PROPOSAL OF A WASTE-TO-ENERGY FACILITY FOR RIO DE JANEIRO: A SENSITIVITY ANALYSIS

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Abstract. *The controversy involving the final disposal of municipal solid waste in the big cities exists for several years. The recent disaster involving a slurry leak from a regulated landfill in Rio de Janeiro called the attention for an important issue, "What if landfills are not the best alternative for waste treatment?" The environmental and social risks and the shortage of available areas to build landfills increase the demand for new processes to dispose urban waste. Waste-to-Energy facilities that treat the waste thermally and generate electricity and/or steam, close to the consuming centers, meet the search criteria for renewable sources of energy production. Doubly advantageous, they are presented as a solution to both the waste disposal problem and the growing energy demand in the cities. This technology is almost non-existent in Brazil, which opens the way for the research of better alternatives for thermal systems applied to the Brazilian waste. This work presents a sensitivity analysis of a thermo-economic study proposing a waste-to-energy facility to receive the urban waste of Rio de Janeiro (Brazil). Three scenarios were assessed and the energy production costs were estimated and compared with other power generating facilities of different sources (wind, hydroelectric, biomass, etc.). The conclusion shows that the energy produced in the proposed facility, combining waste and natural gas, is competitive with fossil and renewable energy power plants.*

Keywords*: Municipal solid waste, incineration, waste-to-energy, thermoeconomic analysis*

1. INTRODUCTION

The so-called Waste-To-Energy (WTE) facilities allow a complete treatment and final disposal of municipal waste, complementing the prior recommended waste management practices: recycling of non-organic material and composting of organic compounds. At the same time, they turn the waste calorific power into heat and/or electricity that can be consumed by closely located industries and households. Besides that, the generated energy is considered renewable and the facility can, thus, profit from State policies and aids for this kind of energy. Municipal solid waste (MSW) incineration with energy recovery is largely unexplored in Brazil, which means that most of its benefits are not being utilized. Some of the incineration advantages are:

- Up to 90% volume and 75% of weight reduction (Hester & Harrison, 1994), facilitating the final disposal;
- Partial or complete destruction of toxic substances, avoiding contamination by slurry leakage;
- Smaller land occupation when compared to landfills;

Following the research of Carneiro & Gomes (2015) that have shown some thermodynamic, energetic and exergetic analysis, this work aims at evaluating different scenarios of the proposed waste-to-energy facility that could operate in a big city of Brazil, such as Rio de Janeiro. Researches from Carneiro (2015) have shown that combining both natural gas and municipal solid waste as fuels to generate electricity in a power cycle is more effective than incinerating the MSW alone because of its low energy content. Zabalgarbi WTE plant located in Bilbao (Spain) is pointed out as one of the most modern and efficient WTE facilities in the world using both fuels, and for that reason has inspired the system that is proposed in this work. The methodology includes determining the thermal efficiency, the environmental performance (based on the atmospheric emissions) and the cost estimate to build and operate the system.

2. CHARACTERIZATION OF THE SYSTEM

As described in Carneiro (2015) and Carneiro & Gomes (2015) the proposed facility is a power cycle combining a gas turbine (GT), fueled by natural gas, and a Rankine steam cycle fueled by municipal solid waste. A heat recovery boiler links the gas turbine and the steam cycle as shown in Fig. 1.

The main thermodynamic characteristics of the proposed system developed by those authors are summarized in Tabs. 1 and 2.

