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Engenharia Mecânica

Thermoeconomic analysis for a trigeneration system in a soluble coffee industry

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Abstract:

Considering that a trigeneration system tends to result in higher thermal efficiency than electricity, heating and cooling generation in separated ways, the purpose of this study is to perform a thermoeconomic analysis of a trigeneration system in a soluble coffee industry in order to improve its energy and economic performance. The current thermal system has a steam generator that provides heating utility for the soluble coffee production, including a refrigeration plant using ammonia/water absorption, while the electricity is bought from the energy concessionary. The proposal is to include an extraction-condensing steam turbine providing 5100 kW of electricity to the industrial plant, besides keeping the same energy demands in the current plant. Heat, cold and power were evaluated for their costs per unit of exergy in the current plant and compared to the proposal of the trigeneration system. The results show that the proposal to integrate a turbo-generator is technically and economically viable, resulting in reduction in the costs for heating, cooling and electricity of up to 72% in a payback period of only 24 months.

Keywords: cogeneration, exergy, food industry.

Introduction

Cogeneration is the simultaneous production of heat and power from a single fuel source and is an alternative to reduce operating costs and improve energy performance. When part of the heat produced by a cogeneration system is used for generating cold by absorption refrigeration plants (ARP), the system is defined as trigeneration and has been carried out in several applications (Kavvadias & Maroulis, 2010; Lian, Chua & Chou, 2010; Aneke, Agnew, Underwood, Wu & Masheiti, 2011; Tse, Wilkins, McGlashan, Urban, & Martinez-Botas, 2011; Al-Sulaiman, Dincer & Hamdullahpur, 2013).

In recent years, the economic and environmental benefits of trigeneration systems have been analyzed in the food industry. Freschi, Giaccone, Lazzeroni and Repetto (2013) studied the application of a trigeneration system to fruit conservation in food industry. The evaluation of opportunities for low-grade heat recovery in the food processing industry reported great options for the use of organic Rankine cycles for electricity generation and ARPs integrated in a cogeneration system (Law, Harvey & Reay, 2013). Suamir, Tassou and Marriott (2012) evaluated the economic and environmental advantages, in addition to the efficiency of energy utilization using a micro-gas turbine in trigeneration systems for supermarket applications. According to Suamir and Tassou (2013), the food industry, both food manufacturing and retailing, has a need for heating and electrical power as well as refrigeration. For this reason, a way of increasing the efficiency of

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energy utilization is through trigeneration. Bassols, Kuckelkorn, Langreck, Schineider and Veelken (2002) presented examples of typical ARPs on different sectors in the food industry and highlighted the economic benefits of trigeneration in situation of low availability and high costs of electric energy, or when political incentives are given to achieve an efficient use of fossil energy by the introduction of cogeneration.

Based on the large potential for the use of cogeneration and trigeneration, Brazilian government has encouraged the use of such technologies to provide private investment incentive in these systems. An example is the public financing incentives available in the Brazilian Development Bank (BNDES), especially in projects qualified by the Incentive Program for Alternative Sources of Electric Energy (Proinfa), created to stimulate the electricity generation from renewable energy sources such as wind, biomass and hydric (Rendeiro, Macedo, Pinheiro, & Pinho, 2011; Pérez et al., 2015).

The exergetic efficiency compares an actual process to an ideal (reversible) process. Based on exergy analysis, Kumari and Sanjay (2015) proposed a trigeneration system using the conventional gas turbine cycle, as well as Açikkalp, Aras and Hepbasli (2014) applied the same methodology to analyze a trigeneration system using a diesel-gas engine and Al-Sulaiman, Dincer and Hamdullahpur (2012) presented energy and exergy analyses of a biomass trigeneration system using an organic Rankine cycle. Besides the different engines, other fuel sources like geothermal energy (Akrami, Chitsaz, Ghamari & Mahmoudi, 2017), hybrid system using biomass fuel and solar power (Karellas & Braimakis, 2016) and solid oxide fuel cell (Tippawan, Arpornwichanop & Dincer, 2015) reported exergy assessments of trigeneration systems.

The analysis of a trigeneration system using the exergetic potential can be performed based on the thermoeconomics (exergoeconomics). The methodology provides average costs based on specific exergy in thermal systems and is discussed in detail by Tsatsaronis (1993) and by Bejan, Tsatsaronis and Moran (1996). In parallel with Frangopoulos (1987), Lozano and Valero (1993) and Spakovsky (1994), these works stimulated the development to apply thermoeconomics systematically after the pioneering studies during the 1960s. The method is widely applied in different processes and systems (Balli, Aras & Hepbasli, 2010; Lozano, Carvalho & Serra, 2011; Kaviri, Jaafar & Lazim, 2012; Ghazi, Ahmadi, Sotoodeh & Taherkhani, 2012; Gungor, Erbay, & Hepbasli, 2012; Flórez-Orrego, Silva, & Oliveira Jr., 2014). Some recent works attempt to solve the major issues still considered opened on thermoeconomics, especially regarding the dissipative equipment, as valves and condensers (Agudelo, Valero & Torres, 2012; Piacentino & Talamo, 2013; Luo et al., 2014; Li, Chen, Sheng, & Li, 2016) .

