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# Thermoeconomic Evaluation of Cogeneration Systems for a Chemical Plant

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## Abstract

This paper presents the comparative exergy and thermoeconomic analysis of three cogeneration systems designed for a chemical plant. These systems must produce steam and electricity for the processes of the plant. These comparisons are developed for two scenarios: in the first one the systems generate steam and electricity for the plant and in the second one the systems generate steam and electricity for the plant and export electricity. The cogeneration systems are: a steam cycle with condensation-extraction steam turbine, a gas turbine based system and a combined cycle based system.

The exergy analysis developed for the cogeneration systems evaluates the exergy efficiency and the exergy destroyed in each set of equipment, as well as the overall cogeneration plant performance. The overall exergy efficiency of the plants and the exergy efficiency of each set of equipment are defined as the ratio of the useful exergetic effect of the equipment/system to the consumed exergy. The importance of each set of equipment in the overall exergy efficiency is quantified by the use of the factor f, defined as the ratio of the supplied exergy in a particular set of equipment to the consumed exergy in the plant. Equality and extraction cost partition methods are utilised (in the steam and gas turbines) in order to determine the production costs of steam (at 6 and 18 bar) and electricity, for each one of the considered operating scenarios of the plants. This comparison indicates the feasibility of the cogeneration systems for each production scenario.

*Key words: exergy analysis; thermoeconomic analysis; cogeneration in chemical plants*

## 1. Introduction

The projected increase of the natural gas consumption in Brazil has motivated several substitution studies in industrial processes in order to analyse the feasibility of the use of this fuel in utility plants. Together with these studies, the possibility of adapting these plants to be converted into cogeneration plants is also considered.

In the Brazilian Chemical Industrial Sector 37% of the energy consumption in 1998 corresponded to steam generation in boilers for heating purposes, with residual fuel oil accounting for 53% of this consumption (Ministry of Mines and Energy, 1999). In these industries the average heat-to-power ratio is 1.88 (Tolmasquim et al., 1999).

This paper presents a thermoeconomic analysis of three cogeneration systems designed to be used in a chemical plant, that intends to increase its steam generation capacity and substitute fuel oil by natural gas, to generate electricity and steam to its processes.

The use of exergy and thermoeconomic analysis provides a rational way to evaluate the production costs of these utilities for different technological options, as well as, in different operating conditions.

In this way, the three cogeneration systems: a steam cycle with condensation-extraction steam turbine, a gas turbine based system and a

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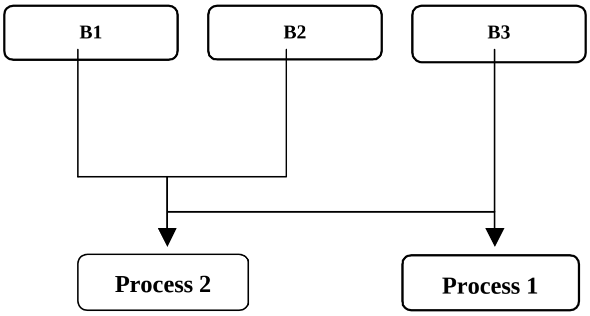

*Figure 1. Scheme of the steam distribution line*

combined cycle based system, are analysed in two operating scenarios: in the first one the systems generate steam (10 t/h at 18 bars and 30 t/h at 6 bars) and electricity for the plant (5 MW) and in the second one the systems generate steam (10 t/h at 18 bars and 30 t/h at 6 bars), electricity for the plant (5MW) and export electricity (12 MW).

## 2. Description of the Plant

The utilities plant of the chemical industry is made up of three steam boilers (B1, B2, B3), generating steam at two pressure levels, 6 bars (to feed process 2) and 18 bars (to feed process 1). The higher pressure line is connected to the lower pressure one, as shown in *Figure 1*. According to the Energy Department of the industry, the average monthly consumption of process steam and electricity (data valid for 1996) are:

- electricity: 3886 MWh
- process steam: 14942 t

The cost of each one of the utilities considered by the industry (1996) is:

- electricity: 68.00 US$/MWh
- process steam: 17.40 US$/t

## 3. Cogeneration Systems

As mentioned before, the considered cogeneration systems are: a steam cycle with condensation-extraction steam turbine, a gas turbine based system and a combined cycle based system.

