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Thermoeconomic Analysis of a Cogeneration System Integrated to a Solid Waste Incinerator

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Abstract

In order to achieve satisfactory incineration, it is required that the combustion reaction occurs in high temperature, resulting in gaseous components with high exergetic potential that can be used for electromechanical power generation. This study makes an exergetic analysis, feasibility study and thermoeconomic evaluation for implanting a cogeneration system integrated to a solid waste incinerator from the Biotery located in the State University of Maringa. First and Second Laws of Thermodynamics are employed, by applying mass, energy, exergy and economic balances of the proposed system. Based on this evaluation it is possible to verify that the integration of a Rankine cycle using a micro-turbine of 123 kW with the incinerator is technically viable. The power generation costs was estimated ~11% lower than from the supplier and the operational costs of the incineration can either be decreased in ~ 22% to present investment return in up to 4.2 years. These cost reductions could make possible the continuous operation of the equipment, supplying conditions for the correct disposal of the solid waste generated by the university and Maringa city.

Keywords: *Incineration; cogeneration; thermoeconomics; exergy*

1. Introduction

The incineration process employs thermal decomposition via thermal oxidation at high temperature to destroy the organic fraction of the waste and reduce the volume in inert ash and combustion gases [1]. The gases must reach a fixed temperature, enough high to the organic contents break their molecular bonds into elementary constituents. The elementary constituents react with oxygen, resulting in stable gases, released to the atmosphere after going through the pollution control devices. Although other undesired products can be produced, the exhaust gases are primarily composed of carbon dioxide, oxygen, nitrogen and water steam, besides the incomplete combustion products, e.g., carbon monoxide.

In Brazil, some standards were established by the Brazilian Association for Technical Norms – ABNT 11175/1990 and National Council for Environment CONAMA 316/2002. Among the recommendations, it is emphasized the operational conditions to promote the destruction of the main hazardous organic component. (PCOP) such as excess of combustion air, temperature of 1200 ^{o}C as the minimum value for gases after the combustion, minimum residence time of 2 seconds at 1200 ^{o}C.

The first incineration units released the gases directly to the atmosphere and the main function was to decrease the residuals volume. Nowadays, besides fulfilling the main function with high efficiency, the gaseous emissions were reduced, mainly because of the technological advances in emission control devices. However, the operational cost and fuel consumption associated with higher temperatures in such devices have also increased.

An alternative to reduce the operational costs is to implant an energy recovery system using the cogeneration. Cogeneration is defined as the simultaneous and sequential production of electrical or mechanical energy (power) and useful thermal energy (heat) from only one energy source (flow). Electricity production in combination with energy recovery from flue gases in thermal treatment plants is an integral part of Municipal Solid Waste (MSW) management for many industrialized nations. In Sweden, MSW is considered as an important fuel resource for partially meeting European Union environmental targets within cogeneration [2]. MSW incineration linked to electrical energy generation has advantages, both on the energetic and the economic point of view. The main objective is waste disposal; the production and sale of electrical energy as an additional product contribute, however, to lessening the incineration and garbage disposal cost [3].

The analysis of a cogeneration system using the exergetic potential of the combustion gases from a solid waste incinerator in this current study is based on the thermoeconomics (exergoeconomics). The thermodynamic inefficiencies associated with any energy conversion process are expressed by the exergy destruction and the exergy losses associated with the process. Combustion processes exhibit very high thermodynamic inefficiencies caused by chemical reaction, heat transfer, friction, and mixing [4].

An exergoeconomic analysis consists of an exergetic analysis, an economic analysis, and an exergoeconomic evaluation, all conducted at the level of plant components [4]. Although other authors conduct pioneering studies in the field of thermoeconomics during the 1960s, the effort to apply thermoeconomics systematically to the analysis of energy systems flourished only after 1980s and 1990s, when a group of specialists in the field (C. Frangopoulos, G. Tsatsaronis, A. Valero, and M. von Spakovsky) decided to compare their methodologies by solving a predefined and simple problem (CGAM Problem) of optimization in order to unify the thermoeconomic methodologies [5].

Valero et al. [6] 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” [7] 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 [8] discussed various exergycosting 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 (Solid-oxide fuel cells – SOFCs, Organic Rankine Cycle, Combined Heat and Power, Trigeneration, Polygeneration) and to use advanced exergetic or exergoenvironmental analyses [9-14].

2. Case Study

The incinerator of Biotery located in the State University of Maringa is composed by two horizontal cylindrical chambers. In the primary chamber, the solid wastes are loaded and under controlled sub stoichiometric conditions, they are heated and pyrolysed, releasing moisture and volatiles. The gases resulting from primary chamber are directed to the secondary chamber, where air is furnished for promoting and completing the hydrocarbon combustion. In this way, the combustion is finished and a perfect incineration is assured. The gases temperature must reach 800 ^{o}C in the primary chamber and 1200 ^{o}C in the secondary chamber. A sudden change in the flow direction after the secondary chamber, allows the airborne particles to precipitate and to be removed from the gaseous stream. This flow configuration also assures the residence time established in the environmental law, resulting in inert gases by the stack. The equipment also employs a water sprinkler system to humidify the residuals. This measure avoids an accelerated combustion in plastics and other residuals, in order to promote an adequate burning velocity. A lower burning velocity prevents heavy fumes and a more complete combustion (Figure 1).