The products generated in trigeneration (heat, cold and power) are different in their qualities. Therefore, the exergy is a suitable thermodynamic property for allocating cost in this system, because it accounts for quality of energy. The irreversibility of the process is related to the loss of resources, which have economic cost; since all process is irreversible, exergy is destroyed. Thus, identifying irreversibility on the system improves the cost of generated products (Lian et al., 2010; Tsatsaronis, Morosuk, Koch & Sorgenfrei, 2013; Ghaebi, Parikhani & Rostamzadeh, 2018).

There is next to nothing about trigeneration and thermoeconomics in the coffee industry reported in the literature. Higa, Yamamoto, Oliveira, and Conceição (2018) presented an application about power-cooling cogeneration system in coffee industry using exergy analysis and evaluating the implementation of Kalina cycle to an absorption refrigeration system. In that work, only the data of the cogeneration system including cooling and power were analyzed. In the present work, evaluations were made to the current thermal plant and compared with the proposed trigeneration system, including the ARP and one turbo-generator to generate 5100 kW of net power output.

Material and methods

Considerations

The conditions of the flows involved in the analyzed systems were calculated taking into account the heating and cooling of an industrial process of soluble coffee production used as case study. The current consumptions were remained constant for the analyses in the current and in the proposed trigeneration systems. In addition, it was considered that the system operates in steady state, while variations in kinetic and potential energy, heat losses to the environment, as well as pressure losses were considered negligible.

Energy equations

The thermal load for each soluble coffee process ($Q_{process}$) was calculated by Equation 1. The heat transfer is proportional to thermal energy contained on a steam flow ($m_{steam\text{-}process}$) until the condensation using the inlet and outlet enthalpies (h).

$$Q_{process} = m_{steam\text{-}process}\,(h_{in\text{-}steam} - h_{out\text{-}condensation})\ [\mathrm{kW}] \qquad (1) \tag{1}$$

The refrigeration capacity ($Qr_{efrigeration}$) is proportional to the sum of evaporation capacity of each evaporator ($Q_{evaporator}$), calculated using Equation 2.

$$\dot{Q}_{refrigeration} = \sum \dot{Q}_{evaporator} = \dot{m}_{ammonia}\left(h_{out} - h_{in}\right)\ [\mathrm{kW}] \qquad (2) \tag{2}$$

The thermal load of the soluble coffee processes ($Q_{process}$) and the refrigeration capacity ($Q_{refrigeration}$) are supplied by steam generation and its capacity (Q_{steam}) is obtained by Equation 3.

$$Q_{steam} = m_{steam}\,(h_{out} - h_{in})\ [\mathrm{kW}] \qquad (3) \tag{3}$$

The heat availability (Q_{fuel}) for steam generation that is supplied for the current thermal system and for power generation in the cogeneration system can be determined by using Equation 4 from the fuel consumption rates (m_{fuel}) and their lower heat values (LHV).

$$\dot{Q}_{fuel} = \sum\left(\dot{m}_{fuel} LHV\right)\ [\mathrm{kW}] \qquad (4) \tag{4}$$

Energy efficiency is an indicator for conversion of fuel to steam of the boiler (n_{SG}) or to the plant utilities ($n_{current\text{-}plan}$). In the current plant, the efficiencies were evaluated using Equation 5 and 6.

$$\eta_{SG} = \frac{\dot{Q}_{steam}}{\dot{Q}_{fuel}} \qquad (5)$$

(5)

$$\eta_{current-plant} = \frac{\sum \dot{Q}_{process} + \dot{Q}_{refrigeration}}{\dot{Q}_{fuel}}$$ (6)

(6)

The principle of conservation of energy applied to a control volume in the Equation 1 to 3 considers that there is not work, but the same principle applied for the turbine or pump, results in Equation 7.

$$W_{turbine/pump} = m_{steam\text{-}turbine/pump}\,(h_{in} - h_{out})\ [\mathrm{kW}]$$ (7)

(7)

For the trigeneration system, energy efficiency was evaluated adding the net power (W_{net}) in the numerator of the Equation 6 to result in the Equation 8.

$$\eta_{trigeneration} = \frac{\dot{W}_{net} + \sum \dot{Q}_{process} + \dot{Q}_{refrigeration}}{\dot{Q}_{fuel}}$$ (8)

(8)

Exergy equations

The exergy rate balance for a control volume is given by Equation 9.

$$\frac{dEx_{CV}}{dt} = \dot{E}x_Q - \left(\dot{W}_{CV} - p_0 \frac{dV_{CV}}{dt}\right) + \sum \dot{E}x_{f_{in}} - \sum \dot{E}x_{f_{out}} - \dot{E}d$$ (9)

(9)

where:

$\frac{dEx_{CV}}{dt}$ is the time rate of change of exergy in control volume,

$\dot{E}x_Q$ represents the time rate of exergy transfer accompanying the heat transfer,

