THERMOECONOMIC ANALYSIS OF A MICROCOGENERATION SYSTEM USING THE THEORY OF EXERGETIC COST

by

Adriano da Silva MARQUES [a], ***Yipsy Roque BENITO*** [b], ***Alvaro Antonio OCHOA*** [c], **and** ***Monica CARVALHO*** [a*]

[a] Department of Renewable Energy Engineering,
Federal University of Paraiba, Joao Pessoa, Brazil
[b] Department of Production and Mechanical Engineering,
Federal University of Juiz de Fora, Juiz de Fora, Brazil
[c] Federal Institute of Technology of Pernambuco, Recife, Brazil

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Cogeneration and trigeneration systems have been broadly employed as part of the strategies oriented toward rational energy use. The assessment of these systems must include simultaneous considerations of costs, irreversibility, energy losses, and their causes. This work presents a step-by-step thermoeconomic analysis of a microcogeneration unit, composed of an internal combustion engine and an NH_3-water single-effect absorption refrigeration chiller. The research employed the Theory of Exergetic Cost method to determine monetary and energy costs and the exergy efficiency of equipment. It is therefore, possible to identify which pieces of equipment present the highest impact and focus on these to improve the overall performance of the energy system. Although not part of the Theory of Exergetic cost, exergoeconomic parameters can be calculated to expand the assessment further. The highest specific exergy cost is associated with the endothermic reaction inside the absorber (282 \$/GJ), while the lowest specific exergy cost is due to electricity consumed by the pump of the refrigeration system (2.16 \$/GJ). The highest exergy efficiency was identified at the condenser (almost 90%, while values under 40% were obtained for the engine, pump, and absorber. The combined analysis of exergoeconomic results indicates that the lowest performances are related to the generator, the absorber, the evaporator, and the regenerator.

Key words: *absorption refrigeration, cogeneration, exergoeconomics, cost allocation, thermoeconomics*

Introduction

Combined energy systems can be employed as alternatives to energy supply issues, producing multiple energy services with higher performance than separate production [1]. Technical and financial feasibility assessments usually follow the First and Second Laws of Thermodynamics and economic indices. The performance of thermal systems can be improved using energy management concepts and exergy parameters [2]. The Theory of Exergetic Cost (TEC) presented by Lozano and Valero [3] combines energy and exergy flows with economics to verify the performance of energy systems. The objective of TEC is to identify the components that have higher exergy destruction and the costs associated with exergy flows in each sub-component of the system.

[*] Corresponding author, e-mail: monica@cear.ufpb.br

There is a deep relationship between irreversibilities, cost, and cause, to the point that Valero *et al.* [4] highlighted an Aristotelic analogy between thermoeconomic concepts and cause. Because TEC considers exergy destruction and carries out calculations from this viewpoint, the actual production cost is not separate from the cost of its exergy destruction [5]. Thermoeconomics has been used to check the viability of thermal energy systems [6] and even as an optimization technique to improve the overall energy system [7], taking into account exergy and monetary costs [8]. Advanced exergy analysis can also be associated with thermoeconomics and has been applied to vapor absorption systems. Yu *et al.* [9] evaluated a cascade lithium bromide (LiBr) system and demonstrated that system optimization could reduce exergy destruction by 25%, the cost rate of exergy destruction by 24%, and capital costs by 18%. Other types of refrigeration systems can also benefit from thermoeconomic assessments, such as the case presented by Yildiz [10], who evaluated a diffusion absorption refrigerator. The energy efficiency of the system increased by 3.90% (from 39.30-43.2%), and exergy efficiency increased by 0.59% (from 10.08-10.67%) after substituting the electric switching system with liquefied petroleum gas – however, the specific cost of exergy increased by 64%.