As previously mentioned, the high temperature for incineration increases the operational costs, however it provides the cogeneration potential to the system. If the cogeneration is applied, the thermal irreversibility for the process and the operational costs are reduced. In the present case, the necessary temperature level for the incineration facilitates the use of the bottoming cycle. Considering that hot gases are available after the incineration process, the classics power generation cycles applicable are Otto, Brayton or Rankine.

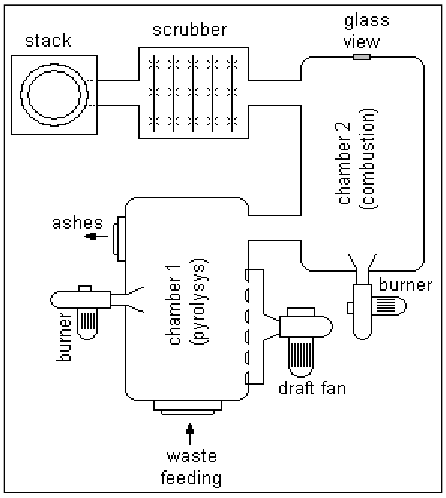

Figure 1. Configuration of the current incinerator [15].

It is possible to get high exergy efficiency using the Otto cycle, but the complete combustion must occur in the internal combustion engine, as presented by Sallustio and Sciubba [16] using a biogas generated in an anaerobic digester. In the present case of the solid incineration, all the carbon and the hydrogen resulting from the gases in the first chamber must be completely burned to carbon dioxide and to water, respectively, in the second chamber, so that this cycle was not considered in this work.

Using the Brayton cycle, the hot gases can be used directly into the gas turbine, however the gases from the incineration are in low pressure. Considering the trouble to use a compressor working with hot gases, the best alternative would be using the hot gases indirectly, introducing a Heat Recovery Steam Generator – “HSRG" (Figure 2). This HRSG must be a water tube boiler because a superheater is necessary to generate the steam in the chosen properties and this component can be located at the better gas temperature region in water tube than in fire tube boiler. The fire tube boiler has either difficulty to come up with a good design if corrosive conditions are present and if slagging is a concern, the fire tube designs are generally not suitable as the tube inlet can be plastered with slag. In water tube boilers, if the gas stream is dirty with dust, soot and tar deposits on the pipe surface, cleaning provision can be made using soot blower or rapping mechanism.

In order to maintain the good operation along the time, a special design must be used to prevent the ash sticking and the subsequent reduction of the steam generation. Also, the university has an automatic feeder system, that has not been operating in the incinerator, but it must be installed to ensure the waste moving through the chamber in automatic mode.

In this way, the steam could be employed for the power generation in a Rankine cycle. This alternative seems to be the more viable, as occurs in 21 installations of power generation in Taiwan, where it is noted that these mass-burn incinerators generate lots of marketable electricity through steam turbine-generator (cogeneration) system [17].

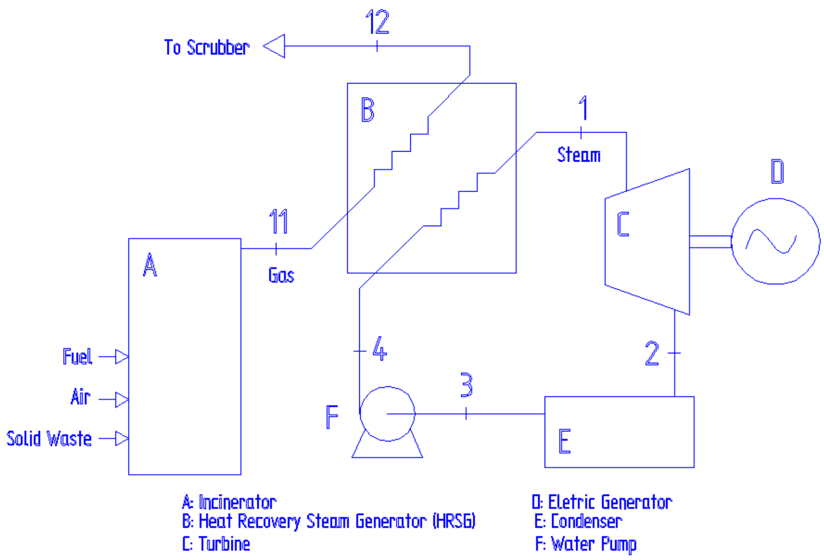

Figure 2. Alternative configuration of the cogeneration system integrated to the incinerator [18].

3. Methodology

3.1 Description

The purpose of the current study is to perform a thermoeconomic analysis of a cogeneration system using the exergetic potential of the combustion gases from a solid waste incinerator. In this analysis, the 1st and 2nd Laws of Thermodynamics are employed, using the mass, energy, exergy and economic balances of the proposed system. Exergetic and thermoeconomic analysis are well known methodologies [19], [20].

The analysis was based on the current fuel consumption rates, i.e., in the current heat potential. The feasibility of installing the system integration was verified with 5, 6 and 7000 hours/year of equipment 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.

In the current situation, the main losses occur in the combustion reaction and in the release of gases to the atmosphere. For the integrated cogeneration system, the irreversibilities are also in the steam and in the power generation.

