COMPARATIVE EXERGY ANALYSIS OF TRIGENERATION SYSTEMS FOR A DAIRY INDUSTRY

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Abstract. *The increasing costs of primary energy sources, like gas and oil, invite consumers to seek a more efficient use of them. High fuel prices and more restrictive ecological implications are giving impulse to technologies that better explore those energy sources. In spite of the efforts that are being made to develop alternative renewable energy sources (biomass, for instance), fossil fuels will be the predominant energy resource. Most of the industrialized countries, especially the United States and in Europe, have been developing energy policies to make better use of fossil fuels. These policies include programs for the efficient use of the energy, development of energy alternative sources, among others. The combined generation of heat and power is one of the technologies often used in industrial processes. A trigeneration process is an alternative to increase the efficiency in the power and thermal generation. The term trigeneration can be defined as the production of power, heat and additional cooling (generally, chilled water for air conditioned purposes). The trigeneration systems produce these three energy forms from a primary energy source such as natural gas or oil. This paper presents a comparative exergy analysis study of different configurations of this type of system for a dairy industry, which involve the use of steam turbines with compression and absorption chillers as well as a combined cycle with absorption chiller.*

Keywords*: Trigeneration, exergy analysis, dairy industry*

1. INTRODUCTION

The increase of fuel prices and ecological implications are giving impulse to technologies that better explore primary sources of energy (Coloma and Gabrielli, 2002). According to an article of the journal "*Carta Petrolera*" (2004), of the Petroleum Colombian Enterprise (Ecopetrol), the main reason for the fluctuation of oil prices is the offer and demand law. Not being a renewable energy source and since its consumption is increased at moments of economical growth, the demand press the offer and raises the prices. At this moment, June of 2008, the price of the barrel is over US$ 120.00. According to Temir and Bilge (2004), with an increase in the demand for these natural limited resources, the energy obtained from them is becoming more valuable. Therefore, the goal to develop new energy systems is to seek for the maximum efficiency with lower costs. Maximum efficiency means the conversion of fuel energy into useful energy in the most effective way. However, the maximum quantity of useful energy obtained from the fuel is limited. Energy conversions are carried out inside the limits caused by the irreversibility. Analyses based only on energy basis do not take into account these limitations.

For instance, conventional power plants convert only 1/3 of fuel energy into electricity. The rest are losses related to irreversibility. The averse effect in the environment been derived from this waste is obvious. The necessity of increasing the process efficiency of electricity generation is thus imperative.

A path towards more rational energy use in the electricity generation is the Cogeneration of Heat (or Refrigeration) and Electric Energy, in which more than 4/5 of the fuel energy is converted into useful energy, with financial and environmental benefits. For Colonna and Gabrielli (2002), when designing a new production plant, it would be necessary to consider an integrated production of utilities. So, the number of installations of the so-called "trigeneration" systems is increasing.

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 (Kwak *et al*. 2003). Exergy analysis of energy conversion plants allows to characterize how the fuel exergy 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.

2. TRIGENERATION SYSTEMS

The term trigeneration can be defined as the combined production o f power, heat and cold (generally, cold water for air condition purposes) from a single energy source. Such definition is in accordance with those proposed by Temir and Bilge (2004) and Teopa Calva *et al*. (2005). According to Temir and Bilge (2004), even though they present very high investment costs, these systems are more economical compared with systems where the power, heat and cold are obtained individually. Teopa Calva *et al*. (2005) consider trigeneration systems a special case of the application of cogeneration system where a fraction of power or residual heat is used in refrigeration systems. According to Emho (2003), trigeneration is a technique introduced in the beginnings of 80´s and used mainly for district heating and cooling. For Goodell, president and executive of Trigeneration Technologies, subsidiary of Ecogeneration Solutions, in the United States, whenever trigeneration systems are found in hospitals, universities, military bases or set of offices buildings, it is called District Energy Systems or Integrated Energy Systems. The same document, also calls to the trigeneration as CHCP of the acronyms in English "Combined heating, cooling and power generation" which allows a higher operational flexibility in places with energy demand in the form of heat and cool, particularly relevant in tropical countries where the buildings need air conditioning and many industries with cooling processes. According with Guo (2004), trigeneration is known also like BCHP (Building, cooling, heat and power) when it is applied in buildings.

