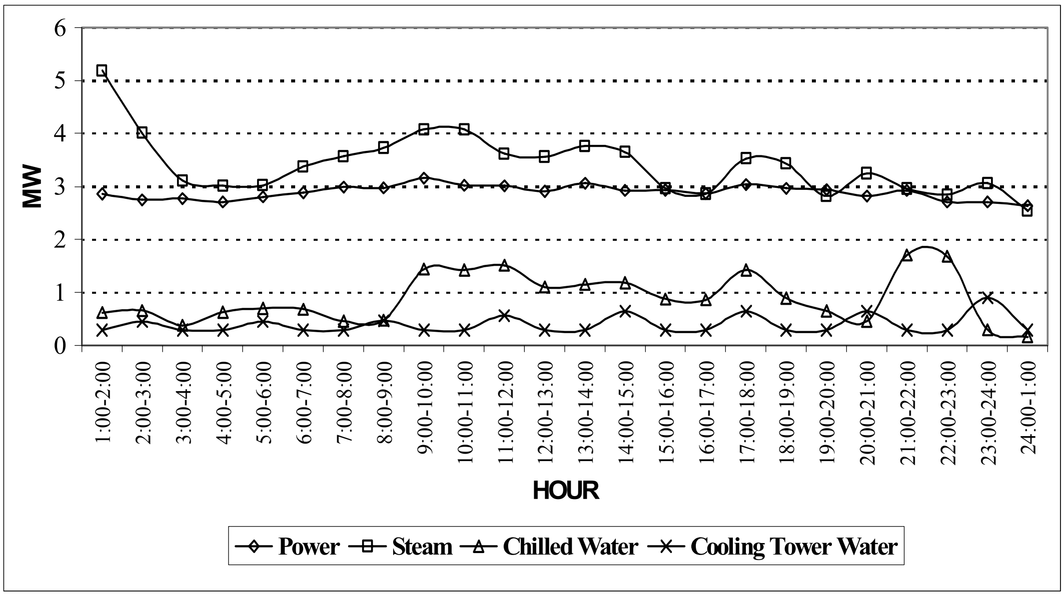

Figure 3. Power, Steam, Chilled Water and Cooling Tower Water Demands.

- Compressed air is employed in processes such as pressing, cutting and packing. The average demand is 0.38 kg/s with a peak demand of 0.45 kg/s (See Fig. (4)). The plant has a system composed of six compressors that can generate 0.69 kg/s of compressed air at 819.82 kPa, 293.15 K and relative humidity of 85%.

- Potable water is used in the manufacture of various products, preparation of ferments and cleaning, among others. The average demand is 15.73 kg/s with a peak demand of 22.10 kg/s (See Fig. (4)). A system of pumps extracts underground water from four wells. The water is then purified in three parallel treatment plants and stored in tanks. The system can supply 22.69 kg/s of water at 274.94 kPa and 291.15 K.