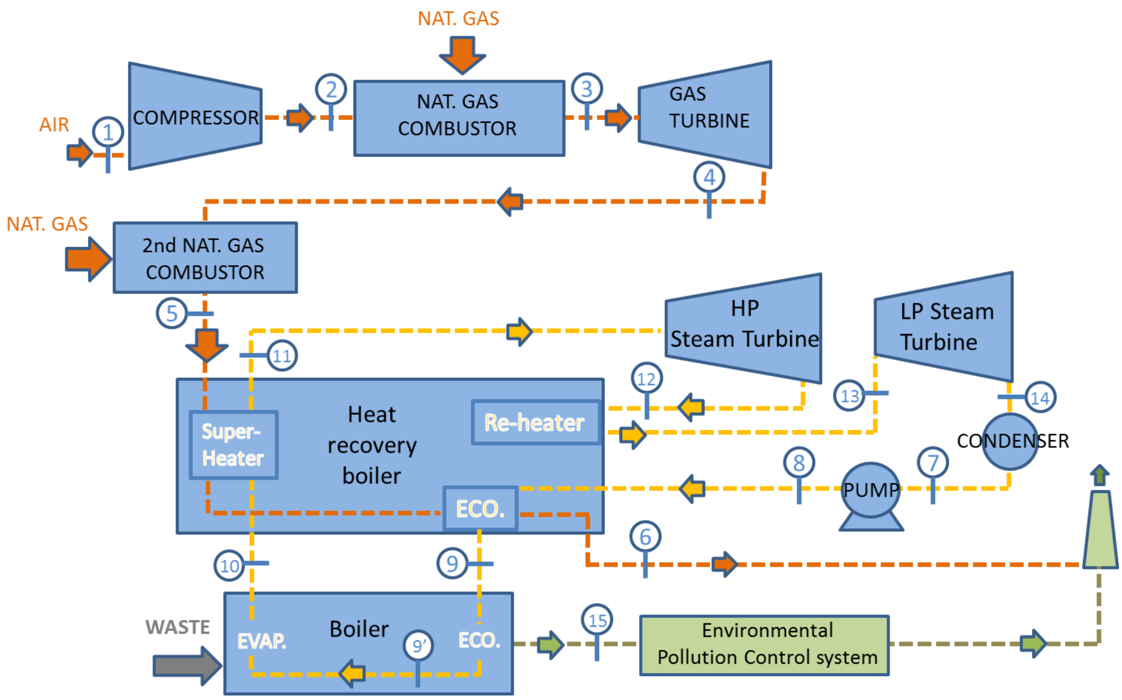

Figure 1. Diagram of the proposed waste-to-energy facility

Table 1. Thermodynamic parameters of the system

Point	T (°C)	P (bar)	h (kJ/kg)	s (kJ/kg.k)	Mass flow (kg/s)	Fluid type (state)
1	20.00	1.01	293.60	6.84	122.4	Air
2	580.70	29.39	881.73	6.99	122.4	Air
3	1233.00	29.39	1643.35	7.65	125.0	Exhaust gases[1]
4	455.00	1.31	743.90	7.71	125.0	Exhaust gases[1]
5	513.70	1.31	807.81	7.79	219.73	Exhaust gases[1]
6	150.00	1.01	424.80	7.21	219.73	Exhaust gases[1]
7	0.10	45.00	188.40	0.64	71.51	Liquid water (x=0)
8	107.00	46.00	201.90	0.65	71.51	Liquid water (saturated)
9	105.00	90.00	385.00	1.19	71.51	Liquid water (saturated)
9’	103.00	313.20	1420.00	3.38	71.51	Liquid water (saturated)
10	100.00	311.10	2725.00	5.61	71.51	Water vapour (x=1)
11	97.00	538.00	3474.00	6.74	71.51	Water vapour (superheated)
12	3.00	133.50	2706.30	6.95	71.51	Water vapour/liquid (x=0.99)
13	2.00	239.60	2950.00	7.67	71.51	Water vapour (superheated)
14	0.15	53.41	2530.60	7.81	71.51	Water vapour (x=0.97)
15	1.01	200.00	475.80	7.33	219.08	Exhaust gases[1]

(1) All exhaust gases are modelled as standard air.

Table 2. Energetic characteristics of the system (Carneiro, 2015)

Symbol	Variable	Value
LHV_{lixo}	Lower heating value of the municipal solid waste per unit mass	16000 kJ/kg (1)
m_{lixo}	MSW mass flow rate at the furnace inlet	48 t/h
W_{tgnet}	Net electrical power generated by the gas turbine	43 MW
N_{cg}	Thermal efficiency of the gas power cycle	42%
V_{gn}	Volumetric flow rate of natural gas consumed	4.9 Nm³/s
W_{TVA}	Electric power generated by the High Pressure steam turbine	55 MW
W_{TVB}	Electric power generated by the Low Pressure steam turbine	30 MW
W_{netTV}	Net electric power generated by the steam cycle	84 MW
N_{CV}	Steam power cycle thermal efficiency	26%
W_{sys}	Net electrical power generated by the system	127 MW
N_{sys}	Thermal efficiency of the system	32%

(1) The MSW LHV is an average of the values proposed by Soares (2011) and CEMPRE (2010).