In order to present the exergetic losses, the Grassmann diagram and the (η_{carnot} versus Enthalpy) curve were constructed. The Grassmann diagram to present the exergetic losses is an adaptation of the Sankey diagram, which is employed to present the energetic losses [20]. The analysis based on (η_{carnot} versus Enthalpy) curve is in accordance with the proposal by Linnhoff and Ahmad [21] and applied by Higa and Bannwart [22].

Finally, the costs from the investment, maintenance and operation were combined with the flow exergy, resulting in the exergetic costs of the incineration for isolated incinerator and also for the integrated cogeneration system.

3.2 Balance equations

The conservation of energy principle applied to a control volume can be written as Eq. (1).

$$\frac{dE_{CV}}{dt} = \dot{Q} - \dot{W}_{CV} + \sum_{in}[\dot{m}(h + \frac{V^2}{2} + gz)]_{in} + - \sum_{out}[\dot{m}(h + \frac{V^2}{2} + gz)]_{out} \quad (1)$$

where dE_{CV}/dt is the time rate of change of energy in the control volume, the terms $\dot{Q}$ and $\dot{W}_{CV}$ represent the time rate of energy transfer by heat transfer and work, respectively, $\dot{m}$ represents the mass rates, h the enthalpy, V the flux velocity, g the acceleration of gravity and z represents the elevation relative to the surface of the ground.

The heat of the incineration process ($\dot{Q}_{fuel}$) that is available for power generation can be determined by using Eq. (2) from the fuel consumption rates ($\dot{m}_{fuel}$) and their lower heat values (*LHV*). Besides the fuel, it is possible to include in the heat accounting, the energy released from the waste fed in the incinerator.

$$\dot{Q}_{fuel} = \sum\left(\dot{m}_{fuel}\, LHV\right) \quad (2)$$

For the integrated power system, the availability for steam generation can be determined from the mass flow rate and temperature of the gases in the *HRSG* exit (Eq. (3)). From this equation, it is possible to observe the increase in the availability with the lowering of the exit gas temperature (T_{out}). However, the temperature should not be decreased up to the dew point in order to prevent condensation and equipment damage.

$$\dot{Q}_{avail} = \dot{m}_{gas} \int_{T_{out}}^{T_{in}} c_{gas} dT \tag{3}$$

where, C_{gas} is the gas specific heat, $c_{gas} / R = A + BT + CT^2 + DT^{-2}$, R is constant for a particular gas according to its molecular weight (*M*) and *A*, *B*, *C* and *D* are constants given for each chemical species [23].

The steam generation capacity is obtained by matching Eqs. (3) and (4).

$$\dot{Q}_{in} = \dot{m}_{steam}(h_{out} - h_{in}) \tag{4}$$

Eq. (4) applied to the *HRSG* and condenser, as well as Eq. (5) applied to the turbine and pump, are simplifications of the Eq. (1) for a control volume at steady state (dE_{CV}/dt = 0) and considering that the change in potential energy from inlet to exit can be neglected.

$$\dot{W}_{out} = \dot{m}_{steam}(h_{in} - h_{out}) \tag{5}$$

The exergy rate balance for a control volume is given by Eq. (6).

$$\frac{dE_{x.CV}}{dt} = \dot{E}_{x.Q} - (\dot{W}_{CV} - p_0 \frac{dV_{CV}}{dt}) + \dot{E}_{xf.in} - \dot{E}_{xf.out} - \dot{E}_d \tag{6}$$

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 exergy transfer accompanying heat transfer is given by

$$\dot{E}_{x.Q} = \sum_j (1 - \frac{T_0}{T_j}) \dot{Q}_j \tag{7}$$

where *j* is specific point of system where instantaneous heat transfer is occurring.

In this study, the calculated exergies were based on the methodologies presented by Kotas [20]. 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. (8).

$$\dot{E}_{xf} = \sum \left(\dot{m}.e_x \right) \tag{8}$$

where the exergy includes physical and chemical exergies ($e_x = e_{x.physical} + e_{x.chemical}$). The physical exergy also includes thermomechanical, kinetic and potential energy. Ignoring the effects of motion and gravity, the thermomechanical exergy was related to the by temperature (T), enthalpy (h), entropy (s), as given in Eq. (9).

$$e_{x.physical} = h(T) - h_0 - T_0[s(T) - s_0] \tag{9}$$

For the gaseous fuel and products of combustion, the chemical exergy was determined by its chemical composition using standard chemical exergies from Kotas [20] and the sum of the exergies of its components according to Eq. (10).

$$e_{x.gaseous-fuel} = \sum_i (x_i e_{x,i}) + RT_0 \sum_i (x_i \ln x_i) \tag{10}$$

where x_i is the mole fraction of the *i*-th component in the mixture and *R* is the universal gas constant.

For solid fuel the exergy presented by Kotas [20] and based on the molar composition and the heating value (Eq. (11)), where the ratio of chemical exergy (Eq. (12)) 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).

$$\varphi_{dry} = \frac{1.0438 + 0.1882\frac{h}{c} - 0.2509(1 + 0.7256\frac{h}{c} + 0.0383\frac{n}{c}}{1 - 0.3035\frac{o}{c}} \tag{11}$$

$$\varphi_{dry} = \frac{e_{x \cdot solid-fuel}}{(LHV)^0} \tag{12}$$

Considering the moisture (*w*) and fraction of sulphur in the fuel, the expression ca be written by Eq. (13).

$$e_{x.solid-fuel} = (LHV + w.h_{fg})\varphi_{dry} + 9417s \tag{13}$$

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).

