TETRA-COMBINED TRIGENERATION SYSTEM. THERMOECONOMIC ANALYSIS.

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Abstract. *This paper presents the description and the exergy and thermoeconomic evaluation of a new trigeneration system, called tetra-combined trigeneration system, that generates electricity, steam and chilled water (for air conditioning purposes). This system is composed of a gas turbine, a heat recovery steam generator, a condensation/extraction steam turbine and a hybrid absorption/steam ejection chiller. The steam extractions from the steam turbine are used for supplying heat to an industrial process, called "process 1" and to power a hybrid absorption/steam ejection chiller. The high-pressure steam generated in the heat recovered steam generator not only feed the steam turbine, but also the ejectors of the hybrid absorption/steam ejection chiller. All these components are coupled in thermal series in order to optimise the exergy efficiency of the whole trigeneration system.*
The exergy and thermoeconomic performance (exergy based costs of electricity, steam and chilled water production) of the tetra-combined trigeneration system is compared with the performance of a conventional trigeneration system, pointing out the advantages and disadvantages of this new system.

Keywords*. trigeneration system, exergy analysis, thermoeconomic analysis*

1. Introduction

Trigeneration systems have been developed to supply thermal and electrical loads with high values of energy utilization factors.

Figure (1) presents a new trigeneration system concept based on the cogeneration system developed by Garagatti Arriola and Oliveira Júnior (2001). This system is composed of a heat engine (working between the temperatures T_{cc} and T_{sc}) coupled in thermal series to a cogeneration system (that receives $(1\text{-}f)Q_2$ and rejects Q_4, Q_5 and Q_3) and to a hybrid refrigeration system (that receives Q_5 and fQ_2, rejects Q_6 and Q_8, providing a cooling effect Q_7 at the temperature T_{ev}). This trigeneration system generates electricity ($W_{gt} + W_{st}$), produces steam / hot water (Q_4) and chilled water (Q_7) to a given industrial process. Eventually, the heat loss to the environment (Q_3) is zero.

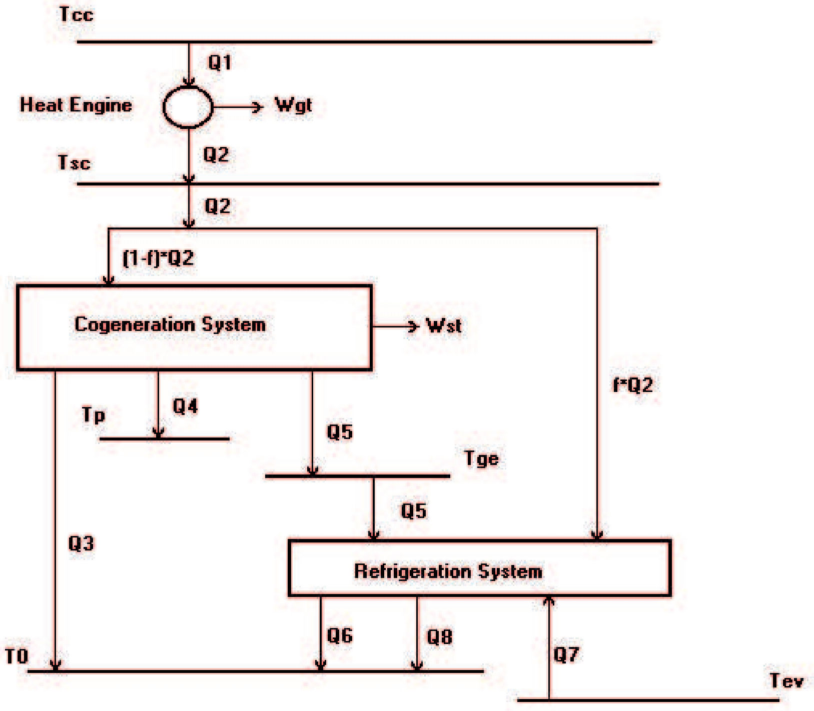

Figure 1 Tetra-combined trigeneration system for electricity production and cooling and heating purposes.

