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Techno-economic and Exergoeconomic Analysis of a micro cogeneration system for a residential use

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ABSTRACT. The aim of the study is to present an economic analysis of a micro cogeneration system using financial analysis (energy view) and exergoeconomic analysis (exergy view). This system uses a natural gas-fueled 30 kW microturbine to generate electricity, and to produce hot water by recovering energy from the waste heat in the exhaust gases by using a heat exchanger, which serves as the drive source of an absorption chiller with a nominal capacity of 35 kW. In the financial analysis economic indicators such as payback, net present value and internal rate of return were used to verify the economic feasibility of this system, while in the exergoeconomic analysis, the Theory of Exergetic Cost was used to determine the exergetic monetary costs. A thermodynamic model was developed on the EES-32 (Engineering Equation Solver) platform. On applying the financial analysis, the results showed that the micro cogeneration system is feasible with positive values of R$ 206,540.00 for NPV, 27% IRR and a 6-year payback. Based on the exergoeconomic analysis, the cogeneration system is also feasible since the monetary cost of the electricity is lower than that charged by the electricity company but this is only possible after the 5th year.

Keywords: net present value, IRR, payback, exergetic costs.

Análise Tecno-econômica e Exergoeconomica de um sistema de microcogeração de para uso residencial

RESUMO. Este trabalho tem como finalidade o estudo econômico de um sistema de microcogeração de energia utilizando a análise financeira (visão energética) e a análise exergoeconômica (visão exergética). Este sistema utiliza gás natural como combustível primário para o acionamento de uma microturbina de 30 kW para produzir eletricidade, e água quente pelo do reaproveitamento da energia do calor residual dos gases de escape por meio de um recuperador de calor, que serve como fonte de acionamento de um chiller de absorção de 35 kW de capacidade nominal. Na análise financeira foram utilizados os indicadores econômicos tais como: o payback, o valor presente liquido, e a taxa interna de retorno, para verificar a viabilidade econômica do sistema de microcogeração, enquanto na análise exergoeconômica, foi considerada a teoria de custos exergéticos para a determinação dos custos monetários exergéticos. Foi desenvolvido um modelo termodinâmico na plataforma EES-32 (*Engineering Equation Solver*). Da aplicação da análise financeira os resultados mostraram que o sistema de microcogeração é viável com valores positivos de R$ 206.540,00 de VPL, 27% de TIR, 6 anos de retorno do capital. A partir da análise exergoeconômica, o sistema de cogeração também mostrou-se viável já que o custo monetário da eletricidade é menor do fornecido pela companhia de eletricidade, mas isso é possível após o 5º ano.

Palavras-chave: valor presente liquido, TIR, payback, custos exergéticos.

Introduction

As giving value to the concepts of promoting environmental and energy sustainability increased, so too did concern for rationalizing and optimizing the use of energy in order to take advantage of consuming energy more efficiently. An excellent ally in achieving this was found to be energy cogeneration, which seeks to produce steam, and hot, cold and chilled water by recovering combustion gas from turbines and generators (Maraver, Uche, & Royo, 2012; Ochoa, Dutra, Henríquez, & Rohatgi, 2014b). Giving value to how to consume energy more rationally has prompted the search for techniques that optimize primary resources, thereby increasing the overall efficiency of power generation systems since various energy applications in the industrial area, as well as in the commercial or residential sectors, may be met from a single source (Ortiga, Bruno, & Coronas, 2011;

Campos, Erkoreka, Martin, & Sala, 2011; Gladysz & Ziebik, 2013). However, this technique of recycling energy is linked to making initial investments in additional equipment such as heat exchangers, pumping systems, cooling chillers and boilers in order to implement a cogeneration system. Hence it is important to undertake technical and economic analyses in order to verify the viability of a system (Mansouri, Ahmadi, Kaviri, & Jaafar, 2012; Edwin & Sekhar, 2014; Okoye & Atikol, 2014; Shamshirband et al., 2014; Ochoa, Diniz, Santana, Silva, & Ochoa, 2015).

Badami, Camillieri, Portoraro, and Vigliani (2014) conducted an energetic and economic comparison of the design data and operating conditions in eleven cogeneration plants, located in Italy. Their paper set out to show how best to take advantage of the incentives laid down in Italian legislation, and which would lead to costs being reduced by between 15 and 20%. Alexis and Liakos (2013) conducted an economic feasibility study on implementing a micro- cogeneration system for a hospital in Greece. Their study showed that the proposal was entirely feasible since the Net Present Value (NPV) was positive; the Internal Rate of Return (IRR) was 19%, which was much higher than the market rate; and electricity consumption was reduced by approximately 28%.