$p_0 \frac{dV_{CV}}{dt}$ is the exergy transfer by the time rate of change of system volume,

$\dot{E}x_{f_{in}}$ and $\dot{E}x_{f_{out}}$ account for exergy transfer where mass enters and exits the control volume, respectively, and $\dot{E}d$ accounts for the time rate of exergy destruction due to irreversibilities within the system. The exergetic flow rates ($\dot{E}x_f$) for all streams of the system are related to the mass flow rates ($\dot{m}$) and specific exergies (e_x), according to Equation 10.

$$\dot{E}x_f = \sum(\dot{m}e_x)\ [\mathrm{kW}]$$ (10)

(10)

where:

The exergy includes physical and chemical exergies ($e_x = e_{x_{physical}} + e_{x_{chemical}}$). The physical exergy also includes thermomechanical, kinect and potential energy. Ignoring the effects of motion and gravity, the thermomechanical exergy is related to temperature (*T*), enthalpy (*h*), entropy (*s*), using the reference state (*0*), as given in Equation 11.

$$e_{x_{physical}} = h(T,p) - h_0(T_0,p_0) - T_0\left[s(T,p) - s_0(T_0,p_0)\right] \text{ [kJ kg}^{-1}\text{]} \qquad (11)$$

(11)

Using the chemical characteristics, the chemical exergy of the solid fuel was determined using Equation 12 and 13, presented by Szargut and Styrylska apud Kotas (1985) and based on the molar composition and the heating value. The ratio of chemical exergy (Equation 13) to the lower heating value (*LHV*) for solid and liquid industrial fuel is the same as for pure chemical substances having the same ratios of constituent chemicals (ϕ_{dry}).

$$\phi_{dry} = \frac{1.0438 + 0.1882\frac{h}{c} - 0.2509\left(1 + 0.7256\frac{h}{c} + 0.0383\frac{n}{c}\right)}{1 - 0.3035\frac{o}{c}} \qquad (12)$$

(12)

$$\phi_{dry} = \frac{e_{x_{solid-fuel}}}{(LHV)^0} \qquad (13)$$

(13)

where:

h, c, n, o and *s* are the mass fraction of H, C, N, O and S. Considering the moisture (*w*) in the fuel and the latent heat of water (h_{fg} = 2442 kJ kg^{-1}), the expression can be written by Equation 14.

$$e_{x.solid-fuel} = \left(LHV + wh_{fg}\right)\phi_{dry} + 9417s \text{ [kJ kg}^{-1}\text{]} \qquad (14)$$

(14)

For chemical exergies of the water and gas mixture, considered as ideal gas, the model and values of the standard chemical exergy ($e_{x.ch.i}$) of each combustion product (*i*) presented by Szargut, Morris, and Stewart apud Moran and Shapiro (2010) were applied using Equation 15.

$$e_{x_{chemical}} = \frac{\sum_i (y_i e_{x.ch.i}) + \bar{R}T_0 \sum_i (y_i \ln y_i)}{M_{gas}} \qquad (15)$$

(15)

where:

y_i is the mole fraction, while M_{gas} and $\bar{R}$ are the molecular weight and universal constant of the gas, respectively.

As well as indicators for energy conversion of the fuel to the steam generator and process, exergy efficiencies of the current plant and of the trigeneration system were evaluated using Equation 16 to 18.

$$\varepsilon_{SG} = \frac{\dot{E}x_{steam}}{\dot{E}x_{fuel}} \qquad (16)$$
(16)

$$\varepsilon_{current-plant} = \frac{\sum \dot{E}x_{process} + \dot{E}x_{refrigeration}}{\dot{E}x_{fuel}} \qquad (17)$$
(17)

$$\varepsilon_{trigeneration} = \frac{\dot{W}_{net} + \sum \dot{E}x_{process} + \dot{E}x_{refrigeration}}{\dot{E}x_{fuel}} \qquad (18)$$
(18)

Thermoeconomic analysis

The balance for the cost rate ($\dot{c}$) in each control volume was performed, associated to the calculated chemical and thermomechanical exergies. Besides the input costs, the output cost must also account for the capital investment (Z) according to the balance presented in Equation 19 t o 22.

$$\sum \dot{C}_{out} = \sum \dot{C}_{in} + \sum \dot{Z} [\text{US\$ hour}^{-1}] \qquad (19)$$
(19)

$$\dot{C} = c_{e_x} \dot{E}x \qquad (20)$$
(20)

$$\dot{Z}_{equipment} = CRF \frac{1.2 Z_{equipment}}{months \dfrac{hours\_year}{12}} \qquad (21)$$
(21)

$$CRF = \frac{i_{month}(1+i_{month})^{months}}{(1+i_{month})^{months} - 1} \qquad (22)$$
(22)

where:

CRF is the capital recovery factor. The feasibility for installing the trigeneration system was verified with 8000 hours year^{-1} of plant operation, as informed by the industry itself, and the interest rate (i) 7% per year applied by Brazilian Development Bank (BNDES) for cogeneration system projects, plus 0.9% of basic remuneration of the bank and 2.87% of credits risks were applied. The factor 1.2 over capital cost of the equipment was also adopted to consider the maintenance and operating costs.

