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Exergy Analysis of a Multipurpose CCHP Layout Based on Natural Gas Engines for Application in the Tertiary Sector

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Abstract. *This manuscript presents the main results of the exergy analysis of a cogeneration layout for supplying electric power, saturated steam, cold water for air conditioning, and sanitary hot water to a hospital facility located at the city of Florianópolis, Brazil. Firstly, some key concepts and general features of the exergy analysis are summarized and the power and thermal demands of the facility are presented. Once the maximum demands for each utility are identified, seven cogeneration scenarios are proposed based on the possible utilities' combinations, as well as on premises commonly used by cogeneration experts. Results obtained from the exergy analysis of each scenario are compared with the efficiency calculated conventionally by the energy balance of the plant, showing that the balance between the amounts of steam and cold water delivered by the plant has the opposite effect over the energy and exergy performances of the plant. On the other hand, the exergy destruction rate calculated for the plant equipment presents the prime mover and the gas-water heat transfer as the operations with the greatest possibility of improvement. Finally, some insights are introduced regarding the practical limitations of the exergy-derived results and further exergy-based analyses.*

Keywords: *Cogeneration, Exergy Analysis, Energy Efficiency, Tertiary Sector*

1. INTRODUCTION

The world population growth and the improvement of standard of living drive a long-lasting increase of energy demand, which implies a greater consumption of natural resources as long as the current-available energy supply technology is used. This fact have encouraged the research and development of more efficient and more environment-friendly energy systems and devices, many of them facing important barriers to be deployed because of their low level of maturity and poor cost-effectiveness (IEA, 2014). In view of this circumstance, improving the design and use of conventional energy technology appears as the best short-term option to meet better efficiency at a reasonable cost-effectiveness. In that direction, Combined Heat and Power (CHP) or cogeneration appears as a high-efficiency practice capable of addressing totally o partially simultaneous power and thermal demands (*e.g.* cold water, hot water, steam, etc.) from a unique energy source (ASHRAE, 2015).

CHP systems can be applied in different types of applications (*i.e.* hospitals, shopping centers, food industry, etc.), and are formed by several interconnected devices (*e.g.* engines, heat exchangers, absorption chillers, etc.); each one with different operational characteristics and different availability. Additionally, the type and number of utility demands, as well as their temporal profiles, are related directly with the type, magnitude and schedule of activities done in a particular place, besides the weather seasonality in that location (Spitler, 2014). All these factors imparts a great level of complexity to the synthesis of CHP facilities and have encouraged numerous publications using in-depth analysis methods applied to CHP systems in diverse contexts, looking for a higher performance (*e.g.* Kanoglu and Dincer (2009); Abusoglu and Kanoglu (2009c,a)).

One of these in-depth methods is the exergy analysis, which is based on the second law of thermodynamics and enables the quantification of the amount of useful energy that is not used nor transferred by a unit operation within a complex system (CHP plants, for instance), providing significant information for the selection of adequate actions to improve its performance (El-Sayed, 2003). In view of this key advantage, this work compares different results obtained by a typical energy-based analysis with those obtained applying the exergy analysis on an arbitrary cogeneration plant, addressing the power and thermal demands of a hospital facility in the city of Florianópolis, Brazil. First, some key aspects of the exergy analysis are summarized and a brief description of the hospital facility together with the CHP plant is presented. Next, seven different CHP scenarios are proposed in order to compare and analyze the impact of various CHP alternatives on the global performance of the system. Through the implementation of the methodology over these scenarios, results illustrate the usefulness and some limitations of the exergy concept applied to CHP facilities, as well as some aspects of the typical energy-based efficiency. Finally, some insights are mentioned regarding the direction of more advanced exergy-based methodologies for imparting more feasibility to the improvements inferred initially by the exergy analysis.

2. EXERGY ANALYSIS

Exergy is an extensive thermodynamic property of a system defined as the maximum work developed in the ideal process from a given state to the environment state (Sciubba, 2005). Or alternatively, as the minimum theoretical useful work required to form a quantity of matter from substances present in the environment and to bring the matter to a specified state (Bejan *et al.*, 1996). It is an attribute of the pair system-environment and it is associated to the quality of different energy forms understood as the measure of its capacity of causing change (Kotas, 1985). In that sense, *'high quality'* forms of energy (*e.g.* potential, kinetic, mechanical, electrical) can be converted into each other with 100% efficiency, while lower forms of energy (internal energy, chemical energy, thermal radiation, turbulent kinetic energy, etc.) cannot be converted into each other without an intrinsic efficiency loss. That loss are 'dissipated' into a low-temperature flux absorbed or provided by the environment and is consequence of the irreversibility (entropy generation) inherent to real processes (Bejan, 2006; Sciubba, 2005).

Consequently, exergy is not conserved: in every real process, there is an exergy destruction caused by irreversibility effects, including the processes where all the initial capability to develop work is destroyed spontaneously. Since no work is needed to effect such a spontaneous change, it follows that the value of exergy is *at least zero and therefore cannot be negative*, comprising those systems receiving thermal energy from environment (Bejan *et al.*, 1996). However, Sciubba and Wall (2007) mentions that there may be particular combinations of the values of the thermodynamic parameters of a system such that its exergy value is negative; in these cases, to bring the system in equilibrium, work must be done on the system by the environment.

