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THERMOECONOMIC ANALYSIS IN COGENERATION SYSTEMS INTEGRATED IN FOOD PROCESSING INDUSTRY

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Abstract. *Food processing industry usually requires large amounts of thermal energy and is an energy-intensive industry. The most commonly thermal demand involves different operations such as heating, drying, evaporation, refrigeration and freezing. Considering the energy crisis in Brazil and the large thermal demand, it is essential to study alternatives for reaching efficient energy utilization in order to reduce processing costs. An alternative that has been shown promising to improve the thermal efficiency of the food industrial plants refers to implement cogeneration systems. The objective of this work was to evaluate the technical and economic viability of cogeneration systems in three case studies. Sugar, coffee and soy industrial plants were selected and evaluated using energetic, exergetic and thermoeconomic analysis. Based on this evaluation, it is possible to verify that the cogeneration cycle is technically viable in all the 3 cases, but the advantage of this integration depends on the retrofit level, scale industry, heat demand of the process and fuel and electric power prices, resulting in different investment return.*

Keywords: *Cogeneration, thermoeconomy, exergy, food industry.*

1. INTRODUCTION

The cogeneration systems are an alternative to reduce operating costs and improve energy performance in food processing industry (Freschi *et al.*, 2013; Law *et al.*, 2012; Aneke *et al.*, 2011; Tassou *et al.*, 2007). Cogeneration is the simultaneous production of heat and power from a single fuel source.

An exergetic analysis and an economic analysis combined and conducted at the level of the plant components consist of an exergoeconomic or thermoeconomic analysis. According to Valero *et al.* (1994a), special effort to apply thermoeconomics systematically to the analysis of energy systems has taken place only after 1980s and 1990s. Valero *et al.* (1994b) formulated the fundamentals and criteria that enable the description of the cost formation process and the assessment of the efficiency in energy systems using "The theory of exergetic cost" (Lozano and Valero, 1993) based on the use of the Second Law of Thermodynamics through a systematic use of the exergy concept. The fuel-product concept based on the productive purpose of a component within an energy system and the mathematical formalization provided by systems theory are the cornerstones of this theory. For the same problem, Tsatsaronis and Piza (1994) discussed various exergy costing approaches, the exergoeconomic variables and the procedures used in evaluating and optimizing energy systems.

In recent years, the thermoeconomics is still being used in other studies, mainly because of the environmental impacts and of the legal obligation to reduce emissions, which leads the companies and businesses to use energy more efficiently in different systems and to use advanced exergetic or exergoenvironmental analyses (Petrakopoulou *et al.*, 2014; Christidis *et al.*, 2012; Morosuk *et al.*, 2012 and Serra *et al.*, 2009).

2. METHODOLOGY

The analysis of cogeneration systems using the exergetic potential in this current study is based on the thermoeconomics (exergoeconomics). The specific exergy costing (Speco) is a cost accounting methodology that provides average costs. The Speco method is widely accepted by the researchers, and, therefore, it is selected in this study (Ghazi *et al.*, 2012; Lazzaretto and Tsatsaronis, 2006; Bejan *et al.*, 1996).

2.1 Description

The purpose of the current study is to perform a thermoeconomic analysis of cogeneration systems in coffee (COFP), soy (SOYP) and sugar (SUGP) industrial plants. In this analysis, the 1st and 2nd Laws of Thermodynamics are employed, using the mass, energy, exergy and economic balances of the proposed systems.

The analysis was based on the current steam process consumptions in these industrial plants. The feasibility of installing the cogeneration systems were verified with 8000 hours/year of plant operation in a continuous and steady-state process. Using the chemical characteristics, the chemical exergy of the fuel and thermomechanical exergies of the gases and water were calculated. This is also true for the exergy destruction rates and thermoeconomical costs related to the irrreversibilities in the processes.

The main exergetic losses occur during the combustion reaction, the steam generation and flowing through the existent throating valves, besides the power generation for the integrated cogeneration systems. The costs from the capital investments were combined with the flows of exergy, resulting in the exergetic costs of the high pressure steam and of the process steam (utility) for the current systems and also for the integrated cogeneration systems.