The cost per unit of exergy (c) was determined for the cost of heating, cooling and electricity. The thermoeconomic balances were applied in the steam generator (Equation 23 and 24), turbine (Equation 25 and 26), valve (Equation 27) and in the absorption refrigeration plants - ARPs (Equation 28 and 29).

In the steam generator:

$$\dot{C}_{steam} + \dot{C}_{gas} = \dot{C}_{fuel} + \dot{C}_{air} + \dot{C}_{water} + \dot{Z}_{SG} \qquad (23)$$

(23)

As the air has no specific cost and the air enters in the environment temperature, this specific cost and exergy may also be considered null, and it does not generate cost rate $c_{air} = \dot{E}x_{air} = 0 \rightarrow \dot{C}_{air} = 0$. Adopting $c_{gas} = 0$ because the total gas cost was allocated in the steam generator itself, results:

$$c_{steam_{HP}} = \frac{c_{fuel}\dot{E}x_{fuel} + c_{water}\dot{E}x_{water}}{\dot{E}x_{steam_{HP}}} + \frac{\dot{Z}_{SG}}{\dot{E}x_{steam_{HP}}} \text{ [US\$ kWh}^{-1}\text{]} \qquad (24)$$

(24)

In the turbine:

$$\dot{C}_{power} + \dot{C}_{steam_{MP}} + \dot{C}_{steam_{LP}} = \dot{C}_{steam_{HP}} + \dot{Z}_{turbine} \qquad (25)$$

(25)

Considering that the specific cost of the high pressure (HP) is maintained by medium pressure (MP) and low pressure (LP) steam from the turbine, $c_{steam_{LP}} = c_{steam_{MP}} = c_{steam_{HP}}$, resulting in:

$$c_{power} = \frac{c_{steam_{HP}}\left(\dot{E}x_{steam_{HP}} - \dot{E}x_{steam_{MP}} - \dot{E}x_{steam_{LP}}\right)}{\dot{W}_{turbine}} + \frac{\dot{Z}_{turbine}}{\dot{W}_{turbine}} \qquad (26)$$

(26)

In the pressure reducing valves:

$$c_{steam-valve_{LP}} = \frac{c_{steam_{HP}}\dot{E}x_{steam_{HP}}}{\dot{E}x_{steam_{LP}}} \qquad (27)$$

(27)

The absorption refrigeration plants (ARPs) is a very complex system, including desorber, absorber, regenerator, valves, pump, evaporator and condenser. In this work, the system was considered as unique and simplified using Equation 28 and 29.

$$\dot{C}_{steam-valve_{10bar}} + \dot{C}_{pump_{ARP}} = \dot{C}_{condensed-water} + \dot{C}_{refrigeration} + \dot{Z}_{ARP} \qquad (28)$$

(28)

$$c_{refrigeration} = \frac{c_{steam-valve_{10bar}}\dot{E}x_{steam-valve_{10bar}} + c_{power}\dot{W}_{pump_{ARP}}}{\dot{E}x_{refrigeration}} \qquad (29)$$

(29)

where:

The waste cost generated in the ARP condenser is internalized in the own ARP subsystem.

For pump and mixing units, the cost rate balances may be solved without the need for auxiliary relations, resulting in the pump, according Equation 30:

$$c_{output} = \frac{c_{input}\dot{E}x_{input} + c_{power}\dot{W}_{pump}}{\dot{E}x_{output}} \quad (30)$$

(30)

In the mixing unit, as desuperheater, deaerator or junction, according Equation 31:

$$c_{output} = \frac{\sum c_{input}\dot{E}x_{input}}{\sum \dot{E}x_{output}} \quad (31)$$

(31)

Case study

An industrial plant, based in Brazil and processing soluble coffee, was used as a case study. The energy, exergy and economic performances of the current thermal system were compared with the performances of the proposed trigeneration system.

The current thermal system (Figure 1) generates steam as utility for refrigeration in an ammonia/water absorption plant (ARP) and for heating in the production process as drying, concentrations and extractions operations. The biomass boiler generates saturated steam at 2100 kPa. Except a part used in the de-aerator, all the steam generated flows through a pressure reducing valve (PRV) that directs steam at 1500 kPa to two secondary streams for the soluble coffee manufacturing. One stream, 34% of the generated steam, goes to a reducing valve before the ARP consuming steam at 1000 kPa. The second stream is directed to drying, concentrations and extractions operations. The most of these operations use other reducing valves (PRVs) before the consumption points, depending on the steam pressure levels. About 70% of the condensate returns to the boiler and the biomass used as fuel consists of firewood and some residues of coffee grounds.

Figure 2 provides the proposal to a trigeneration system with the employment of a steam turbine for electricity generation. The purpose is to integrate 5300 kW of power generation using extraction-condensing turbine to replace the main PRV, reducing pressure from 2100 to 1500 kPa in the current system. The turbine operates in two stages and the extraction of steam occurs at 1500 kPa, according to the process demand and the surplus continues to be used in the turbine until the condensation. The same consumption conditions of the current system for soluble coffee production process and ARPs were maintained. The net power output is 5100 kW after deducting the power consumptions of the pumps, such generation is enough to supply the current demand of around 5 MW of the plant.