Figure 1 shows the principle of a trigeneration system.

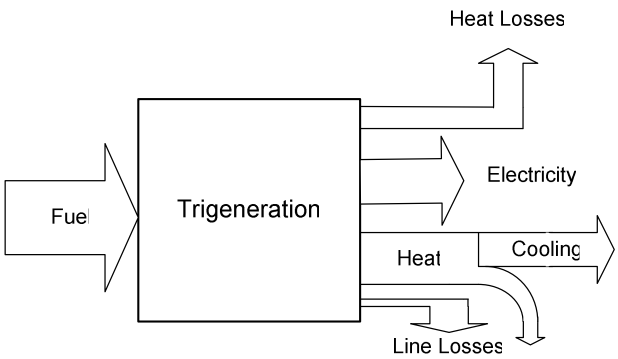

Figure 1. Schematic diagram of a trigeneration system

Maidment *et al*. 2001 present an application of trigeneration systems to supermarkets based on an initiative of the United Kingdom government to promote efficient energy systems. Based on the demands for cold, heat and power of a supermarket, the work evaluates different trigeneration schemes and defines its economical and environmental viability compared with conventional methods to supply of cold, heat and power. The authors conclude that, despite being from a case study, the results are relevant for other applications of refrigeration that have relatively constant loads. ***(What results?)***

In many industrial processes, there is a simultaneous need for electricity and refrigeration at low temperatures (Coloma and Gabrielli, 2002). Examples in the food, petrochemical and pharmaceutical industries are quoted by the authors, ensuring that trigeneration systems using absorption refrigeration system ammonia-water is feasible and, in some cases, an economical option.

Bassols *et al*. (2002) show an application of trigeneration systems to the food industry, introducing several examples of trigeneration plants mainly with absorption refrigeration with ammonia. The authors state that to obtain a complete use of a cogeneration plant, it is necessary a constant heat and power demand. Power demand may be regulated by the sales of the excess power to the grid, but excess heat is usually lost. Thus, the combination of absorption refrigeration with a cogeneration plant allows using all the heat produced for the cold production. The document is clear when it secures that, while the heat or steam demand usually has great fluctuations, the refrigeration demand is more constant, especially in low temperatures, between -15 and -55 °C, where the demand is almost not influenced by the room temperature.

Figure 2 (Teopa Calva *et al*. 2005) shows a diagram of a trigeneration system based on gas turbines. While the heat and the power are supplied by the turbine and the exhaust gases, the refrigeration can be obtained in two different ways, using an absorption system in combination with low grade heat or using a compression system handled electrically. The use of one or other will depend on the necessities of the heat to power ratio in the process and in specific characteristics of place.

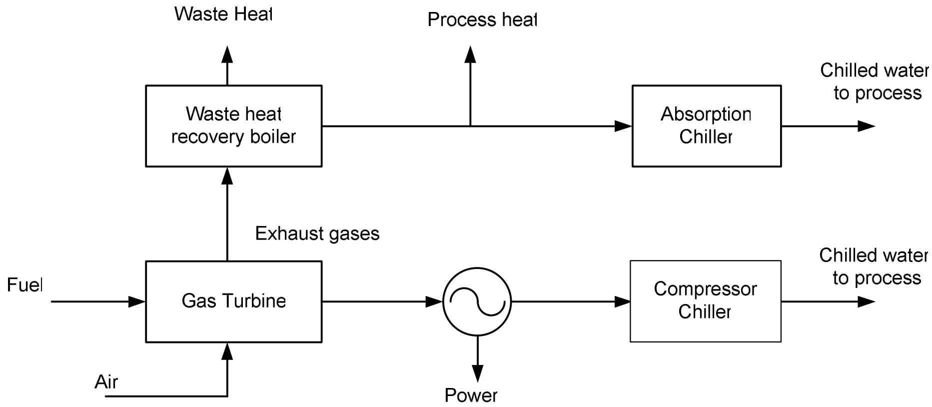

Figure 2. General diagram of a trigeneration system based on gas turbines (Teopa Calva *et al*. 2005)