The goal of the cogeneration process is to use a single fuel so as to maximize the use of the available energy in the fuel, while generating electricity and recovering the residual heat present in the flue gas. This is then converted into another source of energy that may well increase the availability of the thermal and electric energy to meet demand, and hence increase the overall efficiency of the plant (Çakir, Çomakil, & Yuksel, 2012; Armanasco, Colombo, Lucchini, & Rossetti, 2012). Thus, absorption refrigeration systems can use energy recovered from flue gases to activate themselves, which leads to decreasing the consumption of electricity for air conditioning and refrigeration processes (Liang et al., 2013; Ochoa et al., 2014b). Moreover, recovery boilers can be used to generate steam for industrial processes without burning additional fuel, thereby increasing the overall efficiency of the system (Morten, 2012; Shnaiderman & Keren, 2014).

The Second Law of Thermodynamics states that there is no reversible process in Nature, i.e., each process suffers a loss which is associated with destroying available energy. As to energy inputs, this destruction of available useful energy, called exergy, can be quantified by exergy analysis (Wei & Zmeureanu, 2009; Ochoa, Dutra, & Henríquez, 2014a). According to Lozano and Valero (1993), although exergy enables the irreversibilities of a system to be quantified, this is not enough to solve the problem of determining the costs of the physical flows of a plant. Therefore, the introduction of a thermo-economic new variable, called 'exergetic cost', is needed. This represents the amount of exergy required to produce a physical flow in the system (Lee, Ahn, Morosuk, & Tsatsaronis, 2014; Manesh et al., 2014). There are several types of studies related to this exergoeconomic analysis (Lamas, 2013; Esfahani & Yoo, 2013; Jensen, Rothuizen, & Markussen, 2014; Chan, Veje, Willatzen, & Andersen, 2014; Rivarolo, Greco, & Massardo, 2013; Cavalcanti & Motta, 2015). These show the importance of this analysis for improving the performance of the cogeneration system. Ganjehkaviri, Jaafar, Ahmadi, and Barzegaravval (2014) carried out an optimization study on a Combined Heat and Power cycle, based on an exergoeconomic environmental analysis, from which optimum values were found that increased its exergetic efficiency by 6% and decreased CO_2 emissions by 5%. In the same context, Utlu and Hepbasli (2014) developed an exergoeconomic analysis of the drying processes of ceramic production; determined its exergetic performance; improved its energetic and exergetic efficiency; and reduced the overall cost of the process. On the other hand, (Kaushik & Arora, 2009), used a modification in the methodology of economic analysis, based on the Second Law of Thermodynamics, called advanced exergoeconomic analysis, which includes unavoidable and avoidable exergy destructions. This modification in the exergoeconomic methodology has been studied in different energy trigeneration processes (Açikkalp, Aras, & Hepbasli, 2011; 2014a; 2014b); in geothermal systems that produce electrical and thermal energy (Keçebas & Hepbasli, 2014); as well as in chemical processes for the combined production of electricity and heat, and to reduce emissions of CO_2 into the environment (Petrakopoulou, Tsatsaronis, & Morosuk, 2013).

A well-designed cogeneration system should incorporate technical and economic features that can meet the demands for heat and power of a specific use. Therefore, this study set out to investigate the economic feasibility of a cogeneration power plant based on an energy and exergy analysis that took a previously discussed technical analysis into account (Ochoa et al., 2014a). It was assumed that the system runs 24 hours per day, for 8000 hours per year, and that all the electricity and thermal energy that it generates will be used. It did not take local environmental regulations into account. The real novelty of their article is that it presents a case study that focuses on a micro cogeneration system for residential uses by using two classes of methods for assessing the economic viability of a project. The financial analysis was based on the parameters of: NPV, IRR and payback; and for the exergoeconomic analysis, the exergetic cost theory proposed by Lozano and Valero (1993).

Material and methods

Figure 1 shows a schematic diagram of the micro cogeneration system used in this article. It consists of a microturbine with a nominal capacity of 30 kW, a compact heat exchanger, a lithium-bromide-water single-effect absorption chiller with a cooling capacity of 10 RT (tons of refrigeration), and a cooling tower (Ochoa et al., 2014b).

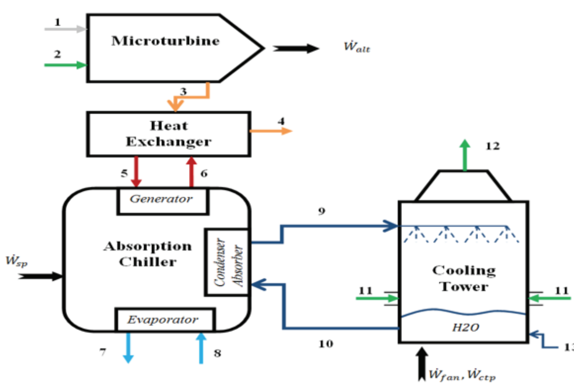

Figure 1. Schematic of the micro cogeneration system used in the simulations (Ochoa et al., 2014b).