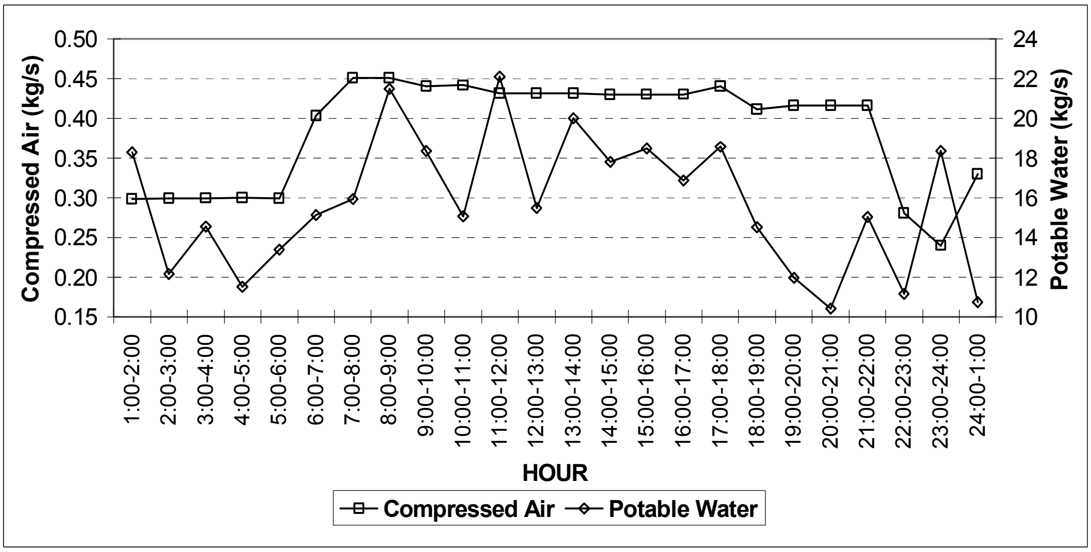

Figure 4. Compressed Air and Potable Water Demands.

3. Cogeneration Systems

Figure (5) shows a scheme of the cogeneration utilities plant. The cogeneration systems analyzed in this study are: a steam cycle with extraction/ condensation steam turbine, a gas turbine based system and a gas engine based system.

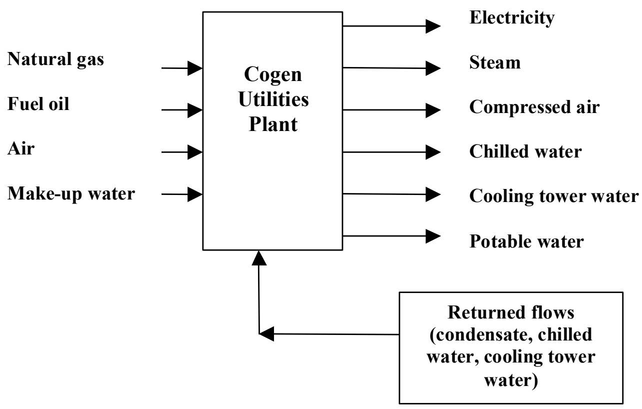

Figure 5. Cogeneration Utilities Plant.

The steam turbine based system is composed of an extraction/condensation steam turbine and a high pressure steam generator. The electricity generation capacity is 5 MW. Figure (6) shows this configuration. Steam is generated at a pressure of 4199.06 kPa and 596.15 K. This steam is sent to the extraction/condensation steam turbine and the required steam flow rate, for each hour of the day, is extracted at 399.91 kPa.

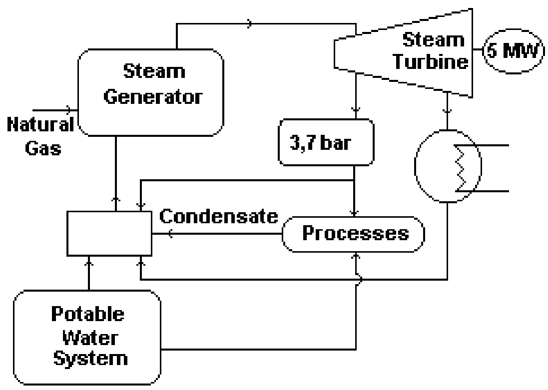

Figure 6. Extraction/Condensation Steam Turbine Based Cogeneration System.

The gas turbine based system is made up of a gas turbine of the same capacity of the steam turbine (the combustion chamber outlet temperature is 1295 K) and a waste heat boiler that can produce the required steam flow for each hour at 889.8 kPa. This configuration is shown in Fig. (7).