The TEC is a crucial instrument to determine the economic costs of internal flows and products of energy systems, even those with intricate internal interactions. The work of Misra *et al.* [11] presented a TEC-based method for thermoeconomic optimization, applied to a single-effect LiBr-water absorption refrigeration system. The results showed that small changes in the configuration of the system led to a significant reduction in all costs. Rangel-Hernandez *et al.* [12] also applied TEC to a hybrid system constituted by a fuel cell and an absorption refrigerator, and obtained the unit exergy cost associated with electricity, refrigeration, and the losses of the system. The TEC has also been applied to combined cooling, heating, and power (CCHP) systems, such as the study case presented Yang *et al.* [13]. The objective was to achieve high efficiency and low costs within a biomass gasification system in different operation modes. Sensitivity assessments were carried out by varying the operation hours of equipment, interest rates, lifetime of equipment, and unit cost of biomass.

The TEC has been applied to cogeneration systems with different fuels, and the thermoeconomic cost of the produced work varied significantly with the complexity of the systems and the type of fuel [14]. Recently, Torres and Valero [15] presented an updated review of the fundamentals of TEC. They mention that the cost formation process of residues is given mainly from a thermodynamic perspective instead of a mostly-economic approach. It is proposed to consider residues as external irreversibilities within industrial processes. A new concept is introduced (*irreversibility carrier*) to help identify the origin, transfer, partial recovery, and destination of residues.

There are other thermoeconomic methods, such as the specific exergy cost (SPECO) [16]. This method was applied to verify the financial behavior and feasibility of a solar system integrated into a Rankine cycle-based power generation facility [17] and also to demonstrate the economic feasibility of a diesel-biodiesel internal combustion system [18].

Environmental considerations can also be added to thermoeconomic models, such as in Santos *et al.* [19], who allocated carbon emissions to the final cost of each energy product. The simultaneous association of thermodynamic, economic, and environmental evaluations is also referred to as *exergoeconoenvironmental* [20]. Trindade [21] used this concept to compare different cost allocation methods in life cycle assessment studies in a combined energy system.

The study presented herein presents a detailed thermoeconomic analysis for a microcogeneration system. The evaluation uses the concepts of thermodynamics and the TEC to show results of monetary and exergy-related costs, exergy efficiency, and relative costs of components and identify which components present the highest impact on global indicators. The significant contribution of this study is the presentation of a didactic, step-by-step application of a well-known TEC to an energy system. Another contribution of the study is towards the dissemination of thermoeconomics to new researchers in energy engineering.

Thermodynamic modelling of the cogeneration system

The microcogeneration system is depicted in fig. 1 and includes a gasoline internal combustion engine and a single-effect NH_3-water absorption refrigerator. The system was devised to supply industrial processes with electricity and cooling, and this experimental set-up was available at the Federal University of Paraiba (Northeast Brazil).

Initially, the First and Second thermodynamic laws were applied to verify its performance, followed by using TEC to demonstrate the financial feasibility, considering the cost based on the exergy flows.

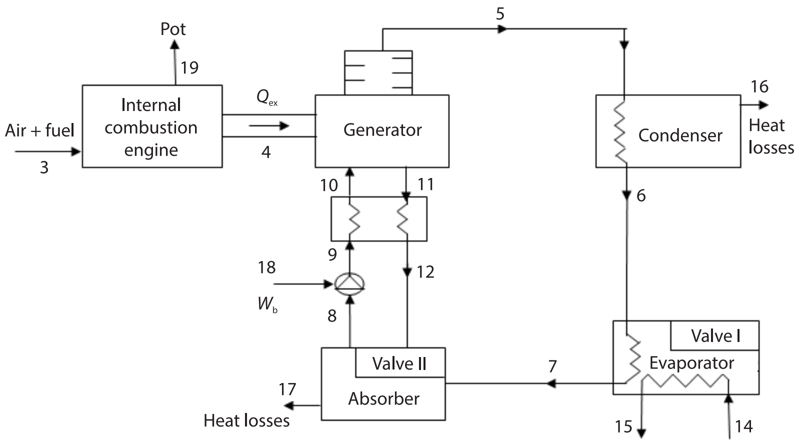

Figure 1. Schematic diagram of the microcogeneration system

A mixture of air and fuel is injected into the engine, where after the combustion phenomenon, hot gases – 4 and mechanical shaft power – 19 are produced. The heat of the combustion gases triggers the generator refrigeration unit, which contains a specific concentration of ammonia (refrigerant) and water (absorbent). The details related to the operation are described in Marques *et al.* [22].