Using the exergetic potential of the proposed cogeneration system presented in the Grassmann Diagram and in the (η_{carnot} versus Enthalpy) curve, the thermoeconomic evaluation of the cogeneration system integrated to the incinerator was carried out based on the potential savings with the electricity generation $(\dot{W}_{net})$. The payback period was obtained when the equivalent expenses ($e.xpense_{month}$) from the electric power to be produced over the period (*months*), also considering the interest rates (*j*), became equal to the investment (Eq. (14)). The factor 1.3 over capital cost of the equipment ($Z_{equipment}$) was also adopted to consider the maintenance and operating costs.

$$1.3\sum(Z_{equipment}) = \frac{months * e.xpense_{month}}{(1+j)^{months}} \tag{14}$$

$$e.xpense_{month} = c_{e_{x\ power}} \dot{W}_{net} \frac{hours\_year}{12}$$

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 ($/h) must also account for the capital investment according to the balance presented in Eq. (15).

$$\sum \dot{C}_{out} = \sum \dot{C}_{in} + \sum \dot{Z} \tag{15}$$

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

$$\dot{Z}_{equipment} = \frac{1.3\, Z_{equipment}}{months \dfrac{hours\_year}{12}}$$

Using the described equation, the exergetic costs were determined (c_{e_x}) for the incinerator flows (Eq. (16)), Steam Generator Heat Recovery (Eq. (17)), turbine (Eq. (18)), condenser (Eq. (19)) and pump (Eq. (20)). In the incinerator:

$$\dot{C}_{incinera} = \dot{C}_{11\text{-}gas} = \dot{C}_{10\text{-}fuel} + \dot{C}_{air} + \dot{C}_{waste} + \dot{Z}_{incinera} \tag{16a}$$

As the air and the solid wastes have no specific costs and the air enters in the environment temperature, these specific costs and exergy may also be considered null, and they do not generate cost rates

$$(c_{air} = c_{waste} = \dot{E}_{x\,air} = 0 \quad \Rightarrow \quad \dot{C}_{air} = \dot{C}_{waste} = 0)\,.$$

In the case of the incinerator, as this equipment has already been purchased, installed and has been operating, its cost can be also neglected $(\dot{Z}_{incinera} = 0)$. The fuels used in the incinerator are firewood and LPG (Liquefied Petroleum Gas).

$$c_{incinera} = c_{e_{x\,11\text{-gas}}} = \frac{(c_{e_x} \dot{E}_x)_{\text{firewood}} + (c_{e_x} \dot{E}_x)_{\text{(LPG)}}}{\dot{E}_{x11\text{-gas}}} \tag{16b}$$

In the heat recovery steam generator:

$$\dot{C}_{1\text{-}stMP} + \dot{C}_{12\text{-}gas} = \dot{C}_{4\text{-}wMP} + \dot{C}_{11\text{-}gas} + \dot{Z}_{HRSG} \tag{17a}$$

Adopting: $c_{e_{x12-gas}} = 0$ because the combustion products are discharged directly to the surroundings with negligible cost, results:

$$c_{e_{x\,1\text{-}stMP}} = \frac{c_{e_{x\,4wMP}} \dot{E}_{x4MP}}{\dot{E}_{x1\text{-}stMP}} + \frac{c_{e_{x\,gas}} \dot{E}_{x11\text{-}gas}}{\dot{E}_{x1\text{-}stMP}} + \frac{\dot{Z}_{HRSG}}{\dot{E}_{x1\text{-}stMP}} \tag{17b}$$

In the turbine:

$$\dot{C}_{5\text{-}power} + \dot{C}_{2\text{-}stLP} = \dot{C}_{1\text{-}stMP} + \dot{Z}_{turb} \tag{18a}$$

Considering that the specific cost of the medium pressure (*MP*) is maintained by low pressure steam, from the back-pressure turbine, $c_{e_{x\,2-stLP}} = c_{e_{x1-stMP}} = c_{e_{x\,st}}$, resulting in:

$$c_{e_{x\,5\text{-}power}} = \frac{c_{e_{x\,st}} \left| \dot{E}_{x1\text{-}stMP} - \dot{E}_{x2\text{-}stLP} \right|}{\dot{W}_{turb}} + \frac{\dot{Z}_{turb}}{\dot{W}_{turb}} \tag{18b}$$

In the condenser:

$$\dot{C}_{3\text{-}wLP} + \dot{C}_Q = \dot{C}_{2\text{-}stLP} + \dot{Z}_{cond} \tag{19a}$$

Considering that the costs associated with the rejection of exergy from condenser to heat transfer ($c_Q = 0$):

$$c_{e_{x\,3wLP}} = \frac{c_{e_{x\,st}} \dot{E}_{x2\text{-}stLP}}{\dot{E}_{x3wLP}} + \frac{\dot{Z}_{cond}}{\dot{E}_{x3wLP}} \tag{19b}$$