As discussed by Guo, (2004), trigeneration systems were proved to be convenient in a wide variety of buildings, for instance, hotels, hospitals, sport centers, school buildings, airports, supermarkets and great shops. Some of the advantages, according to the document, are summarized below:

- *Fuel saves*: CHP/CHCP plant leads to the reduction of the fuel consumption in approximately 25 % in comparison with the production of conventional electricity.
- *Emissions Reduction*: it follows the same proportion. With the use of natural gas, and not oil or coal, the emissions of SO_2 and smoke are reduced to zero.
- *Economical benefits*: The energy prices of trigeneration units are lower than the "conventional" units. As an indication, the price reduction can be in the range of 20-30 %.
- *Increase in the reliability of the energy supply*. A CHP station might be connected to the electric grid, where it provides or takes electricity, guaranteeing uninterrupted operation of the unit.
- *Increase in stability of the electricity network*: Trigeneration units offer significant relief for the electricity network during the hot summer months, regarding the change of the cooling process from compression cycles to absorption ones. Besides increasing the stability of the electricity network, such change improves the system efficiency, because summer peaks very often are served by electric companies through inefficient unities of reserve and overload electricity transmission lines.

3. AVAILABLE TECHNOLOGIES OF TRIGENERATION

A trigeneration system can be divided into two parts: the CHP (Combined Heat and Power) unit, which produces electricity and heat. The second part is the chiller (compression or absorption type), which produces cold using electricity and/or heat from the CHP unit.

3.1 CHP unit

According to Guo (2004), technologies available in the market for CHP units are: gas turbines, steam turbines, combined cycles, internal combustion engines, fuel cells and Stirling engines. A good description of the technologies previously quoted is given in the TriGeMed project (2003). The global objective of the TriGeMed project is to promote the adoption of trigeneration in the tertiary sector in the Mediterranean countries. As reported by this project, most commonly applied units to trigeneration are Internal Combustion Engines, usually in groups of more than one to handle load variations. Gas turbines are used for large building complexes such as Hospitals or district heating/cooling schemes. Steam turbines are not used in the tertiary sector. Fuel cells are ideal for operation in the tertiary sector, due to their efficient and silent operation and could be installed if their prices were lower. Balestieri (2002) shows also technologies with potential use in cogeneration systems like CIC/STIG (coal integrated gasifier/steam injected gas turbine), use of PFB (pressurized fluidized bed) boilers, IGCC (integrated gasification combined cycle), among others.

Table 1, adapted from the TriGeMed project, summarizes the main characteristics of technologies for CHP units.

Table 1. Summary of CHP technologies and associated indices (TriGeMed Project, 2003).

Engine	**Gas Turbine**	**Steam Turbine**	**Combined Cycle**	**ICE Otto/ Diesel**	**Fuel Cell**
Power (MWe)	0,2-100	0,5-100	4-100	0,015-30	0,01-0,25
Heat/Power ratio	1,25-2	2-10	0,5-1,7	0,4-1,7	1,1
Electricity Efficiency (%)	15-35	10-40	30-40	25-45	35-40
Thermal waste (%)	40-59	40-60	40-50	40-60	20-50
Overall Efficiency (%)	60-85	60-85	70-90	70-85	55-90
Lifetime (yrs)	15-20	20-35	15-25	10-20	> 5
Minimum Load (%)	75	20	75	50	No limits
Availability (%)	90-98	99	90-98	92-97	> 95
Installation Cost (€/kWe)	600-800	700-900	600-800	700-1400	> 2500
Service cost (€/MWe)	2-7	3	2-6	6-12	2-12
NOx (kg/MWh)	0,2-2	0,9	0,2-2	1-14	< 0,01
Usable Temp. (oC)	450-800	-	450-800	300-600	250-550
Use of Heat	Heat, DHW, LP-HP steam, district heating	LP-HP steam, district heating	LP-HP steam, district heating	Heat, DHW, LP steam, district heating	DHW, LP-HP steam
Fuel	Gas, liquid	All	Gas, liquid	Gas, petrol, diesel	Gas