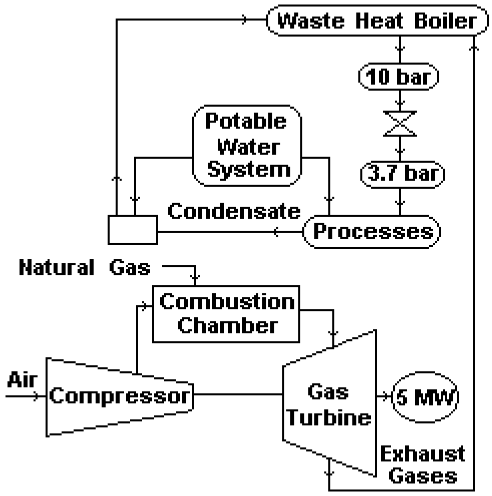

Figure 7. Gas Turbine Based Cogeneration System.

The gas engine based system, shown in Fig. (8), is made up of a gas engine with an electricity generation capacity of 4.5 MW and a waste heat boiler with a steam generation capacity of 0.75 kg/s at 849.81 kPa. The remaining steam that is required is generated in the existing boilers.

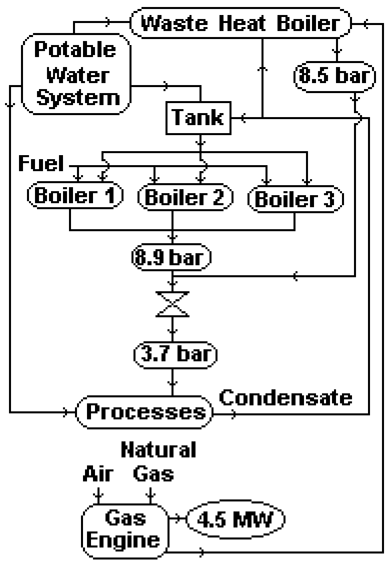

Figure 8. Gas Engine Based Cogeneration System.

4. Comparative Exergy And Thermoeconomic Analysis

The exergy performance of the utilities production systems was quantified by calculating the overall exergy efficiency of the plants (Oliveira and Van Hombeeck, 1997 and Tsatsaronis, 1995).

The exergy efficiencies were calculated for the utilities plant in the its original operating condition and with the described cogeneration systems. Their values are presented in Tab.(1). The reference atmosphere has as pressure of 73.98 kPa, temperature of 291.15 K and relative humidity of 75%.

Table 1. Exergy Efficiency of the Utilities Plant.

Production System	Exergy Efficiency (%)
Original	24.0
Steam turbine cogeneration	21.3
Gas turbine cogeneration	30.4
Gas engine cogeneration	30.5

The gas turbine and the gas engine based systems present the best exergy efficiency values. The exergy efficiency of the steam turbine based system is smaller than the original one because in the calculation of the exergy efficiency of the original system it was not considered the fuel required to generate the purchased electricity.

The performance behaviour of the plant in the original operating condition and for each one of the considered operating scenarios of the cogeneration plants was simulated by modeling all the processes with the aid of the software EES (2000). The corresponding production costs of each utility and the costs of the utility streams along the plant were estimated in an hourly basis.

The production costs of electricity and steam in the gas turbine and steam turbine based cogeneration systems, were calculated based on two programs in EES elaborated for the assessment of such systems in Teixeira and Oliveira (2001). The programs were modified in order to be dimensioned and coupled to the dairy industry model developed in the present work. The production costs of electricity and steam in the gas engine based cogeneration system as well as all the cost streams along the plant, were calculated with programs specifically elaborated for this purpose.

The following parameters were used:

- Steam turbine based system cost (including installation and commissioning costs): US$ 5,694,000
- Gas turbine based system cost (including installation and commissioning costs): US$ 3,139,500
- Gas engine based system cost (including installation and commissioning costs): US$ 4,680,000
- Connection to the gas grid: US$ 22,682
- Annual operational and maintenance costs: 10% of investment cost
- Natural gas price: 2.5, 3.5 and 4.5 US$/MMBtu
- Interest rate: 9% per year
- Capital recovery period: 10 years
- Load factor: 0.89
- Average operation time: 7796 h/year
- Inflation is not considered

The natural gas price at present is around 4.5 US$/MMBtu, but being able to negotiate as a not regulated user, the plant will be capable of obtaining better prices.