The heat exchanger under the generator in fig. 1 is the intermediate heat exchanger, responsible for preheating the ammonia solution that is pumped from the absorber to the steam generator – 10. The hot water contained in the generator flows to the absorber by chemical affinity with ammonia – 11 exchanging heat with the ammonia solution before reaching the generator.

Point – 5 is ammonia vapor (concentration over 99.8%) that flows to the condenser. This concentration is the result of the evaporation of ammonia, which is more volatile than water, and occurs due to the heat from the engine exhaust gases – 4 that enter the generator. The *strong* ammonia solution evaporated in the generator passes through the steam rectifier so that any residual water vapor condenses and returns to the generator. Point – 11 is a *weak* solution in ammonia (saturated liquid) that flows into the absorber, preheating the "strong" solution that is pumped from the absorber to the generator – 9.

Point – 3 (mixture of air and fuel) and point – 18 (electricity consumption from the pump) are classified as fuels. Point – 15 (chilled water) and point – 19 (power) are classified as products, and points – 16 and – 17 (cooling air from heat exchangers) are the losses.

Thermodynamic analysis

All components were individually evaluated, except for the valves that were incorporated into the following equipment. Mass, m, energy, E, entropy, S, and exergy, Ex balances were used to this end, eqs. (1)-(4), respectively. The following assumptions were considered:
- Steady-state conditions and internally reversible processes.
- Ideal gas mixtures are considered for combustion air and exhaust gases.
- Compression and expansion processes were considered adiabatic.
- Effects of kinetic and potential energy and load losses were negligible.
- Expansion valves were considered isoenthalpic.
- The exhaust gases from the steam generator were excluded from the analysis.

$$\left(\frac{\partial m}{\partial t}\right)_{cv} = \sum_{\text{in}}(\dot{m}) - \sum_{\text{out}}(\dot{m}) \tag{1}$$

$$\left(\frac{\partial E}{\partial t}\right)_{cv} = \dot{Q}_{cv} - \left(\dot{W}_{cv}\right) + \sum_{\text{in}}(\dot{m}h) - \sum_{\text{out}}(\dot{m}h) \tag{2}$$

$$\left(\frac{\partial S}{\partial t}\right)_{\text{cv}} = \sum_{\text{in}}(\dot{m}s) - \sum_{\text{out}}(\dot{m}s) + \sum \frac{\dot{Q}_{\text{cv}}}{T} + \dot{S}_{\text{gen}} \tag{3}$$

$$\left(\frac{\partial Ex}{\partial t}\right)_{\mathbf{cv}} = Ex_{\text{in}} - Ex_{\text{out}} - Ex_{\text{dest}} \tag{4}$$

where $\dot{m}$ is the mass-flow rate, $\dot{Q}_{cv}$ and $\dot{W}_{cv}$ are the rate flows of heat and the work through the control volumes, and h is the enthalpy. The subscripts in and out indicate the inlet and outlet of the streams, s refers to entropy, T is the temperature, and $\dot{S}_{\text{gen}}$ is the entropy generated, while Ex is the exergy, and the subscript dest expresses the share of exergy destroyed. The terms on the left (variations of mass, energy, entropy, and exergy in control volumes) were disregarded due to the steady-state analysis.

The thermodynamic analysis was first developed for the engine, then for each cooling system component. The thermodynamic and thermoeconomic models were built within the engineering equation solver (EES) platform.