3. THERMOECONOMIC ANALYSIS

3.1 Cost equations

The initial investment to purchase and install the facility can be estimated through cost equations that take into account the thermodynamic parameters of the main equipment. Different authors have proposed equations and some of them were applied to the main equipment of the proposed system as shown on Tabs. 3 to 8.

Table 3. Gas turbine (GT) power cycle cost equations.

Symbol	Variable	Equation	Source	Unit
Z_{tg1}	GT cost	$Z_{cg1} = 450*W_{tgnet}$	Boyce (2012) (1)	US$ of 2012
Z_{tg2}	GT cost	$Z_{tg2} = 300*W_{tgnet}^2 + 105900*W_{tgnet} + 6277800$	Manesh et al. (2013)	US$ of 2013
Z_{cp}	Compressor cost	$Z_{cp}=c_{11}*m_{ar1}*P_2/P_1*\log(P_2/P_1)/(c_{12}-N_{cp})$;	Frangopoulos (1994) (2)	US$ of 1994
Z_{cc}	Combustion chamber cost	$Z_{cc}=c_{21}*m_{ar1}/(c_{22}-P_3/P_2)*(1+\exp(c_{23}*T_3-c_{24}))$	Frangopoulos (1994) (2)	US$ of 1994
Z_{tg3}	GT and generator cost	$Z_{tg3}=c_{31}*m_{tg}*\log(P_3/P_4)*(1+\exp(c_{33}*T_3 - c_{34}))/(c_{32}-N_{tg})$	Frangopoulos (1994) (2)	US$ of 1994
Z_{cg3}	GT cost	$Z_{cg3}= Z_{cp}+ Z_{cc} + Z_{tg3}$	Frangopoulos (1994)	US$ of 1994

(1) Aeroderivative 40.000 kW model with 39% efficiency
(2) c_{11}=39.5 [$/(kg/s)]; c_{12}=0.9; c_{22}=1; c_{21}=25.6 [kg/s]; c_{23}=0.018 [K-1]; c_{24}=26.4; c_{31}=266.3 [$/(kg/s)]; c_{32}=0.99 (adapted); c_{33}=0.036; c_{34}=54.4; T_3= 1252 [°K]. N_{cp} and N_{tg} are the isentropic efficiencies of the compressor and gas turbine, respectively; T_3 is the fluid temperature at point 3 at GT cycle [K], P_i is the fluid pressure at point i [bar], m_{ar1} is the air mass flow rate [kg/s] and m_{tg} is the mass flow rate of the gases at the GT outlet.

Table 4. Heat recovery boiler (with supplementary firing) cost equations.

Symbol	Variable	Equation	Source	Unit
Z_{aq}	2nd combustor cost	$Z_{qa}= PCS_{gn}\ m_{gn2} / 1390 + 30\ F + 20$	Foster-Pegg (1986) (1)	Thousands US$ of 1986
C_{CR1}	HRB (without sup. firing) cost	$C_{CR1}= 5.805 – 0.1653 * \Delta T_{pp} + +0.0153*m_5$	Manesh et al. (2013) (2)	Mi US$ of 2013
Z_{cr1}	HRB (w/ sup. firing) cost	$Z_{cr1}= C_{CR1}*10^{-3} + Z_{qa}$	Manesh et al. (2013)	Thousands US$ of 1986
Z_{cr2}	HRB (w/ sup. firing) cost	$Z_{cr2}=0.11*Z_{cg} + Z_{qa}*10^3$	Silva (2004)(3)	US$ of 2004

(1) PCS_{gn} is the superior calorific power of the fuel [BTU/kg] = 47391 BTU/kg (considering PCS_{gn} = 50 MJ/kg); m_{gn2} is the mass flow rate of natural gas in the supplementary firing chamber [kg/s] and F is the number of fuels (F=1).
(2) ΔT_{pp} is the pinch point temperature difference [°C] imposed as 30°C, m_5 is the mass flow rate [kg/s] of the fluid at point 5.
(3) $Z_{cg}= (Z_{tg1}+ Z_{tg2}+ Z_{cg3})/3$.

Table 5. Steam turbines cost equations.

