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Exergoeconomic optimization of tetra-combined trigeneration system

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Abstract
This work aims at obtaining optimal configurations of trigeneration systems in order to satisfy required demands for electricity and thermal loads for heating and cooling, evaluating the impact of the electricity, steam and chilled water production costs. A trigeneration system produces electricity, heat and cooling effect using electricity or heat available. Emphasis is made on systems using absorption chillers, including one using a hybrid absorption ejecto-compression chiller, here called tetra-combined trigeneration system. The performance evaluation of systems is carried out by the application of exergy and exergoeconomic analysis of the proposed alternatives in order to determine exergy efficiency and exergy based costs on production of system utilities. The Genetic Algorithms method has been chosen for optimization to show the applicability of evolutionary techniques in trigeneration plants. The optimization shows important profits in the exergy based costs of products, by means of the exergetic efficiency maximization of the different trigeneration systems.

Keywords: trigeneration; absorption ejecto-compression chiller; exergoeconomic analysis; optimization; genetic algorithms.

Optimización exergoeconómica de sistema tetra-combinado de trigeneración

Resumen
Se pretende obtener configuraciones óptimas de sistemas de trigeneración para satisfacer demandas de electricidad y cargas térmicas de calentamiento y enfriamiento, evaluando el impacto de los costos de producción de electricidad, vapor y agua fría. Un sistema de trigeneración produce electricidad, calor y enfriamiento usando esa electricidad o calor disponible. Se hace énfasis en sistemas que usan refrigeración por absorción, incluyendo uno que usa refrigeración hibrida de absorción eyecto-compresión, llamado sistema tetra-combinado de trigeneración. La evaluación del desempeño de los sistemas se lleva a cabo mediante el análisis exergético y exergoeconómico de las alternativas propuestas para determinar la eficiencia exergética y los costos exergéticos de la producción de las utilidades del sistema. Se usó el método de Algoritmos Genéticos para la optimización de las plantas de trigeneración. La optimización muestra beneficios importantes en los costos exergéticos de los productos por medio de la maximización de la eficiencia exergética de los diferentes sistemas.

Palabras clave: trigeneración; refrigerador de absorción eyecto-compresión; análisis exergoeconómico; optimización; algoritmos genéticos.

1. Introduction

Trigeneration, the combined production of power, heat and cold (generally, cold water for air conditioned purposes) from a single energy source is a very effective way of utilizing the primary energy of a fuel more efficiently, economically, reliably and with less harm to the environment than centralized, dedicated electric production [1,2]. A trigeneration system can be divided into two parts: the CHP (Combined Heat and Power) unit, which produces electricity and heat, and the second part, the chiller (compression or absorption type), which produces refrigerating effect using electricity and/or heat from the CHP unit. Combined heating and power (CHP) technology has been in use in industrial applications from the end of 19th century. However, the rapid development of the technologies involved through the last decades made easier the penetration of CHP technology in buildings, hotels, hospitals, schools, community heating or waste treatment sites. Most recent advances incorporate the use of alternative fuels such as hydrogen or biomass, or the exploitation of excess heat converting it into cooling power, which is used in air conditioning or in various industrial

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processes [3]. Trigeneration plant has become economically viable due to the commercial spread of absorption chillers [3,4]. Absorption chillers are generally classified as direct or indirect-fired, and as single, double or triple-effect. In direct-fired units, the heat source can be gas or some other fuel that is burnt in the unit. Indirect-fired units use steam or some other heat transfer fluid that brings in heat from a separate source, such as a boiler or heat recovered from an industrial process.

Trigeneration includes various technologies like: gas turbines, steam turbines, combined cycles, internal combustion engines, fuel cells and Stirling engines. Some works show diverse applications of the trigeneration systems: [5] in supermarkets, [6] in the petrochemical industry, [7] in the food industry, [8] in hospitals or the work of [9] that proposes a conceptual system of trigeneration based on gas turbine.