The overall energy use factor, η_e, and the exergy efficiency, η_b, of this trigeneration system can be written as a function of the energy performance parameters of each system of the tetra-combined trigeneration system:

$$\eta_e = \eta_1 + (1 - \eta_1) * (\eta_2 - f + f * COP) + r * (COP - 1) \qquad (1)$$

were:

$$\eta_e = \frac{W_{gt} + W_{st} + Q_4 + Q_7}{Q_1} \qquad (2)$$

f = the fraction of the rejected heat of the heat engine that is sent to the refrigeration system;

η_1= thermal efficiency of the heat engine;

$$\eta_2 = \frac{W_{st} + Q_4 + Q_5}{Q_2 * (1 - f)} = \text{energy utilisation factor of the cogeneration system} \qquad (3)$$

$$COP = \frac{Q_7}{(f * Q_2 + Q_5)} = \text{coefficient of performance of the chiller} \qquad (4)$$

$$r = \frac{Q_5}{Q_1} \qquad (5)$$

Equation (1) shows the influence of the performance parameter of each component, as well as the rejected heat distribution, in the overall performance of the cogeneration system.

The exergy efficiency, η_b, of this trigeneration system is calculated by Equation (6), where ($Q_4\theta_4$), ($Q_7\theta_7$) are, respectively, the exergy rate transfered to the steam/hot water and to the chilled water (θi is the Carnot factor associated to the temperature T_i):

$$\eta_b = \frac{W_{gt} + W_{st} + Q_4\,\theta_4 + Q_7\,\theta_7}{Q_1\,\theta_1} \qquad (6)$$

In this paper, the performance evaluation of this new system is conducted applying the exergy and thermoeconomic analysis of processes, in order to determine the exergy efficiency and the production costs of the utilities (electricity, steam and chilled water) for a given application. The obtained results are compared to the results obtained with a conventional trigeneration system.

2 Description of the tetra-combined trigeneration system

The tetra-combined trigeneration system, shown in Figure (2), is composed of three subsystems connected in thermal series: a gas turbine, a cogeneration system based on a steam cycle and a hybrid absorption-ejecto compression chiller. The expression tetra-combined is derived from the fact that this system is based on two power cycles (Brayton and Rankine cycles) and two refrigeration cycles (absorption and steam ejection cycles).