Symbol	Variable	Equation	Source	Unit
Z_{tv1}	Steam turbine cost	$Z_{tv1} = 57.761*(W_{tv}/4.187*3600)^{0.68} + +0.0085*(W_{tv}/4.187*3600)^{0.95}$	Silveira (1990) (1)	US$ of 1990
Z_{tv2}	Steam turbine cost	$Z_{tv2} = 6000*W_{tv}^{0.7}$	Villela (2007)	US$ of 2007
Z_{tva3}	High pressure steam turbine cost	$Z_{tva3} = 57.761*(W_{tva}/4.187*3600)^{0.68} + +0.0085*(W_{tva}/4.187*3600)^{0.95}$	Holanda (2003)	US$ of 2003
Z_{tvb3}	Low pressure steam turbine cost	$Z_{tvb3}=7490*W_{tvb}^{0.7}\{1+[(1-0.95)/(1-N_{tvb})]^3\}*\{1+5*\exp[(T_{13}-866)/10.42]\}$	Holanda (2003)	US$ of 2003
Z_{tv3}	Steam turbine cost	$Z_{tv3} = Z_{tva3} + Z_{tvb3}$	Holanda (2003)	US$ of 2003
Z_{tv4}	Steam turbine cost	$Z_{tv4}=52*(W_{tv}/265)^{0.9}$	Gomes (2001) (2)	Mi US$ 2001
Z_{tva5}	High pressure steam turbine cost	$Z_{tva5}=3000*W_{tva}^{0.7}\ g_{2\eta} * g_{2T}$	Frangopoulos (1983) (3)	US$ of 1982
Z_{tvb5}	Low pressure steam turbine cost	$Z_{tvb5}=3000*W_{tvb}^{0.7} *g_{2\eta} * g_{2T}$	Frangopoulos (1983) (3)	US$ of 1982
Z_{tv5}	Steam turbine cost	$Z_{tv5} = Z_{tva5} + Z_{tvb5}$	Frangopoulos (1983)	US$ of 1982
Z_{tva6}	High pressure steam turbine cost	$Z_{tva6}=6.191*10^6-5573*m_v-115600*P_{11}- +3.743*10^{-6}\ m_v^2+341.5\ m_v\ P_{11}+594.8\ P_{11}^2$	Manesh et al. (2013) (4)	US$ of 2013
Z_{tvb6}	Low pressure steam turbine cost	$Z_{tvb6}=3.165*10^6 + 104800*m_v + 0.01636*P_{13}$	Manesh et al. (2013) (4)	US$ of 2013
Z_{tv6}	Steam turbine cost	$Z_{tv6} = Z_{tva6} + Z_{tvb6}$	Manesh et al. (2013)	US$ of 2013

(1) W_{tv} is the power generated by the steam turbine in [kW];
(2) W_{tv} is the power generated by the steam turbine in [MW]
(3) $g_{2\eta}$ is a constant calculated through $g_{2\eta} = 1 + \{(1-0.953)/ (1-\varepsilon_{tv})\}^3$, where ε_{tv} is the exergetic efficiency of the steam turbine. $g_{2T} = 1 + 5*\exp\{(T_e-866)/10.42\}$ where T_e is the temperature at the turbine inlet [K]
(4) m_v is the steam mass flow rate [kg/s], P_{11} and P_{13} are the steam pressures at the steam turbines inlets [bar].

Table 6. Boiler cost equations.

Symbol	Variable	Equation	Source	Unit
Z_{inc1}	Boiler cost	$Z_{inc1}=2567.645*(m_v*3600)^{0.67}$	Silveira (1990)	US$ of 1990
Z_{inc2}	Boiler cost	$Z_{inc2}=183000*m_v^{0.8} * \Phi_p * \boldsymbol{\Phi_n} * \Phi_t * \Phi_s$	Frangopoulos/El Sayed (1983) (1)	US$ of 1982
Z_{inc3}	Boiler cost	$Z_{inc3}=740*y_{inc}^{0.8}* \Phi_p *g_{1n}* \Phi_t$	Frangopoulos (1983) (2)	US$ of 1982