It was considered that the capital invested in the utilities production system, presently in use, has already been recovered. However, labor costs have been calculated from information furnished by the accounting department of the plant and included in the analysis.

The generalized cost balance equation for any equipment can be written, in terms of cost rates (US$/s), as:

$$\Sigma\, c_i B_i + C_{equip} = \Sigma\, c_o B_o \qquad (1)$$

To determine the cost structure of the plant, the adoption of cost partition methods is necessary (Vertiola and Oliveira, 1996). Two methods were considered: equality and extraction. In the gas engine, due to the available system information, only the equality method was used. Results for the utilities costs are presented from Fig. (9) to Fig. (15).

With natural gas at 4.5 US$/MMBtu, only the gas turbine based system with the equality method can produce electricity, compressed air, potable water and cooling tower water at a lower cost than in the original operating condition. With the gas price at 2.5 or 3.5 US$/MMBtu, only the steam turbine based system produces these utilities at a considerably higher cost, as shown in Fig. (9) to (12).

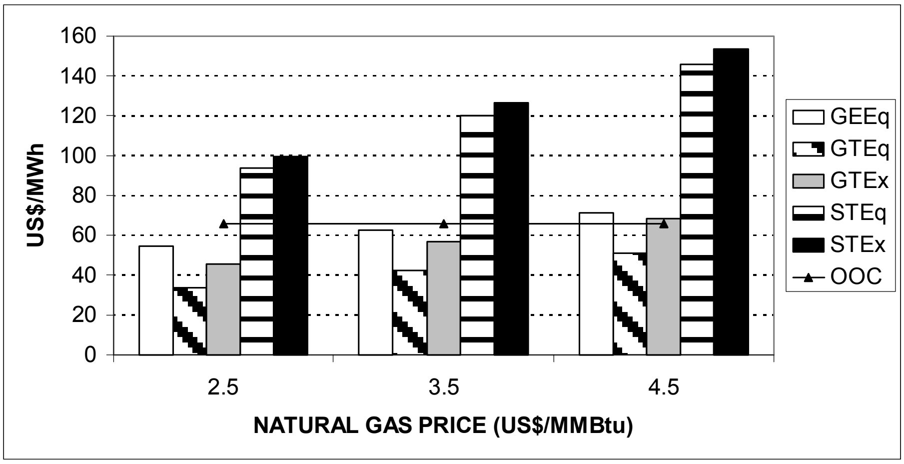

Figure 9. Mean Electricity Cost.

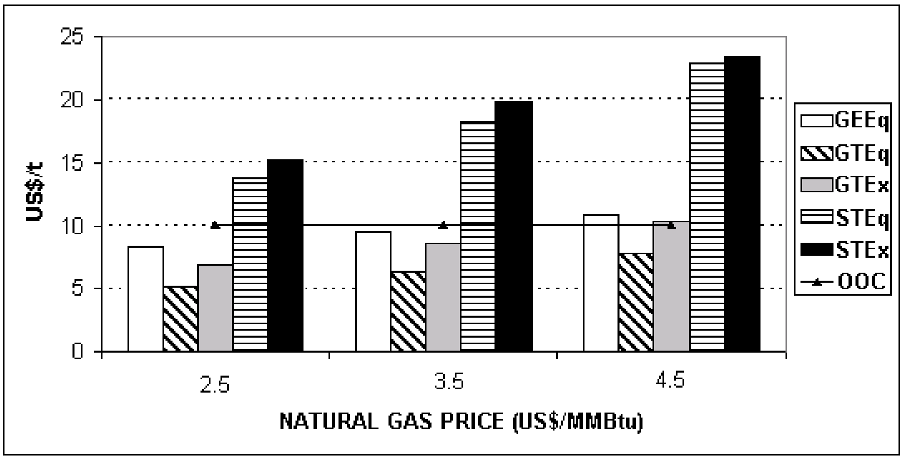

Figure 10. Mean Compressed Air Cost.