Internal combustion engine

The engine is a 16 valve I4 Ford with 16 valves, four cylinders, and a 10:1 compression rate [23]. Considering gasoline (C_8H_{18}), this equation provides the stoichiometric balance for the complete combustion:

$$C_8\text{H}_{18} + exc \times a\left(\text{O}_2 + 3.76\text{N}_2\right) \rightarrow b\text{CO}_2 + c\text{H}_2\text{O} + d\text{N}_2 + e\text{O}_2 \tag{5}$$

where exc expresses the amount of excess air, and a, b, c, d, and e are the parameters that balance out the equation. O_2, N_2, CO_2, and H_2O are oxygen, nitrogen, carbon dioxide and water, respectively.

For the engine, the air-fuel ratio was then determined, followed by the air-fuel combustion energy. Solution of the thermodynamic equations yielded the energy of exhaust gases and exergy of combustion products.

Cooling system

Figure 2 illustrates a scheme of the absorption chiller, which includes a generator with a vapor rectifier, a condenser, an absorber, one evaporator, an intermediate heat exchanger (IHX), a pump, and two expansion valves.

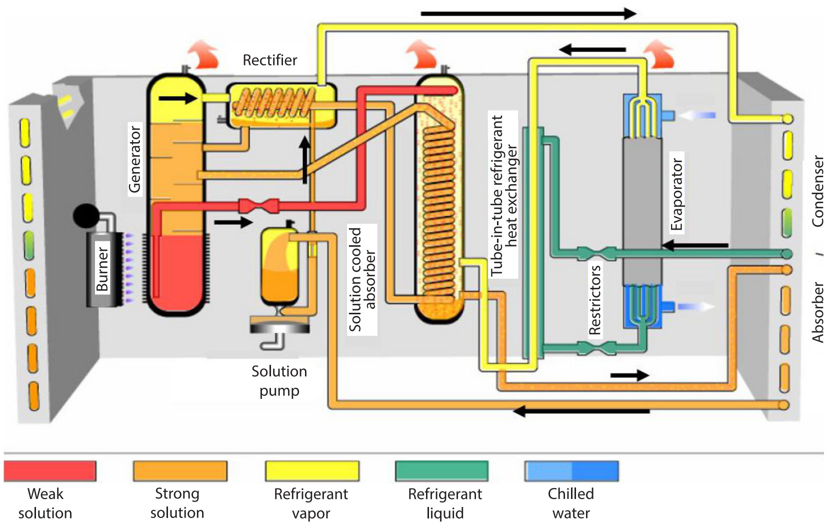

Figure 2. Scheme of the absorption refrigeration chiller [24]

For the cooling system, the condenser temperature is considered as ambient temperature plus 10 °C [24], evaporator temperature 5 °C [25], refrigerant concentration at the vapor rectifier is 0.999634 [24], and the concentrations of strong and weak ammonia solutions are, respectively, 0.368 and 0.268 [24].

Thermoecoonomics: Theory of exergetic cost

The TEC [3] introduced the exergy cost concept to the thermoeconomic field for the first time, and was initially formulated to solve cost allocation problems and optimization in thermal systems. The methodology is based on the concepts of product, P, (exergy that contains the benefits obtained), fuel, F, (exergy provided through the resources), and unit exergy cost, which refers to the external exergy required to make an exergy stream available within a specific production process. The difference between fuel and product within a process equals its irreversibility, which is always equal or higher than zero. The unit exergy cost of any product is always equal to or higher than one.

The TEC follows four propositions [3]:

– the P#1 – the exergy cost of a flow B, fuel F, or product P, is the amount of exergy required for its productions,
– the P#2 – in the absence of an external assessment, the exergy cost of flows entering the system equals their exergy,
– the P#3 – all costs generated by the productive process must be present in the cost of final products, and

– the P#4 – this is divided into *P*#4a (if an output flow of a unit is part of the fuel of another unit, the unit cost is the same as that of the original input flow) and *P*#4b (if a unit has a product constituted by several flows, the same unit exergy flow is assigned to all flows).