(1) $\Phi_p=\exp[(P_{10}-28)/150]$; P_{10} is the steam pressure at the furnace outlet [bar]; $\boldsymbol{\Phi_n} =1+[(1-0.9)/(1-N_{inc})]^7$; N_{inc} is the thermal efficiency of the furnace; $\Phi_t =1+5*\exp((T_{10}-866)/10.42)$; T_{10} is the steam temperature at the furnace outlet [°K]; $\Phi_s =1 + (T_{10}-T_{10s})/T_{10}$; with $T_{10} = T_{10s}$; $\Phi_s=1$;

(2) $g_{1n}=1+[(0.45-0.405)/(0.45-\varepsilon_{inc})]^7$; ε_{inc} is the furnace exergetic efficiency; $y_{inc} = m_v*(\psi_{f10}- \psi_{f9} + v_9 *(P_9-P_{10}))$; v_9 is the specific volume of the steam at the furnace inlet [m³/kg]; P_9 e P_{10} are the pressures [bar] at the furnace inlet and outlet, respectively; ψ_f is the specific flow exergy of the steam.

Table 7. Pump cost equations.

Symbol	Variable	Equation	Source	Unit
Z_{bo1}	Pump cost	$Z_{bo1}=3*378*(y_{bomba}')^{0.71}*1.41*\{1+[(1-0.808)/(1-\varepsilon_{bomba})]^3\}$	Frangopoulos (1983)(1)	US$ of 1982
Z_{bo2}	Pump cost	$Z_{bo2}=2*387*(W_{b,is}/2)^{0.71}*1.41*\{1+[(1-0.80)/(1-N_b)]^3\}$	Frangopoulos/El Sayed (1983)(2)	US$ of 1982
Z_{bo3}	Pump cost	$Z_{bo3}=375000*(W_b/315)^{0.48}$	Silva (2004)(3)	US$ of 2004
Z_{bo4}	Pump cost	$Z_{bo4}=3540*(W_b)^{0.71}$	Villela (2007)(3)	US$ of 2007
Z_{bo5}	Pump cost	$Z_{b5}= 1000*4*(68.7/10)^{0.52}$ $Z_{motor}= 1000*0.67*(W_b / 0.7457 / 10)^{0.87}$ $Z_{bo5}= 9*Z_{b5}+ Z_{motor}$	Bohem (1987)(4)	US$ of 1987

(1) The expression was adapted, v. Carneiro (2015). ε_{bomba} is the exergetic efficiency of the pump. y_{bomba}' = $m_v/3*(\psi_{f8}-\psi_{f7})$ and ψ_f is the specific flow exergy of the fluid.
(2) The expression was adapted, v. Carneiro (2015). $W_{b,is} = m_v*v_{78}*(P_8-P_7)$ in [kW]; v_{78} is the average specific volume of water between points 7 and 8. P_8 and P_7 are the pressures [kPa] at the pump outlet and inlet, respectively; N_b is the pump isentropic efficiency.
(3) W_b is the pump power in [kW].
(4) The expressions were adapted, v. Carneiro (2015). Z_{motor} is the motor cost, Z_{b5} is the pump cost, Z_{bo5} is the pump + the motor cost.

Table 8. Condensing unit cost equations.

Symbol	Variable	Equation	Source	Unit
Z_{UC1}	Condensing unit cost	$Z_{UC1} = (217*n_c*1/U+577/c_{pw})*[(T_{14})*y_{cond}/T_{0w}/(T_{wout}-T_{win})]$	Frangopoulos (1983) (1)	US$ of 1983
Z_{UC2}	Condensing unit cost	$Z_{co2}= 1000*3*(Q_{cond}^{(2)}/10)^{0.55}$ $Z_{tr}^{(4)}=560000*(m_w*v_w^{(3)}/60/100)^{0.64}$ $Z_{wd}^{(4)}=160000*(m_w*v_w^{(3)}/1)^{0.7}$ $Z_{UC2} = Z_{co2}+ Z_{tr}+ Z_{wd}$	Bohem (1987)	US$ of 1987
Z_{UC3}	Condensing unit cost	$Z_{UC3} = 2.9*Z_{co2}$	Bartlett (1958)	US$ of 1987
Z_{UC4}	Condensing unit cost	$Z_{co4}=3000*(Q_{cond}/10)^{0.6}$ $W_{wb}=m_w*v_w * (P_{win}-P_{wout})/ N_b$ $Z_{br}=375000*(W_{wb} / 315)^{0.48}$ $Z_{UC4} = Z_{co4} + Z_{br}$	Silva (2004)(5)	US$ of 2004