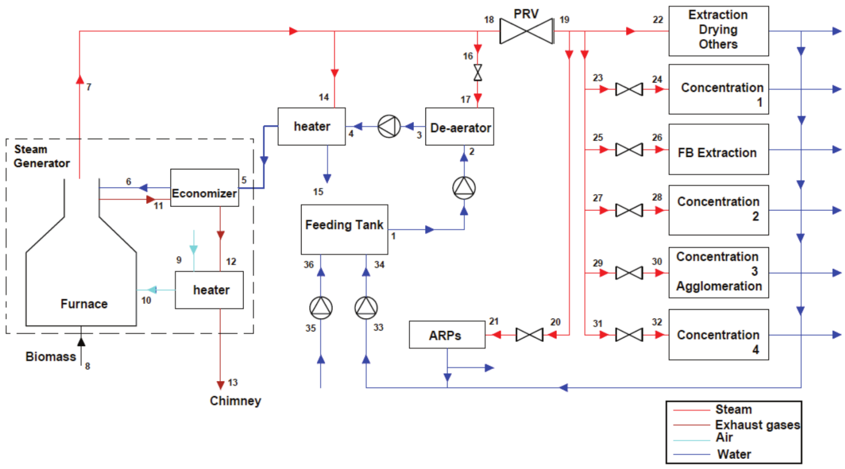

FIGURE 1.
Current thermal system.

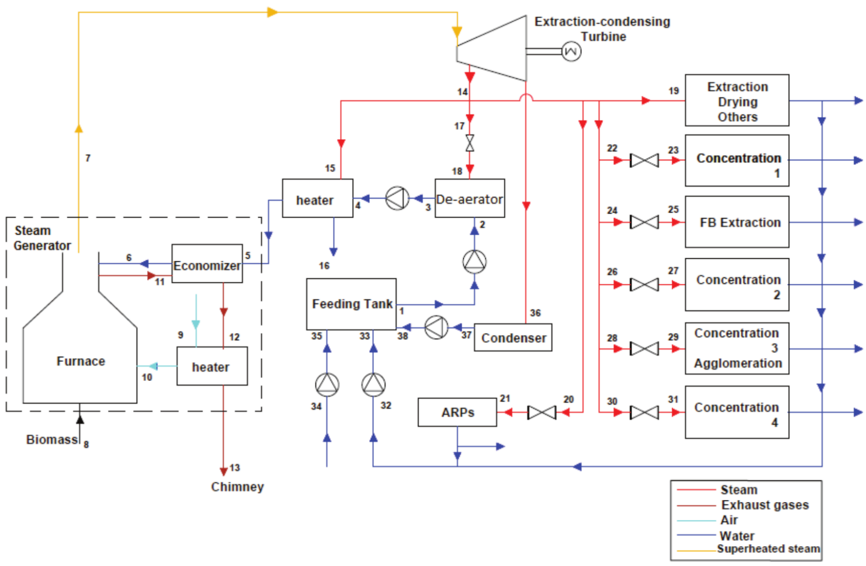

FIGURE 2.
Trigeneration system.

Parameters of systems components

The operating parameters of the steam generator in the current system and in the proposed system are presented in Table 1 and more detailed data are in Appendix 1. For the implementation of the trigeneration system, the plan is to use the same boiler in operation, reducing the required investment costs, because the equipment was already been purchased previously in order to integrate the power generation system. Anyway, a superheater should be placed in the current boiler in order to generate superheated instead saturated steam. Besides, the steam flow should use total capacity of the steam generator. These higher levels of the parameters also increase the firewood consumption.

The chemical composition and other fuel data are shown in Table 2 and in Appendix 2. The residue of the production process, the coffee grounds are free of charge. The moisture (w) of the biomass used is high, which reduces the combustion efficiency.

Operating parameters from the two ARPs ammonia/water for the process of freeze-drying coffee are shown in Table 3. The reliability and low maintenance using steam as the source of thermal energy were decisive for the industry choice of these systems in the process. These systems operate with low coefficient of performance (COP) compared to compression refrigeration systems (Colorado & Rivera, 2015; Mohammadi & Ameri, 2016).

As mentioned, there is no change prediction of the steam demands in the production process and in the ARPs. Table 4 shows the pressure drop in the PRVs and the steam flow in order to meet the unit operations in soluble coffee processing, while Table 5 shows operation data of the 5200 kW extraction-condensing turbo-generator. The turbine works with isentropic efficiency of 85%.

Table 6 contains the necessary investments to buy and install the turbo-generator, besides the costs to retrofit and include the superheater in the steam generator. The data were provided by the industrial plant processing soluble coffee of the case study.

Results and discussion

Energetic and exergetic analyses

The energetic and exergetic analyses were applied for the current and trigeneration systems. Thus, it was possible to determine the thermal load in the process, refrigeration capacity, besides the heat availability and fuel consumption from the steam generator. Exergetic analysis was either applied to verify the potential that could be converted into power and the amount of exergy destroyed due to irreversibility (Figure 3).