The process of micro cogeneration is as follows: the natural gas and air mixture is burned in the combustion chamber, inside the microturbine, and then flows to the turbine and generates electricity. The heat that is generated which is not converted into electricity is carried away by the exhaust gases. Part of this heat is recovered by means of a compact, counter-current gas-liquid heat exchanger. One of the fluids, water, flows through the inside of the pipes and the other fluid, exhaust gases, flows along the outside of the pipes where it skims over fine tubes, thereby enabling heat transfer between the two fluids, namely it heats the water and cools the exhaust gas. Then, the hot fluid is sent to start up the absorption chiller. This absorption process is exothermic, which means that it generates heat. Next, this heat is removed by chilled water from the cooling tower. The chilled water produced in the evaporator of a single-effect LiBr-H_2O absorption chiller can reach values of between 7 and 12°C, depending on the temperature of the hot water supplied (Ochoa et al., 2014b).

The system was mathematically modeled using a mass and energy balance based on the First and Second Laws of Thermodynamics. This model can predict the behavior of the system and produce data that make it possible to calculate the price of the electricity generated, the volume of hot and chilled water, and the prices of these parameters from the energy and exergy point of view.

Advantage/disadvantage of financial and exergoeconomic analysis

The main advantage of using exergoeconomic analysis is that it enables the monetary costs associated with exergetic flows to be checked, i.e., on the basis of the useful energy of the system which includes the irreversibilities of each component. Therefore, these costs already take into account the actual losses of micro cogeneration system since the Second Law of Thermodynamics has been used. However, in this analysis, the exergetic flows must be calculated for each stream (entropy generation) for which, sometimes, (depending on the type of working fluids and setup configuration), data are not easily available and therefore, certain subjective assumptions must be established based on the system setup and the analysis data. In addition, energy-monetary costs must be introduced to round off the incidence matrix created by the Theory of Exergetic Costs such as: electricity rates, water, fuel, monetary value of the steam.

On the other hand, the traditional way of analyzing the economic feasibility of a power system (by financial analysis) presents the easy way of finding the energy flows (from the First Law of Thermodynamics) and a simple data function of a system, such as: the efficiency of equipment, flow rates, etc., which enable the feasibility of the system to be judged (design study). However, the determination of costs (income and costs) depends on investment factors and percentages. These are very often not easy to find in the open literature, since they depend on the type of configuration, generation capacity, the equipment used, the ultimate goal of the system - electricity, heat and/or cold, and so forth.

Another disadvantage of these two analyses is the inclusion of an inflation indicator which is a very complex variable that needs to be estimated and simulated for each configuration.

Financial analysis

The method of analysis applied enables the economic viability of the micro cogeneration system to be checked from an energy point of view. The payback period, the NPV and the IRR parameters were used as comparative cost methods. These criteria, take into account the costs of the design of the system as a whole, which includes all income (profits) that comes from generating electricity, producing chilled water, and selling the surplus electric energy.

Costs involved in the financial analysis of micro cogeneration system

The main costs of installing a micro cogeneration energy plant are: the Initial Investment ($Inv_{initial}$), which is the total cost of the project plus the cost of financing construction, which includes all purchases, project costs and operating and maintenance costs, expressed as in Equation 1, by following the rate shown in Table 1 (Bejan, Tsatsaronis, & Moran, 1996).

$$Inv_{initial} = \sum_{i=1}^{n} Cost(i) \quad (1)$$

6% of initial investment was assumed to estimate the operational and maintenance costs (Caliskan & Hepbasli, 2010; Ghaebi, Amidpour, Karimkashi, & Rezayan, 2011).

Investment revenues

In the micro cogeneration system, the revenue accumulated at the end of each year until the end of the lifetime of the project is the result of saving energy when generating electricity and also of producing chilled water by using an absorption refrigeration system that has replaced a conventional, mechanical cooling system. The absorption refrigeration system could be driven by the hot water produced by recovering the waste of exhaust gases. Hence, the electricity that would be consumed by the mechanical refrigeration chiller is saved. The reduction in electricity needed by the micro cogeneration system was calculated by the set of Equations 2 to 6, and these represent the system's revenues:

$$E_{produce} = \dot{W}_{generated} \cdot t_{op} \quad (2)$$
$$E_{consumed} = F_{con\_ene} \cdot \dot{W}_{generated} \cdot t_{op} \quad (3)$$
$$E_{sold} = E_{produce} - E_{consumed} \quad (4)$$
$$Rev_{surplus\_energy} = E_{sold} \cdot F_{cons\_power} \quad (5)$$
$$Rev_{themal\_energy} = E_{chiller_{abso}} \cdot p_{ee\_cons} \cdot t_{op} \quad (6)$$

where:
$E_{produce}$ is Energy produced by the plant [kW hour^{-1}];
$\dot{W}_{generated}$ is Power generated by the plant [kW];
t_{op} is operation time [hr];
$E_{consumed}$is Energy consumed by the plant [kW hour^{-1}];
F_{con_ene} is the Power factor consumed by the plant [-];
E_{sold} is the Energy exported or sold to utilities [kW hour^{-1}];
F_{cons_power} ,is the Selling factor given by the utilities to companies exporting the excess energy [R$ MW^{-1} hour^{-1}];
$E_{chiller_{abso}}$ is the Power used by the absorption refrigeration chiller [kW];
p_{ee_cons} is the Electricity tariff that would be charged by the utility for the electricity consumption of a compression chiller [R$ kW^{-1} hour^{-1}];
is the Revenue from excess power sold to utilities [R$ year^{-1}];
Rev_{themal_energy} is the Revenue from saving electric power when using the absorption refrigeration system, i.e., energy that would be expended by the same cooling system if mechanical compression were used [R$ kW^{-1} hour^{-1}].