As stated by Bejan (2002), main benefits from these characteristics are that it makes it possible to compare on a common basis different interactions (inputs, outputs, work, and heat) and that by accounting for all exergy streams within a system, it is possible to determine the extent to which a system destroys exergy. In thermal systems engineering, exergy is commonly expressed as the sum of four addends:

$$B = \underbrace{B^{KN} + B^{PT} + B^{PH}}_{\text{thermomechanical}} + \underbrace{B^{CH}}_{\text{chemical}} \tag{1}$$

where B^{KN}, B^{PT} and B^{PH} are, respectively, the kinetic exergy, the potential exergy and the physical exergy, their sum is commonly referred as the thermomechanical exergy; on the other hand, B^{CH} corresponds to the chemical exergy.

2.1 Physical Exergy

Considering a system at rest relative to the environment ($B^{KN} = B^{PT} = 0$), the physical exergy is the maximum theoretical work obtainable as the system passes from its initial state at T and P to a state in thermal and mechanical equilibrium with the environment (at T_0 and P_0). For an open system at specified state, the physical exergy is given by the expression

$$B^{PH} = (H - H_0) - T_0\,(S - S_0) \tag{2}$$

where H and S denote, respectively, the enthalpy and the entropy at the specified state, while H_0 and S_0 are the values of the same properties when the system is at thermomechanical equilibrium with the environment.

2.2 Chemical Exergy

The chemical exergy is defined as the maximum useful work obtainable as the system passes from the thermomechanical equilibrium to a complete equilibrium with the environment. For the calculation of the chemical exergy of a system, the substances comprising the system must be referred to the properties of a suitable selected set of environmental substances.

Given the difficulty and the inconvenience of modeling thoroughly the composition of the natural environment, the notion of the standard chemical exergy of a substance was introduced, with the assumption that the conventional mean concentrations of a set of reference species contained in the reference environment (RE) have been taken into account. These species generally fall into three groups: gaseous components of the atmosphere, solid substances from the lithosphere, and ionic and nonionic substances from the oceans resembling as closely as possible the chemical makeup of natural environment. The reasoning of this approach and the detailed procedure of calculation of standard chemical exergy ($\bar{b}^{o}_{ch}$)

are presented by Szargut *et al.* (1988); values for reference species, as well as for many common substances are tabulated in molar basis.

In order to calculate properly the chemical exergy of an non-tabulated substance, there are two identifiable methods according to Querol *et al.* (2013): One based on the elemental composition and the free energy of formation of the compound (similar approaches are presented by Kotas (1985) and Lozano and Valero (1988)) and other for substances not found in the RE, but stoichiometrically linked with substances only from RE.

2.3 Exergy accounting

Like mass, energy, and entropy, exergy is an extensive property, so it too can be transferred into or out of a control volume where streams of matter enter and exit. In a general form, we can express the exergy balance of a control volume as:

$$\underbrace{\frac{dB_{cv}}{dt}}_{\text{ex. change rate}} = \underbrace{\overbrace{\dot{B}_{HT}}^{\text{heat transfer}} - \overbrace{\dot{B}_{WT}}^{\text{work transfer}} + \overbrace{\dot{B}_{MT}}^{\text{mass transfer}}}_{\text{rates of exergy transfer}} \underbrace{-\dot{B}_D}_{\text{ex. destr. rate}} \tag{3}$$

where

$$\dot{B}_{HT} = \sum_j \left(1 - \frac{T_0}{T_j}\right) \dot{Q}_j \tag{4}$$

$$\dot{B}_{WT} = \left(\dot{W}_{cv} - P_0 \frac{dV_{cv}}{dt}\right) \tag{5}$$

$$\dot{B}_{MT} = \sum_i \dot{m}_i b_i - \sum_e \dot{m}_e b_e \tag{6}$$

$$\dot{B}_D = T_0 \dot{S}_{gen} \tag{7}$$

subscripts *i* and *e* denote inlets and outlets, respectively. The relation between the entropy generation S_{gen} and the rate of exergy destruction B_D is given by the Gouy-Stodola theorem (see Eq. 7), whose demonstration is presented by Bejan *et al.* (1996). Hence, for steady-state processes

$$\sum_j \left(1 - \frac{T_0}{T_j}\right) \dot{Q}_j - \dot{W}_{cv} + \sum_i \dot{m}_i b_i - \sum_e \dot{m}_e b_e - \dot{B}_D = 0 \tag{8}$$

A useful way to represent the exergy accounting is through a *Grassmann diagram*, in which each stream (mass or energy) is represented by an arrow whose width is proportional to its exergy. Exergy transfers between operations forming a complex system are represented by linking exergy streams to operation blocks (squares). The exergy destruction in each operation block is represented by a decrease of its width (or height). For example, Fig. 1 shows a simplified Grassmann diagram for a cogeneration plant (de Oliveira, 2013).

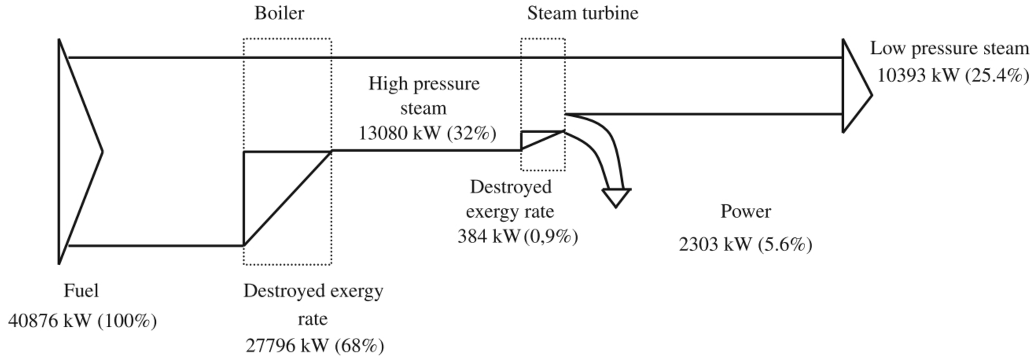

Figure 1. Example of a Grasmann Diagram for a cogeneration plant (de Oliveira, 2013).