The steam turbine based system is composed of a condensation-extraction steam turbine and a high pressure steam generator (B4). The electricity generation capacity is 5 MW. *Figure 2* shows a simplified flowsheet of this configuration. Steam is generated in the boiler B4 at a pressure of 42 bars and 573 K. This steam is sent to the condensation-extraction steam turbine, where 10 t/h of steam are extracted at 18 bars (process 1) and 30 t/h are extracted at 6 bar (process 2).

The gas turbine based cycle is made up of a gas turbine of the same capacity as the steam turbine (the combustion chamber outlet temperature is 1295K) and a waste heat boiler (B4) that can produce 16.67 t/h of steam at 20 bars. This waste heat boiler must operate with supplementary consumption of natural gas to attain the plant steam demand. This configuration is shown in *Figure 3*.

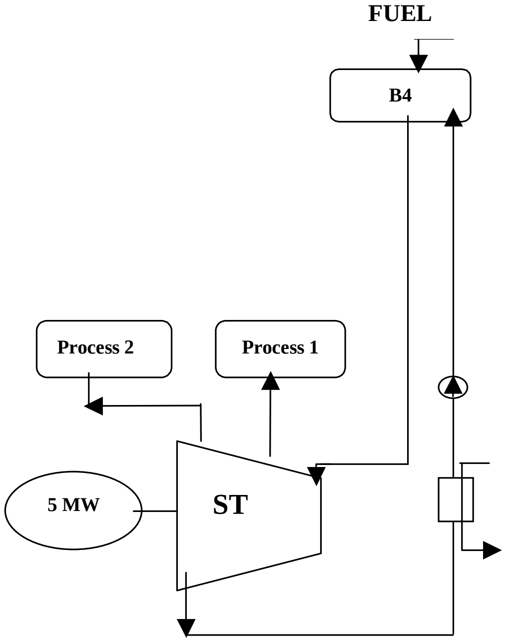

*Figure 2. Simplified flowsheet of the utilities plant with condensation-extraction steam turbine.*

*Figure 4* shows the combined cycle based cogeneration system. In this configuration the gas turbine based system is coupled with a steam cycle with a waste heat boiler. The extraction steam conditions and flow rates are the same of the steam turbine based system. In this system the electricity generation capacity is fixed to 6.3 MW because the steam based system must produce 40 t/h of steam to supply the processes demand, implying that the industry is able to export 1.3 MW of electricity. This means that the waste heat boiler must consume supplementary fuel to increase the steam production. In *Figure 4* it is indicated that the gas turbine generates 3.0 MW and the steam turbine generates 3.3 MW. This power distribution is obtained by the simulation of the whole system.

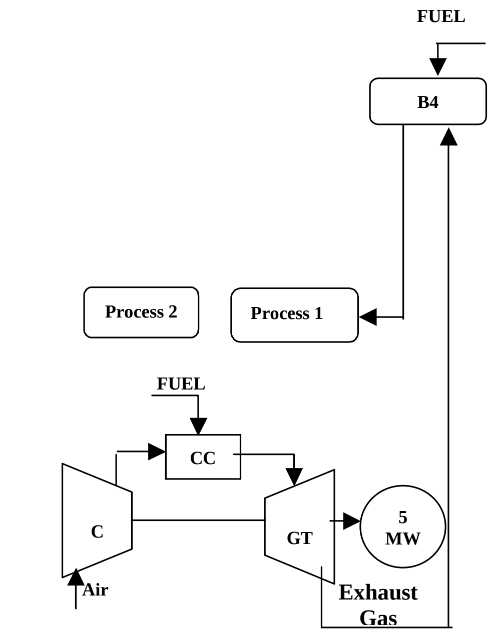


*Figure 3. Simplified flowsheet of the utilities plant with the gas turbine based system.*