Exergy analysis predicts the thermodynamic performance of an energy system and the efficiency of the system components by accurately quantifying the entropy-generation of the components [10]. Exergy analysis of energy conversion plants allows characterizing how the available exergy (e.g. a fuel, employed as energy source) is used and destroyed in the existent processes of energy conversion in the plant, by means of a quantitative evaluation of the destruction and loss of exergy associated to the system. The basis of exergoeconomic approach is the consideration that exergy is an objective measure of the thermodynamic value of an energy carrier. Furthermore, it is considered that it is closely related to the economic value of the energy carrier. Hence, when a cost is attributed to an energy carrier, exergy is taken as the basis for allocating costs. In this paper an exergetic and exergoeconomic comparison of different trigeneration systems, including a tetra-combined one, is carried out in order to calculate the efficiencies and exergy based cost of electricity, steam and exergy transferred to chilled water. Then, genetic algorithms are applied to obtain optimal configurations of trigeneration systems.

2 System description

The trigeneration system analyzed in this work and here called tetra-combined trigeneration system is formed by three subsystems in thermal cascade: 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) and two refrigeration technologies (absorption and ejecto-compression). The performance of this system is compared with the performance of different conventional trigeneration systems, analyzed in [11], for the same operation conditions.

In a Tetra-combined trigeneration system, the gas turbine produces power and it uses natural gas as energy source. The cogeneration subsystem, based on a steam cycle, uses the rejected gases from the gas turbine to produce superheated steam in a HRSG. A minimum part of superheated steam goes to the ejectors of the hybrid absorption ejecto-compression chiller. The rest of superheated steam feeds an extraction/condensation steam turbine. The steam turbine produces power and has two steam extractions. The first extraction is imposed by the process. This process steam is highly superheated and in certain applications saturated steam is needed, so it is necessary to include a desuperheater to take the superheated steam down to the saturated state. In the desuperheater a mixture of superheated steam and water is produced and therefore the saturated steam is obtained. The second steam extraction in turbine is used as heat source to feed the generator of hybrid absorption ejecto-compression chiller. The remaining steam goes out from turbine and enters into the condenser to be recovered like feed water for boiler.

Fig. 1 shows a schematic diagram of the tetra-combined trigeneration system.

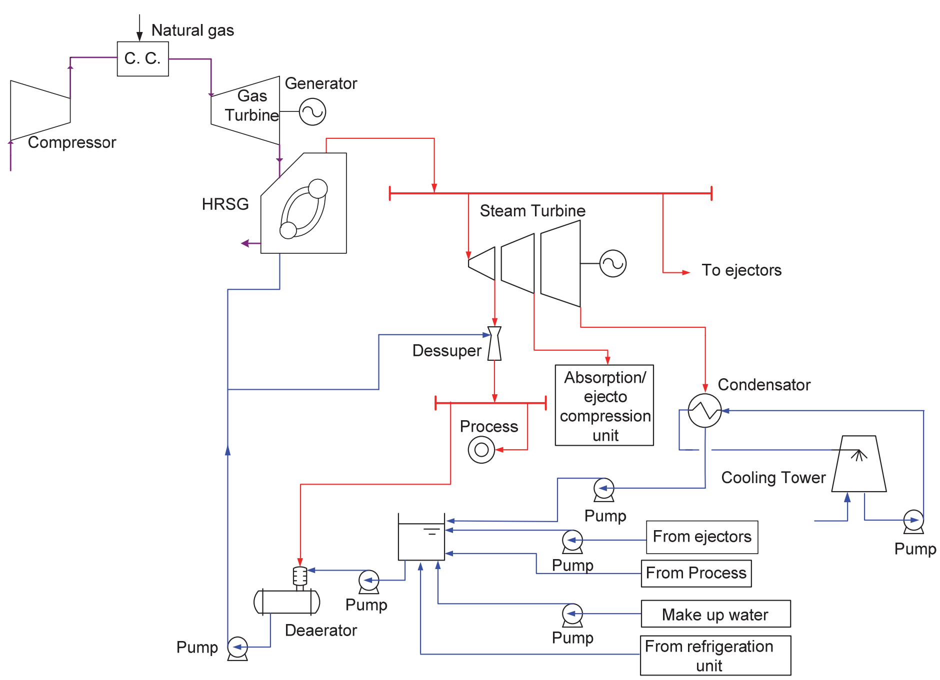
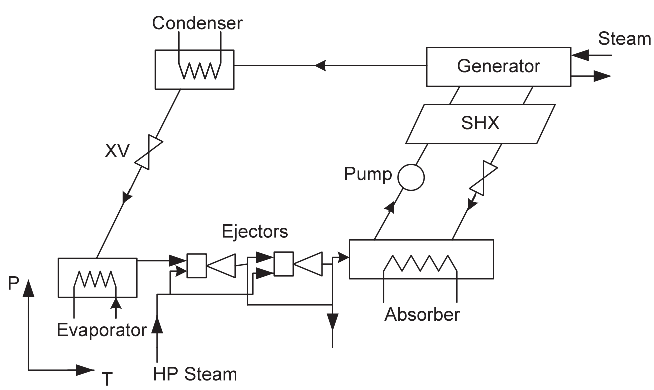