2.4 Limitations of energy efficiency

The efficiency of a process assess its capability for doing a desired effect (or effects) and enables its comparison with other processes that performs the same function (or functions). Criteria for determining a particular process efficiency depends on the definition of its main purpose (or purposes). Thus, for energy transformation processes, the efficiency of a plant is commonly calculated as the ratio between the energy supplied / exported by the process and the energy fed into it. Conventional expression for the energy efficiency is based on the 1^{st} law of thermodynamics:

$$\eta_I = \frac{\text{Energy delivered}}{\text{Energy inlet}} \tag{9}$$

This parameter indicates how much energy is delivered in a useful form (*e.g.* electricity) from a unit of energy taken from a source (*e.g.* biomass); the more energy the system supply (sold), for a given amount of energy fed (bought), better its performance. For this reason, the main interest of the engineering of this type of processes is to improve the efficiency with a reasonable cost. However, since the energy is conserved, it follows that the energy that is not delivered is considered totally wasted, without indication about any further improvement able to ensure a positive impact on its efficiency. Moreover, for the same reason, this value acts only as an indicator and do not enable the proper identification of the reasons (or sources) of energy waste in the process. In that sense, as mentioned by Bejan Bejan *et al.* (1996), the idea that something can be destroyed is useful to be considered in the design and analysis of thermal systems. This idea does not apply to energy, however, but to exergy.

2.5 Sources of inefficiency

A key advantage of the exergy analysis is that it allows calculation of numerical values of process irreversibility Kotas (1985), which are clearly related to at least a part of the whole process inefficiency. It is at least a part, because for many processes is recognized that there are streams (of matter or energy) directly discharged to the environment, implying an inherent loss of exergy. In most of the cases, these outflows are defined based on the process structure itself and their rational use is generally limited by physical, technological, economic and other constraints. This fact is addressed by distinguishing between internal irreversibility (or exergy destruction $\dot{B}_D$, adopting the terminology used by Bejan *et al.* (1996)) and external irreversibility (or exergy loss $\dot{B}_L$, adopting the terminology used by Bejan *et al.* (Bejan *et al.*, 1996)).

2.6 Exergy efficiency

Exergy is presented as the most rational basis for assess the actual efficiency of energy transformation processes (Kotas, 1985). The fact that for every real process the exergy is not conserved due to irreversibility effects, makes it useful for pinpointing and quantifying energy inefficiencies, provisioning insights for system improvement, and enabling automation of some features of optimization (El-Sayed, 2003). Specifically, Bejan (2002) remarks that accounting exergy in smaller and smaller subsystems enables the mapping of how the destruction of exergy is distributed over the overall system, which enormously aids the search for improving efficiency, because it tells how to allocate engineering effort and resources. Generally, the exergy efficiency can be expressed as

$$\eta_{II} = \frac{\text{Exergy of product (or desired effect)}}{\text{Exergy of fuel}} \tag{10}$$

The definition of product and fuel must be defined for each case and depends on the process nature and purpose; Bejan *et al.* (1996) summarizes some formulation for commonly used equipment (heat exchanger, turbines, etc.). Besides, when analyzing systems comprising interaction between subsystems, it is interesting to ponder the exergy destruction in each subsystem by using the exergy destruction ratio:

$$y^*_{D,j} = \frac{\dot{B}_{D,j}}{\dot{B}_{D,tot}} \tag{11}$$

where $\dot{B}_{D,j}$ is the exergy destruction rate of the element *j* and $\dot{B}_{D,tot}$ is the total exergy destruction rate of the system.

3. Hospital facility

Currently, the hospital facility is located in the city of Florianópolis, Brazil and offers inpatient care and specialized ambulatory services during 365 days a year, with a mean occupation of 200 beds. Required services include the following:

- *Electricity*: for air conditioning, illumination, medical appliances, elevators, etc. All the electricity is imported from local concessionary. Figure 2 presents the monthly consumption of electricity along a recent year.

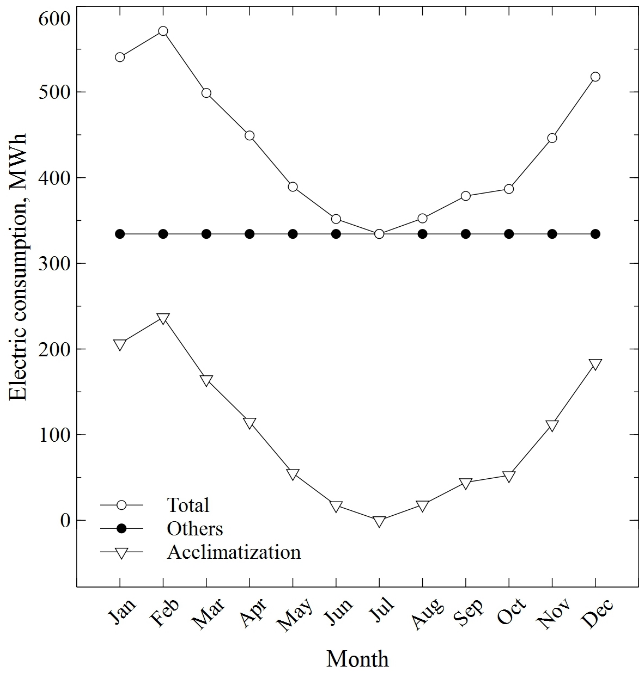

Figure 2. Electric profiles of the hospital facility.