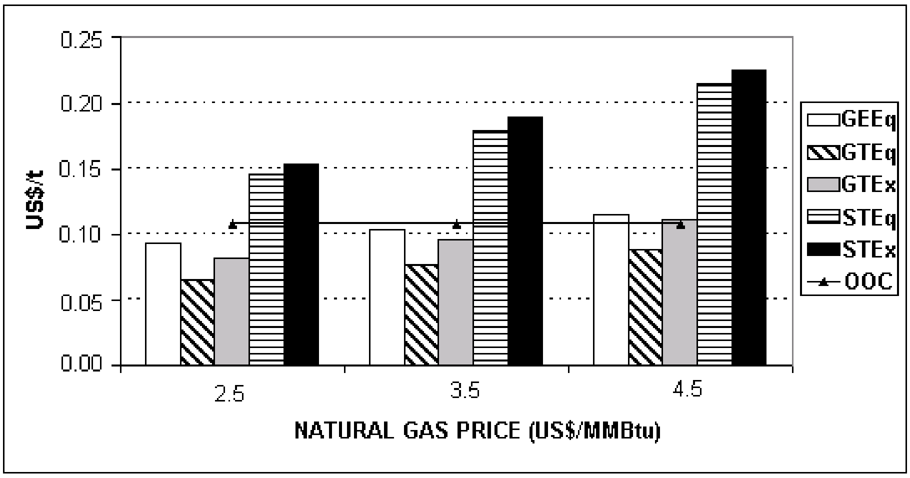

Figure 11. Mean Potable Water Cost.

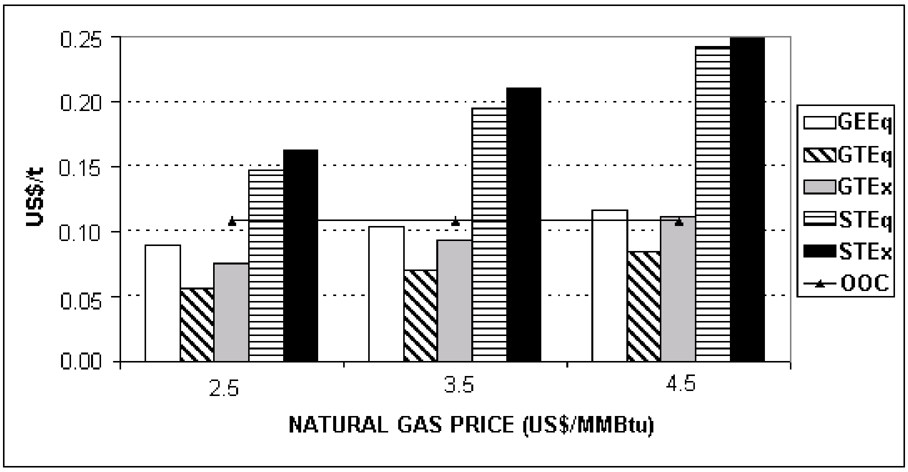

Figure 12. Mean Cooling Tower Water Cost.