Table 1. Percentage values on the costs involved in economic analysis of projects.

Directs Costs		Indirect Costs	
Cost	Initial Investment (%)	Cost	Initial Investment (%)
Additional Equipment purchase	40	Engineering and Supervision	21
Equipment installation	14	Construction and Installation	22
Piping	20	Contingencies	20
Instrumentation and control	8	Other	
Equipment and electric material	10	Plant Start up	12
Land	2		
Civil work, architecture and structure	23	Operation Capital	20
Services	20		

Methods for making an economic evaluation of a micro cogeneration system

- Time of return on Invested Capital (Payback):

This quantifies how many years it would take to recover the cash invested in the system based on Costs and Revenue - see Equation 7:

$$\sum Costs = \sum Revenue \tag{7}$$

Net Present Value (NPV)

This technique is used for long-term analysis and is used to calculate the difference between the present value of all investments and the present value of all revenues referenced to a single date, for the rate of return on the project in which investment is made. The NPV is calculated prior to implementing a system – see Equation 8 (Alexis & Liakos, 2013).

$$NPV = Inv_{initial} + \sum_{j=1}^{N} \frac{CF(j)}{(1+i)^j} \tag{8}$$

where:
CF(j), it is the cash flows for a period *j*, and the term *i* represent the attractive minimum rate, and *N* years of investment.

Internal Rate of Return (IRR)

This is the interest rate that applies to the cash flow values, and is referenced to the start date of the project, which makes the net present value zero – see Equation 9 (Fortunato, Torresi, & Deramo, 2014).

$$NPV = Inv_{initial} + \sum_{j=1}^{N} \frac{CF(j)}{(1+IRR)^j} = 0 \tag{9}$$

Exergoeconomic analysis

The goal of exergoeconomic analysis is to determine the exergetic unit costs of the rational use and conservation of energy (Manesh et al., 2014; Bagdanavicius & Jenkins, 2014).

Exergetic Costs based on exergetic analysis

In determining the exergetic costs of the micro cogeneration system, it is necessary to define and identify the production units of the system, while putting control volumes in the main components, as shown in Figure 2 which represent the units of the productive system (Pantaleo, Camporeale & Shah, 2013; Fazelpour & Morosuk, 2014).

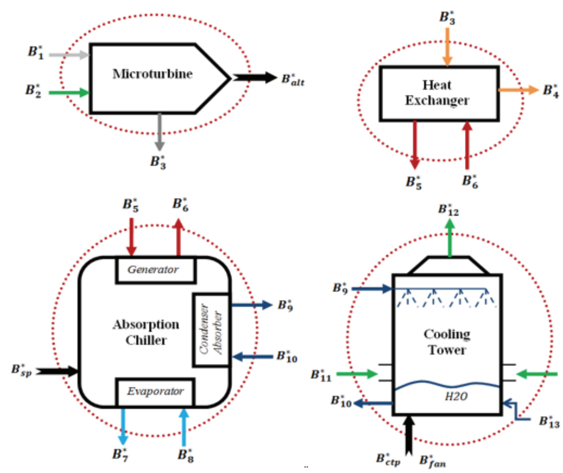

Figure 2. Control volumes used in the economical analysis.

On applying the Theory of the Exergetic Cost (Lozano & Valero, 1993) on the system, the incidence matrix for the productive units could be expressed as shown in Table 2.

Monetary costs based on exergetic analysis

To determine the monetary flows, the unit of production must be defined by using the initial costs (input), final costs (products), initial investment, operating and maintenance costs of the equipment that comprises the micro cogeneration installation – see Equations 10 at 12.

Table 2. Equation of the Incident Matrix of the cogeneration system.