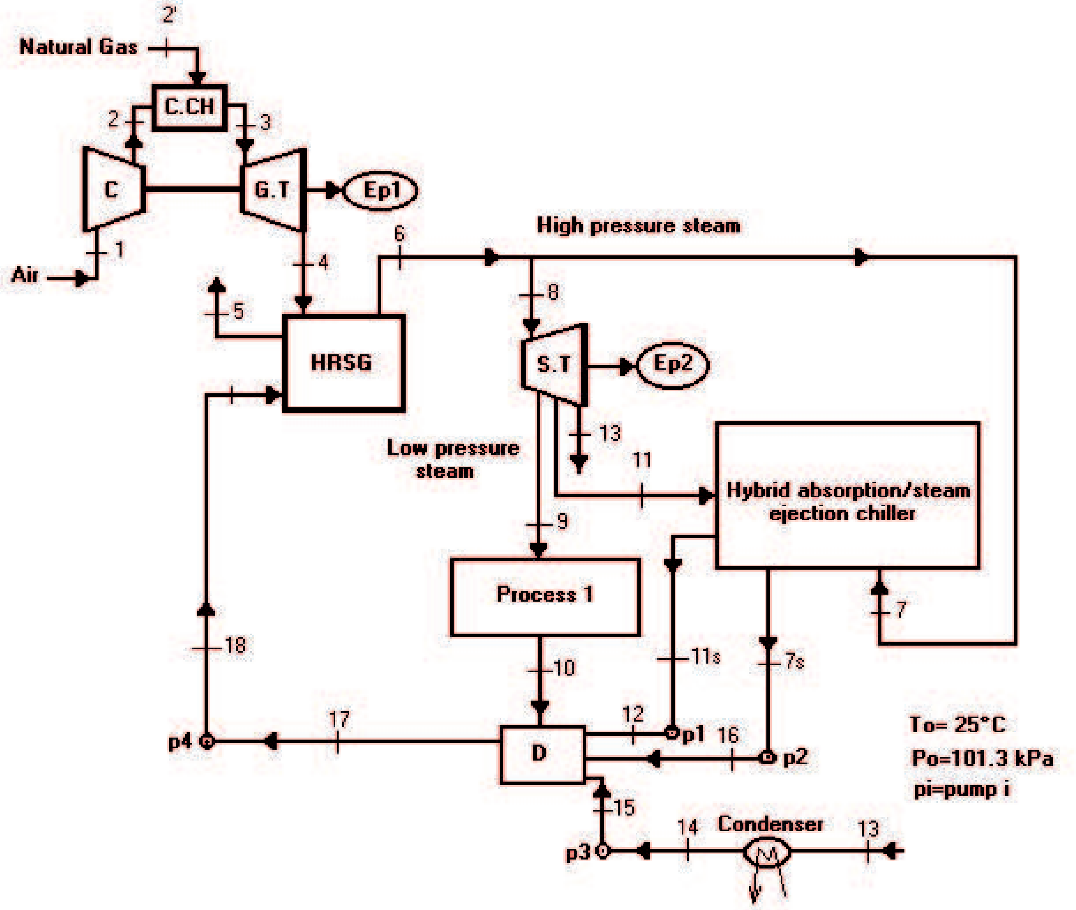

Figure 2: Tetra-combined trigeneration system

The characteristics of each subsystem are described below.

- Gas turbine: The gas turbine uses natural gas as fuel (section 2' in Figure (2)), generates electric power (Ep1) and rejects the combustion gases to a heat recovery steam generator (section 4 in Figure (2)).

- Cogeneration system: The steam generated in the heat recovery steam generator (HRSG) is sent to a condensation-extraction steam turbine (ST, section 8 in Figure (2)), that generates the electric power Ep2. The steam extracted from the steam turbine in section 11 is the energy input of a hybrid absorption ejecto-compression chiller that operates with the pair H_2O-LiBr. The steam extracted in section 9 is sent to process 1. The condensed water, from the condenser, the chiller and process 1 (sections 14, 7s, 11s and 10) is pumped to section 18, that is the inlet of the heat recovery steam generator.

- Hybrid absorption/ steam ejection chiller: The chiller, which operates as a hybrid absorption-ejecto-compression cycle (Oliveira Jr. (1991)), has two energy inputs. One of them is the heat rate being transferred to the H_2O-LiBr solution in its generator (caused by the condensation of the flow of the steam extracted from the steam turbine, section 11, Figure (2)). The other one is the enthalpy flow rate of the high pressure steam sent to the ejector (section 7, Figure (2)). This ejector, shown in Figure (3), must increase the steam pressure level from the evaporator one (Ev) up to the absorber one (Ab). This pressure difference appears due to the values of temperature and concentration of the H_2O-LiBr solution imposed in the generator ((Ge) that is one of the components of the separator), in the absorber (Ab) and in the water in the evaporator (Ev).

The processes of the H_2O-LiBr solution (that take place in the generator and absorber) and of the water (in the condenser and evaporator) are the same processes that occur in a conventional absorption chiller (Figure (3)): exit of steam in the generator, with the consequent increase of the concentration of the solution at the exit of the generator (ds); condensation of the steam in the condenser (Cd); pressure drop of the water flow (cs - ee) from the condenser to the evaporator and pressure drop of the strong solution (ds - ae) from the generator to the absorber; vaporisation of the water in the evaporator, with the consequent cooling of the chilled water flow (from 12 °C to 7 °C); the steam liberated by the evaporator (or by the ejector in the tetra-combined system) is absorbed by the strong solution in the absorber (ae - as); cooling of the the strong solution (process ds - ae) and heating of the diluted solution (process as - de) in the heat exchanger, in order to increase the performance of the chiller.