TABLE 1.
Operating parameters of steam generator.

Parameter	Current system	Trigeneration	Unit
Steam pressure	2100	4200	[kPa]
Steam temperature	215	410	[°C]
Feed water temperature	110	110	[°C]
Steam flow	37	46.3	[t hour^{-1}]
Coffee grounds consumption	1.47	1.47	[t hour^{-1}]
Firewood consumption	12.27	16.95	[t hour^{-1}]

TABLE 2.
Parameters of fuel.

Fuel	LHV [kJ kg^{-1}]	Price [US$ ton^{-1}]	C [%]	H [%]	O [%]	N [%]	*w* [%]
Coffee grounds	5995.5	-	48.5	9.6	35.8	-	60
Firewood[1]	9097.9	32.81	47	6	44	-	45

Source 1: Vlassov (2001).

TABLE 3.
Operating parameters of absorption refrigeration plants.

Parameter	Value	Unit
Steam consumption	13.73	[t hour^{-1}]
Evaporation temperature	-50 to -60	[°C]
Cooling capacity	3652.4	[kW]
COP	0.471	-
Heat consumption	7740	[kW]
Steam pressure	1000	[kPa]

TABLE 4.
Operating parameters of each process for soluble coffee production.

Process	Input pressure [kPa]	Output pressure [kPa]	$m_{steam\text{-}process}$ [t hour^{-1}]
Extraction	2100	1500	8.29
Drying	2100	1500	5.00
Others	2100	1500	1.29
Concentration 1	1500	1000	0.53
FB extraction	1500	900	0.21
Concentration 2	1500	850	2.70
Concentration 3	1500	800	1.26
Agglomeration	1500	800	0.30
Concentration 4	1500	600	2.69

TABLE 5.
Turbine operating data1.

Parameter	Value	Unit
Inlet pressure	4200	[kPa]
Inlet temperature	410	[°C]
Inlet steam flow	45.26	[t hour^{-1}]
Extraction pressure	1500	[kPa]
Extraction flow	34.42	[t hour^{-1}]
Outlet pressure	12	[kPa]
Outlet flow	11.84	[t hour^{-1}]

1: Impulse turbine: TGM TMC 5001.

TABLE 6.
Equipment investment costs.

Equipment	Costs [US$]
Steam generator	284 610.00
Turbo-generator	1 265 053.00
Electric generator, systems and instrumentation	1 590 588.00
Piping, engineering services and others	1 879 842.00
Total [US$]	5 020 093.00

The chemical exergies of fuel were determined using Equation 12 to 14 and chemical composition data (Table 2). The exergy destruction of combustion ($Ed_{combustion}$) refers to the difference between the fuel and combustion gases exergies, while the exergy destruction of the steam generator (Ed_{SG}) refers to the difference between the combustion gases and steam exergies, besides other losses as exhaust gases, bottom outlets and soot. Other exergy destructions (Ed_{others}) are related to pressure reducing valves, de-aerators, economizers and air pre-heaters, including the turbine that is also included in the proposed system. The exergy destructions in the coffee processing are not considered in this work.

Energetic and exergetic efficiency

The final results for energetic (η_{SG}) and exergetic (ε_{SG}) efficiencies of the steam generator and for global plant (η_{plant}, ε_{plant}) are described in Table 7.

Despite the irreversibilities intrinsic to the combustion process, a way to reduce the thermodynamic inefficiency in the steam generator may be obtained by increasing the steam pressure and temperature. So that, the steam generator efficiencies increase mainly due to the increases of the steam pressure and temperature. In the case of global plant, exergetic efficiency tends to increase as a function of the power of generation, since the process exergy remains the same. For the energetic efficiency, the value of the trigeneration system is lower than that of compared with the current index. This follows because this system is of condensing turbine and the low pressure steam at 12 kPa is not used in the process during the condensation.

Thermoeconomic evaluation

The costs per exergy unit were utilized to determine the cost steam for heating process, refrigeration and electricity for the current plant and for the trigeneration system (Table 8).

For trigeneration system, the costs were analyzed for the payback period, when all capital investments are included in the thermoeconomic balances, and for the period after the payback, considering that these initial investments were returned. It was observed that all costs were reduced in the trigeneration system, even during the payback period. In relation to the fuel, the cost per exergy unit had a small increase, because the proportion of coffee grounds used as fuel decreases when the total cost consumption increases. The payback was determined when the electric power costs generated become equal to or less than that provided by the Paraná state electricity concessionaire (Copel), that is US$ 148.5 MWh^{-1} on localization where the plant is installed. The payback period for the investment was 24 months.

The biggest impact of the integration of the power generation in the trigeneration compared to the current system is the 72% reduction in the cost of electricity. These costs depend mainly on the fuel price, the investment capital, the electricity cost and also of exergetic efficiencies. Thus, one way to reduce costs is by reducing the irreversibilities. The results either point to the necessity of a strategic review on the better integration of the ARPs because the cost per unit of exergy in the refrigeration became higher than electricity after payback. A compression system in the plant using electric power instead heating in ARPs presents higher COP. A detailed analysis could bring better comparison between these systems integrating ARPs or compression cycle.