Proposition	Equation
P1	$B_1^* + B_2^* - B_3^* - B_{alt}^* = 0$ (Micro turbine) $B_3^* + B_6^* - B_4^* - B_5^* = 0$ (Heat Exchanger) $B_5^* + B_{sp}^* + B_7^* + B_{10}^* - B_6^* - B_8^* - B_9^* = 0$ (Absorption Chiller) $B_{ctp}^* + B_9^* + B_{11}^* + B_{fan}^* + B_{13}^* - B_{10}^* - B_{12}^* = 0$ (Cooling Tower)
P2	$B_1^* = Ex_1$; $B_{ctp}^* = \dot{W}_{ctp}$; $B_2^* = Ex_2$; $B_{sp}^* = \dot{W}_{sp}$; $B_{alt}^* = \dot{W}_{alt}$; $B_{13}^* = Ex_{13}$; $B_{fan}^* = \dot{W}_{fan}$; $B_{11}^* = Ex_{11}$
P3	$\frac{B_5^*}{Ex_5} = \frac{B_3^*}{Ex_3}$
P4	$\frac{B_9^*}{Ex_9} = \frac{B_8^*}{Ex_8}$
P5	$B_{12}^* = 0$; $B_4^* = 0$

$$\sum C_{inp}^{*} + Z_{inv} = \sum C_{pro}^{*} \quad (10)$$
$$C_{inp}^{*} = c_{inp} Ex_{inp} \quad (11)$$
$$C_{pro}^{*} = c_{pro} \cdot Ex_{pro} \quad (12)$$

Z_{inv} represents the investment costs, operation and maintenance of the equipment in [R$ hour^{-1}], C_i^{*} the monetary cost per unit of time [R$ hour^{-1}], Ex_{ins}, Ex_{pro} the exergetic flows input and products [kW], and c_{inp} the cost per exergetic unit [R$ kW^{-1} hour^{-1}].

The costs from Table 1 were used to determine all of the costs of the system, thereby expressing the financial value of the equipment arising from the recovery factor of capital (*A/P*), the investment in initial equipment (F_i), its annual operation time (t_{op}) and (γ_{om}) which is the operation and maintenance factor – see Equations 13 and 14 (Soltani et al., 2013; Lee et al., 2014).

$$Z_i = \frac{(A/P)}{t_{op}} \cdot F_i \cdot \gamma_{om} \quad (13)$$
$$\frac{A}{P} = \left[\frac{i \cdot (1+i)^n}{(1+i)^n - 1}\right] \quad (14)$$

System costs

Table 3 shows the values of the initial investment in each unit of the micro cogeneration system, based on the prices established by suppliers (Yazaki Energy System, 2003; Capstone Turbine Corporation, 2004).

Table 3. Initial investment of each component that is part of the cogeneration system.

Microturbine (MT)	Heat Exchanger (HE)	Absorption Chiller (AC)	Cooling Tower (CT)
R$ 140,000.00	R$ 12,000.00	R$ 85,000.00	R$ 10,000.00

Costs of inputs

The main inputs are the electricity grid, water, and natural gas, the costs of which in the form of tariffs are the basis for the energetic and exergetic analysis. Costs per exergy unit of natural gas flows, water supply and electricity were provided, using the rates charged by water, electricity and natural gas companies in the city of Recife. The prices charged for water, electricity and natural gas are R$ 1.18 m^{-3}, R$ 0.52 kW^{-1} hour^{-1}, R$1.12 m^{-3}, respectively. (Compesa, Celpe, Copergas). The tariff model used in this study (for the costs of electricity, water and natural gas) is the commercial one (rate of exchange used: 1 USD = R$ 3.0, Banco Central do Brasil [BCB], 2015a).

Economic parameters

In this analysis, an annual interest rate of 12% was used (market interest rates, Banco Central do Brasil [BCB], 2015b), as were a time period of 15 years as the lifetime investment, and 8000 hours of operation per year but monetary inflation was not taken into account (Luo et al., 2014; Instituto Brasileiro de Geografia e Estatística [IBGE], 2010).

Discussion and results

The energetic and exergetic analysis of the micro cogeneration system proposed was obtained from earlier studies (Ochoa et al., 2014a; 2014b). These analyze all data from the system, namely energy flows, energetic and exergetic efficiencies, exergy destruction and irreversibilities). This study seeks to make an economic analysis of the micro cogeneration system and takes the methodology presented in Section 2 into account.

Financial analysis (energetic view)

The data needed for the financial analysis of the cogeneration system was selected. Starting with the selling factor (given by the concessionaires to the exporters of surplus energy), the revenue arising from the sale of surplus electricity is calculated. This value (F_{cons_power}) was provided by the National Electric Energy Agency (Aneel), and the value of R$ 0.170 kWh^{-1} (Ministério de Minas e Energia [MME], 2009) was selected to which 10% of the energy consumed by the cogeneration plant itself was added (F_{con_ene}) (Caliskan, Dincer, & Hepbasli, 2013).

The cost of the electricity that would be charged by the utility for the electricity consumption of a compression chiller, which would provide the cooling energy (in this case chilled water for air conditioning), was determined by using the cost of average consumption of a mechanical chiller ($Consumption_{ele,ave}$) with the same capacity as an absorption chiller (35 kW) – see Equations 15 and 16:

$$Consumption_{ele,ave} = f\left(Pow_{chiller}; t_{op,ave}\right) \quad (15)$$

where:
($Pow_{chiller}$) is the compressor power of the mechanical chiller [kW], and the ($t_{op,ave}$) is the average operation time [hour].