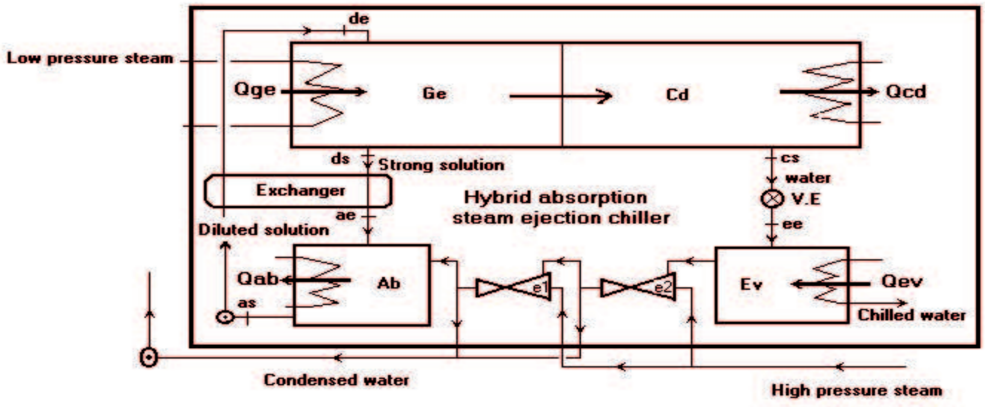

Figure 3: Hybrid absorption/steam ejection chiller

3. Performance of the tetra-combined trigeneration system

The performance evaluation of the Tetra Combined Trigeneration system is based on the construction of models of the behaviour of the components of the system. These models were developed with the aid of the software EES (2002). The performance of the system can be quantified by using the overall energy use factor (η_e) and exergy efficiency (η_b), as defined by Oliveira Jr. (1998):

$$\eta_e = \frac{Ep1 + Ep2 + Q_{ev} + Q_p}{m_{fuel}\, LHV_{fuel}} \tag{7}$$

$$\eta_b = \frac{Ep1 + Ep2 + Q_{ev}\,\theta_{ev} + Q_p\,\theta_p}{m_{fuel}\, b_{fuel}} \tag{8}$$

Where ($Q_p\theta_p$), ($Q_{ev}\theta_{ev}$) are, respectively, the exergy rate transfered to the process 1 and to the chilled water, m_{fuel} is the mass flow rate of the fuel, LHV $_{fuel}$ is the lower heating value of the fuel and b_{fuel} is the specific exergy of the fuel, determined according to Szargut et al.(1988).

The relation 'heat to power ratio' (β) is used to characterise the type of cogeneration application:

$$\beta = \frac{Q_{ev} + Q_p}{(Ep1 + Ep2)} \tag{9}$$

In order to optimise the performance of the trigeneration system, it was studied the evolution of the exergy efficiency of the system (η_b) with the pressure of the steam generated in the heat recovery boiler (P_{bo}), due to the influence that this pressure has in the overall performance of the system. Figure (4) shows the evolution of η_b and β as a function of the P_{bo} . The maximum value of η_b is obtained for a pressure of 6000 kPa.

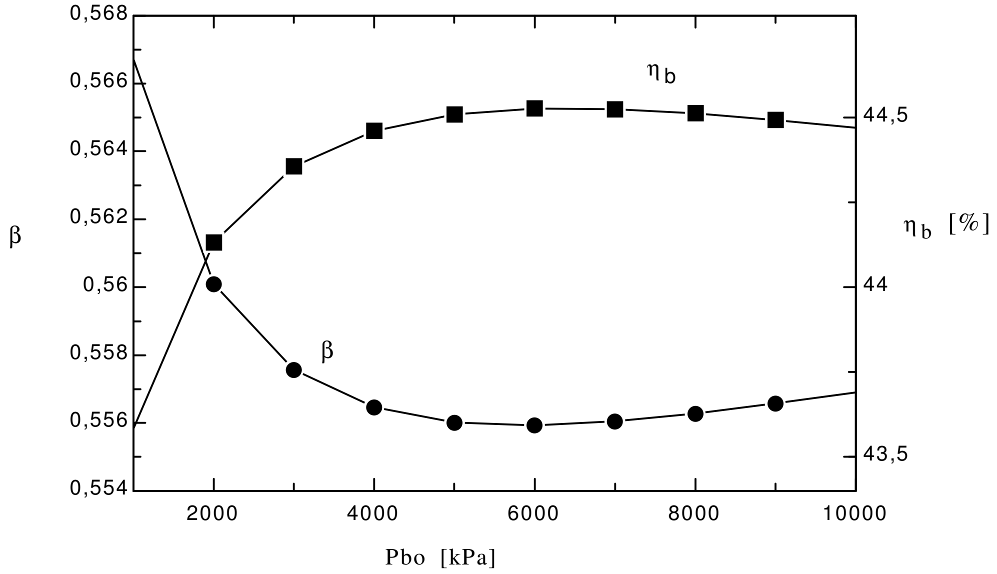

Figure 4: Evolution of the exergy efficiency and the heat to power ratio with the pressure in the heat recovery steam generator (P_{bo}).

The following technical characteristics were defined in order to evaluate the thermodynamic and thermoeconomic performance of the tetra-combined system:

- electric power generated by the gas turbine: 13.3 MW;.
- heat recovery steam generator capacity: 18.39 t/h at 6000 kPa and 363°C (without supplementary gas burning)

Tables (1), (2) and (3) present the values of pressures and temperatures in the sections defined in Figures (2) and (3), for the gas turbine, cogeneration and chiller subsystems.