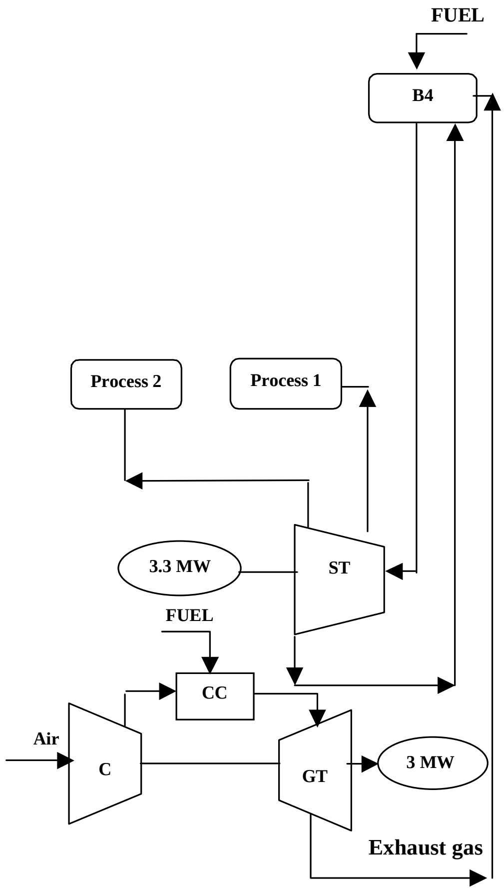


*Figure 4. Simplified flowsheet of steam distribution line including the proposed combined cycle.*

## 4. Exergy Analysis of the Cogeneration Systems

The exergy performance of cogeneration and combined cycle plants can be derived from a general performance definition (Oliveira and van Hombeeck, 1997 and Bejan, Tsatsaronis and Moran, 1998):

$$\eta = \frac{\text{useful effect}}{\text{consumed energy, exergy}} \tag{1}$$

The expressions of the energy ($\eta_e$) and exergy ($\eta_b$) efficiencies are shown in Equations 2 and 3 where W = power generated by the plant, $\Delta H_{proc}$ = change of steam enthalpy flow rate in the process, $m_{fuel}$ = fuel mass flow rate, FHV= fuel lower heating value, $\Delta B_{proc}$ = change of steam exergy flow rate in the process, $b_{fuel}$ = fuel specific exergy, as:

$$\eta_e = \frac{W + \sum \Delta H_{proc}}{m_{fuel} FHV} \tag{2}$$

$$\eta_b = \frac{W + \sum \Delta B_{proc}}{m_{fuel} b_{fuel}} \tag{3}$$

In a similar way the exergy efficiencies of the main components ($\eta_{bi}$) of a cogeneration and a power plant (compressor, turbine, pump, combustion chamber, steam generator, heat recovery steam generator, compression refrigerating system and absorption refrigerating system) can be defined. A factor $f_i$ can also be defined for each component of the plant as the ratio of the exergy supplied to each component to the exergy consumed by the whole plant (Oliveira and van Hombeeck, 1997; see also Beyer, 1970).

$$f_i = \frac{\text{exergy supplied to component i}}{\text{total consumed exergy}} \tag{4}$$

With the definitions of $\eta_{bi}$ and $f_i$ it is possible to obtain an expression that relates the overall exergy efficiency of the plant, $[\eta_b]_G$, with $\eta_{bi}$ and $f_i$.