Figure 4 shows the impact of fuel price on the costs per unit of exergy of the products after payback period. If fuel price reaches US$ 116.50 ton-1 (US$ 35.06 MWh^{-1}), then the integration of trigeneration system will become unviable, because the cost of generated electricity will be higher than COPEL cost (US$ 148.5 MWh^{-1}). The impact of fuel price on payback period is presented using the figure (Appendix 3).

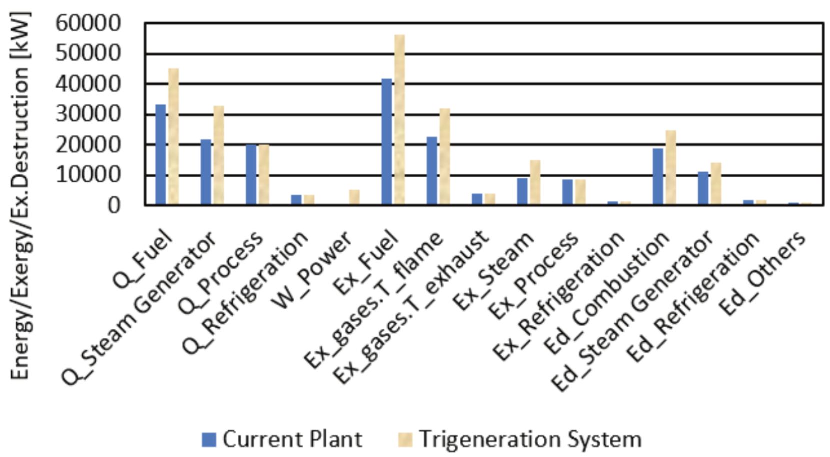

FIGURE 3.
Energy, exergy and exergetic destruction in the current and trigeneration systems.

TABLE 7.
Energetic and exergetic efficiencies.

Parameter	Current	Trigeneration
n_{SG}	0.717	0.786
ε_{SG}	0.215	0.266
n_{plant}	0.712	0.640
ε_{plant}	0.235	0.264

TABLE 8.
Costs per exergy unit.

Cost	Current [US\$ MWh^{-1}]	Payback period [US\$ MWh^{-1}]	After payback [US\$ MWh^{-1}]
Fuel	9.67	9.87	9.87
High-pressure steam	44.36	39.67	36.89
Process	48.58	41.40	38.50
Refrigeration	120.2	102.90	91.50
Power	148.50[1]	146.00	41.85

1 From concessionaire of the electric energy of Paraná (Copel).

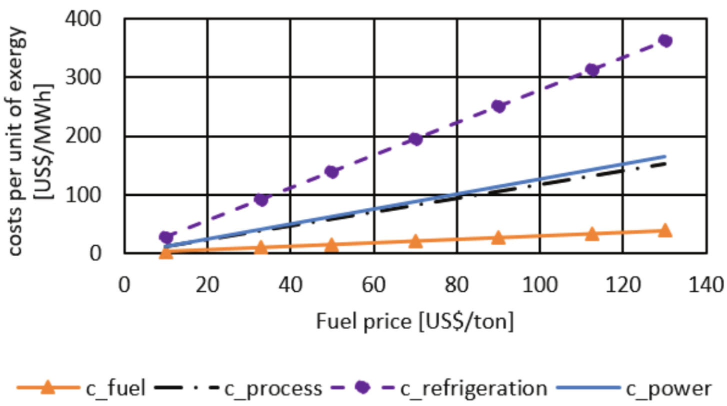

FIGURE 4.
Impact of fuel price on costs per unit of exergy.

Conclusion

The trigeneration proposal integrates one turbo-generator into the current system to generate 5100 kW of net power. There was a decrease in the energy efficiency for global plant (η_{plant}) compared to the current system. However, the increment of the power generation produced in the proposed system results in an increase of the exergy efficiency (ε_{plant}), what emphasizes the importance of exergetic analysis. The payback period for the investment is 24 months. The costs per unit of exergy for all products of the system are reduced. The biggest impact of the trigeneration is the 72% reduction in the cost of electricity.