Equation 16 expresses the cost of electricity used by a refrigeration chiller to produce chilled water. This therefore is the value that would be saved by a micro cogeneration system that uses an absorption chiller instead of a cooling system driven by mechanical compression.

$$p_{ee_{cons}} = \frac{Cost_{uni\_mechanical} + Consumption_{ele,ave} \cdot p_{ee}}{Consumption_{ele,ave}} \quad (16)$$

where:
$Cost_{uni\_mechanical}$; is the cost of the mechanical chiller [R$], ($p_{ee}$) is the electricity tariff of the electricity company. The (p_{ee_cons}) was calculated and resulted in an average value of R$ 1.95 kW^{-1} $hour^{-1}$.

The overall results of the financial analysis of the micro cogeneration system show that the system is feasible economically, since the values of the economic parameters (NPV, IRR and Payback), namely an NPV of R$ 206,540.00; 26.64% IRR and a 6-year payback period, were above the minimum values recommended. A parametric analysis (Figures 3a and b) was made of the NPV and the IRR based on the cost of electricity to produce chilled water using a mechanical refrigeration chiller (and savings were made due to using an absorption system instead of a mechanical compression system) in order to verify the viability of the system. Several values of (p_{ee_cons}) were selected to check the payback period.

The results show that the payback time will be shorter when the rate is equal to 2.0 (which represents the amount saved by producing chilled water using an absorption chiller instead of a mechanical refrigeration system), and longer when the price of electricity tends towards its minimum value, i.e., R$ 1.8 kW^{-1} $hour^{-1}$, where, given the years of the investment, the system will never be economically viable. It is expected that as the electricity tariffs increase, the payback period tends to decreases, since the micro-CHP system will produce electricity that the absorption chiller will consume with any surplus electricity being available for export. This will increase revenues, hence making the system economically feasible, depending on the investment costs and the tariffs for generating and exporting electricity from the system. Higher revenues establish more savings of energy (cost savings) that are brought about by the capacity of the micro cogeneration system to recover heat so as to drive the absorption chiller and thus to replace the mechanical chiller.

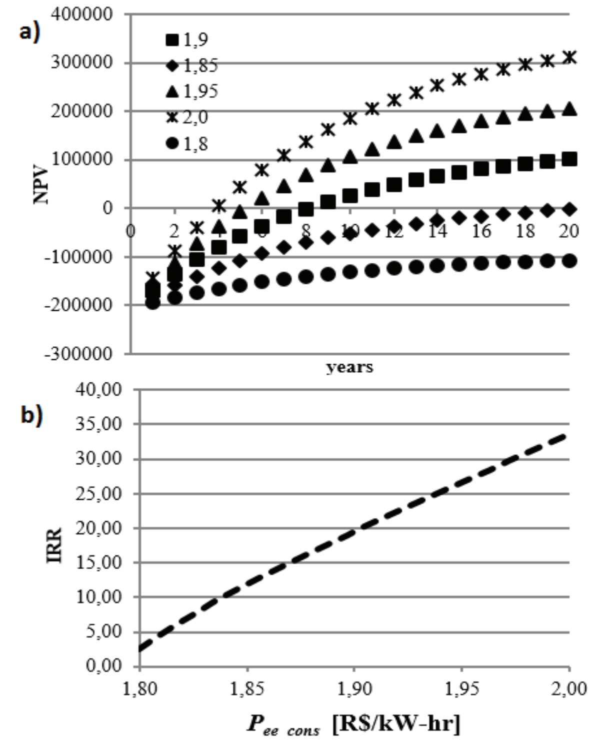

Figure 3. a) NPV variation for different values saved rate due to the use of absorption refrigeration system, instead of using mechanical refrigeration systems. b) IRR variation for different values saved rate due to the use of absorption refrigeration system, instead of using mechanical refrigeration systems.

Thermoeconomic analysis (exergetic view)

For the simulation condition, it was considered that the electricity consumed by the components of the plant (fan, solution and cooling power pump) was supplied to generate electric energy for the micro cogeneration system and the costs associated with these components were expressed as in Equation 17:

$$c_{ctp} = c_{sp} = c_{fan} = c_{alt} \quad (17)$$

The cost associated with the gas products from the combustion of the microturbine was determined based on the electricity production, Equation 18. This is because the main goal of the microturbine is to generate electricity. Hence, all the costs involved in the purchasing and operation should be included in the cost of generating electricity (Luo et al., 2014; Ganjehkaviri et al., 2014).

$$c_3 = c_4 \quad (18)$$

Tables 4 and 5 show the results of the exergoeconomic analysis of the system at 100% micro turbine load.

Table 4. Results of the exergetic and monetary costs applied on the micro cogeneration system.