Table 1. Pressures and temperatures of the gas turbine subsystem.

Section	**Temperature** (^oC)	**Pressure** (kPa)
1	25	101.3
2	421	1510.0
2'	300	1510.0
3	1247	1510.0
4	586	101.3

*combustion with air ratio of 179.5%

Table 2. Pressures and temperatures of the cogeneration subsystem.

Section	**Temperature** (^oC)	**Pressure** (kPa)
4	586	101.3
5	186	101.3
6	363	6000.0
7	363	6000.0
8	363	6000.0
9	165	700.5
11	80	47.4
13	45	9.6
17	80	700.5
18	82	6000.0

Table 3. Temperatures and pressures in the components of the chiller.

Component	**Section**	**Temperature** (^oC)	**Pressure** (kPa)	**Thermal Load** (kW)
Evaporator	ev	2.0	0.7	3872
Absorber*	ae as	39.1 33.0	2.8	4277
Condenser	cd	40.0	7.4	4032
Generator*	de ds	50.7 57.6	7.4	4297

*the concentration of the strong solution is 46% and the concentration of the weak solution is 41%

The performance evaluation results are presented in Table (4) where are shown the values of the electric power generated (E_{pt}), refrigerating capacity (Q_{ev}), heat to power ratio (β), energy efficiency (η_e) and exergy efficiency (η_b).

Table (4) also presents the performance parameters of a conventional trigeneration system designed to generate electricity and to produce steam and chilled water in the same conditions of the tetra-combined trigeneration system (same electric power, heating and cooling loads).

The conventional trigeneration system, shown in Figure (5), is composed of a gas turbine, a heat recovered steam generator and an absorption chiller.

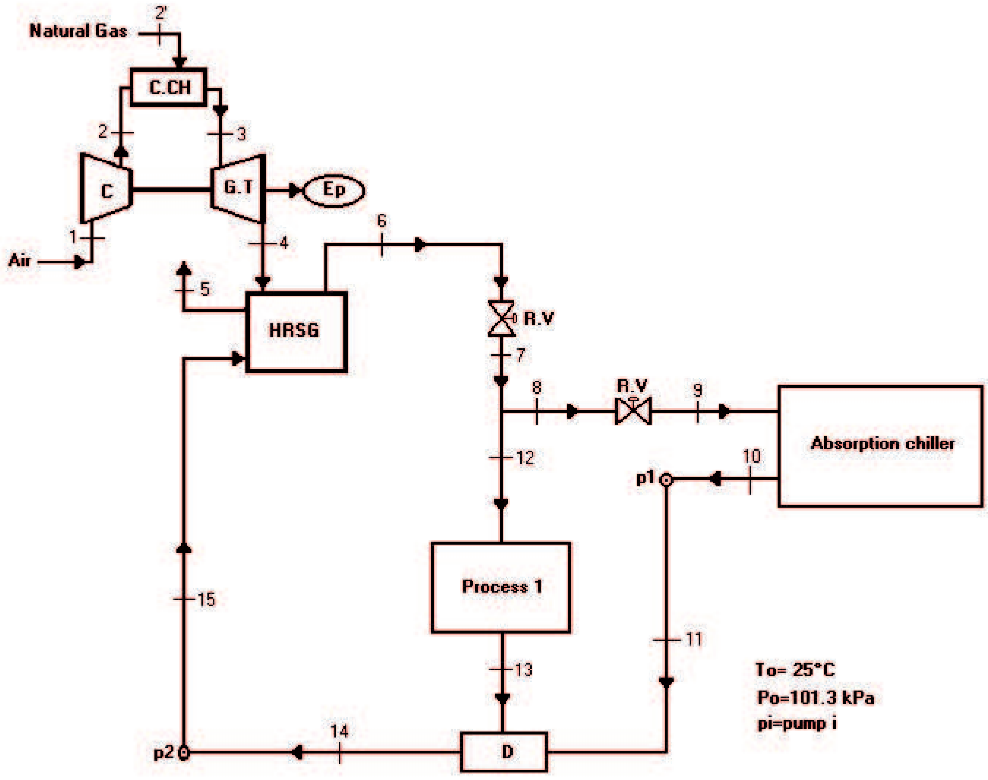

Figure 5. Conventional trigeneration system

Table 4. Performance parameters of the tetra-combined trigeneration and conventional trigeneration system

System	**E_{pt}** (kW)	**Q_{ev}** (kW)	**Q_p** (kW)	β	η_b (%)	η_e (%)
Conventional trigeneration system (without supplementary gas burning)	15853	3872	4941	0.556	42.6	51.3
Tetra-combined trigeneration system (without supplementary gas burning)	**15853**	**3872**	**4941**	**0.556**	**44.6**	**66.1**

The results shown in Table (4) indicate a better performance of the Tetra Combined Trigeneration system (without supplementary gas burning in the heat recovery steam generator) when compared to the conventional trigeneration system.