2.2 Mathematical equations

The heat availability ($\dot{Q}_{fuel}$) for steam generation that is available for power generation can be determined by using Eq. (1) from the fuel consumption rates ($\dot{m}_{fuel}$) and their lower heat values (*LHV*).

$$\dot{Q}_{fuel} = \sum\left(\dot{m}_{fuel}\, LHV\right) \quad \text{[kW]} \tag{1}$$

The steam generation capacity ($\dot{Q}_{steam}$) is obtained by Eq. (2).

$$\dot{Q}_{steam} = \dot{m}_{steam}(h_{out} - h_{in}) \quad \text{[kW]} \tag{2}$$

Equation (2) applied to the steam generator, as well as Eq. (3) applied to the turbine, are simplifications of the principle of conservation of energy applied to a control volume at steady state and considering that the change in potential energy from inlet to exit can be neglected.

$$\dot{W}_{turbine} = \dot{m}_{steam}(h_{in} - h_{out}) \quad \text{[kW]} \tag{3}$$

The exergy rate balance for a control volume is given by Eq. (4).

$$\frac{dE_{x.CV}}{dt} = \dot{E}_{x.Q} - (\dot{W}_{CV} - p_0\frac{dV_{CV}}{dt}) + \dot{E}_{xf.in} - \dot{E}_{xf.out} - \dot{E}_d \tag{4}$$

where $dE_{x.CV}/dt$ 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 time rate of energy transfer by work time rate of change of system volume,. $\dot{E}xf_{in}$ and $\dot{E}xf_{out}$ 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 $(\dot{E}_{xf})$ for all streams of the system are related to the mass rates $(\dot{m})$ and specific exergies (e_x), according to Eq. (5).

$$\dot{E}_{xf} = \sum\left(\dot{m}.e_x\right) \quad \text{[kW]} \tag{5}$$

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 the by temperature (T), enthalpy (h), entropy (s) and to the environment conditions (T_0, P_0), as given in Eq. (6).

$$e_{x.physical} = h(T) - h_0 - T_0[s(T) - s_0] \text{ [kJ/kg]} \tag{6}$$

For solid fuel, the exergy was determined using Eq. (7) and (8), presented by Szargut and Styrylska *apud* Kotas (1985) and based on the molar composition and the heating value. The ratio of chemical exergy to the lower heating value (LHV) for solid industrial fuel is the same as for pure chemical substances having the same ratios of constituent chemicals (φ).

$$\varphi_{dry} = \frac{1.0438 + 0.1882\frac{h}{c} - 0.2509(1 + 0.7256\frac{h}{c} + 0.0383\frac{n}{c}}{1 - 0.3035\frac{o}{c}} \tag{7}$$

$$\varphi_{dry} = \frac{e_{x \cdot solid-fuel}}{(LHV)^0} \tag{8}$$

Considering the moisture (w) in the fuel, the expression ca be written by Eq. (9).

$$e_{x.solid-fuel} = (LHV + w.h_{fg})\varphi_{dry} + 9417s \text{ [kJ/kg]} \tag{9}$$

where h, c, n, o, and s are the mass fraction of H, C, N, O and S and h_{fg} is the latent heat of water ($h_{fg} = 2442$ kJ/kg). The energetic and exergetic efficiencies of the steam generator (*SG*) and of the global plant can be determined by Eq. (10)-(13).

$$\eta_{ST} = \frac{\dot{Q}_{steam}}{\dot{Q}_{fuel}} \tag{10}$$

$$\varepsilon_{ST} = \frac{\dot{E}x_{steam}}{\dot{E}x_{fuel}} \tag{11}$$

$$\eta_{plant} = \frac{\dot{W}_{turbine} + \dot{Q}_{process}}{\dot{Q}_{fuel}} \tag{12}$$

$$\varepsilon_{plant} = \frac{\dot{W}_{turbine} + \dot{E}x_{process}}{\dot{E}x_{fuel}} \tag{13}$$