The unit exergy cost, *k*, is defined as the relationship between the exergy of the fuel, Ex_f, and the exergy of the product, Ex_p, [26], and equivalent to the inverse of exergy efficiency, ε:

$$k = \frac{Ex_F}{Ex_P} = \frac{1}{\varepsilon} \tag{6}$$

where B_i^* is the exergy cost and Ex_i is the minimum amount of exergy corresponding to the ideal process

A TEC-based thermoeconomic assessment requires the study object to be characterized in productive units. Therefore, each productive unit of the system studied corresponds to one-component (control volume). The expansion devices are incorporated into the following corresponding equipment (evaporator and absorber), as the economic significance of the inputs and outputs of these devices is negligible.

Table 1. Cost balance for each piece of equipment, following [3]

Equipment	*P*#1	*P*#2	*P*#5	Cost	Auxiliary
ICE	$B_1^* - B_4^* - B_{19}^* = 0$	NA	$B_3^* = Ex_3$ $B_{19}^* = Ex_{19}$	$Pc_4 + Pc_{19} = Pc_3 + Z_\mathrm{ICE}$	$\frac{Pc_4}{Ex_4} = \frac{Pc_{19}}{Ex_{19}}$
Generator	$B_4^* + B_{10}^* - B_5^* - B_{11}^* = 0$	$\frac{B_{10}^*}{Ex_{10}} = \frac{B_5^* + B_{11}^*}{Ex_5 + Ex_{11}}$	NA	$Pc_5 + Pc_{11} = Pc_4 + Pc_{10} + Z_\mathrm{generator}$	$\frac{Pc_{10}}{Ex_{10}} = \frac{Pc_5 + Pc_{11}}{Ex_5 + Ex_{11}}$ $\frac{Pc_5}{Ex_5} = \frac{Pc_{11}}{Ex_{11}}$
Condenser	$B_5^* - B_6^* - B_{16}^* = 0$	NA	NA	$Pc_6 + Pc_{16} = Pc_5 + Z_\mathrm{condenser}$	NA
Evaporator	$B_6^* + B_{14}^* - B_7^* - B_{15}^* = 0$	$\frac{B_6^*}{Ex_6} = \frac{B_7^*}{Ex_7}$	$B_{14}^* = Ex_{14}$	$Pc_7 + Pc_{15} = Pc_6 + Pc_{14} + Z_\mathrm{evaporator}$	$\frac{Pc_7}{Ex_7} = \frac{Pc_{15} - Pc_{14}}{Ex_{15} + Ex_{14}}$
Absorber	$B_7^* + B_{12}^* - B_8^* - B_{17}^* = 0$	$\frac{B_8^*}{Ex_8} = \frac{B_7^* + B_{12}^*}{Ex_7 + Ex_{12}}$	NA	$Pc_8 + Pc_{17} = Pc_7 + Pc_{12} + Z_\mathrm{absorber}$	$\frac{Pc_8}{Ex_8} = \frac{Pc_7 + Pc_{12}}{Ex_7 + Ex_{12}}$
Pump	$B_8^* + B_{18}^* - B_9^* = 0$	NA	$B_{18}^* = Ex_{18}$	$Pc_9 = Pc_8 + Pc_{18} + Z_\mathrm{pump}$	NA
Regenerator	$B_9^* + B_{11}^* - B_{10}^* - B_{12}^* = 0$	$\frac{B_9^*}{Ex_9} = \frac{B_{10}^*}{Ex_{10}}$	NA	$Pc_{10} + Pc_{12} = Pc_9 + Pc_{11} + Z_\mathrm{regenerator}$	$\frac{Pc_9}{Ex_9} = \frac{Pc_{10}}{Ex_{10}}$

The exergy cost balances for each control volume of the microcogeneration unit considering the propositions (P#) of Lozano and Valero [3] are shown in tab. 1, where NA is *non-applicable*. Columns P#1, P#2, and P#5 of tab. 1 refer to the propositions of the TEC method, and the columns *cost* and *auxiliary* refer to the cost equations of the TEC method. Propositions 3 and 4 did not apply to all equipment.