Streams	B* (kW)	K	C (R$ kW^{-1} hour^{-1})
1	100.5	1	0.114
2	1.319	1	0
3	74.16	3.542	0.114
4	0	0	0
5	654.1	3.542	0.114
6	580	3.241	0.114
7	153.3	2.012	0.1267
8	75.85	1	0.06108
9	541.4	2.05	0.08258
10	538	2.012	0.07779
11	0.1458	1	0
12	0	0	0

Table 5. Balance of monetary costs of the micro CHP system.

Input			Output	
Streams	(R$ year^{-1})		Streams	(R$ year^{-1})
1	91,680.00	Cogeneration System	4	0
2	0		7	77,216.00
8	37,064.00		12	0
11	0		Alternator	91,600.00
13	931.2			
Solution Pump	2.584			
Fan	2,783.2			
Cooling Tower	3,355.2			
Investment	32,999.816			
Total	168,816.00		Total	168,816.00

The exergetic value of a flow equals the amount of exergy required to produce this flow. Thus, 654.1 kW is needed to produce the hot water that will trigger the absorption chiller, and its exergetic unit cost of 3.542 (Table 4). Similarly, 74.16 kW of hot water is needed to produce 77.45 kW of net chilled water. The exergetic cost of gas rejected by the combustion chamber of the microturbine is 74.16 kW, and its exergetic unit cost is 3.542. The cost of producing electricity from the micro cogeneration system is R$ 0.4122 kW^{-1} hour^{-1}, so any value above this is interesting for self-consumption and/or selling the electricity produced, which represent profits for the micro cogeneration system. The monetary costs of the cogeneration system were R$ 168,816.00 year^{-1}, taking the inflows and outflows into consideration (Table 5). The investment (a value of R$ 32,999.00 year^{-1}) for purchasing a micro cogeneration unit after applying the capital recovery factor is amortized over its unit of life.

A parametric analysis was made of the costs associated with generating electricity (Alternator cost), the chilled and make-up water of micro cogeneration system and these were compared with the cost of electricity supplied by the electricity company in Pernambuco - Celpe (cost of electricity) and of gas by the natural gas company - Copergas. Figure 4a compares the costs involved in the cogeneration system producing electricity and the tariffs charged by Celpe and Figure 4b compares the monetary costs of the cogeneration system producing electricity and chilled water with the power supplied by the utility based on the load of the gas microturbine.

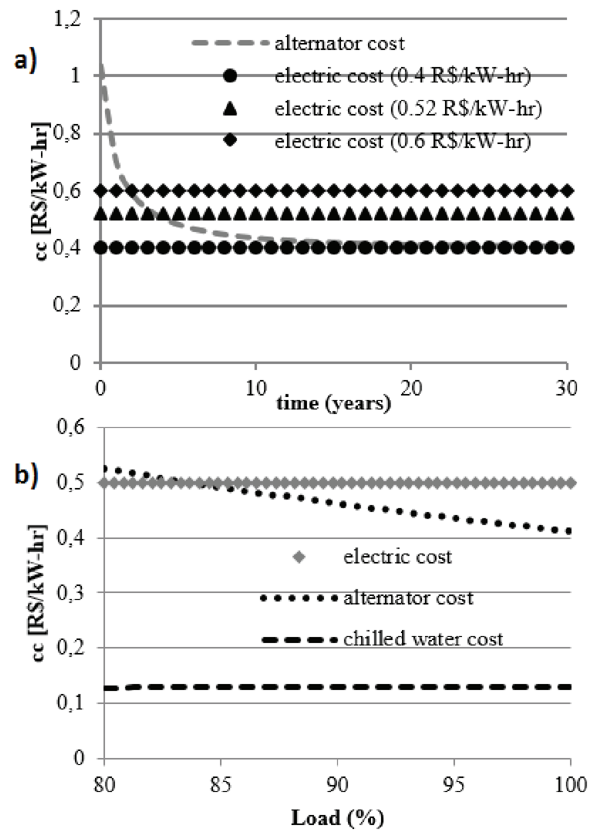

Figure 4. a) Monetary cost of electricity produced over the operating time. b) Comparison of monetary costs of electricity and chilled water produced and electricity supplied by Celpe as function of the microturbine load.

The monetary cost of producing electricity is lower, while a minimum profit is achieved for a period of approximately six years. Thereafter, the micro- cogeneration system is economically feasible, since the cost of producing electricity is lower than the charges that Celpe would raise for the supply of the same amount of electricity.

This is the main factor in favor of using cogeneration systems, namely generating electricity and thermal energy to produce chilled water, and thereby making the most of its fuel energy capacity, which, in this case, is natural gas.

In Figure 4b, in accordance with the simulated data obtained from (Ochoa et al., 2014a; 2014b), in order to produce enough power to drive the absorption chiller, a load operation of at least 80% is required during which combustion gases could be recovered and hot water produced at a minimum temperature of 70°C so as to drive the absorption chiller (Yazaki Energy System, 2003). It may be noted that if the microturbine load is over 90%, the micro cogeneration system produces benefits, since it produces electricity that it can not only consume but also sell, and since it also produces chilled water. Figures 5a and b show the variation in the production costs of cogenerating electricity, chilled water and make-up water and the cost of electricity provided by Celpe using its tariffs (cost of electricity).