The payback period was obtained when the equivalent expenses ($expense_{month}$) from the electric power to be produced over the period (*months*), also considering the interest rates (j), became equal to the investment (Eq. 14 and 15).

$$\sum(Z_{equipment}) = \frac{months * e.xpense_{month}}{(1+j)^{months!}} \tag{14}$$

$$e.xpense_{month} = c_{e_x\,power}\,\dot{W}_{net}\,\frac{hours\_year}{12} \tag{15}$$

In addition to the calculated chemical and thermomechanical exergies and using the payback period, the balance for the cost rate in each control volume was performed. Besides the input costs, the output cost must also account for the capital investment according to the balance presented in Eq. (16).

$$\sum \dot{C}_{out} = \sum \dot{C}_{in} + \sum \dot{Z} \quad \text{[R\$/s]} \tag{16}$$

$$\dot{C} = c_{e_x} \dot{E}_x$$

$$\dot{Z}_{\text{equipment}} = \frac{Z_{\text{equipment}}}{months \dfrac{hours\_year}{12}}$$

Using the described equation, the exergetic costs were determined (c_{e_x}) for the steam generator (Eq. 17), turbine (Eq. 18) and valve (Eq. 19). In the steam generator:

$$\dot{C}_{\text{steam}} + \dot{C}_{\text{gas}} = \dot{C}_{\text{fuel}} + \dot{C}_{\text{air}} + \dot{C}_{\text{water}} + \dot{Z}_{\text{SG}} \tag{17a}$$

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 combustion products are discharged directly to the surroundings with negligible cost, results:

$$c_{\text{steam-HP}} = \frac{c_{water}\,\dot{E}x_{\text{water}}}{\dot{E}x_{\text{steam-HP}}} + \frac{c_{fuel}\,\dot{E}x_{\text{fuel}}}{\dot{E}x_{\text{steam-HP}}} + \frac{\dot{Z}_{\text{SG}}}{\dot{E}x_{\text{steam-HP}}} \tag{17b}$$

In the turbine:

$$\dot{C}_{power} + \dot{C}_{steam\text{-}MP} + \dot{C}_{steam\text{-}LP} = \dot{C}_{steam\text{-}HP} + \dot{Z}_{turbine} \tag{18b}$$

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

$$c_{power} = \frac{c_{steam}\left|\dot{E}x_{steam\text{-}HP} - \dot{E}x_{steam\text{-}MP} - \dot{E}x_{steam\text{-}LP}\right|}{\dot{W}_{turbine}} + \frac{\dot{Z}_{turbine}}{\dot{W}_{turbine}} \tag{18b}$$

In the throating valve:

$$c_{steam-valve-LH} = \frac{(c\dot{E}x)_{steam-HP}}{\dot{E}x_{steam-valve-LP}} \tag{19}$$

3. CASE STUDIES

Coffee (COFP) and sugar (SUGP) industrial plants located in Paraná state and soy plant (SOYP) located in Minas Gerais state were selected and evaluated using thermoeconomic analysis. Figure 1 refers to a generic configuration of the systems. COFP and SOYP have only one steam generator (SG) producing saturated vapor, while SUGP has 3 units producing superheated vapor. In the current SOYP, the steam is conducted straight to the process after the generation, while in the COFP the steam goes through throating valve decreasing the initial pressure before goes to process. In the current SUGP, most of steam goes through the 2 turbo-generators (10 MW and 20 MW) producing electric power and after goes to process in a cogeneration system, but there is part of the steam that goes through throating valve.