In the pump:

$$\dot{C}_{4\text{-}wMP} = \dot{C}_{3\text{-}wLP} + c_{e_{x\,power}} \dot{W}_{pump} + \dot{Z}_{pump} \tag{20a}$$

$$c_{e_{x\,4\text{-}wMP}} = \frac{c_{e_{x3wLP}} \dot{E}_{x3\text{-}wLP}}{\dot{E}_{x4\text{-}wLP}} + \frac{c_{e_{x\,power}} \dot{W}_{pump}}{\dot{E}_{x4\text{-}wLP}} + \frac{\dot{Z}_{pump}}{\dot{E}_{x4\text{-}wLP}} \tag{20b}$$

Using Eqs. (19) and (20), Eq. (17) can be written as Eq. (21):

$$c_{e_{x\,1\text{-}stMP}} = \frac{c_{e_{x\,gas}} \dot{E}_{x11\text{-}gas} + c_{e_{x\,power}} \dot{W}_{pump}}{\dot{E}_{x1\text{-}stMP} - \dot{E}_{x2\text{-}stLP}} + \frac{\dot{Z}_{HRSG} + \dot{Z}_{pump} + \dot{Z}_{cond}}{\dot{E}_{x1\text{-}stMP} - \dot{E}_{x2\text{-}stLP}} \tag{21}$$

Eqs. (16)-(21) show that the unit costs are determined by two contributions related, respectively, to the cost of exergy destruction (irreversibility cost) and the cost of owning and operating the equipment.

4. Results

4.1 Program development

Using the previous assumptions and equations, a computational program was developed to perform the thermoeconomic analysis of the power system integrated to the incinerator. The program performs the combustion, mass, energy and exergy balances for the proposed system.

Using this tool, it is possible to change the fuel composition, consumption rate, the air excess, and other variables allowing the estimates to be made in order to determine the potential of steam and power generation. The program also calculates the process irreversibilities, energy and exergy efficiency.

The potential and thermal efficiency of the *Rankine* cycle can be determined according to the pressure and temperature levels in the generation and in the steam condensation. Besides, according to the investment, operation and maintenance costs and to the income proceeding from the power generation, the return on the necessary investments can be verified for the integration of the proposed power cycle. The thermoeconomic analysis was accomplished in order to verify the real viability of the power cycle integration.

4.2 Exergetic analysis

This study was based on current consumption of firewood and LPG (Liquefied Petroleum Gas), used as fuel in the incinerator as shown in Table 1, according to Barro's report [24]. Basically, the solid wastes employed in the incinerator are rat labs, which can be used as fuel, because their heat value are comparable to the bovine meat (*LHV* = 16180 kJ/kg) [25]. For the current study, the fuel potential of the solid waste was neglected, mainly due to the composition variation. It is expected that the fuel potential of the solid waste would affect positively the proposed power system.

Table 1. Properties of the fuels

Fuel	$\dot{m}$ [kg/s]	LHV [kJ/kg]	$\dot{Q}_{fuel}$ [kW]	$\dot{E}_x$ [kW]
Firewood	0.056	12560	698	785
LPG	$1.86\ 10^{-4}$	47313	8.8	9.1

The chosen data from the *Rankine* cycle are in Table 2. The steam properties were obtained from Moran and Shapiro [26]. The gas mass flow, gas composition and the dew point were determined using chemical reaction and energy balances for reacting systems (Table 3). The exit *HRSG* temperature was 100 ^oC above the dew point for preventing water vapor condensation.

Table 2. Properties of the Rankine cycle

Flow	*T* [^{o}C]	*P* [kPa]	*h* [kJ/kg]	*s* [kJ/kg.K]
Steam – MP	320	2200	3064	6.795
Steam – LP	111.4	150	2582	6.934
Water – LP	111.4	150	467	1.434
Water – MP	111.6	2200	469	1.435

Table 3. Results based in combustion reaction

$\dot{m}_{gas}$ [kg/s]	0.517
T_{11} [^{o}C]	1200
$T_{dew\text{-}point}$ [^{o}C]	49
T_{12} [^{o}C]	149
$\dot{m}_{steam}$ [kg/s]	0.256

Using the Eqs (1)-(5), calculations were performed estimating the rate of heat transfer of 664 kW, in a boiler of 22 bar and 320° C. With this value, it can be generated 0.256 kg/s of steam to be utilized in the power cycle. Under these conditions, the result is 122.6 kW of electric power generation for the isentropic efficiency of 90% for the turbine and pump. It is important to consider that the load of the incinerator can be unstable, and this efficiency can decrease.

For the reference environment or dead state (*0*) in temperature, T_0= 298.15 K, and pressure, p_0= 100 kPa, the thermomechanical exergies were calculated using Eq. (9). For using Eqs. (3) and (9), as the incinerator works at high temperatures, the relations available for the specific heat were employed for the accounting of these temperatures [23].

For calculating the firewood chemical exergy, the composition (Table 4) was approximated according to Bazzo [27]. This assumption is justified because the exact composition of the firewood has also variation in composition. The ratio between chemical exergy and the lower heating value for the solid fuel (γ = 1,091: Eq. (11)) was calculated and then, the firewood chemical exergy was determined using Eq. (13).

Table 4. Firewood chemical composition [27]

Element	C	H	O	z	w
[%] mass	49	6	44	1	30

Using the LPG chemical composition (Table 5) and the corresponding chemical exergies (Table 6), the chemical exergy of LPG (Table. 7) was determined using the Eq. (10).