- *Steam*: for laundry, kitchen and sterilization of medical instrumentation. Currently it is supplied by a diesel-fueled boiler with a nominal capacity of 2000 kg/h. The average demand is 750 kg/h of saturated steam at 7 barg, along 10 hours a day.

- *Cold water*: for air conditioning. It is provided by three electric (mechanical compression) chillers with a total installed nominal capacity of 310 TR (one chiller of 150 TR and 2 chillers of 80 TR each one). Additionally, there is a set of local electric air conditioners with an unknown total capacity.

- *Hot water*: for lavatories and general cleaning. It is supplied by the same diesel-fueled boiler that provides the steam. The average demand is 25 m^3 per day of hot water supplied at 62 °C.

4. Cogeneration plant

Figure 3 presents a general layout of a cogeneration plant using a natural gas generator set and a hot water-driven absorption chiller, capable of supplying all or some the required services simultaneously. Technical features can be imported from a database of available equipment.

Natural gas (01) and combustion air (02) streams are fed into the engine M01 for generating the electricity delivered to the hospital facility. The thermal energy associated with the exhaust gases (03) is used for producing saturated steam in the heat recovery steam generator (HRSG) H01. On the other hand, the heat coming from the engine water jackets is transferred to an internal hot water circuit through the heat exchanger E01, where the hot water leaving the engine block (04) heats up the water stream coming from the accumulation vessel V01 (07). Stream 08 subsequently is heated up in the heat exchanger E02 with the remnant thermal energy of exhaust gases leaving H01 (16). Heated water (09) is then divided for activating the absorption chiller C01 and feeding the heat exchanger E03; streams leaving these devices (10 and 23 respectively) are returned to V01.

This general layout represents how the equipment of the plant are interconnected and each block can represent in fact a set of equipment of the same type (*e.g.* M01 representing a set of five engines). Another feature is that as shown, this layout is providing all the services; however, supply of certain thermal services can be neglected by removing the corresponding equipment (*e.g.* removing C01 when chilled water is not required, or H01 when steam is not required). This feature enables various combinations among thermal services.

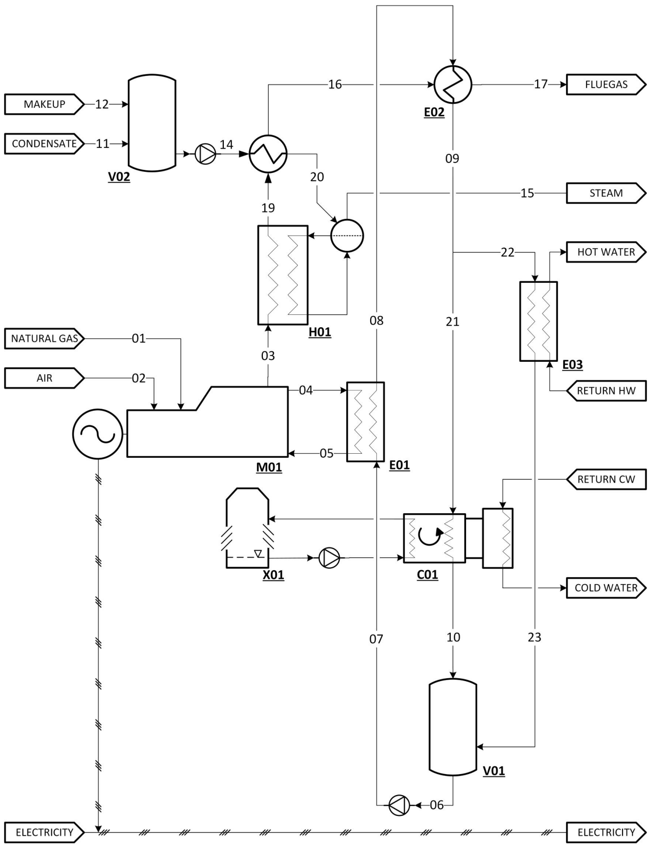

Figure 3. Cogeneration plant layout.

5. Methodology

5.1 Estimation of cold water demand

The cold water demand for air conditioning can be inferred from the electric consumption of installed chillers, through their coefficient of performance (COP). However, this consumption is not measured separately from other electric consumption in the facility. Consequently, reasonable assumptions should be done for estimating this parameter from available data. Taking into account that only total monthly electric consumption are available, the following premises are adopted, similarly to the work of Chung and Park (2015): (i) during the coldest month, consumption associated with air conditioning can be neglected and (ii) monthly consumption not associated with air conditioning is not altered significantly by weather seasonality. Assuming these premises, it follows that the electric consumption of the coldest month can be adopted as the average monthly consumption of non-air conditioning devices along the year; this approach results in the lower curves shown in Fig 2. Additionally, for calculation of the average air conditioning demand, another assumption must be done: air conditioning is required only during periods whose average temperature is greater than 22 °C. In this way, formulation used for estimating the monthly electric demand not associated with air conditioning ($\tilde{D}_{na,j}$) and the monthly electric demand associated with air conditioning ($\tilde{D}_{ac,j}$) is presented in Eqs. 12 and 13.