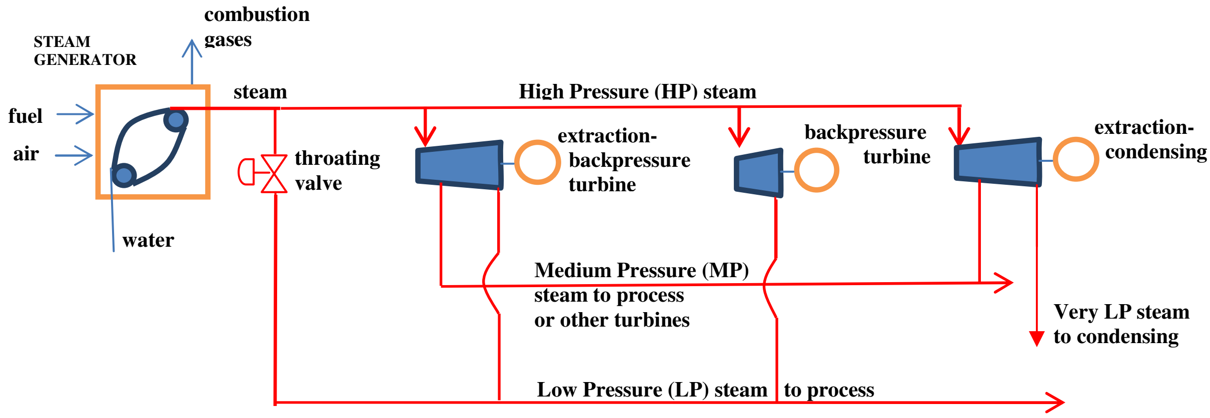

Figure 1. Generic cogeneration systems.

Table 1 contains the data for the steam generators in the current industrial plants and in the proposed cogeneration projects, besides the process consumption data. Both in the COFP and in the SOYP are proposed to increase the pressure and temperature from saturated state to superheated vapor. In the case of COFP, the flow of steam production also increases. In the SUGP, the steam is already generated in superheated conditions for cogeneration using three existing boilers and keeps the initial conditions. In the process, the demands with medium (MP) and low pressure (LP) steam were maintained under the same initial conditions. In the case of SUGP the MP steam demand refers to the vapor utilization in medium pressure turbo-millings (2200 kPa) before being used in the process.

Table 1. Steam generator properties at initial and cogeneration condition.

	COFP		SOYP		SUGP
	current	cogen	current	cogen	current/cogen
P_{steam} (kPa)	2100	4200	1000	6600	4300
T_{steam} (C)	215	410	180	480	400
T_{water} (C)	110	110	110	110	105
m_{steam} (t/h)	40.7	50	38.4	38.6	429.2
m_{fuel} (t/h)	1.47(1) + 12.26	1.47(1) + 16.92	11.74	12.52	207.3
$P_{m,process}$ (kPa)	1500	1500	1000	1000	2200
$m_{MP,process}$ (t/h)	36.0	36.0	34.52	34.52	72.2
$P_{LP,process}$ (kPa)	-	12	-	-	250
$m_{LP,process}$ (t/h)	-	-	-	-	399.2

(1) coffee grounds consumption

The COFP uses 1.47 t/h of coffee grounds of production as an additional fuel. As there are no process changes, this consumption keeps the same in the current and cogeneration systems (Tab. 1). The fuel used in SUGP is the bagasse, while in the COFP and SOYP is firewood, differing in moisture (w), which is greater in the COFP (Tab. 2). The fuel prices differ due to moisture and also to the localization, Paraná and Minas Gerais states.

Table 2. Fuel composition.

plant	fuel	LHV (kJ/kg)	price (R$/t)	c	h	o	n	w
coffee	firewood	9098	105,00	47	6	44	-	45
	coffee grounds	5996	-	48,5	9,6	35,8	-	60
soy	firewood	9755	145,00	49,7	5,8	42,3	1,4	40
sugar	bagasse	7434	120,00	49,5	6,2	44,3	-	50,1

The studies are based on the industry proposals to integrate 4.5 MW of power generation using extraction-condensing turbine to replace the main throating valve in the COFP and of 4.2 MW using backpressure (noncondensing) turbine in the SOYP (Tab. 3). In SUGP, the proposal is replace a throating valve for a new extraction-backpressure turbine of 11.5 MW. For that, it is necessary to buy and install the new turbo-generators in all plants and to retrofit the steam generator only in COFP and SOYP, using the current generators in SUGP under the same conditions.