Figure 1. Schematic diagram of the tetra-combined trigeneration system.
Source: Authors

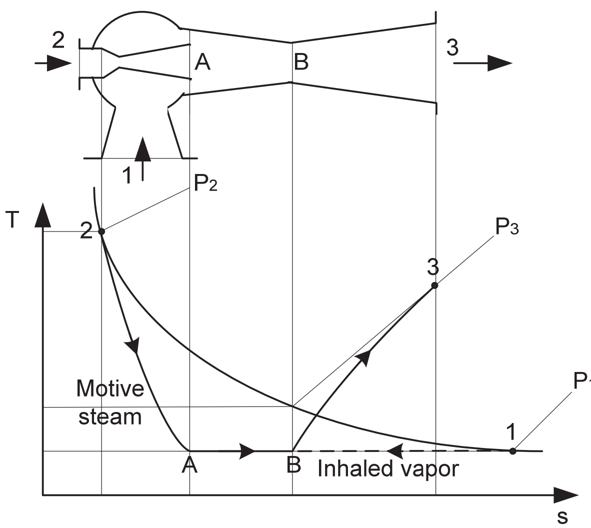
2.1. Hybrid Absorption ejecto-compression chiller

The absorption ejecto-compression refrigeration system had its origin in the work of [12]. The system is characterized by having ejectors between the evaporator and absorber. The operation is similar to the single-effect absorption system, with the variation of using ejectors. A detailed description of this system is provided in [13]. To reduce the motive steam consumption, there is a mass flow rate deviation in each ejector exit that is sent again to the boiler, or used in another process, if the pressure conditions allow. An exergoeconomic comparison of absorption refrigeration systems including this hybrid chiller was made by the authors in [14]. A double effect and combined ejector-double effect absorption refrigeration systems are compared in [15].

Fig. 2 (a) and (b) shows a water/lithium-bromide absorption ejecto-compression refrigeration system and the evolution of motive steam and the refrigerant drawn vapor throughout ejector, respectively. Configurations of absorption refrigeration systems using ejectors are described in [16].



(a)



(b)

Figure 2. (a) Absorption-ejecto compression refrigeration system Dühring chart schematic. (b) Evolution of motive steam and drawn vapor throughout ejector.

Source Oliveira Jr, S., 1991.

Table 1.
Assumed parameters used to simulate the trigeneration system.

Parameter	Value
Compressor Isentropic Efficiency (%)	85
Gas Turbine Isentropic Efficiency (%)	87
Saturated Steam Pressure (bar)	10
HRSG heat losses (%)	2
HRSG Pinch (°C)	10
HRSG Approach (°C)	5
Pump Isentropic Efficiency (%)	70
Electric Generator Efficiency (%)	95
Steam Pressure (bar)	42
Steam Temperature (°C)	420
Turbine (condensing-extraction) Isentropic Efficiency (%)	82-85
Pump Isentropic Efficiency (%)	70

Source: Authors

3. Modelling and Simulation

The tetra-combined trigeneration system was developed to satisfy the energy requirement of a dairy industry [17], thus it is possible to compare it with the performance of trigeneration systems described, developed and analyzed in [11] and others like systems based in steam turbines, gas turbines and combined cycle.

The trigeneration system using gas turbine, combined cycle and tetra-combined cycle were modeled using a gas turbine commercial type, choosing it according to energy demand. For all systems, except for trigeneration system with gas turbine, a pressure drop between boiler and steam turbine was considered. Thus, the steam pressure in turbine inlet is 3% lower than the boiler output. Also, a drop of 5 °C in steam temperature between boiler exit and steam turbine inlet was considered.