The term *Pc* [$ per hour] represents the monetary cost of the exergy flow. Proposition #3 of Lozano and Valero [3] applies only to the generator, eq. (7), while proposition #4 is not applicable herein as no losses to the external environment are considered:

$$\frac{B_5^*}{Ex_5} = \frac{B_{11}^*}{Ex_{11}} \tag{7}$$

The monetary cost of each piece of equipment, $\dot{Z}$, is given by eq. (8) [27], which depends on the capital recovery factor, CRF, [27], in eq. (9):

$$\dot{Z} = \frac{(CRF)}{n} C \tag{8}$$

$$CRF = \left[\frac{i\left(1+i\right)^n}{\left(1+i\right)^n - 1} \right] \tag{9}$$

The CRF accounts for the interest rate, *i*, and the lifetime of the equipment, *n*, and *C* represents the purchase cost of each piece of equipment within the unit.

The capital cost of the cooling unit was split into its components, according to their importance to the unit [22]: generator 25%, absorber 25%, evaporator 20%, condenser 14%, regenerator 14%, and pump 2%.

Although not part of TEC, two other parameters are calculated based on SPECO [16]: the relative difference cost, r_k, and exergoeconomic factor, f_k. The former is the difference between the specific cost of the product, $c_{P,k}$, and the fuel, $c_{F,k}$, and the latter relates the portion of non-exergy-related costs (capital costs plus operation and maintenance) to the overall costs of the component, as shown, respectively [16]:

$$r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} \tag{10}$$

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + c_{F,k}\left(Ex_{\text{dest},k} + Ex_{L,k}\right)} \tag{11}$$

where $\dot{Z}_k$ is the monetary costs of equipment, and $Ex_{\text{Dest},k}$ and $Ex_{L,k}$ refer to the destruction of exergy and exergy associated with losses, respectively.

Results and discussion

The results of the TEC method are presented in tab. 2, which includes exergy flows, *B*, exergy cost flows, B^*, unit exergy costs, *k*, monetary costs, *Pc*, and monetary costs per exergy unit, c^*.

The results of *Pc* were obtained from the simultaneous resolution of the equations presented in tab. 1. The results of c^* were obtained from the solution of the system of linear equations of the SPECO method as presented in [22].

Table 2. Results of thermoeconomic evaluation

Flow	Description	B [kW]	B^* [kW]	k [kWkW^{-1}]	Pc [\$h^{-1}]	c^* [\$/GJ^{-1}]
3	Fuel	138.50	138.50	1.00	9.33	18.70
4	ICE gases	25.08	92.98	3.71	3.31	36.67
5	Refrigerant	7.76	67.95	8.76	2.42	86.62
6	Refrigerant	6.88	34.17	4.97	2.16	87.21
7	Refrigerant	2.98	14.78	4.97	0.93	87.21
8	Strong solution	0.53	5.39	10.25	0.24	126.17
9	Strong solution	0.81	7.08	8.76	0.25	86.62
10	Strong solution	5.66	49.58	8.76	1.77	86.62
11	Weak solution	8.52	74.61	8.76	2.66	86.62
12	Weak solution	1.60	32.11	20.08	1.14	198.66
14	Inlet water	1.44	1.44	1.00	0.01	2.16
15	Outlet water	2.80	20.83	7.45	1.24	122.92
16	Condenser heat	0.80	33.78	42.01	0.26	90.02
17	Absorber heat	1.81	41.49	22.94	1.84	282.47
18	Electricity: pump	1.69	1.69	1.00	0.01	2.16
19	ICE power	45.55	45.55	1.00	6.01	36.67

Point #15 represents the product of this cogeneration unit, chilled water for the refrigeration process. Losses are represented by currents #16 and #17, which correspond to the heat exchanges in dissipative components (condenser and absorber). The fuels of the cogeneration system are points #3, #14, and #18, which are the entries of fuel, water, and the work consumed by the re-circulation pump, respectively.