Table 3. Turbogenerator data

	COFP	SOYP	SUGP
P_{in} (kPa)	4200	6600	4300
T_{in} (℃)	410	480	400
m_{in} (t/h)	45.35	35.77	127
$P_{extracion}$ (kPa)	1500	-	2200
$m_{extracion}$ (t/h)	37.0	-	72.2
P_{out} (kPa)	12	1000	250
m_{out} (t/h)	8.39	35.77	54.8
$W_{turbine}$ (kW)	4503	4200	11527
η_s	0.85	0.84	0.88

As previously mentioned, in SUGP there are already two turbo-generators and the proposed turbo-generator is to replace a throating valve, which reduces the pressure of 4300 to 2200 kPa without taking advantage of the HP steam exergy. Therefore, investment costs (Tab. 4) are lowest for the SUGP and similar in the COFP and SOYP. The investments in the adaptation of steam generator in the COFP are lower than SOYP because it has already been purchased previously predicting a future integration of the cogeneration system.

Table 4. Equipment investment costs

	Equipment investment costs (R$)		
	COFP	SOYP	SUGP
steam generator	910 750.50	2 500 000.00	-
turbogenerator	3 167 019.00	3 040 000.00	4 250 000.00
electric generator, systems and instrumentation	5 089 882.50	3 917 000.00	2 517 000.00
piping, engineering services and others	6 015 495.00	4 650 000.00	250 000.00
total (R$)	15 183 147.00	14 107 000.00	7 017 000.00

4. RESULTS AND DISCUSSIONS

Based on the mentioned data and considering the environment conditions (*T_0=273 K, P_0=100 kPa*), it was possible to determine the exergies and exergy destructions (Tab. 5).

Table 5. Exergy and exergetic destruction.

	COFP		SOYP		SUGP	
	current	cogen	current	cogen	current	cogen
ex_{fuel} (kJ/kg)	7636[1] 11305	7636[1] 11305	11504	11504	9433	9433
Exe_{fuel} (kW)	3118[1] + 38509	3118[1] + 53197	37515	39996	543228	543228
Exe_{a} (kW)	10406	16924	8751	13496	143928	143928
$Exe_{process}$ (kW)	8412	9229	7858	7858	68865	68865
$Ed_{combustion}$ (kW)	20568	26736	19175	20443	308015	308015
Ed_{SG}(kW)	9134	11728	8106	5485	70926	70926
Ed_{others}(kW)	1852	1674	268	351	17921	12556

[1] coffee grounds consumption

The chemical exergy (Tab. 5) were determined using equations (7)-(9) and chemical composition data (Tab. 2). The exergy destruction of combustion ($Ed_{combustion}$) refers to the difference between the fuel and combustion gases exergies and the exergy destruction of the steam generator (Ed_{SG}) refers to the difference between the combustion gases and steam exegies, besides other losses as exhaust gases, bottom outlets and soot. Other exergy destructions (Ed_{others}) are related to throating valves, deaerators, economizers and air pre-heaters. The exergy destructions in food processing are not considered in this work.

The final results for energetic (η_{SG}) and exergetic (ε_{SG}) efficiency of the steam generator and for global plant (η_{plant}, ε_{plant}) are described in Tab. 6. The steam generator efficiencies increased mainly due to steam pressure and temperature increases. In the case of global plant, energetic and exergetic efficiencies tend to increase as a function of the power of generation, since the process exergy remains the same. The exception is found in the energetic efficiency of the COFP in which the value decreased when compared with the current index. This follows because this system is of condensing turbine and the low pressure steam is not used in the process as well.

Table 6. Energetic and exergetic efficiencies.

	COFP		SOYP		SUGP	
	current	cogen	current	cogen	current	cogen
η_{SG}	0.7901	0.85	0.777	0.85	0.77	0.77
ε_{SG}	0.2377	0.2929	0.2207	0.3248	0.2556	0.2556
η_{plant}	0.6032	0.589	0.6073	0.6935	0.6689	0.6928
ε_{plant}	0.2021	0.2438	0.2095	0.3015	0.2086	0.2274

In relation to exergetic costs (Tab. 7), it is observed that in the cogeneration systems, the steam and process costs were reduced in all cases, even during the payback period. In relation to the fuel, the exergetic costs remain the same, because they only depend on the exergy and on the mass cost that are the same in current and cogeneration systems. The unique case where there was a small variation in the fuel cost was for the COFP, in which the proportion of coffee grounds used as fuel decreases, as the total cost consumption increases.