$$\tilde{D}_{na,j} = \frac{C_{min}}{t_{tot,j}} \tag{12}$$

$$\tilde{D}_{ac,j} = \frac{C_{ac,j}}{t_{22,j}} \tag{13}$$

where C_{min} is the minimum electricity consumption along the year (kWh) and $t_{tot,j}$ is the total number of hours of the month *j*. In a similar way, $C_{ac,j}$ is the electric consumption (kWh) associated with air conditioning and $t_{22,j}$ is the number of hours whose average temperature is greater than 22 °C, both during the month *j*; these data are available in datasets of specialized computational tools like TRNSYS (Thermal Energy System Specialists, 2017). Figure 4 displays the curves obtained for the estimated monthly demands, together with their average values (data of the month with the lowest electric consumption are not considered).

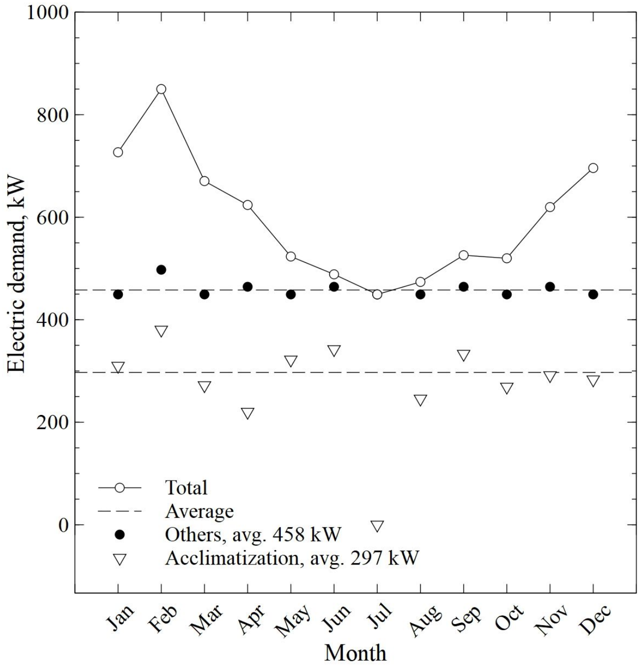

Figure 4. Estimated electric demands for air conditioning and non-air conditioning devices.

Adopting a typical COP of 3.6 for used electric chillers, it can be estimated an average cooling demand of 304 RT (refrigeration tons). Under certain circumstances, average demand values can be considered as design parameters for CHP plant sizing. However, generally it is found that sizing the CHP plant for addressing maximum demands is more convenient, specially when there is not a rapid respond to instantaneous demand rises (ASHRAE, 2015). For this reason, the design parameters considered in this work are 388 TR for cold water demand and 497 kW for electricity demand not associated with air conditioning (see values reported for February).

5.2 Cogeneration simulation scenarios

As previously stated, the proposed CHP layout (see Fig. 3) is modeled in such a way that various combinations of thermal services can be simulated. Therefore, there are 7 possible cogeneration scenarios, listed in Tab. 1.

Table 1. Simulation scenarios for CHP plant

Scenario	Thermal Services
1	Steam
2	Cold water
3	Hot water
4	Steam + Cold water
5	Steam + Hot water
6	Cold water + Hot water
7	Steam + Cold water + Hot water

Assumptions adopted in each simulation are formulated in such a way that obtained results are comparable to actual CHP projects; this was possible through the consultation of various CHP experts. The most significant assumptions are listed as follows:

1. Average natural gas composition: 89.5% methane, 5.9% ethane, 2.5% propane, 0.7% nitrogen and 1.4% carbon dioxide (data supplied by natural gas distributor of the Santa Catarina state).

2. Cold water supply can be complemented by using existing electric chillers. Engines capacity should be enough to feed these chillers (if required).

3. According to the later assumption, the size of the CHP plant is based on two generators of 507 kW (1014 kW total) (Caterpillar, 2014). This enables the operation of both during the summer and only one generator during the winter.

Table 2. Formulations for exergy destruction rates of devices forming the CHP plant

Device	Formula $\dot{B}_D$
M01	$\dot{B}_{01} + \dot{B}_{02} + \dot{B}_{05} - \left(\dot{B}_{03} + \dot{B}_{04} + \dot{W}_{M01}\right)$
E01	$\dot{B}_{04} + \dot{B}_{07} - \left(\dot{B}_{05} + \dot{B}_{08}\right)$
H01	$\dot{B}_{03} + \dot{B}_{14} - \left(\dot{B}_{15} + \dot{B}_{16}\right)$
E02	$\dot{B}_{08} + \dot{B}_{16} - \left(\dot{B}_{09} + \dot{B}_{17}\right)$
E03	$\dot{B}_{22} - \left(\dot{B}_{23} + \dot{B}_{24}\right)$
C01	$\dot{B}_{21} + \dot{B}_{28} + \dot{B}_{25} - \left(\dot{B}_{10} + \dot{B}_{27} + \dot{B}_{26}\right)$

4. Engines work at their nominal capacity. Power surplus is supposed to be exported to the grid.
5. Steam supply can be complemented by using existing boiler.
6. Supply of hot water has the lowest priority, *i.e.* it is supplied only if there is available thermal energy after delivering the other utilities.
7. Priority between steam and cold water for air conditioning (when delivered simultaneously) can be adjusted through a distribution factor.
8. Equipment information and operational parameters are extracted from available commercial catalogs and consultation with local providers.