The cost of producing chilled water is 0.28 $ per ton, so selling this energy service for any value above this cost results in economic benefits for the unit. Heat losses in dissipative components are high: 0.26 $ per hour in the condenser and 1.84 $ per hour in the absorber, and the cost of fuel is 9.33 $ per hour. According to Lozano and Valero [3], there are challenges associated with applying TEC when losses (residues) originate in dissipative components, such as condensers in vapor-driven absorption chillers. These results were expected once the TEC approach provides higher monetary and exergy unit costs in these components that dissipate heat.

Figure 3 shows the monetary unit costs of the cogeneration system. The highest monetary unit cost is associated with flow #3, which corresponds to the natural gas inlet. The cost of flow #11 is 2.66 $ per hour, associated with the pre-heating of the strong solution, pumped from the absorber to the generator. This is necessary to ensure the operation of the system. The engine's mechanical power (flow #19), one of the products of the system, is evaluated at 6.01 $ per hour.

Figure 4 presents the specific exergy costs of the cogeneration system evaluated. The highest specific exergy cost is identified at the heat loss (flow #17) due to the endothermic reaction between water and ammonia inside the absorber (282 $/GJ), followed by flow #12 with a specific exergy cost of 199 $/GJ. This weak solution flows from the generator to the absorber, losing heat in the regenerator to pre-heat the strong solution that is pumped back into the generator. It must be highlighted that the lowest specific exergy costs are present in the inputs of the microcogeneration system: natural gas (flow #3, with 18.70 $/GJ), the minimal amount of

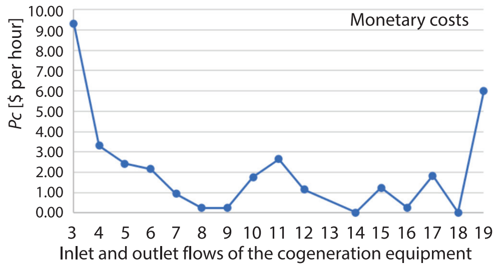

Figure 3. Monetary costs for the exergy flows

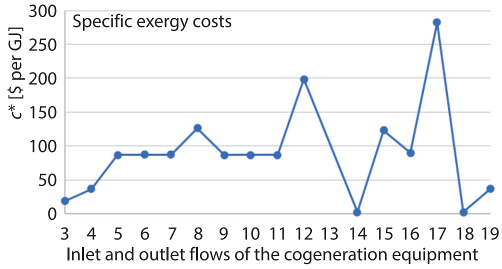

Figure 4. Specific exergy costs

water that enters the evaporator (flow #14, with 2.16 $/GJ) and the small amount of electricity consumed by the pump of the refrigeration system (flow #18, with 2.16 $/GJ).

Figure 5 shows the results of the exergy efficiency of each subsystem. The exergy efficiency values under 40% are present in the generator, ICE, pump, and absorber. These are the components that should be prioritized in an energy optimization proposal. Because the ICE and the pump are commercially available equipment, optimization efforts should concentrate on the generator and absorber.

Figure 6 presents the results of the relative cost difference per component. The highest values correspond to the evaporator, followed by the generator and regenerator – indicating that these components should be the focus of cost-effectivess improvements. The condenser and pump presented negligible r_k. As aforementioned, neither the relative cost difference nor the exergoeconomic factor are parameters of TEC-based assessments. Despite being parameters used in exergoeconomic SPECO-based evaluations, these were included herein for clarification purposes.