(1) U=10000 W/m².K; T_{0w} is the cooling water temperature in the environment [K]; T_{win} and T_{wout} are the cooling water temperature at the inlet and outlet, respectively; m_w is the cooling water mass flow rate [kg/s]; $y_{cond} = m_v*T_{0w}*(s_{14}-s_7)$; $n_c= \ln [(T_{14}-T_{win})/(T_{14}-T_{wout})]$ and c_{pw} is the specific heat of the cooling water.
(2) $Q_{cond} = m_v (h_{14}-h_7)$; Z_{co2} is the steam condenser cost.
(3) v_w is the specific volume of the cooling water at the condenser inlet.
(4) Z_{tr} is the cooling tower cost; Z_{wd} is the water distribution cost from/to the cooling tower.
(5) Pressures are in [kPa]. N_b = 0.8; Z_{br} is the cost of the water pump; W_{wb} is the power of the water pump [kW] and m_w is the cooling water mass flow rate in [kg/s].

3.2 Costs update

The mathematical equations to estimate the purchase costs of the main equipment are not up-to-date. According to Bohem (1987), the factor that has the greatest influence on the market prices over time is the inflation/deflation. In this sense, the following equation allows to update the costs obtained from the previous equations.

$$Cost\ X = \frac{Index\ X}{Index\ Y} Cost\ Y \tag{1}$$

Where:
Cost X = cost on the date of interest; *Cost Y* = cost on the reference date;
Index X = index on the date of interest; *Index Y* = index on the reference date.
The index used by the US Inflation Calculator (2015) is the Consumer Price Index (CPI), as presented by Carneiro (2011).

3.3 Evaluated scenarios

3.3.1 Equipment costs

As described in Carneiro & Gomes (2015) based on the methodology described by Villela (2007), the Ecological Efficiency (EE) of the proposed system is 89%. Equation (2) determines the cost of all the main equipment of the proposed waste-to-energy facility, including the environmental control system accounted indirectly through EE:

$$Z_{equip} = \left(Z_{cg} + Z_{tv} + Z_{bb} + Z_{inc} + Z_{UC} + Z_{cr}\right)/EE \tag{2}$$

Where: Z_{equip} is the cost of the main equipment of the system, Z_{cg} is the cost of the gas power cycle equipment; Z_{tv} is the cost of the steam turbine; Z_{bb} is the cost of the pump; Z_{inc} is the cost of the boiler in the waste furnace; Z_{UC} is the cost of the condensing unit, Z_{cr} is the cost of the heat recovery boiler and EE is the ecological efficiency.

Three scenarios were analyzed:
- **Minimum cost**: is the scenario that considers the lowest equipment costs obtained from the cost equations;
- **Medium cost**: is the scenario that considers the average equipment costs obtained from the cost equations;
- **Maximum cost**: is the scenario that considers the highest equipment costs obtained from the cost equations.

Figure 2 shows the equipment costs (in millions of US$ of 2015) for each scenario. CG corresponds to Z_{cg}, UC to Z_{UC}, BB to Z_{bb}, CR to Z_{cr}, INC to Z_{inc}, TV to Z_{tv} and CPA to the cost of the environmental pollution control equipment.

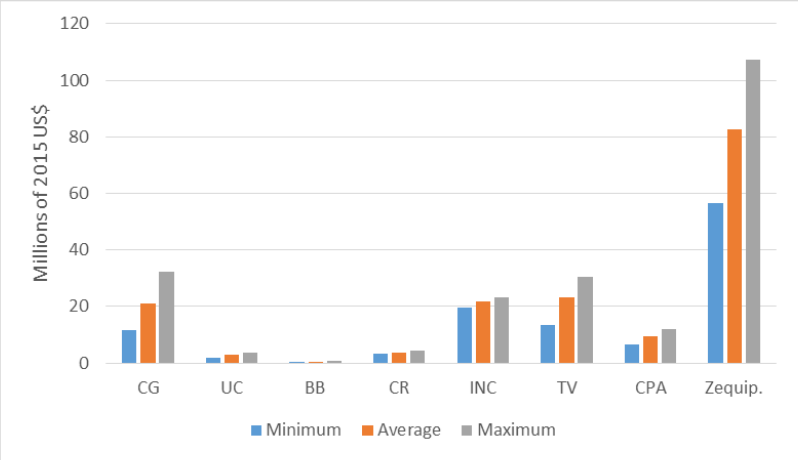

Figure 2. Equipment costs of the proposed facility in the three analyzed scenarios (minimum, maximum and average cost).