Some assumed parameters used to simulate the trigeneration systems are shown in Table 1.

For the purpose of analysis of absorption refrigeration systems, the following assumptions are made: the analysis is made under steady state conditions; the refrigerant at the outlet of the condenser is saturated liquid; the refrigerant at the outlet of the evaporator is saturated vapor; the outlet temperatures from the absorber and from generators correspond to equilibrium conditions of the mixing and separation, respectively; pressure losses in the pipelines and in heat exchangers are negligible; heat exchanges between the system and surroundings, other than the prescribed at the generator, high temperature generator (in double-effect absorption system), evaporator, condenser and absorber, are negligible; the reference environmental state for systems is water at 25 °C (T_0) and 1 bar pressure (p_0).

In hybrid absorption ejecto-compression chiller, the following assumptions were considered for ejectors energy balance: adiabatic flow; the kinetic energy in different points of ejector is negligible; one dimensional flow; steady state condition.

The calculation of high-pressure steam flow entering into the ejector, energy and exergy consumed by ejector was made by the authors in [13,14]. The models presented above were implemented in the Engineering Equation Solver [18], and simulated considering a steady-state operation.

For evaluating the costs, the idea is the development of cost balances for each component in the system.

$$\sum \left(c\dot{B}\right)_{input} = \sum \left(c\dot{B}\right)_{exit} \qquad (1)$$

Where $\dot{B}$ the exergetic rate and c is expresses the average costs per exergy unit of product. Considering the exergy-based cost for fuel equal to 1 kJ/kJ, it is possible to calculate the cost of the different plant flows. For distribution costs in control volumes with more than one product, the equality criterion was adopted. That is, each product has the same importance and consequently their exergy based cost were set equal (i.e. electricity and process steam, in cogeneration systems). Thus, the cost associated to the irreversibilities in the control volume is distributed equally among the exergy content of the outlet product flows.

4. Optimization of Trigeneration Plants

The trigeneration plants optimization process is carried out trying to find optimal parameters in their sub-systems. Initially, optimization of absorption refrigeration systems: simple effect, hybrid absorption/eject compression, and double effect, will be performed. Then, the optimized refrigeration systems will be used in the optimization of entire trigeneration plant. The Genetic Algorithms method is used in this work in order to obtain optimal configurations.

4.1. Optimization of absorption refrigeration systems

The performance and efficiency of reverse cycles are independent of the properties of any fluid. In contrast, the performance and efficiency of an actual cycle are determined to a great degree by the properties of the working fluid. The initial cost and operating cost of an absorption system are strongly dependent on the properties of the working fluid [19].

Thermodynamic variables considered important in projecting an absorption system are pressure, temperature and solution concentration. The idea is to find values of solution concentrations that optimize the system. Thus, the objective function of optimization problem was defined as the maximization of exergy efficiency of absorption refrigeration systems, and the solution concentration lithium bromide/ water was defined as an independent variable.

Genetic Algorithms were applied to the different absorption refrigeration systems in order to optimize them.

Fig. 3 shows the solution concentration evolution and its influence on exergetic efficiency and its evolution process of the hybrid absorption/ejecto compression refrigeration system in optimization process with genetic method.

Optimization results for the hybrid absorption/eject compression refrigeration system are shown in Table 2.