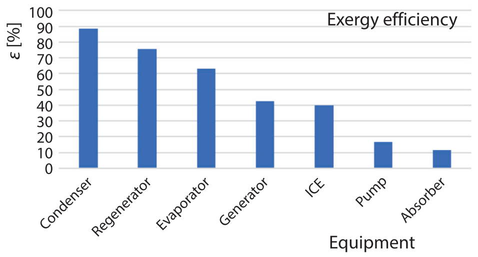

Figure 5. Exergy efficiencies

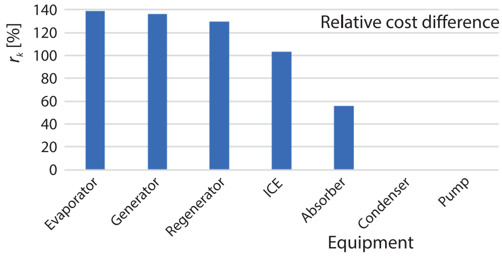

Figure 6. Relative costs difference

Figure 7 shows the exergoeconomic factors. According to Lazaretto and Tsatsaronis [28], the lowest values of this parameter indicate the need of reducing the costs of inputs and the exergy destroyed within a component. According to this criterion, improvements should be directed to the absorber, generator, regenerator, and evaporator.

The combined evaluation of exergy efficiency with thermoeconomic parameters is the basis for the diagnosis of thermodynamic and economic inefficiencies, helping prioritize investments in the energy optimization of specific components of an industrial system.

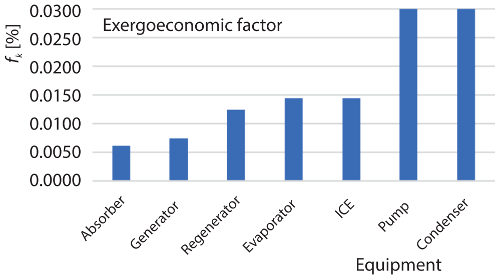

Figure 7. Exergoeconomic factor

Conclusions

The TEC was applied to a microcogeneration system to determine the exergy efficiency of each component, along with the monetary cost rates and exergy destruction costs associated with each internal flow and final product. This work presented a step-by-step application of TEC as a valuable tool for the thermoeconomic assessment of energy systems.

The results of the exergy assessment indicate that energy optimization efforts should be directed to the generator and absorber of the refrigeration system.

The monetary evaluation of the exergy flows demonstrated that the highest cost rates are associated with the flows of the generator due to the need to pre-heat the solution pumped by the absorber. The generator, engine, solution pump, and absorber presented exergy efficiency values under 40% – this suggests that further studies are required to propose improvements in these components and achieve increases in exergy efficiency. The analysis of exergoeconomic parameters (although not part of TEC, these can be calculated) pinpointed that the generator, absorber, and regenerator must be prioritized regarding monetary investment aimed at improving processes and mitigating thermoeconomic impacts.

Although the relative cost difference and exergoeconomic factor are characteristic parameters of SPECO-based assessments, these can be quantified from thermodynamic and exergy-related TEC data, providing a hybrid model for thermoeconomic assessment. The combined evaluation of both parameters pointed to the generator, absorber, evaporator, and regenerator as the thermoeconomic *villains* of the energy system. Particular attention should be given to these components regarding the design, thermal insulation, heat exchange area, and refrigerant fluid, especially when vapor absorption systems are coupled with an energy generation unit.

From this study, specific computational tools are being developed for the thermoeconomic diagnosis of energy systems within the industrial and tertiary sectors. The latter includes shopping centers, hotels, hospitals, and supermarkets. The results of the exergy assessments can be employed as inputs in the exergoenvironmental analysis, which also includes the life cycle assessment of the equipment and energy flows of the microcogeneration system.

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