3.3.2 Total initial investment

The second step of an economic analysis is estimating the total capital to be invested on the facility building (Z_{in}). It includes direct and indirect costs such as installation, tubing, instrumentation, engineering, etc. According to Silveira (1990) and Branco (2005), Z_{in} is twice the cost of the main equipment; i.e., $Z_{in} = 2*Z_{equip}$. Figure 3 shows the minimum and maximum Z_{in} of the proposed facility compared to other existing/proposed facilities.

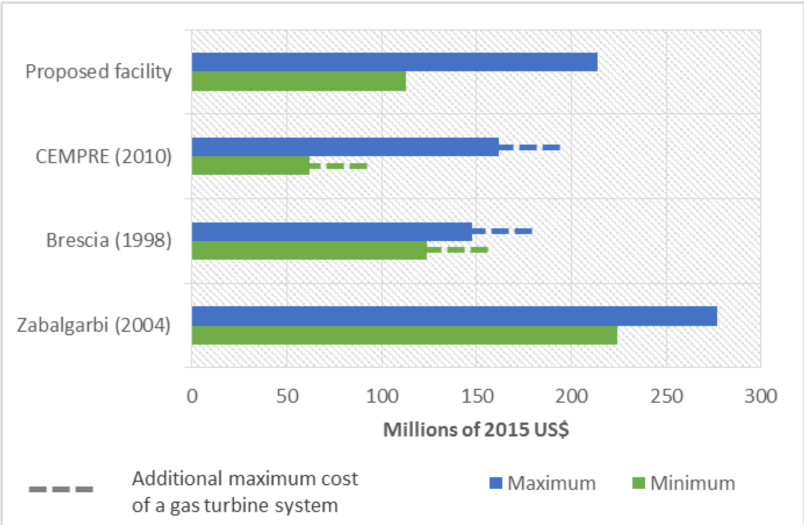

Figure 3. Total initial investment (Z_{in}) of the proposed facility (maximum and minimum scenarios) compared to the existing facilities (Zabalgarbi and Brescia) and to the theoretical WTE facility proposed by CEMPRE.

Z_{in} is between US$ 113 and 214 million, which is equivalent to US$ 285-542 per ton of MSW. This value is competitive with the existing European facilities of Brescia and Zabalgarbi, which present US$ 314-374 and US$ 567-702 per ton of MSW, respectively. The facility proposed by CEMPRE is the only Brazilian plant, but it does not include the combustion of additional fuel (it considers MSW as the only fuel), which may explain the lower investment value observed in Fig. 3. If the cost of a gas turbine system (around US$ 30 million) was added to both the minimum and maximum scenarios of the facility proposed by CEMPRE, it can be observed from Fig. 2 (dashed lines) that its Z_{in} becomes similar to the one of the proposed facility.

3.4 Maintenance and operation cost

In general, initial economic assessments of thermal power plants estimate the cost of operation (Z_{op}) and maintenance (Z_{man}) as a percentage of the initial capital investment. In this work we assume Z_{man} = 5.5%*Z_{in} and Z_{op} = 2%*Z_{in} [US$/year]. Additionally, it should be considered the cost of the separation of recyclable materials (e.g. batteries, metals) and the disposal of non-combustible residues (e.g. flying and bottom ashes) on hazardous and non-hazardous landfills. The estimated annual cost of the ash disposal in regulated landfills is C_{dest} = US$ 2 million.

3.5 Electricity generation cost

As described in Carneiro (2015) and Carneiro & Gomes (2015), the cost of 1 MWh of electricity produced (CG [US$/MWh]) in the proposed facility can be estimated through the following equation:

$$CG = 1000\left(\frac{Z_{am} + Z_{op} + Z_{man} + C_{dest}}{H_r\, W_{sys}} + \frac{Q_{fuel}\, C_{fuel}}{W_{sys}} \right) \tag{3}$$

The variables in Eq. (3) that were not mentioned so far are C_{fuel} = 0.0095 US$/kWh (cost of the natural gas), Q_{fuel} = 181 MW (thermal power of natural gas), H_r=8270 h (number of operating hours per year) and the amortization cost, which is calculated as Z_{am} = f*Z_{in} (where f = 0.191 [dimensionless] is the capital recovery factor). The only costing fuel is the natural gas, since the MSW is considered as a free fuel. The CG values in the three evaluated scenarios are given in Tab. 9.