As stated by the “Green Building Program” (2005) of the European Commission, among all cogeneration technologies, the most relevant ones to buildings are: gas turbines with heat recovery, internal combustion engines, micro gas turbines, Stirling engine and fuel cells.

3.2 Chiller

As discussed previously, the second part of a trigeneration installation is the chiller (compressor or absorption type), which is responsible for cold production using electricity and/or heat from the cogeneration process.

In a vapor-compression chiller, the refrigeration is obtained in the evaporator where heat is absorbed through the vaporization of the refrigerant, and rejected in condenser where the refrigerant is condensed. Vapor generated in the evaporator is compressed to the condenser pressure with a mechanical compressor, consuming electric power.

In its most simple conception, an absorption machine consists of an evaporator, a condenser, an absorber, a generator and a solution pump. The absorption refrigeration was first developed by Nairn in 1777 and the first commercial refrigerator built by Carré in 1823 (Cost a, 1982). In an absorption chiller, the compression of the steam refrigerant is effectuated by the absorber, by the solution pump and by the generator in combination, instead of using a mechanical compressor.

Refrigerant and absorbent in an absorption cycle form what is designated by couple of work. Many couples have been proposed along the years, but only two have been widely used: Ammonia together with water as absorbent and water together with an aqueous solution of lithium bromide as absorbent. The couple ammonia-water is found in applications of refrigeration with low temperatures (lower than 0 ºC). The couple water-lithium bromide is very much used in applications for air conditioning, in which it is not necessary to cool below 0 ºC.

A good review of absorption refrigeration technologies can be found in the work of Srikhirin *et al.* (2001). The TriGeMed project presents some technical characteristics of the absorption chillers frequently used in the trigeneration projects (Tab. 2).

Table 2. Technical characteristics of the absorption chillers frequently used in the trigeneration projects (TriGeMed project, 2003).

Indices	**NH_3 - absorption**	**LiBr – absorption**	
Effect	Single	Single	Double
Cooling capacity (kW)	20 - 2500	300 - 5000	300 - 5000
Thermal COP	0,6 -0,7	0,5 – 0,6	0,9 – 1,1
Temp. range (^{o}C)	120 - 132	120 - 132	150 - 170
Equipment costs (€/ton)	1250 to 1750	890 to 920	930 to 980

4. MODELLING AND SIMULATION

Trigeneration systems developed in this paper are applied to satisfy the energy requirement of a dairy industry, taking a Colombian dairy-industry as case study (Larrazábal and Oliveira Jr, 2002). The industry requirements are:

- 2,3 MW of electric power;
- 25 kg/s of chilled water at 5°C;
- 2 kg/s of saturated steam to 5 bar pressure for process.

This paper presents four configurations for the trigeneration system:

i. Steam turbines and vapour-compression refrigeration (Fig. 3)
ii. Steam turbines and absorption refrigeration (Fig. 4)
iii. Gas turbine and absorption refrigeration (Fig. 5)
iv. Combined cycle with absorption refrigeration system (Fig. 6)

For the purpose of analysis of absorption refrigeration systems, the following assumptions are made: in the generator and in the absorber, the lithium bromide solution is assumed to be in equilibrium; refrigerant (water) at condenser and evaporator exit is saturated; solution pump work and pressure losses in all the heat exchangers and the pipelines are negligible.

The set of data defining operational conditions of compression and absorption refrigeration system is shown in Tab. 3.

Table 3. Set of data defining operation conditions of refrigeration systems.