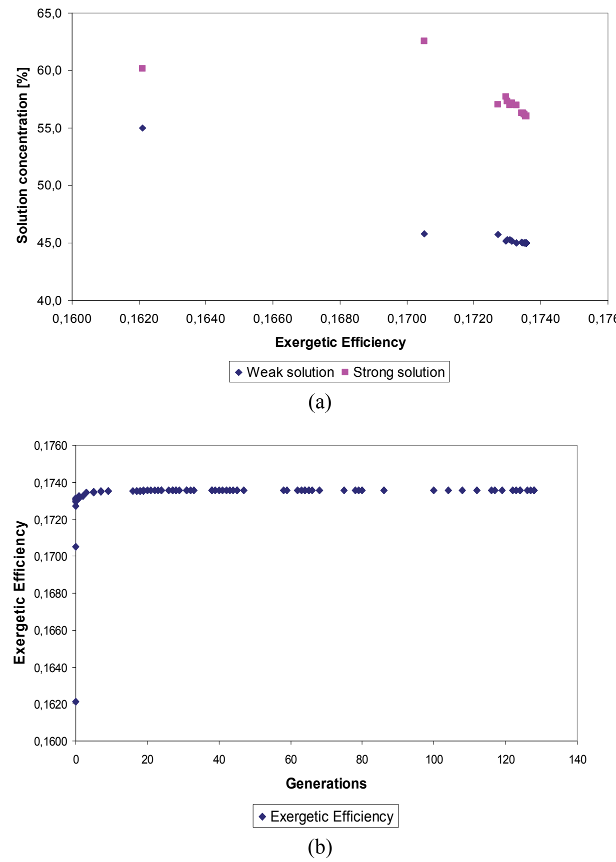


Figure 3. (a) Solution concentration evolution and its influence on exergetic efficiency (b) Evolution process of exergetic efficiency of hybrid absorption/ejecto compression refrigeration system.
Source: Authors.

Table 2.
Assumed Optimization results for hybrid absorption/eject compression refrigeration system.

Description	Base Case	Optimized Case Genetic Method
Weak solution concentration [%]	55,59	45
Strong solution concentration [%]	60,15	56
Coefficient of performance (COP)	0,7763	0,8418
Exergetic Efficiency	0,161	0,1736

Source: Authors

4.2. Global optimization of trigeneration plants

The decision variables are subjected to equality constraints imposed by the physical and thermodynamic model, as well as the inequality constraints imposed by upper and lower limits. For trigeneration systems using gas turbine like combined and tetra-combined cycles, the commercial gas turbine models were chosen based on its power capacity and the corresponding pressure ratio. Thus, variables considered for global optimization of trigeneration systems have to do with the Rankine cycle of these systems.

Table 3.
Assumed Optimization

Description	Minimum	Maximum
Boiler Pressure [MPa]	2	12
Steam Temperature [°C]	280	580
Extracted steam pressure for simple effect absorption chiller [kPa]	80	160
Extracted steam pressure for double effect absorption chiller [kPa]	300	450

Source: Authors

Additional restrictions are placed in the optimization process: (a) ensuring that the extracted steam from the steam turbine that goes to the simple effect absorption refrigeration unit and the hybrid absorption/eject compression unit is at least saturated steam; (b) the quality of the steam at turbine output is at least 86%; (c) the mass flows are positive in the cycle.

Table 3 presents the decision variables of the optimization problem and its initial boundaries.

5. Results

The results are presented and discussed for three scenarios, as carried out in [13]: the first one, for steam turbine configurations satisfying the plant requirements: 2.3 MW of electric power, 25 kg/s of chilled water at 5 °C and 2 kg/s of saturated steam at 5 bar for process. The second one includes a gas turbine with HRSG and absorption refrigeration system capable of generating 1662 kW of electricity surplus under modelling parameters. The last one includes a combined cycle with absorption refrigeration system and the tetra-combined trigeneration system generating 3143 kW of electricity surplus. The results of the optimization process presented are product of successive approximations to the optimum operation point by reducing the limits of the independent variables. This is because the average curve of the best individuals in various experiments shows the average performance of a genetic algorithm and serves to adjust parameters. The genetic method is very sensitive to changes in the limits of the independent parameters due to initial population and subsequent stochastic selections are chosen within limits.

Fig. 4 shows the evolution process of exergy efficiency of some trigeneration systems for the best values obtained in the optimization with genetic method. The same methodology was used for the rest of the trigeneration systems under study.

Table 4 shows the results of energetic and exergetic efficiency in the optimization performed in trigeneration systems using steam turbine, combined cycle and tetra-combined cycle, able to generate 3143 kW electricity surplus.