Simulations were developed using the software *Engineering Equation Solver* (EES) considering steady state regime. Moreover, for the present analysis, simulation outputs are compared with the maximum demand of each thermal service, assuming it constant. Further analyses will consider the whole profile and operational scheduling.

5.3 Exergy analysis

Taking into account the nomenclature shown in the Fig. 3 and the description given in section 2.6, the formulation for the exergy efficiency of the proposed CHP plant is presented in Eq. 14, followed by the expressions used for calculation of the exergy destruction rate of each device (see Tab. 2).

$$\eta_{II} = \frac{\dot{W}_{M01} + \left(\dot{B}_{15} - \dot{B}_{13}\right) + \left(\dot{B}_{26} - \dot{B}_{25}\right) + \dot{B}_{24}}{\dot{B}_{01} + \dot{B}_{11}} \tag{14}$$

6. Results

6.1 Balances

Obtained results are summarized in Tab. 3, according to the description of each scenario presented as follows:

- *Scenario 1 (power + steam):* This scenario corresponds to the delivery of 850 kW of electric power together with 700 kg/h of saturated steam. It is assumed that the cold water supply strategy remains unchanged (existing electric chillers + electric air conditioning systems), thus the maximum electricity demand for the CHP plant corresponds to the total reported for February (≈850 kW). Hot water would be produced externally by auxiliary equipment.
- *Scenario 2 (power + cold water):* It corresponds to the delivery of 500 kW of electric power together with 388 RT of cold water for refrigeration. The size and number of absorption chillers is determined according to the available heat for activating them. Steam and hot water are supplied by existing boilers.
- *Scenario 3 (power + hot water):*For this scenario, 850 kW of electric power and 25 m^3 per day of hot water are supplied by the CHP plant. Steam and cold water production remains as they currently are.
- *Scenario 4 (power + steam + cold water):* For this scenario, 500 kW of electric power, 700 kg/h of saturated steam, and 388 RT for air conditioning should be supplied. Absorption chillers can be complemented with existing electric

Table 3. Balance of utilities for each case.

Parameter	**Scn1**	**Scn2**	**Scn3**	**Scn4**	**Scn5**	**Scn6**	**Scn7**
# Movers	2	2	2	2	2	2	2
# Abs. chillers	0	3	0	2	0	3	2
Electricity, kW	**1014**	**1014**	**1014**	**1014**	**1014**	**1014**	**1014**
Base	850	500	850	500	850	500	500
Absorption chillers	0	63	0	42	0	63	42
Electric chillers	0	206	0	301	0	206	301
Importation	0	0	0	0	0	0	0
Exportation	*164*	*245*	*164*	*171*	*164*	*245*	*171*
Steam, kg/h	**700**	**700**	**700**	**700**	**700**	**700**	**700**
% Heat to HRSG	100	0	0	35	100	0	35
CHP	700	0	0	268	700	0	268
Boiler	0	0	0	432	0	0	432
Cold water, RT	**388**	**388**	**388**	**388**	**388**	**388**	**388**
CHP	0	225	0	150	0	225	150
Electric chillers	388	163	388	238	388	163	238
Hot water, m^3/d	**25**	**25**	**25**	**25**	**25**	**25**	**25**
CHP	0	0	25	0	25	25	24
Auxiliary	25	25	0	25	0	0	1
Energy input, kW	2607	2607	2607	2607	2607	2607	2607
Useful heat, kW	495	989	44	849	539	1034	891
Disipated heat, kW	1098	603	1548	743	1053	558	701

chillers and the HRSG can be complemented with the existing boiler; hot water would be produced by the existing boiler. The proportion between steam and cold water production can be altered to favoring one or the other. A sensibility analysis was carried out for determining an adequate proportion, varying the percentage of delivered heat from the exhaust gases to the HRSG. Figure 5 illustrates the criteria applied for the selection of the operation point.

Obviously, the greater the steam production by the CHP plant, the lesser its capacity for delivering cold water for air conditioning. However, it is generally advisable that equipment operate as close as possible to their nominal capacity. In this way, four horizontal lines are included on the graph, each one corresponds to the capacity that the absorption chillers of the CHP plant would have, assuming different combinations among existing chillers at their nominal capacity (as indicated) for meeting the total demand (388 RT). Some inferences are evident: (i) for percentages greater than 70% (shaded area), the capacity of absorption chillers would be too small and the sum of it and the installed capacity would not be enough for meeting the maximum cold demand; (ii) maximum capacity of absorption chillers (0% heat delivered to HRSG) is not enough for addressing the maximum demand, and it would be necessary the aid of at least the two existing chillers of 80 RT; (iii) during the most part of the time, the cold demand will be smaller than the maximum, hence it is more convenient to choose medium-size absorption chillers that operate under normal conditions and that are enough to cover maximum conditions together with the existing chillers. For these reasons, scenario 4 considers the operation of two absorption chillers of 75 RT each one (150 RT total) LG (2015) and 35% of heat delivered to the HRSG from the exhaust gases (signalized on fig. 5).

- *Scenario 5 (power + steam + hot water):* It corresponds to the supplying of 850 kW of electric power, 700 kg/h of saturated steam, and 25 m^3 per day of hot water. Cold water for air conditioning is supplied entirely by existing electric equipment.