Compression Refrigeration System		Absorption Refrigeration System	
Compressor power	107,7 kW	Solution generator temp.	52 - 80 °C
Condensation temp.	40 °C	Condensation temperature	40 °C
Evaporation temperature	3 °C	Evaporation temperature	3 °C
Refrigerant	R 134a	Solution absorber temp.	25 - 30 °C
Environmental condition	25 °C and 1 bar	Environmental condition	25 °C and 1 bar
Chilled water inlet temp.	10 °C	Chilled water inlet temp.	10 °C
Chilled water outlet temp.	5 °C	Chilled water outlet temp.	5 °C

For trigeneration systems operating using steam turbines, it is also assumed parameters shown in Tab. 4.

Table 4. General parameters used for the simulated trigeneration systems operating based on Rankine Cycle.

Parameter	**Value**
Boiler Efficiency (%, LHV basis)	85
Electric Generator Efficiency (%)	95
Steam Pressure (bar)	42
Steam Temperature (°C)	420
Turbine Stages Isentropic Efficiency (%)	78-80
Pump Isentropic Efficiency (%)	70

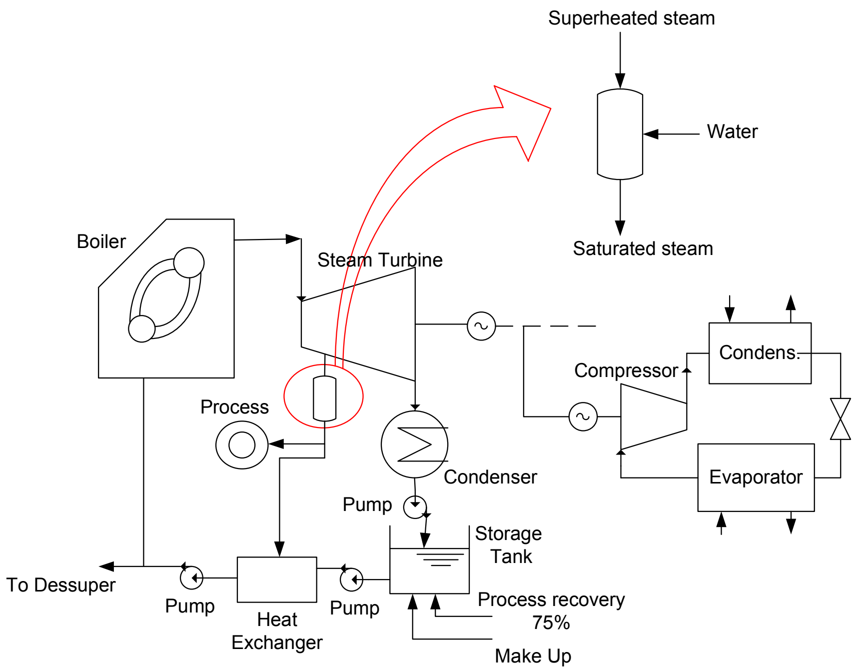

Figure 3. Schematic diagram of first trigeneration system: Rankine cycle with compression refrigeration system