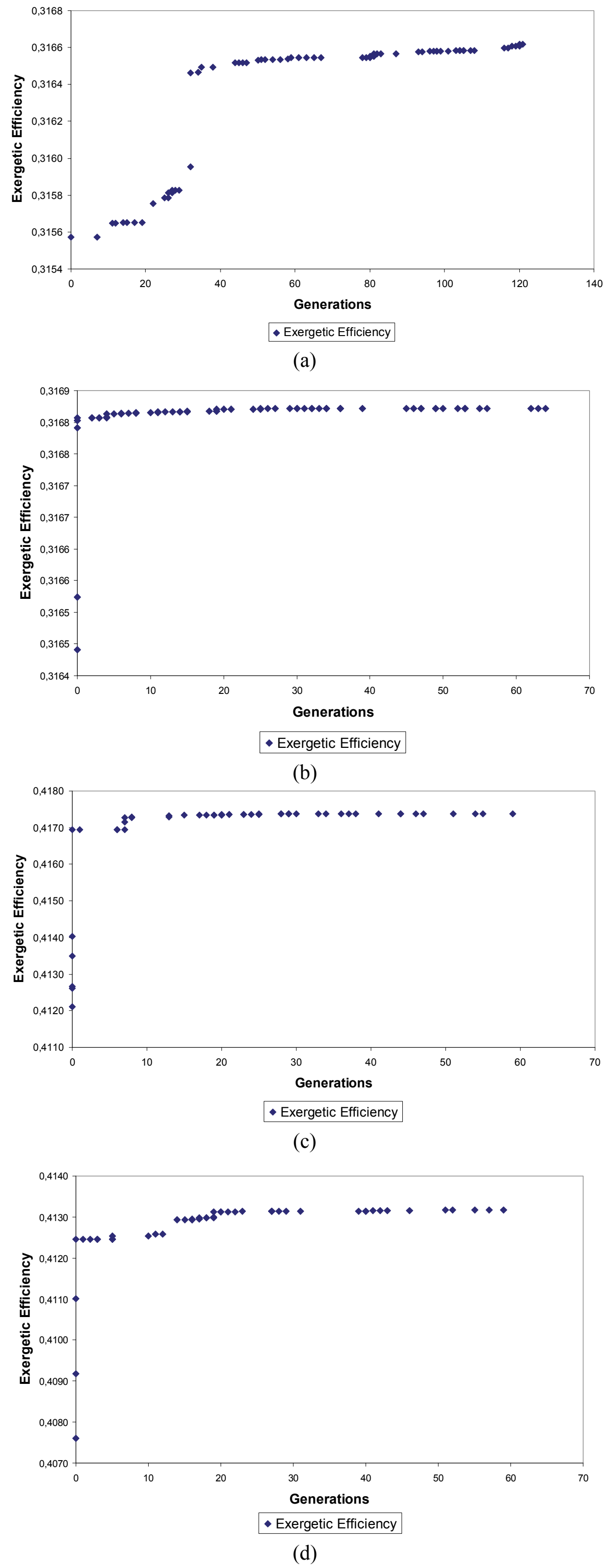


Figure 4. Exergetic efficiency evolution for some trigeneration systems: (a) Steam turbine and simple effect absorption refrigeration unit. (b) Gas turbine and double effect absorption refrigeration unit. (c) Combined cycle and double effect absorption refrigeration unit. (d) Tetra-combined system.
Source: Authors.

Table 4.
Energetic and exergetic efficiency in the optimization of trigeneration plants able to generate 3143 kW electricity surplus.

Trigeneration System	Energetic Efficiency		Exergetic Efficiency	
	Base Case (%)	Optimized Case (%)	Base Case (%)	Optimized Case (%)
Steam turbine and compression refrigeration unit.	41,63	49,1	25,32	29,87
Steam turbine and simple effect absorption refrigeration unit.	41,93	48,34	25,51	29,41
Steam turbine and double effect absorption refrigeration unit.	41,91	49,53	25,50	30,31
Combined cycle and simple effect absorption refrigeration unit.	66,08	67,4	40,21	41,48
Combined cycle and double effect absorption refrigeration unit.	66,04	67,67	40,17	41,74
Tetra-combined cycle	66,01	67,3	40,14	41,32

Source: Authors

In order to show the results of exergoeconomic optimization for the trigeneration systems, exergy destruction rate and exergy-based costs for each configuration were calculated and are discussed below.

Fig. 5 shows the exergy destruction rate (kW) of each configuration studied; next to the value of each system, the value of optimized system is provided.