Table 5. LPG composition [28]

	Propane (C_3H_8)	Butane (C_4H_{10})
[%] vol.	75.7	24.3

Table 6. Chemical exergies of propane and butane

$e_{x.C3H8}$ [kJ/kmol]	$e_{x.C4H10}$ [kJ/kmol]
2163190	2818930

Table 7. Chemical exergies of LPG and wood

$e_{x.LPG}$ [kJ/kg]	$e_{x.wood}$ [kJ/kg]
53313	14121

The way the transfer of exergy occurs between the combustion gases and the steam, as well as the way largest exergies process occur can be more easily seen in (η_{carnot} X Enthalpy) curve (Figure 3) and in Grassmann diagram (Figure 4).

In the η_{carnot} versus Enthalpy curve, regarding the incinerator, the point of the gas line intersection with the abscissa represents the fuel exergy and the region below the gas curve represents the exergy of the combustion gas; the region below the steam curve represents the exergy of the steam boiler generated by combustion gas. The region between the gas curve and the steam curve represents the destruction of the exergy of the HRSG, as the region below the condensate curve, represents the destruction of the exergy of the condenser system. The generation of power is represented in the region between the steam curve and the condensate. These representations are conceptualized in the transfer of exergy associated with heat, which is defined as multiplication of the Carnot's factor by the available heat, in accordance with the Eq. (7).

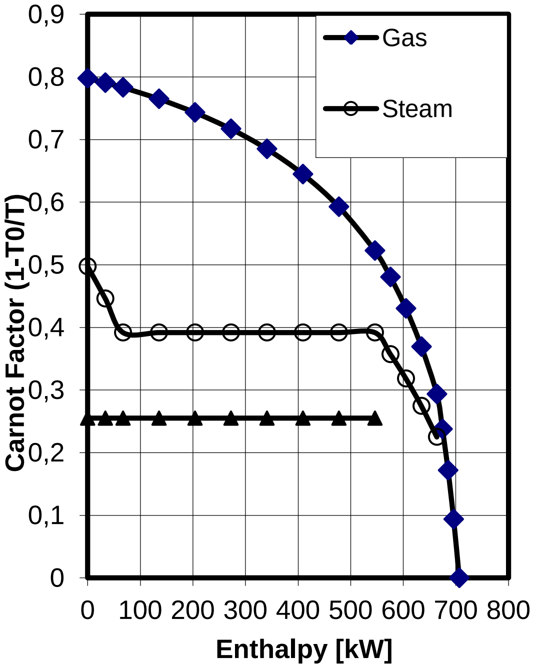

Figure 3. Carnot factor changing with Enthalpy, representing exergy transfer and destruction among the combustion gases and the steam.

It is observed that in the steam generation region, the losses are associated with the steam pressure level produced. As evaporation occurs at constant temperature, and it is pressure-dependent of the phase change region, the elevation of these properties levels would lead to exergetic loss reduction. The exergetic efficiencies can be improved by higher temperatures and pressures, and technical feasibility should increase resulting from that possible alteration. This fact can be observed in previous studies, but considering the difficulties in finding information and quotes from other turbines in this range of pressure, this study was limited to the model of micro-turbine mentioned above.

Although the amount of electromechanical energy produced is not in large scale, it can contribute to the provision of the university, which is currently quite critical. An example is related to the air conditioning. In order to install a single unit of 2930 W (10000 BTU/h) it is necessary to obtain a permit from the city campus. The electrical power is enough to supply around 90 machines of 2930 W, based on the average of 1350 W per device (FIEC: www.fiec.org.br/acoes/energia/informacoes/consumo_medio.htm).

4.3 Thermoeconomic Evaluation

The payback period of the cogeneration system integrated to the incinerator was carried out based on the Eq. (14) considering the electric energy expenses, maintaining the same fuel consumption and costs, electric energy cost (Table 8), as well as the investment costs associated with the Rankine cycle (Table 9).

Table 8. Fuel and electric energy costs

	Cost
LPG [USD/ton] [1]	1545.33
Firewood [USD/ton]	43.86
Electric Energy [USD/kWh] [2]	0.163

Source: [1] ANP: http://www.anp.gov.br/preco/prc/Resumo_Por_Municipio_Seleciona_Municipio.asp; [2] Copel: http://www.copel.com/hpco pel/root/index.jsp.

Table 9. Capital cost for the turbine and the steam generator

	Cost [USD]
Turbo-generator [3]	154018.00
Steam Generator [4]	178571.00
Condenser	31390.00
Pump	1000.00

Source: [3] TGM: (www.grupotgm.com.br/home.php); [4] Rampelotto's Boilers: (www.caldeirasrampelotto.com.br).