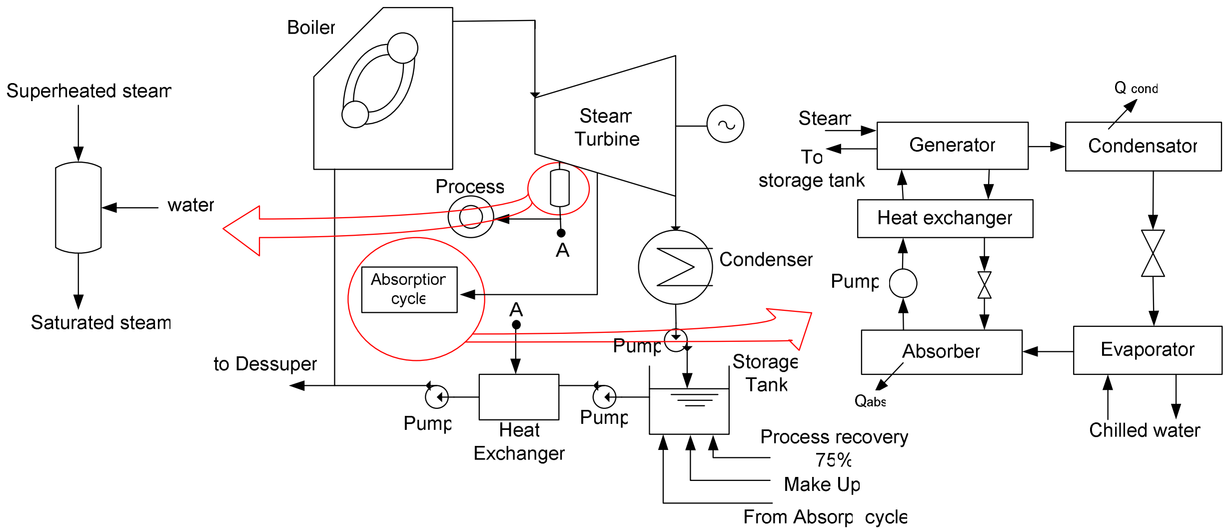

Figure 4. Schematic diagram of second trigeneration system: Rankine cycle with absorption refrigeration system

The assumed parameters used to simulate the third trigeneration system: gas turbine and heat recovery steam generator (HRSG) with absorption refrigerator system are shown in Tab. 5.

Table 5. Assumed parameters used to simulate the third trigeneration system.

Parameter	**Value**
Turbine inlet temperature (TIT) (°C)	1200
Gas Turbine Efficiency (%)	87
Saturated Steam Pressure (bar)	10
HRSG efficiency (%)	98
HRSG Pinch (°C)	10
HRSG Approach (°C)	5
Pump Isentropic Efficiency (%)	70

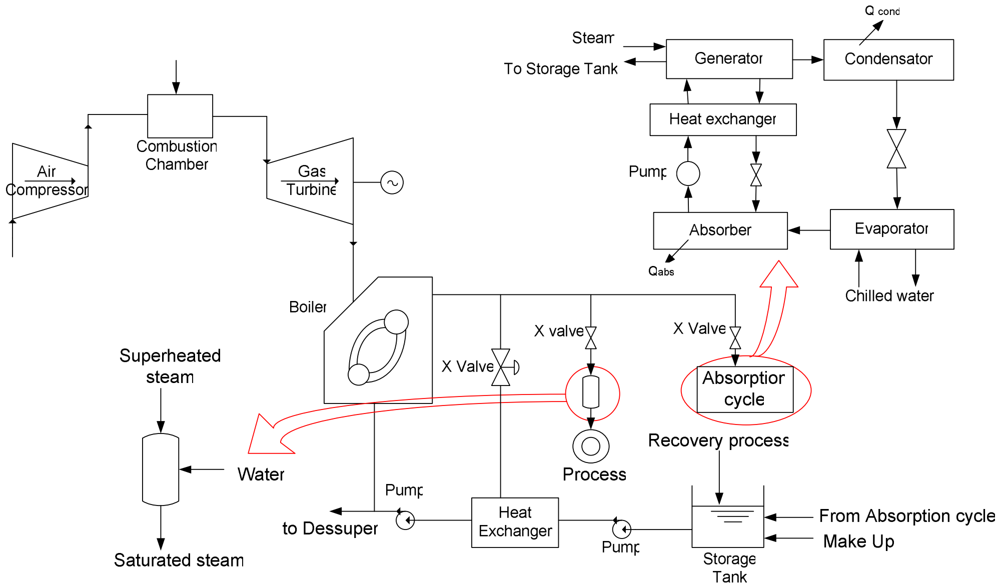

Figure 5. Schematic diagram of third trigeneration system: gas turbine and HRSG with absorption refrigeration system

For the last configuration, in addition to the assumed parameters previously, the ones shown in Tab. 6 are also are considered.