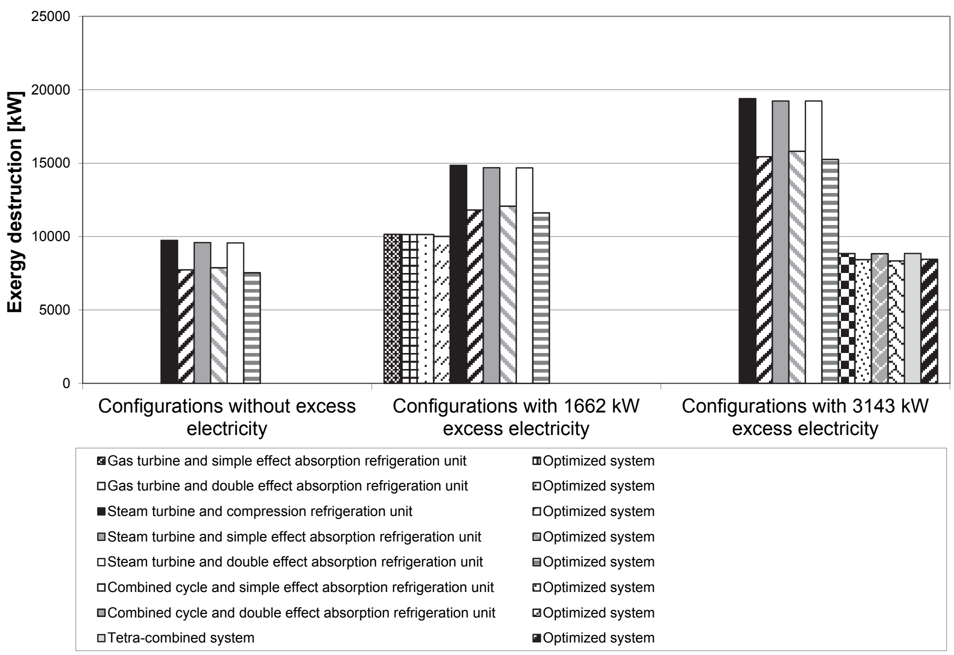


Figure 5. Exergy destruction rate (kW) of each configuration studied in comparison with optimized systems.
Source: Authors.

As Fig. 5 shows, the exergy destruction in optimized trigeneration systems presents a decrease compared to the base cases as follows: for the three scenarios under study, trigeneration systems with steam turbines and compression refrigeration unit showed a drop of around 20%. For the scenario of 1662 kW electricity surplus where there are trigeneration systems with gas turbine and absorption refrigeration units of simple and double effect, the decrease in exergy destruction was 0.5% and 1.4% respectively. For 3143 kW electricity surplus scenario, combined cycles and tetra-combined present approximately 5% reduction in exergy destruction in comparison to their base cases.

Fig. 6 shows a comparison of exergy based costs (kW/kW) of electricity, process steam and exergy transferred to chilled water for the configurations studied producing 3143 kW excess electricity and its corresponding optimized systems. The optimization of trigeneration systems presents the following results in decreased exergy based costs of products: in the electricity and process steam cases, the trigeneration systems with steam turbines have an average decrease of 14%. For electricity, combined cycles and tetra-combined cycle have a decrease of about 1% for this product. For process steam, combined cycle and simple effect absorption refrigeration unit, a decrease of 7.16% is obtained, varying from 2.4 kJ/kJ to 2.228 kJ/kJ; combined cycle and double effect absorption refrigeration unit presents a decrease of 8.5%, varying from 2.4 kJ/kJ to 2.198 kJ/kJ and tetra-combined cycle shows a decrease of 7.2%, varying from 2.4 kJ/kJ to 2.227 kJ/kJ.