For the cogeneration configuration proposed in *Figure 2*, (st = steam turbine, p = pump, proc = process), the expression of $\eta_{bG}$ is:

$$\eta_{bG} = \frac{W_{st} - W_p + \sum \Delta B_{proc}}{B_{fuel}} \tag{5}$$

Rewriting the above equation in terms of $\eta_{bi}$ and $f_i$ gives:

$$\eta_{bG} = \eta b_{st} f_{st} - f_p + \sum \eta b_{proc} f_{proc} \tag{6}$$

The gas turbine based system has the following expression of $\eta_{bG}$ (gt = gas turbine, c = compressor):

$$\eta_{bG} = \eta_{bgt} f_{gt} - f_c + \Sigma \eta_{bproc} f_{proc} \quad (7)$$

And, in the same way, the combined cycle based system has the expression:

$$\eta_{bG} = \left(\eta_{bgt} f_{gt} - f_c\right) + \left(\eta_{bst} f_{st} - f_p\right) + \\ + \Sigma\left(\eta_{bproc} f_{proc}\right) \quad (8)$$

It must be pointed out that the exergy efficiency and the parameter $f_i$, evaluated for each one of the components, indicate the impact of the performance and the exergy consumption of the components in the overall performance of the plant. This information is very important not only in terms of the thermodynamic evaluation of the system, but also in terms of its thermoeconomic evaluation.

The methodology described before is applied to analyse the three cogeneration systems, considering the following basic data of each plant:

- Thermodynamic reference state: $T_o$ = 298 K; $P_o$ = 1 bar
- Fuel: natural gas (lower heating value = 48160 kJ/kg )
- Gas turbine pressure ratio: 10:1
- Isentropic efficiency of the air compressor and gas turbine: 90%
- Thermal efficiency of the gas turbine combustor: 100%
- Gas turbine combustor outlet temperature: 1295 K
- Gas turbine excess air ratio: 275 %
- Gas turbine exhaust temperature: 788 K
- Steam generation pressure: 42 bar
- Steam generation temperature: 573 K
- Steam condensation pressure: 0.05 bar
- Thermal efficiency of the conventional boiler: 90%
- Thermal efficiency of the heat recovery steam generator: 80%
- Isentropic efficiency of the steam turbine stages: 85%
- Isentropic efficiency of the pumps: 80%
- Mechanical, generator and transmission efficiency: 95%
- Steam pressure of first process : 18 bar
- Average steam temperature of process 1 : 450 K
- Steam pressure of second process : 6 bar
- Average steam temperature of process 2 : 403 K

The performance behaviour of each system was simulated by means of models developed with the aid of the software EES (EES, 1999). TABLES I, II and III present the values of $f_i$ and $\eta_{bi}$ for each component of the three cogeneration systems.

In TABLE I it can be seen that the steam turbine and process 2 are the main consumers of fuel exergy. Boiler 4 is the component with the lowest value of $\eta_{bi}$ due to the heat transfer and combustion irreversibilities that take place in this equipment during the processes of energy conversion.

TABLE I. PARAMETERS $f_i$ AND $\eta_{bi}$ OF THE COMPONENTS OF THE STEAM TURBINE BASED COGENERATION SYSTEM SHOWN IN FIGURE 2 (W =5 MW).

| Equipment | $f_i$ | $\eta_{bi}$ |
|---|---|---|
| Boiler | 1.00 | 0.37 |
| Turbine | 0.17 | 0.75 |
| Process 1 | 0.05 | 0.89 |
| Process 2 | 0.13 | 0.84 |
| Pumps | 0.00 | 0.75 |
| Deaerator | 0.04 | 0.97 |
| Preheater | 0.03 | 0.97 |

TABLE II summarises the results obtained with the gas turbine based cogeneration system. It is interesting to notice the changes in the values of $f_i$ and $\eta_{bi}$ of the waste heat boiler when it operates with supplementary use of natural gas, indicating a reduction of the exergy efficiency in the steam generation process.

TABLE II. PARAMETERS $f_i$ AND $\eta_{bi}$ OF THE COMPONENTS OF THE GAS TURBINE BASED COGENERATION SYSTEM WITH AND WITHOUT SUPPLEMENTARY BURNING (sb) OF FUEL.