Table 6. Parameters used to simulate the last trigeneration system: combined cycle and absorption refrigeration system.

Parameter	**Value**
Electric Generator Efficiency (%)	95
Steam Pressure (bar)	42
Steam Temperature (°C)	420
Turbine (condensing-extraction) Isentropic Efficiency (%)	78-80
Pump Isentropic Efficiency (%)	70

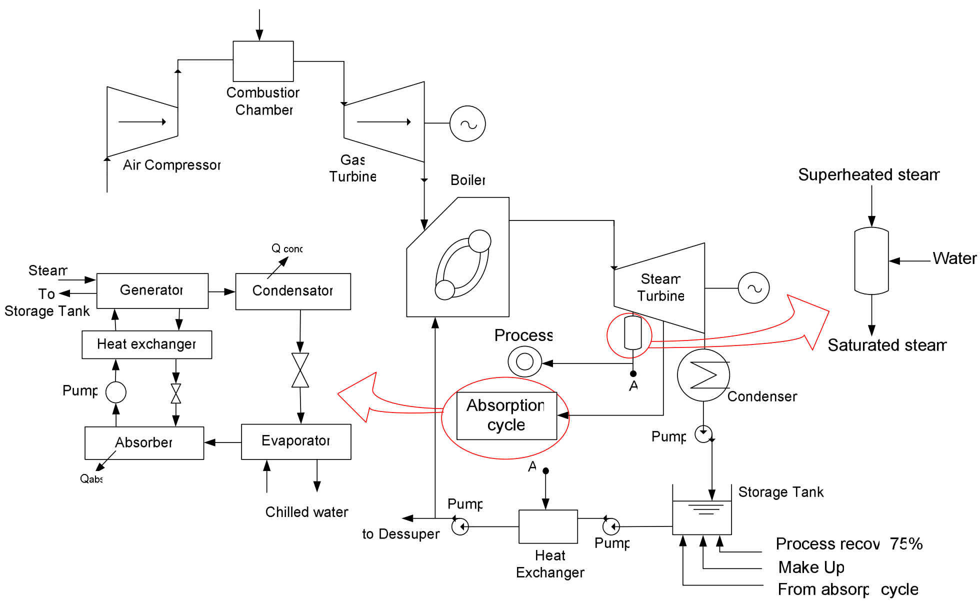

Figure 6. Schematic diagram of the last trigeneration system: combined cycle with absorption refrigeration system

The models presented above were implemented in the Engineering Equation Solver (EES®) (F-Chart, 2007), and simulated considering steady-state operations.

4. RESULTS

The only variable that unequivocally characterizes the performance of a component from a thermodynamic point of view is exergy efficiency (Tsatsaronis, 1999). Thus, for the thermal processes analysis the exergy efficiency might be defined as:

$$\eta_{ex} = \frac{useful\ \ produce\ exergy}{exergy\ consumption} \tag{1}$$

Consequently, the exergy efficiency of the trigeneration systems in study is given by:

$$\eta_{ex} = \frac{\dot{W}_{plant} + \dot{W}_{NET} + \Delta\dot{B}_{process} + \Delta\dot{B}_{chilled\ water}}{\dot{m}_{fuel} b_{fuel}} \tag{2}$$

Where $\dot{W}_{plant}$ is the electric power requirement of the dairy industry, $\dot{W}_{NET}$ is the amount of excess electricity that can be generated by the trigeneration systems and sold to the grid, $\Delta\dot{B}_{process}$ is the variation of the steam exergy flow rate used in the process, $\Delta\dot{B}_{chilled\ water}$ is the variation of the exergy flow rate of chilled water, $\dot{m}_{fuel}$ is the mass flow rate of fuel and the b_{fuel} is the specific exergy of fuel.