- *Scenario 6 (power + cold water + hot water):* It corresponds to the supplying of 500 kW of electric power, 225 RT of cold water for air conditioning (three chillers of 75 RT each one), and 25 m^3 per day of hot water. The capacity of absorption chillers is determined by the upper limit obtainable from the available heat coming from the generators, without considering production of steam (236 RT, according to Fig. 5). Existing boiler provides the saturated steam demand entirely.

- *Scenario 7 (power + steam + cold water + hot water):* It covers the delivering of 500 kW of electric power, 150 RT of cold water for air conditioning (see scenario 4), 25 m^3 per day of hot water. Saturated steam is supplied taking advantage from 35% of the available heat in the exhaust gases stream.

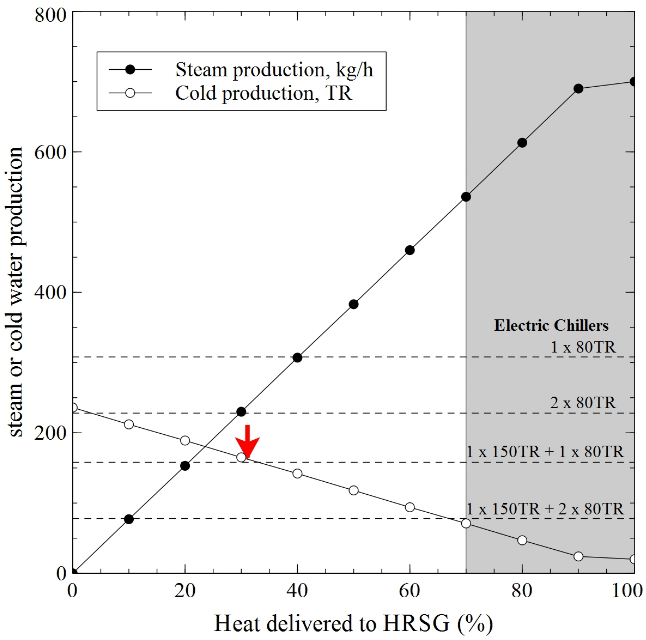

Figure 5. Cold water and saturated steam production vs heat delivered to HRSG.

6.2 Exergy analysis

Figure 6 presents how the exergy fed into the CHP plant is distributed among the exergy destruction rate, the exergy delivered as utilities (products), and the exergy rate discharged to the atmosphere as exergy losses, together with the energy and exergy efficiencies (lower section). While the conventional energy efficiencies are greater than 50% (except for scenario 3), exergy efficiencies do not exceed the same value. This feature is explained by the fact that the exergy efficiency is related to how much of the maximum power obtainable from the natural gas is still obtainable from the products of the plant (observe that hatched bars have the same behavior in upper and lower sections of the fig. 6), taking into account the amount of that power that is not effectively transferred because of the non-ideality inherent to real processes. On the other hand, conventional energy efficiency is related to how much of the energy fed into the plant is actually transferred to its exported utilities (products) and since the energy is conserved, it follows that the behavior of the energy efficiency is similar to the exergy destruction share (see gray bars in upper and lower sections of the fig. 6) and opposite to the exergy losses.

The similarity between the pattern of energy efficiency and the exergy destruction rate could be seen as follows: for a given energy transition, the greater the exergy destruction rate, the greater the amount of energy that is degraded but still transferred to the process outputs. Analogously, the greater the exergy losses, the smaller the portion of energy transferred to process products, since the streams associated with exergy losses generally are not associated with products.

On the other hand, it seems that the delivery of thermal services improves significantly the energy efficiency of the plant, but not so much the exergy efficiency. Clearly, the exergy rate associated with thermal services is not as high as that of electric power. Specifically, the cold water for air conditioning favors the energy efficiency of the plant, but impairs its exergy efficiency, or conversely, saturated steam production impairs the energy efficiency of the plant, while improves its exergy efficiency. In this case, this feature does not bring by itself new information that can be used directly as a criterion for choosing one scenario or other. However, another key advantage of the exergy analysis is its capability of distinguishing where the exergy destruction is taking place. In that direction, Fig. 7 presents the exergy destruction rate of equipment forming the plant in each scenario.

As already found in previous works focused on the exergy analysis of CHP plants (*e.g.* Arteaga Flores (2010); Barja (2006); de Carvalho (2010); Abusoglu and Kanoglu (2009a,b); Kanoglu and Dincer (2009)), the highest exergy destruction is reported for the prime mover, reporting shares greater than 85% of total destruction rate; it is due principally to the combustion of natural gas. The rest of the equipment report exergy destruction rates lesser than 11%, and particularly, heat exchangers water-water (E01 and E03) present shares lesser than 1% (note that vertical axis is in log scale). The HRSG and the absorption chiller C01 destroy exergy almost in the same extend for the scenarios with simultaneous production of steam and cold water; additionally, the heat exchanger gas-water E02 (when operating) appears with a greater destruction rate than both equipment.