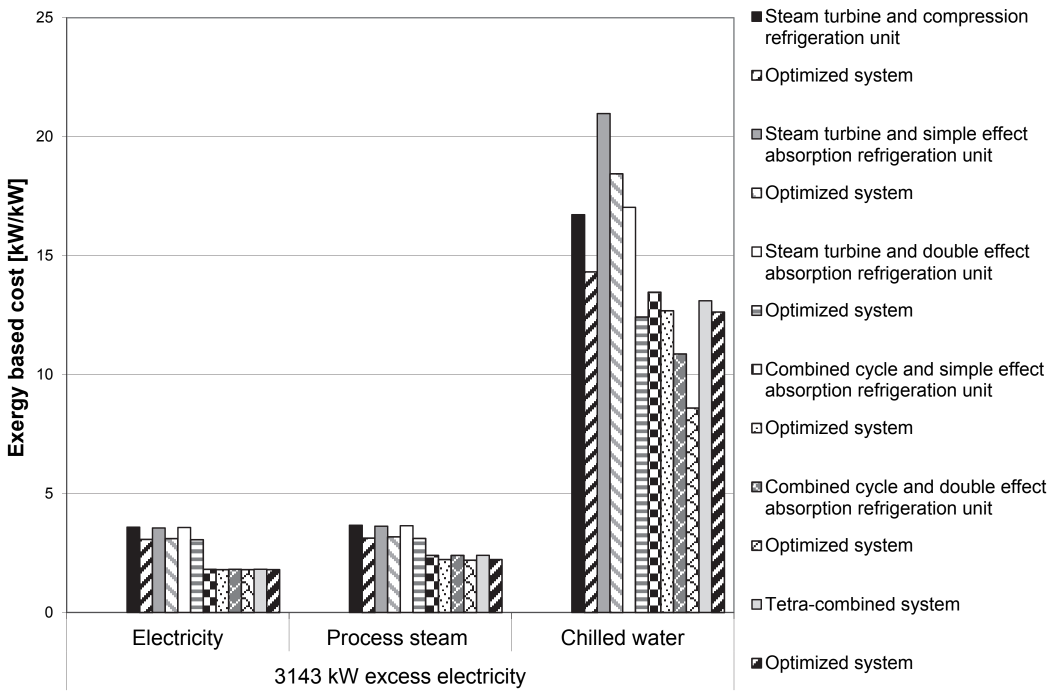


Figure 6. Exergy-based costs (kW/kW) of electricity, process steam and chilled water for 3143 kW excess electricity cases.
Source: Authors.

With respect to the exergy based cost transferred to chilled water, the following reductions with optimized configurations are presented: 14.35% for trigeneration system with steam turbine and compression refrigeration unit, varying from 16.72 kJ/kJ to 14.32 kJ/kJ; 12% for trigeneration system with steam turbine and simple effect absorption refrigeration unit, varying from 20.97 kJ/kJ to 18.44 kJ/kJ and 27% for trigeneration system with steam turbine and double effect absorption refrigeration unit, varying from 17.03 kJ/kJ to 12.42 kJ/kJ; combined cycle and simple effect absorption refrigeration unit presents a decrease of 5.8%, going from 13.46 kJ/kJ to 12.68 kJ/kJ; combined cycle and double effect absorption refrigeration unit has decreased by 20.94%, varying from 10.87 kJ/kJ to 8.593 kJ/kJ and tetra-combined cycle shows a decrease of 3.5%, varying from 13.1 kJ/kJ to 12.65 kJ/kJ.

5. Conclusions

The trigeneration represents a quite interesting alternative of producing electricity and reducing the production costs of utilities. In this work, an analysis and optimization of different trigeneration systems, including a tetra-combined system, was performed by means of exergoeconomic analysis to quantify its energetic and exergetic efficiency and the impact in the production of electricity, process steam and chilled water for air conditioning purposes. The results show that hybrid absorption/ejecto compression refrigeration system is an appropriate alternative for chilled water production due to the coefficient of performance (COP) and exergetic efficiency are higher than the simple effect absorption refrigeration system. Noting the impact on costs formation of energy conversion for proposed trigeneration systems, systems using double effect absorption refrigeration unit are the ones that have a lower impact. The tetra-combined system has a lower impact, when compared with the combined cycle and simple effect absorption refrigeration unit. Optimization with genetic algorithms showed significant gains in exergy based costs of products, by maximizing the exergetic efficiency of different trigeneration systems. The results indicate that maximizing the exergetic efficiency leads to minimization of exergy based costs of products. The Genetic Algorithms method is shown as a robust method for the optimization of energy conversion systems, although it requires a large computational effort. The optimization process showed that genetic method is very sensitive to changes in the limits of independent parameters as the initial population and subsequent stochastic selections are chosen within limits.

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