| Equipment | $f_i$ (1) | $f_{sbi}$ (2) | $\eta_{bi}$ (1) | $\eta_{b(sb)i}$ (2) |
|---|---|---|---|---|
| Air Compressor | 0.40 | 0.21 | 0.90 | 0.90 |
| Combustion Chamber | 1.36 | 0.73 | 0.75 | 0.75 |
| Turbine | 0.74 | 0.40 | 0.91 | 0.91 |
| Waste Heat Boiler | 0.26 | 0.60 | 0.51 | 0.40 |
| Process 1 | 0.03 | 0.06 | 0.89 | 0.89 |
| Process 2 | 0.08 | 0.15 | 0.84 | 0.84 |

(1) W=17 MW; (2) W=5 MW

TABLE III shows the results of the combined cycle based system for the second operating scenario (W=17 MW). As the steam turbine must produce 5 MW, the heat recovery steam generator needs to burn natural gas. As a consequence of this operating condition, the value of the exergy efficiency of the waste heat boiler is similar to the values of this component obtained for the steam and gas turbine based systems.

TABLE IV presents the overall energy and exergy efficiencies of the cogeneration systems for both operating scenarios. In the first scenario, the combined cycle based system is the most efficient one based on an exergy analysis. In the second operating scenario, the gas turbine based system is the most efficient system, in energy and exergy analysis, because it is not necessary to burn supplementary fuel in the waste heat boiler to attain the steam demand in the processes.

TABLE III. PARAMETERS $f_i$ AND $\eta_{bi}$ OF THE COMPONENTS OF THE COMBINED CYCLE BASED COGENERATION SYSTEM (W=17 MW).

| Equipment | $f_i$ | $\eta_{bi}$ |
|---|---|---|
| Air Compressor | 0.25 | 0.90 |
| Combustion Chamber | 0,84 | 0.79 |
| Gas Turbine | 0.49 | 0.91 |
| Waste Heat Boiler | 0.56 | 0.38 |
| Steam Turbine | 0.10 | 0.79 |
| Process 1 | 0.03 | 0.89 |
| Process 2 | 0.08 | 0.84 |
| Pumps | 0.00 | 0.74 |
| Deaerator | 0.02 | 0.97 |
| Preheater | 0.02 | 0.98 |

TABLE IV. OVERALL ENERGY ($\eta_{eG}$) AND EXERGY EFFICIENCIES ($\eta_{bG}$ ) OF THE PROPOSED COGENERATION SYSTEMS FOR TWO OPERATING CONDITIONS (W=5 MW / W=17 MW).

| System Configuration | $\eta_{eG}$ | $\eta_{bG}$ |
|---|---|---|
| Gas Turbine | 0.80 / 0.63 | 0.31 / 0.36 |
| Steam Turbine | 0.72 / 0.43 | 0.29 / 0.25 |
| Combined Cycle | 0.76*/ 0.60 | 0.32*/ 0.35 |

* W=6.3 MW

## 5. Thermoeconomic Analysis of the Cogeneration Systems

In a multi-product utility plant the determination of the production cost of each utility can be done by the application of cost balances and cost partition methods to the components of the plant. In a thermomechanical conversion plant cost balances based on exergy balances provide a rational way to obtain the production costs of the utilities.

For a cogeneration plant, the combination of exergy analysis with cost partition methods is used to determine the production costs of electricity and process steam (Cespedes and Oliveira, 1995).

The generalised cost balance equation for any equipment can be written, in terms of cost rates ($/s), as (c = specific cost, B = exergy rate, $C_{equip}$ = equipment cost rate, i = inlet, o = outlet):

$$\Sigma c_o B_o = \Sigma c_i B_i + C_{equip} \quad (9)$$

By applying this equation to the steam turbine, shown in *Figure 2*, gives ($C_{turb}$ = steam turbine cost rate, $W_e$ = electric power, hp = high pressure, e = electricity, p1 = steam demanded by process 1, p2 = steam demanded by process 2, cd= condenser):

$$c_e W_e + c_{p1}\Delta B_{p1} + c_{p2}\Delta B_{p2} + c_{cd} B_c = \\ = c_{hp} B_{hp} + C_{turb} \quad (10)$$

In this equation $B_{hp}$, $W_e$, $\Delta B_{p1}$ and $\Delta B_p$ are determined by the exergy analysis of the plant. $C_{turb}$ is known and $c_{hp}$ is obtained by applying the cost balance to boiler 4, where there is only one product (high pressure steam).