For the energy efficiency of the trigeneration systems, it is used:

$$\eta_{ene} = \frac{\dot{W}_{plant} + \dot{W}_{NET} + \dot{Q}_{process} + \dot{Q}_{chilled\ water}}{\dot{m}_{fuel} LHV} \tag{3}$$

Where $\dot{Q}_{process}$ is the heat rate transferred to the industrial process. $\dot{Q}_{chilled\ water}$ is the heat rate in the evaporator of refrigeration system and *LHV* is the lower heating value of fuel.

In order to show the obtained results of the exergy analysis, it is possible to consider two scenarios: the first one without production of excess electricity and only carrying out the requirements of the plant, that is to say, the necessary electrical power production, steam for process and the chilled water for air conditioning purpose; the second one, generating, in addition to the needs of the plant, excess electricity that is sold to the grid.

Table 7 shows the results obtained in the simulation for the first scenario: without excess electricity.

Table 7. Results for energetic and exergetic efficiencies for trigeneration systems without excess electricity.

	Energy Efficiency (%)	Exergy Efficiency (%)
Rankine cycle with compression refrigeration system.	56.88	26.47
Rankine cycle with absorption refrigeration system.	57.51	26.76
Gas turbine and heat recovery steam generator with absorption refrigeration system.	88.98	41.40
Combined cycle with absorption refrigeration system.	88.66	41.25

All obtained values of exergy efficiency are better than that of the original utilities plant (24%), which used imported electricity and fuel oil (Larrazábal and Oliveira Jr, 2002). It must be pointed out that in the calculation of the exergy efficiency of the original utilities plant, it was not considered the efficiency of electricity generation and transmission processes.

For the second scenario, it was supposed a 7500 kW of excess electricity for all systems in order to evaluate the behavior of energy and exergy efficiencies. The results are shown in Tab. 8.

Table 8. Results for energy and exergy efficiencies for trigeneration systems with 7500 kW of excess electricity.

	Energy Efficiency (%)	Exergy Efficiency (%)
Rankine cycle with compression refrigeration system.	33.53	23.85
Rankine cycle with absorption refrigeration system.	33.85	24.07
Gas turbine and heat recovery steam generator with absorption refrigeration system.	41.20	29.30
Combined cycle with absorption refrigeration system.	40.92	29.11

The decrease in the energy and exergy efficiency of different configurations studied, in comparison to the trigeneration systems without excess electricity, is the increase of fuel consumption to get the excess electricity.

For the first and second configuration, it was developed a simulation with steam production of 15 kg/s (according to steam production of boiler commercial model), in order to evaluate the behavior of the refrigeration systems in energy and exergy efficiency and also in the excess electricity production. The results appear in Tab. 9.

Table 9. Comparative energy, exergy efficiency and excess electricity for the first and second configuration with steam production of 15 kg/s.

	Energy Efficiency	Exergy Efficiency	Excess Electricity (kW)
Rankine cycle with compression refrigeration system.	0,33	0,24	7682
Rankine cycle with absorption refrigeration system.	0,34	0,24	7786

It is clear that the trigeneration system operating under Rankine cycle with absorption refrigeration system has better energy and exergy efficiency than the cycle with compression refrigeration system, and also it is possible to have greater excess electricity, confirming the advantage of absorption refrigeration system.

5. CONCLUSIONS

An exergy analysis for four configurations of trigeneration systems was made in this work: Rankine cycle with compression refrigeration system, Rankine cycle with absorption refrigeration system, gas turbine and heat recovery steam generator with absorption refrigeration system and combined cycle with absorption refrigeration system. Those configurations were applied to a dairy industry as a case study. The results show how in the case of only satisfying the requirement of the plant, as in the case of having excess electricity, gas turbine and heat recovery steam generator with absorption refrigeration system has the better performance with higher energy and exergy efficiency. The results show also the advantage of absorption refrigeration system on the compression refrigeration system.

A trigeneration system is an alternative design to increase the efficiency in the thermal and electric generation and to achieve energy saving in cogeneration plants. The authors are researching new alternatives for trigeneration systems, which involve changes in the absorption refrigeration system, as proposed by Garagatti and Oliveira (2003), technologies for CHP unit and the exergoeconomic evaluation of them.

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