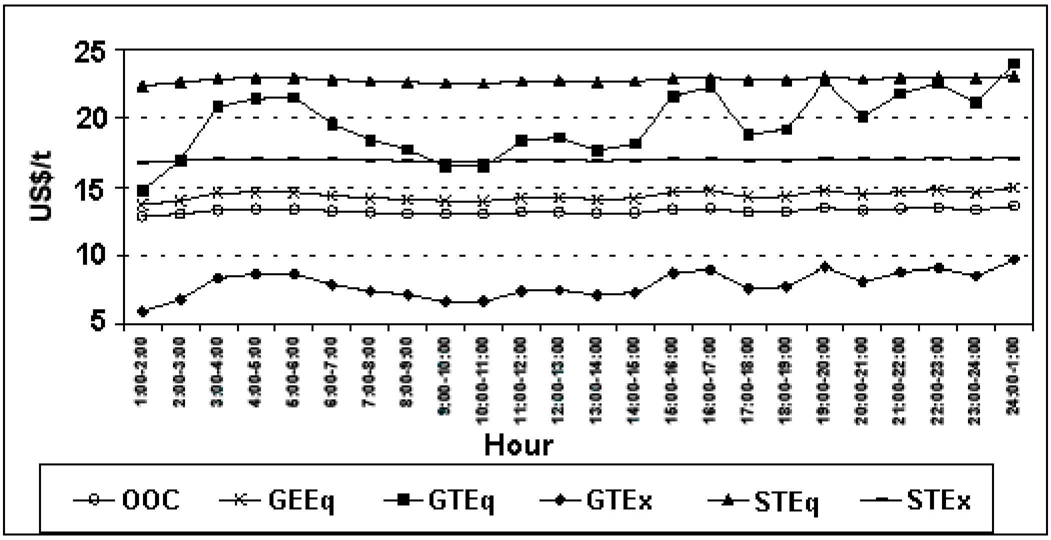

Figure 13. Steam Cost for Natural Gas at 3.5 US$/MMBtu.

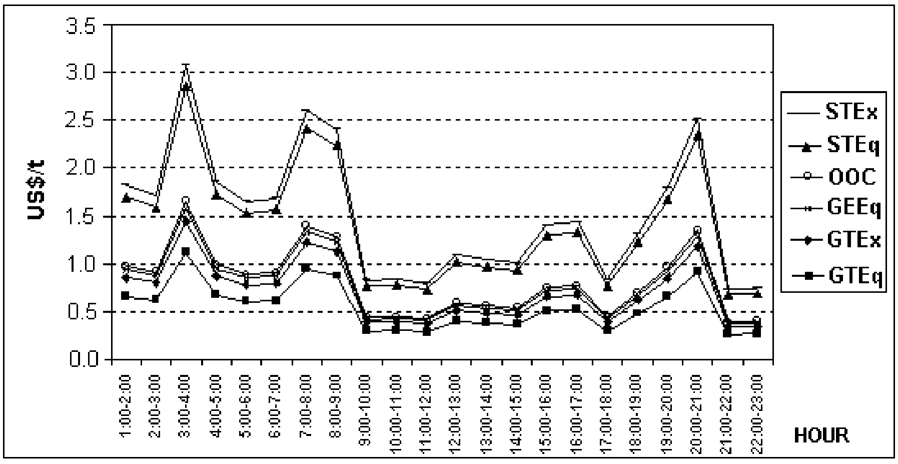

Figure 14. Chilled Water Cost for Natural Gas at 3.5 US$/MMBtu. (Part 1).