4. Thermoeconomic evaluation of the tetra combined trigeneration system

The determination of the production costs of the utilities is done based on the application of the cost balances, in exergy basis, to the three subsystems that compose the tetra-combined system. Equality cost partition method is used in the gas and steam turbines to obtain the electricity and steam production costs (Garagatti, 2000).

Cost balances can be written for each equipment/component of the analysed systems in terms of cost rates (US$/s), as presented by Equation (10) (c = specific cost, B = exergy flow rate, C_{equip} = equipment cost rate, prod = product, feed = feed):

$$\Sigma\, c_{prod}\, B_{prod} = \Sigma\, c_{feed}\, B_{feed} + C_{equip} \tag{10}$$

The auxiliary relations due to the use of the equality cost partition method are:

Equality method for the trigeneration system:

$$c_{Ep1} = c_4 \text{ (for the gas turbine)} \tag{11}$$

$$c_{Ep2} = c_9 = c_{11} = c_{13} \text{ (for the steam turbine)} \tag{12}$$

Equality method for the conventional trigeneration system :

$$c_{Ep1} = c_4 \text{ (for the gas turbine)} \tag{13}$$

In the thermoeconomic analysis developed for the tetra - combined and conventional system the following data are used, considering a gas turbine electricity capacity of 13.3 MW and 18.39 t/h of steam flow rate produced in the heat recovery steam generator, without supplementary gas burning:

· fuel cost:	US$ 10.70/MWh (Comgas, 2003);
· gas turbine system cost:	US$ 5,308,000;
· steam turbine system cost:	US$ 5,047,000;
· heat recovery steam generator cost:	US$ 1,435,000;
· chiller cost:	US$ 400/TR;
· cost of the auxiliary equipment:	US$ 400,000

The other economic parameters employed in the thermoeconomic analysis are:

· capital recovery period:	10 years;
· load factor:	0.800;
· time factor:	0.913;
· interest rate:	12% per annum;
· annual operational and maintenance cost:	10% of the investment cost.

The results of the thermoeconomic evaluation are shown in Table (5), where c_e, c_s and c_{cw} are, respectively, the specific average cost of electricity, produced in the gas turbine and in the steam turbine, the mass based cost of steam and the mass based cost of chilled water.

Table 5. Production costs of the utilities in exergy and mass basis (for steam and chilled water)

Partition Method	**Equality**		
System	**c_e (US$/MWh)**	**c_s (US$/t)**	**c_{cw} (US$/t)**
Conventional trigeneration system (without supplementary gas burning)	24.10	25.49	0.51
Tetra Combined Trigeneration system (without supplementary gas burning)	**33.84**	**16.45**	**0.11**

The results shown in Table (5) indicate that the production costs of steam and chilled water of the tetra-combined trigeneration are lower than those of the conventional system, and the cost of electricity of the tetra-combined trigeneration system is higher.

Table (6) gives the overall cost rates of the analysed systems (C_t for the overall cost rate), during the capital recovered period.

Table 6. Overall cost rates of the analysed systems.

Systems / Cost Rates	Conventional trigeneration system	Tetra-combined trigeneration system
C_t (US$/h)	824.3	**759.1**

The results shown in Table (6) indicate that the Tetra Combined system, without supplementary gas burning, is the less expensive of the analysed systems, when compared with the cost rates of the conventional trigeneration system (759.1 US$/h against 824.3 US$/h).

5. Concluding remarks

The results obtained with the thermoeconomic analysis developed in this paper show that the Tetra Combined Trigeneration System is an efficient and less expensive option to produce electricity, steam and chilled water for industrial processes, as well as for applications in the tertiary sector.

Further studies must be conducted to optimise the configuration of this trigeneration system as well as its operational conditions, in order to reduce its cost rate and the environmental impact generated during its operation.

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