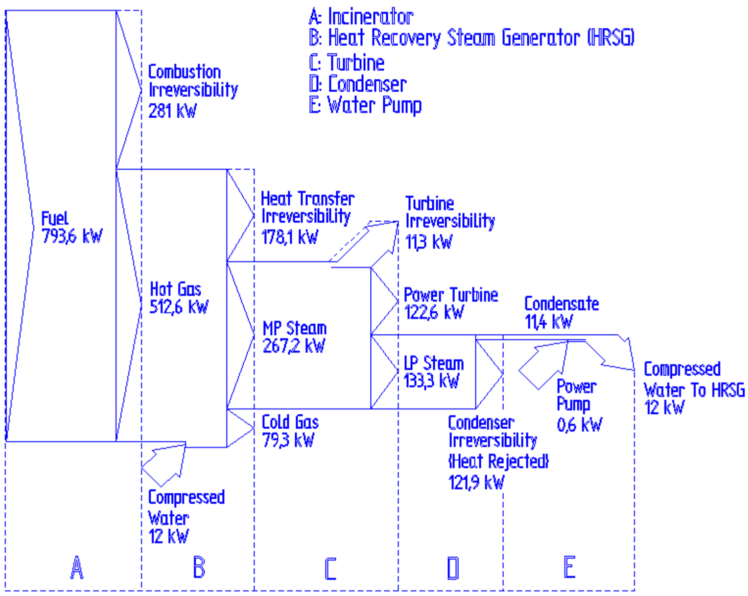

Figure 4. Grassmann diagram representing exergy rates of the cogeneration system integrated into the incinerator [18].

Currently, the equipment does not operate continuously due to the high incineration costs. However, there is great shortage related to the management and proper disposal of animal and solid wastes in the region of Maringa City [29]. Continuous effort towards the implementation of the integrated system should contribute to solve the deployment problem, probably reducing waste and operating costs, since the shutdowns impair the system efficiency with the starting-up process being out of the optimal temperature conditions.

In this study, it was verified the feasibility of installing the system integration with 5, 6 and 7000 hours/year of the equipment operation in a continuous and steady-state process. Based on the number of operating hours in a year and the Eq. (14), it was also possible to estimate the payback period for the capital investment in the Rankine cycle (Table 10). The interest rate of 0.86% per month (~ 10.8% per year) was used to estimate from Brazilian Development Bank (BNDES). If the system annual operation is 7000 hours, 4 years and 2 months would be required for the produced electricity to save the investment. In the case of 5000 hours, 6 years and 6 months would be required for the recovery. This saving is related to avoid buying electricity from the supplier.

Table 10. Payback period based on the number of operating hours in a year.

Hours in a year	Fuel cost [USD/month]	Electric cost [5] [USD/month]	Payback months
5000	4086	8326	78
6000	4904	9992	61
7000	5721	11657	50

[5] For 122.6 kW.

Using fuel, gas and steam exergetic flow rates in Eqs. (15)-(21), the specific exergetic costs of the proposed flow system were calculated. In Table 11, the exergetic costs are presented for 6000 operating hours/year considering 3 cases: **1st case**, the fuel costs are borne completely by the incineration process; **2nd case**, the fuel costs are borne completely by the power generation system; and **3rd case**, the fuel cost are divided between the incineration process and the power generation system. In this last condition, the cost for the power generation system is the difference between electric cost and fuel cost, or US$ 5088 from the difference between US$ 9992 and US$ 4904 in reference to 6000 operating hours/year.

In the 2nd case, considering that the power generation system pays completely the fuel costs, the electric power costs is estimated in 0.2067 USD/kWh, higher than 0.163 USD/kWh from the supplier. This condition is not interesting for the university and can be rejected. In the 1st and the 3rd cases, when the incineration process pays completely the fuel costs or they are divided between the incineration process and the power generation system, the electric power costs of 0.1271 and 0.1445 USD/kWh are lower than the electric energy cost from the supplier and the electric energy costs can be reduced in 22.0% to 11.3%, respectively. The 1st case can be interesting for the power generation, but the incineration cost continues with high cost. In the 3rd case, in addition to the lower electric energy cost, the incineration cost can either be decreased in ~22%, reducing from 0.01913 USD/kWh to 0.01494 USD/kWh.

These relation costs are reversed to the exergy processes variations. That is, when the exergy destruction is reduced the exergetic cost increases, or the higher the exergy destruction, the higher the exergetic cost. However, the proportion of the cost increasing is not always the same of the exergy destruction. This is due to the cost of the capital investment about the HRSG and the turbine. As the incinerator is already installed, its costs were not considered for obtaining the results. In order to better understand these specific exergetic costs, capital costs from the investment costs were also carried out (Table 11: 7th column).

These results show that the costs are associated with the capital cost of the equipment, as well as with the irreversibility of the process. Comparing the results, it is possible to construct the cost diagram (Figure 5), making it possible to visualize the factors which influence the increase of specific costs.

5. Conclusions

Based on the current demand of fuel in the incineration process of solid waste from the biotery located in the State University of Maringa, and considering the gases exergy destroyed in the process, it was verified that the exergies from the combustion products are enough to boost a Rankine cycle, using a micro-turbine of 122.6 kW. The graphic image of the processes of transfer and destruction of exergy were presented by the Grassmann diagram and the "Carnot´s factor versus enthalpy" curve. This power generation can contribute for an extra supply of electrical energy to complement the university demand.