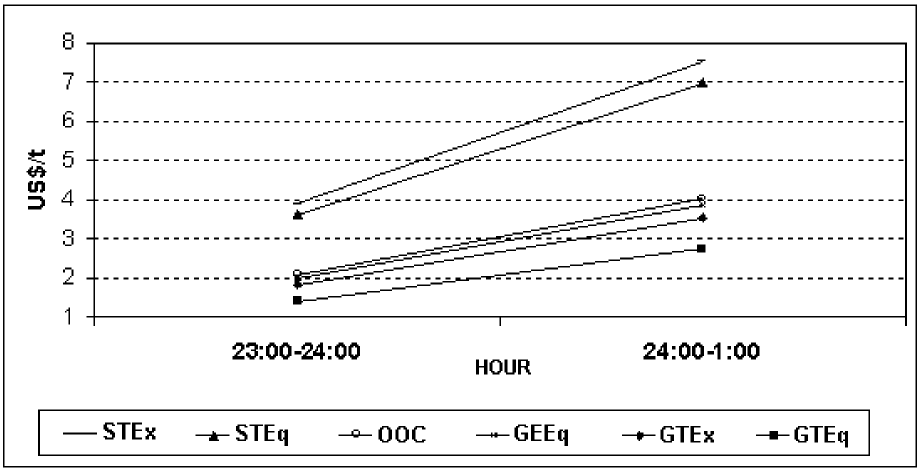

Figure 15. Chilled Water Cost for Natural Gas at 3.5 US$/MMBtu. (Part 2).

Steam production costs are presented for the 24 hours of the day because, for the gas turbine based cogeneration system, the quantity of steam generated and consequently the investment cost per unit of mass varies appreciably. With natural gas at 3.5 US$/MMBtu, only the gas turbine based system with the extraction method can produce steam at a lower cost than the original operating condition, as shown in Fig. (13).

Chilled water production costs are also presented for the 24 hours of the day. There are hourly variations in this case because the cost is calculated per unit of mass of chilled water consumed and the consumption varies during the day. With the gas price at 3.5 US$/MMBtu, only the steam turbine based system produces chilled water at a considerably higher cost, as shown in Fig. (14) and Fig. (15).

The economic performance of the systems can be assessed by means of the Total Cost Rate (*TCR*) of the systems, considering the investment cost (including the costs of the equipment, installation, and connection to the pipeline, operation and maintenance) and the cost associated to the fuel:

$$TCR = I + c_{fuel}\, B_{fuel} \qquad (2)$$

Table (2) presents the *TCR* for the analyzed cogeneration systems and for the three natural gas prices.

These values can be compared with 268.39 US$/h, corresponding to the *TCR* in the original operating condition. Only the gas turbine based system with natural gas at 2.5 US$/MMBtu presents a *TCR* somewhat lower.

Table 2. Total Cost Rate (US$/h).

NATURAL GAS PRICE (US$/MMBtu)	SYSTEM		
	STEAM TURBINE	GAS TURBINE	GAS ENGINE
2.5	411.16	267.05	326.45
3.5	503.41	331.68	368.98
4.5	595.76	396.38	411.54

But the cogeneration systems considered produce more electricity than is required in the plant. Then, the surplus could be negotiated in the Colombian Electricity Pool or directly with an electricity retailer or a non regulated user. Taking the mean price in the Electricity Pool during 2000 as a reference, a *TCR* considering these revenues can be obtained. See Tab. (3).

Table 3. Total Cost Rate Selling Electricity Surplus (US$/h).

NATURAL GAS PRICE (US$/MMBtu)	SYSTEM		
	STEAM TURBINE	GAS TURBINE	GAS ENGINE
2.5	380.31	236.20	304.22
3.5	472.55	300.83	346.74
4.5	564.90	365.52	389.31

Again, only the gas turbine based system with natural gas at 2.5 US$/MMBtu presents a lower *TCR*.

5. Concluding Remarks

The use of the exergy concept allows calculating the production costs of the utilities in a rational way, characterizing the real value of each utility.

From a thermoeconomic standpoint it is interesting to note the differences of the utilities costs resulting of different cost partition methods. The utilization of these methods evidences the importance of costs of products in a cogeneration plant according to its objectives.

The results show that the gas turbine based system is a good alternative for the implementation of cogeneration in the Colombian dairy industry. But, besides the results given by the thermoeconomic analysis some other aspects must be considered to choose the best cogeneration system. Aspects such as environmental impacts, operational flexibility and reliability of the equipment must also be taken into account.

The results also indicate that the panorama for the dissemination of the cogeneration technology in the sector is not satisfactory due to the high price of natural gas and relative low price of electricity. This situation could be improved with a natural gas tariff policy that stimulates cogenerators with lower natural prices.

6. References

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