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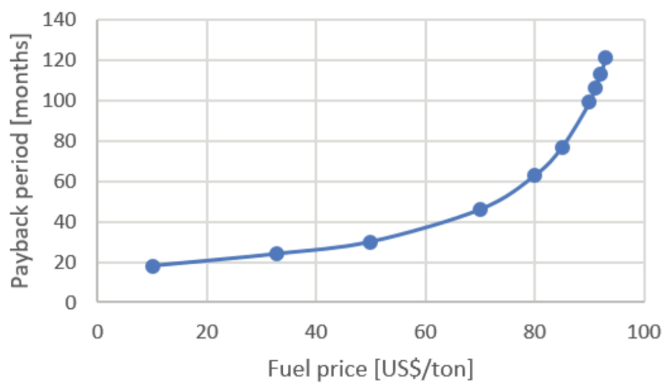
Stream	P [kPa]	T [°C]	$\dot{m}$ [t hour^{-1}]	h [kJ kg^{-1}]	s [kJ kg.K^{-1}]	$\dot{E}x$ [kW]
1	140	98	40.2	410.7	1.284	362.6
2	350	98.1	40.2	411.2	1.285	365.8
3	350	105	40.7	440.4	1.363	437.7
4	2100	105.4	40.7	443.4	1.366	461.4
5	2100	110	40.7	462.8	1.417	509
6	2100	156.5	40.7	661.4	1.906	1106
7	2100	215	37.0	2800	6.322	9448
8	100	25	13.74	-	-	41650
9	100	35	70.62	308.6	5.733	3.06
10	100	96	70.62	370.1	5.915	144.7
11	100	416	83.82	-	-	5506
12	100	336	83.82	-	-	4297
13	100	293	83.82	-	-	3702
14	2100	215	0.42	2800	6.322	107.1
15	140	109.3	0.42	844.9	1.411	47.7
16	2100	215	0.50	2800	6.322	126.9
17	350	170.1	0.50	2800	7.099	95.0
18	2100	215	36.04	2800	6.322	9214
19	1500	201,4	36.04	2800	6.462	8798
20	1500	201,4	13.73	2800	6.462	4022
21	1000	188,8	13.73	2800	6.635	3155
22	1500	201,4	14.62	2800	6.462	3569
23	1500	201,4	0.53	2800	6.462	130.1
24	1000	188,8	0.53	2800	6.635	122.4
25	1500	201,4	0.21	2800	6.462	50.9
26	900	186,1	0.21	2800	6.68	47.13
27	1500	201,4	2.70	2800	6.462	659.2
28	850	184,7	2.70	2800	6.705	604.8
29	1500	201,4	1.56	2800	6.462	380.7
30	800	183,3	1.56	2800	6.732	345.9
31	1500	201,4	2.69	2800	6.462	657
32	600	177,6	2.69	2800	6.858	568.7
33	120	104,8	29.3	439.3	1.361	311.8
34	140	104,8	29.3	439.4	1.361	312
35	100	74	10.5	309.8	1.003	44.5
36	140	74	10.5	309.9	1.004	44.7

APPENDIX 1.
Data of the current thermal system.

Stream	P [kPa]	T [°C]	$\dot{m}$ [t hour^{-1}]	h [kJ kg^{-1}]	s [kJ kg.K^{-1}]	$\dot{E}x$ [kW]
1	140	87.7	48.62	367.3	1.166	329.9
2	350	87.8	48.62	367.9	1.167	333.6
3	350	105	50	440.4	1.363	537.8
4	4200	105.9	50	447.1	1.37	601.7
5	4200	110	50	464.3	1.415	653.9
6	4200	156.5	50	662.6	1.904	1387
7	4200	410	46.26	3234	6.777	15657
8	100	25	18.41	-	-	56315
9	100	35	94.73	308.6	5.733	4.10
10	100	140	94.73	414.6	6.078	473.6
11	100	371	112.4	-	-	6433
12	100	296	112.4	-	-	5016
13	100	219	112.4	-	-	3796
14	1500	283.8	34.42	3001	6.852	9208
15	1500	283.8	0.40	3001	6.852	106.9
16	140	109.3	0.40	844.9	1.411	47.6
17	1500	283.8	1.34	3001	6.853	368.3
18	350	267.2	1.34	3001	7.508	293.5
19	1500	283.8	13.22	3001	6.853	3537
20	1500	283.8	12.45	3001	6.853	3330
21	1000	276.8	12.45	3001	7.033	3144
22	1500	283.8	0.48	3001	6.853	129.2
23	1000	276.8	0.48	3001	7.033	122.0
Stream	P [kPa]	T [°C]	$\dot{m}$ [t hour^{-1}]	h [kJ kg^{-1}]	s [kJ kg.K^{-1}]	$\dot{E}x$ [kW]
24	1500	283.8	0.19	3001	6.853	50.58
25	900	275.4	0.19	3001	7.08	47.01
26	1500	283.8	2.45	3001	6.853	655.0
27	850	274.7	2.45	3001	7.106	603.6
28	1500	283.8	1.41	3001	6.853	378.3
29	800	273.9	1.41	3001	7.133	345.5
30	1500	283.8	2.44	3001	6.853	652.8
31	600	271	2.44	3001	7.263	569.9
32	120	104,8	29.3	439.3	1.361	311.8
33	140	104,8	29.3	439.4	1.361	312
34	100	74	7.1	309.8	1.003	30.12
35	140	74	7.1	309.9	1.004	30.21
36	11.99	49.4	11.84	2328	7.273	544
37	11.99	49.4	11.84	206.9	0.6961	12.91
38	140	49.4	11.84	207.1	0.6963	13.35

APPENDIX 2.
Data of the trigeneration thermal system.



APPENDIX 3.
Impact of the fuel price on the payback.

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