In general, results suggest that further improvements should be addressed on devices with highest exergy destruction rates, resulting in a 'priority' order starting with the prime mover, the heat exchanger E02, followed by the HRSG, the

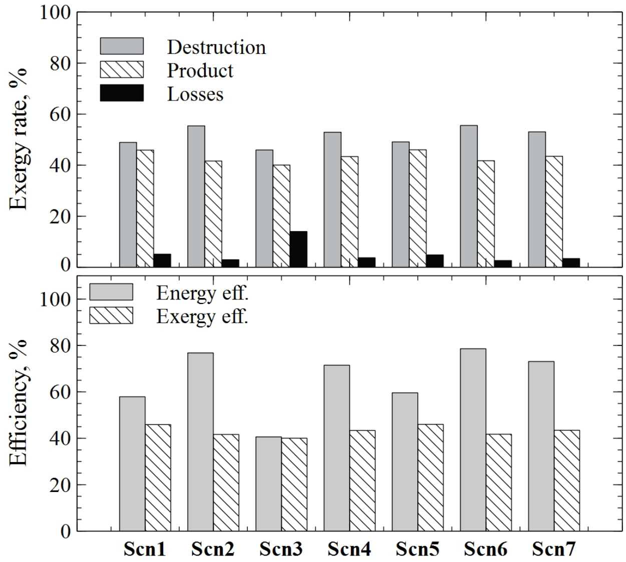

Figure 6. Exergy efficiencies and exergy rate distribution for analyzed scenarios.

absorption chiller, and finally the heat exchangers E01 and E03. However, in practice, some improvements on the first elements are too hard, if not impossible, to execute in order to reduce significantly their destruction rates. For instance, the most of the exergy destruction takes place in the combustion of natural gas, which is a spontaneous process and whose inherent destruction of exergy (irreversibility) is unavoidable given that the combustion is necessary for the operation of the mover.

Regarding the HRSG and the heat exchanger E02, improvements on these devices design can be oriented toward better heat transfer rates, in such a way that the pinch point (in the HRSG) and the terminal temperature differences on the heat exchanger E02 can be reduced. In the case of the absorption chiller C01, the alternative would be the selection of equipment with better performance (or changing the technology for cold supply). Finally, the enhancement of the operation of heat exchangers E01 and E03 does not imply necessarily a noticeable improvement on the exergy performance of the plant, although that can result in a convenient reduction of the operation costs of the plant.

In general, the findings of the present work are aligned with considerations presented previously by Rucker and Gruhn (1999), summarized as follows:

- Process elements showing the highest exergy losses (destruction) generally appear as better candidates for optimization routines.
- Typical solution strategy (optimization) is restricted to favoring better technology where applicable.
- When considering changes to specific elements (devices), the structural interactions of the process should be included, neglecting that can lead to inferior solutions rather than improvements.
- In practice, exergy functions do not show a great significance when compared with conventional cost functions.
- Including economic constraints is important in order to avoid optimal solutions with large capital costs.

7. Final considerations

In general, the exergy analysis gives the possibility of identifying operations and components responsible for the thermodynamic irreversibilities of a process and quantifying their magnitude, which by itself provides valuable information for addressing any further improvement of the analyzed system. However, for the scope of this study, inferences derived merely from this analysis are not conclusive for taking a decision regarding which combination of thermal services is the more convenient for the analyzed facility. Moreover, it was realized that for executing any practical improvement, it becomes necessary a certain level of knowledge in cogeneration projects, sometimes based on criteria of experts rather than on thermodynamic fundamentals.

Nevertheless, the usefulness of the exergy analysis is the basis of more advanced methodologies headed toward the optimization of thermal systems. Particularly, the exergoeconomics and the entropy generation minimization (EGM) are

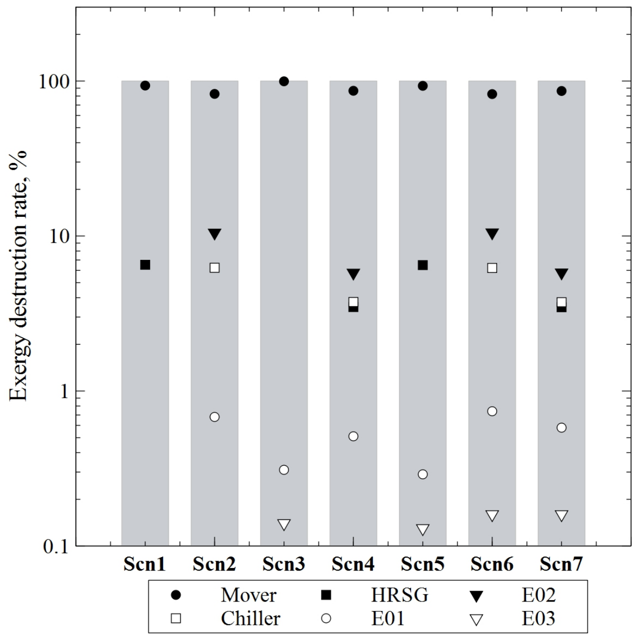

Figure 7. Exergy efficiencies and exergy rate distribution for analyzed scenarios.

two approaches that incorporate 2^{nd} law-aided minimization to find an optimal process structure and design (Sciubba, 2005). The first looks for systems having higher energy efficiency and lower unit production cost than an existing one under the same boundary conditions (El-Sayed, 2003), while the EGM method pursues the minimization of thermodynamic losses subject to the global constraints in the design of thermal systems and devices (Bejan, 2002).

In that direction, further exergy-based studies of cogeneration applied to the hospital facility can be carried out including additional cogeneration features as part-load operation for equipment, thermal storage, detailed demand profiles and operation scheduling; moreover, optimization routines based on the theory of exergoeconomics and EGM can be incorporated in order to determine the more convenient set of CHP layout, equipment, operation conditions and schedule for the addressed problem.

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