To determine the values of $c_e$, $c_{p1}$ and $c_{p2}$ it is necessary to consider a cost partition criterion. According to Bejan, Tsatsaronis and Moran (1998) the extraction partition method must be used for an extraction–condensation steam turbine. This gives:

$$c_{hp} = c_{p1} = c_{p2} = c_{cd} \quad (11)$$

Since the cost partition method can also be used as a reference to define the prices of the utilities, the equality method can be applied, giving the relations:

$$c_e = c_{p1} = c_{p2} = c_{cd} \quad (12)$$

In this work both methods are used in steam and gas turbines, resulting the auxiliary relations shown in TABLE V.

TABLE V. AUXILIARY RELATIONS

| Cost Partition Method | Steam Turbine | Gas Turbine |
|---|---|---|
| Extraction | $c_{hp} = c_{p1} = c_{p2} = c_{cd}$ | $c_{gas} = c_{eg}$ |
| Equality | $c_e = c_{p1} = c_{p2} = c_{cd}$ | $c_e = c_{eg}$ |

The compared thermoeconomic analysis of the three cogeneration systems shown in Figures 2, 3 and 4 is obtained based on the following parameters (the components costs were evaluated for a power generation of 5 MW):

- Natural gas cost: 10.40 US$/MWh (3 US$/MBtu);
- Capital recovery period: 10 years;
- Interest rate: 12% per annum;
- load factor: 0.80;
- time factor 0.85;
- Condensation-extraction steam turbine cost: US$ 2,500,000;
- Conventional boiler cost: US$ 1,650,000;

- Gas turbine cost: US$ 1,950,000;
- Waste heat boiler cost: US$ 1,100,000;
- Auxiliary equipment cost: US$ 277,000;
- Annual operational and maintenance cost: 10% of the investment cost;
- Inflation is not considered.

The equipment cost rate is evaluated according to the following equation:

$$C_{equip\ i} = C_{0i}\ [(n/(1-(1+n)^{-r}) + f_{om}] / (3600 N_h f_t f_l) \quad (13)$$

TABLE VI presents the specific production costs of process steam (US$/t) and electricity (US$/MWh), for the three cogeneration systems and using the equality and extraction cost partition methods.

For the combined cycle based system, the average electricity cost calculated from the values of the electricity cost of the steam and gas turbines is presented. It is interesting to notice that, for this system, the electricity generated by the gas turbine is less expensive than the electricity generated by the steam turbine, in both cost partition methods (28,66 US$/MWh against 52,21 US$/MWh and 46,80 US$/MWH against 72,17 US$/MWh).

Values of TABLE VI indicate that only the electricity cost of the steam turbine based system, using the extraction method, is higher than the electricity price paid by the industry (68.00 US$/MWh). In this table it is important to verify that all obtained costs of process steam are lower than the value considered today by the industry.

Another interesting scenario to compare the performance of the systems is the one in which all the three systems are capable to generate more electricity than needed in the industry. In this scenario the company will be capable to export electricity to other industries or to the electricity grid. The thermoeconomic analysis is done, in this case, for an electricity generation capacity of 17 MW (Tolmasquim et al., 1999). In this scenario the gas turbine based system operates without use of supplementary fuel in the heat recovery steam generator because of the higher capacity of the gas turbine. The combined cycle based system needs to burn supplementary fuel in the heat recovery steam generator to attain the steam demand of the processes (in this system the gas turbine generates 12 MW and the steam turbine generates 5 MW).

The new equipment costs were determined by using some relations presented by Boehm (1987) and information given by equipment manufacturers.

TABLE VII summarizes the new values of electricity and process steam production costs. The electricity costs obtained for the gas turbine based system and for the combined cycle based system are lower than those calculated for the same type of systems in the first scenario. As observed in the first scenario, the steam turbine based system gives the higher electricity production costs.