Table 11. Fuel, combustion gases and steam exergy cost (6000 operating hours in a year)

Flow - points	T [°C]	$\dot{E}_x$ [kW]	c_{ex} [USD/kWh] 1st case	2nd case	3rd case	Capital costs
Fuel	25	794	0.01235	0.01235	0.00123	-
Incineration	1200	513	0.01913	0.00	0.01494	-
Gases – A			0.00	0.01913	0.00419	-
Steam – 1	320	267.2	0.06797	0.14124	0.08401	0.06718
E. power	-	122.6	0.12710	0.20670	0.14450	0.05326

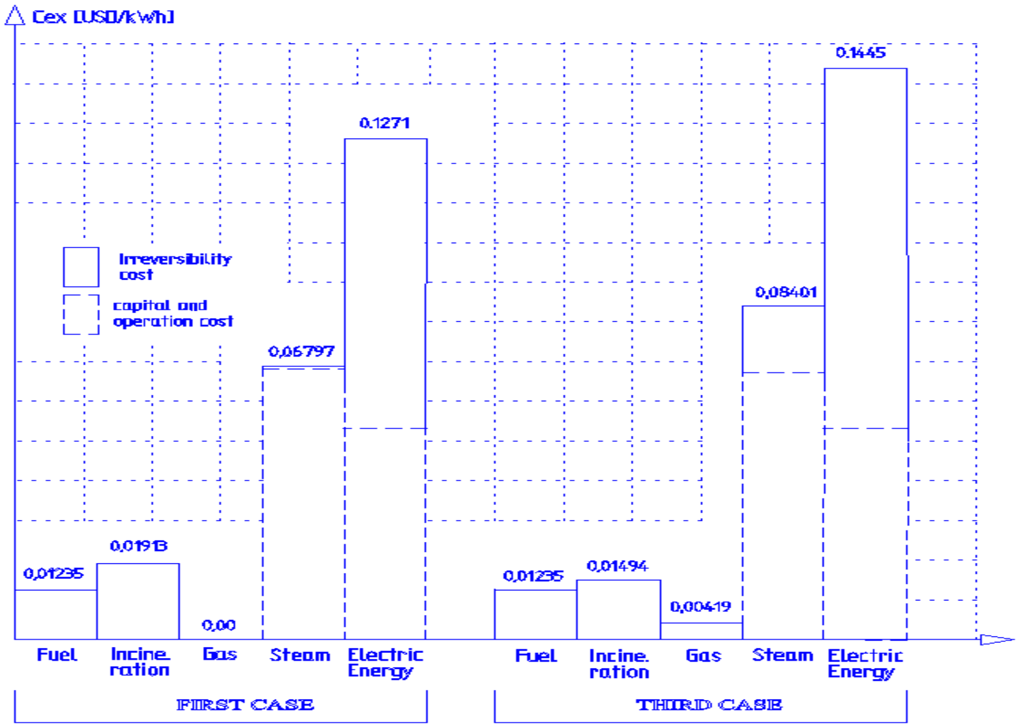

Figure 5. Specific costs (6000 operating hours in a year).

The specific exergetic costs of the proposed flow system were calculated. for 6000 operating hours/year considering 3 cases: **1st case**, when the fuel costs are borne completely by the incineration process, it can be interesting for the power generation because the estimated power costs are 22,0% lower than the one from the supplier, but the incineration cost remains high. In the **2nd case**, when the fuel costs are borne completely from the power generation system, it is not interesting for the university and it can be rejected, because the estimated power costs are 26,8% higher than the one from the supplier; and finally in the **3rd case**, when the fuel cost is divided between the incineration process and the power generation system, it can be interesting because the estimated power costs are 11,3% lower than the one from the supplier and the incineration cost can either be decreased in ~ 22%.

The thermoeconomic feasibility is one of the advantages for the implantation of the proposed system. As the necessary resources to install a power generation system should be provided by the local government, the main question resides in to payback the costs with the generated electricity. This cost reduction could make possible the continuous operation of the equipment, supplying conditions for the correct disposal of the solid waste generated by the university and Maringa city.

Nomenclature

$\dot{C}$:	Cost rate	[USD/h]
c_{ex} :	Exergetic cost	[USD/kWh]
e_x :	Specific exergy	[kJ/kg]
E :	Energy	[kJ]
$\dot{E}_d$:	Exergy destruction	[kW]
E_x :	Rate of exergetic flux	[kW]
$\dot{E}_x$:	Exergy	[kJ]
h :	Specific enthalpy	[kJ/kg]
h_{fg} :	Latent heat	[kJ/kg]
HRSG:	Heat Recovery Steam Generator	
LHV:	Lower Heat Value	[kJ/kg]
LPG:	Liquefied Petroleum Gas	
$\dot{m}$:	Mass flux	[kg/s]
n :	Stoichiometric coefficient	[kmol]
$\dot{Q}$	Rate of heat transfer	[kW]
R :	Universal gas constant	[kJ/kmol.K]
s :	Specific entropy	[kJ/kg.K]
T :	Temperature	[K]
t:	Time	[s]
x :	Mole fraction of the component	
z:	Elevation relative to the surface	[m]
$\dot{Z}$:	Rate of capital and operational cost	[USD/h]
Z:	Investment capital	[USD]
V:	Velocity	[m/s]
V:	Volume	[m^3]
$\dot{W}$	Rate of energy transfer by work	[kW]
φ_{dry} :	ratio of chemical exergy to the heating value	

Subscript

0	Reference environment
CV	Control volume
MP	Medium pressure
i	Component in the mixture
j	Point of system occurring heat transfer
f	Flow rate
LP	Low pressure
LPG	Liquefied petroleum gas
P	Product components of combustion
Q	Heat Transfer
R	Reagent components of combustion
st	Steam
w	Water

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