In Figure 5a, the price of natural gas is a critical parameter for the viability of the cogeneration system.

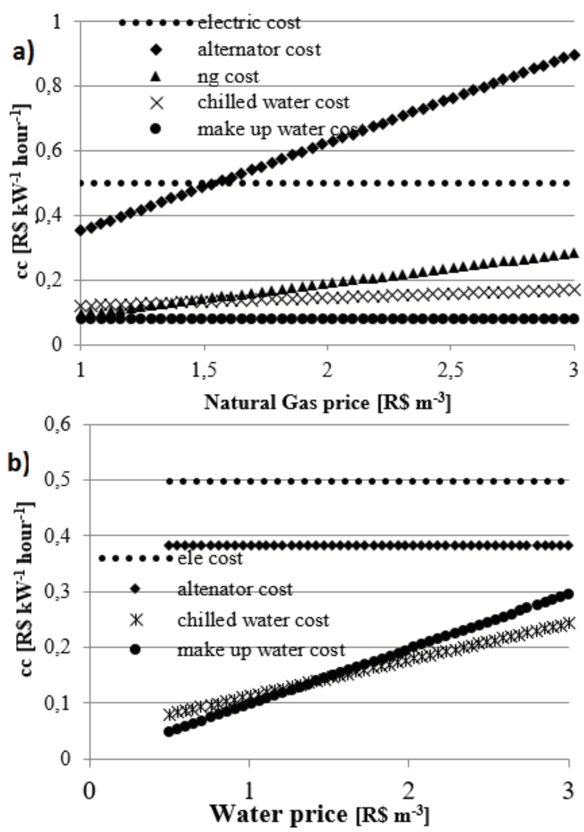

Figure 5. a) Comparison of monetary costs of electricity (alternator cost), chilled water, make up water, natural gas, and electricity provided by Celpe (electricity cost) depending on the natural gas price; b) Comparison of monetary costs of electricity, chilled water, make up water, natural gas, and electricity provided by Celpe as function of water price.

The system is economically feasible for natural gas rates lower than R$ 1.6 m^{-3}, i.e., all the electricity generated in the microturbine (alternator cost), with values from R$ 0.4 to 0.5 kW^{-1} $hour^{-1}$, is cheaper than that provided by Celpe R$ 0.52 kW^{-1} $hour^{-1}$, which is an advantage for the export of electricity, and represents revenue for the system. This may also represent an energy saving because the mechanical refrigeration system has been replaced by an absorption refrigeration system and so the cost for the absorption chiller in the micro-generation system to produce chilled water was R$ 0.1267 kW^{-1} $hour^{-1}$ cheaper than using a mechanical refrigeration system which may also expend more energy because it uses a compressor.

The variation in the price of the water tariff used in the cogeneration system (makeup water), Figure 5b, does not change the cost of generating electricity (alternator cost), since the only variation of these costs is subject to changes in the price of natural gas (drive source of the cogeneration system). However, the exergetic monetary costs of makeup water (R$ 0.03 to R$ 0.2 kW^{-1} $hour^{-1}$) and chilled water (R$ 0.08 to R$ 0.25 kW^{-1} $hour^{-1}$) increases as the water rates increase (R$ 0.5-3.00 m^{-3}), due to the fact that the price of water changes proportionally with the costs related to the (hot, cold and chilled) water circuit of the system.

Final considerations on the economic methodologies

From the energy point of view, the parameters of NPV, IRR and payback enable the viability of the system to be determined, which represents a positive value for generating electricity for its own consumption and export. Moreover, chilled water is produced by replacing a mechanical refrigeration system with an absorption refrigeration system. This substitution represented economizing the electric consumption of the mechanical compressor by the significant amounts of R$ 206,540.00 $year^{-1}$, 27% NPV and a 6-year IRR and payback respectively for the case study.

From the exergetic point of view, the exergetic and monetary costs determine the feasibility of the micro cogeneration system based on producing electricity and chilled water by using natural gas as feedstock for the system. The results show that after six years, the cost of generating electricity (R$ 0.42 kW^{-1} $hour^{-1}$) is lower than that charged by the concessionaire (R$ 0.50 kW^{-1} $hour^{-1}$).

Conclusion

A techno-economic and exergoeconomic analysis was performed to verify the economic viability of a micro cogeneration system.

From the energy point of view, the system is economically viable due to the values achieved (R$ 206,540.00 $year^{-1}$ of NPV, 27% of IRR and a 6-year payback period.

From the exergy point of view, the absorption chiller produced chilled water at a net monetary cost of R$ 0.0109 kW^{-1} $hour^{-1}$, while the exergetic monetary cost to produce electricity was R$ 0.4122 kW^{-1} $hour^{-1}$, representing a total production of R$ 91,600 $year^{-1}$. Hence, any value above of this, it is positive for the system.

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