TABLE VI. SPECIFIC PRODUCTION COSTS OF ELECTRICITY AND PROCESS STEAM (MASS WEIGHTED AVERAGE VALUE OF THE TWO PROCESSES).

| Method | Equality | | Extraction | |
|---|---|---|---|---|
| System Configuration | Electricity. (US$/MWh) | Steam (US$/t) | Electricity. (US$/MWh) | Steam (US$/t) |
| Steam Turbine | 50.26 | 10.78 | 70.92 | 7.73 |
| Gas Turbine | 29.06 | 9.70 | 48.02 | 7.25 |
| Combined* Cycle | 40.82 | 11.26 | 59.90 | 7.83 |

* W = 6.3 MW

TABLE VII. SPECIFIC PRODUCTION COSTS OF ELECTRICITY AND PROCESS STEAM (MASS WEIGHTED AVERAGE VALUE OF THE TWO PROCESSES) CONSIDERING PRODUCTION OF 17 MW.

| Method | Equality | | Extraction | |
|---|---|---|---|---|
| System Configuration | Electricity (US$/MWh) | Steam (US$/t) | Electricity (US$/MWh) | Steam (US$/t) |
| Steam Turbine | 59.25 | 12.71 | 67.98 | 8.33 |
| Gas Turbine | 26.01 | 12.97 | 41.88 | 5.99 |
| Combined Cycle | 35.75 | 13.40 | 47.24 | 7.48 |

## 6. Concluding Remarks

The methodology of exergy and thermoeconomic analysis presented in this paper is a useful guideline to quantify the overall thermodynamic performance of cogeneration plants, to characterise the role of each component of the plant in the utilisation of fuel exergy, as well as, to provide a rational determination of the production cost of process steam and electricity.

The results given by the thermoeconomic analysis indicate that the three-cogeneration systems have attractive performance and production costs of the utilities, which are competitive with the prices paid today by the industry. During the capital recovery period, the system that presents the lowest overall cost rate is the gas turbine one, in both operating scenarios.

Besides the results given by the thermoeconomic analysis, some other aspects must be considered to choose the best cogeneration system; aspects such as operational flexibility and reliability of the equipment. Environmental impacts resulting from cogeneration systems operation must also be taken into account, in order to indicate the best system.

### Nomenclature

| | |
|---|---|
| $b_{fuel}$ | fuel specific exergy (kJ/kg) |
| B | exergy rate (kW) |
| $\Delta B_{proc}$ | change of steam exergy flow rate in the process (kW) |
| c | specific cost (US$/kWh, US$/kJ or US$/t) |
| $C_{0i}$ | cost of equipment i (US$) |
| $C_{equip\ i}$ | equipment i cost rate (US$/s) |
| $C_{turb}$ | steam turbine cost rate (US$/s) |
| FHV | fuel lower heating value (kJ/kg) |
| $f_i$ | ratio of the exergy supplied to component i to the exergy consumed by the whole plant |
| $f_l$ | load factor |
| $f_{om}$ | annual operational and maintenance factor |
| $f_t$ | time factor |
| $\Delta H_{proc}$ | change of steam enthalpy flow rate in the process (kW) |
| $m_{fuel}$ | fuel mass flow rate (kg/s) |
| n | annual interest rate |
| $N_h$ | 8760 hours/year |
| $P_0$ | reference pressure (bar) |
| r | capital recovery period (year) |
| $T_0$ | reference temperature (K) |
| W | power generated by the plant (kW) |
| $W_e$ | electric power (kW) |

Greek Symbols

| | |
|---|---|
| $\eta_b$ | exergy efficiency |
| $\eta_e$ | energy efficiency |

Subscripts

| | |
|---|---|
| c | compressor |
| cd | condenser |
| e | electricity |
| eg | exhaust gas |
| G | concerning the whole plant |
| gas | natural gas |
| gt | gas turbine |
| i | inlet, component i |
| o | outlet |
| proc | process |
| p | pump |
| p1 | steam demanded by process 1 |
| p2 | steam demanded by process 2 |
| st | steam turbine |

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