Table 7. Thermoeconomic costs.

	COFP			SOYP			SUGP		
	current	payback period$^{(1)}$	after payback	current	payback period$^{(2)}$	after payback	current	payback period$^{(3)}$	after payback
c_{fuel} (R$/kWh)	0.03093	0.03158	0.03158	0.04537	0.04537	0.04537	0.04579	0.04579	0.04579
$c_{steam\text{-}HP}$ (R$/kWh)	0.1267	0.1125	0.1073	0.2194	0.1678	0.1462	0.1728	0.1728	0.1728
$c_{process}$ (R$/kWh)	0.1387	0.1173	0.112	0.2443	0.1892	0.1648	0.1866	0.1741	0.1741
c_{power} (R$/kWh)	0.4752$^{(4)}$	0.4633	0.1585	0.4853$^{(5)}$	0.483	0.1628	0.1932	0.2571	0.192

$^{(1)}$ 16 months; $^{(2)}$ 14 months; $^{(3)}$ 4 months; $^{(4)}$ From COPEL; $^{(5)}$ From CEMIG.

As these costs depend on the fuel price, the investment capital and also of the exergetic efficiencies, could be expected that the current costs would be the lowest in SUGP because it has the lowest investment costs. However, the low specific exergy of the bagasse resulted from its higher humidity increases the exergetic cost of fuel. Despite the higher cost of the firewood for SOYP, its exergetic cost is still slightly lower than in the SUGP. On the steam generation, the fuel humidity also generates greater irreversibility and exergy destruction during the bagasse combustion, resulting in a highest exergetic cost for steam in the SUGP.

The payback periods for the investments are 4 months for SUGP, 14 months for SOYP and 16 months for COFP. In all cases, the paybacks were determined when the electric power costs generated become equal to or less than that provided by the concessionaires of the electric energy of Paraná (COPEL) and Minas Gerais (CEMIG). This criterion is adopted also for the SUGP using the same electric energy price from COPEL (R$ 0.4752/kWh), but in the table contains the media of the exergetic costs including the other two existing turbo-generators in this plant (media: R$ 0.1932/kWh). An important fact is that in SUGP there would be no cost to the bagasse, which is a residue in the sugar and alcohol production. The sale cost of the bagasse was considered in this study in order to have the same standard of comparison with the COFP and SUGP. The interest rate of 11.4% per year from Brazilian Development Bank (BNDES) was used to estimate the payback period for the investments.

5. CONCLUSIONS

Coffee (COFP), soy (SOYP) and sugar (SUGP) industrial plants were selected and evaluated using energetic, exergetic and thermoeconomic analysis. The evaluations were performed for the current industrial plants and for the proposed cogeneration projects to integrate 4.2 MW of power generation in the SOYP, 4.5 MW in the COFP and to replace a throating valve for a new turbogenerator of 11.5 MW in the SUGP.

The power generation produced in proposed systems by the new turbo-generators will result in a decrease in their exergy destructions compared to the current systems. The efficiencies increase mainly due to the power of generation and also due to the steam pressure and temperature increase. The steam and process exergetic costs are reduced in all cases, even during the payback period. Despite the highest cost of the firewood for SOYP among the selected industrial plants, the highest humidity in the bagasse fuel used in the SUGP compared with firewood used in the SOYP and in the COFP resulted in a highest exergetic cost of the fuel and of the process vapor.

The payback periods for the investments were determined in only 4 months for SUGP, 14 months for SOYP and 16 months for COFP. Based on these evaluations, it is possible to verify that the cogeneration systems are technically and economically viable in all the 3 cases, but the advantages of these integrations depend on the retrofit level, scale industry, heat demand of the process and fuel and electric power prices, resulting in different investment return.

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