Table 9. Electricity production costs in the proposed facility at the evaluated scenarios.

Minimum cost scenario (CG_{Min})	Average cost scenario (CG_{Med})	Maximum cost scenario (CG_{Max})
44,06 [US$/MWh]	57,36 [US$/MWh]	69,77 [US$/MWh]

4. COMPARISON WITH OTHER ENERGY SOURCES

An interesting information involves comparing the electricity generation cost of the proposed facility with other power generating plants, such as the ones powered with natural gas, biomass and other renewable power systems. An indicator that allows this comparison is the *Benefit Cost Index* (translation to the Brazilian term "Índice de Custo Benefício" – ICB). In Brazil, a complex methodology[1] regulates the calculations of the ICB in real power plants. For the purpose of this work a simplified approach is assumed and the ICB (US$/MWh) is estimated as the ratio between the total electricity production cost and the generated electric power.

Figure 4 shows the ICB obtained for the three evaluated scenarios compared with other power sources. It is important to highlight that Fig. 4 has the purpose of showing an order of magnitude for comparison between different power sources and the proposed facility. Before drawing further conclusions more studies are necessary.

[1] ICB complete calculation methodology is described on the technical report Nr. EPE-DEE-RE-102/2008-r5: "Índice de Custo Benefício (ICB) de Empreendimentos de Geração" by EPE (http://www.epe.gov.br.).

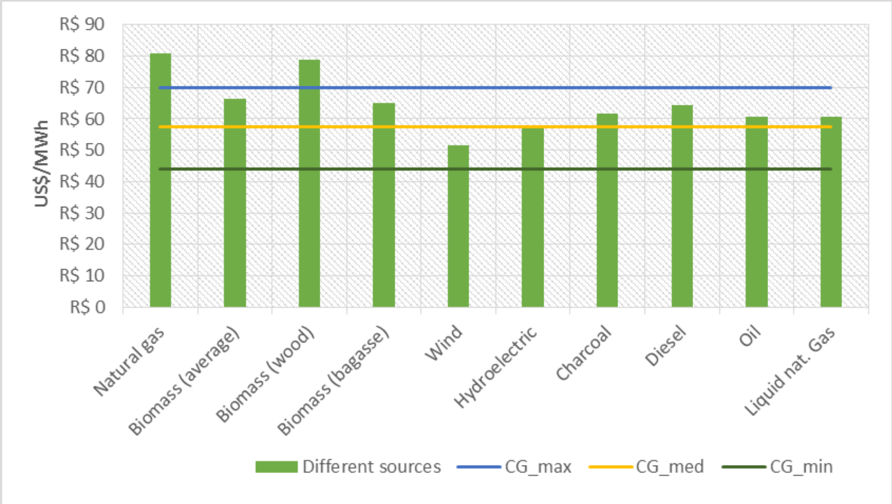

Figure 4. Benefit Cost Index (ICB) [US$/MWh] of the proposed facility (three generation cost scenarios: maximum [CG_max], minimum [CG_min], average [CG_med]) compared with other energy sources (Carneiro, 2015)

Part of the electricity production cost is associated with the fuel cost, which is variable and depends, among others, on the market conditions. Hence, another indicator can be used to measure this kind of cost, i.e., the *Unitary Variable Cost* (translation to the Brazilian term "Custo Variável Unitário" - CVU), measured in US$/MWh. Assuming in a simplified form that CVU = CG - Z_{am}; Fig. 5 shows the CVU values obtained for the proposed facility in the maximum CG scenario compared to other power plants. It is interesting to notice on Fig. 5 that the obtained CVU is around 50% lower than the one of a power plant fueled 100% with natural gas. This result makes sense, since, as described in Carneiro (2015) and Carneiro and Gomes (2015), approximately 50% of the net electrical power generated in the proposed facility comes from the free fuel (MSW).

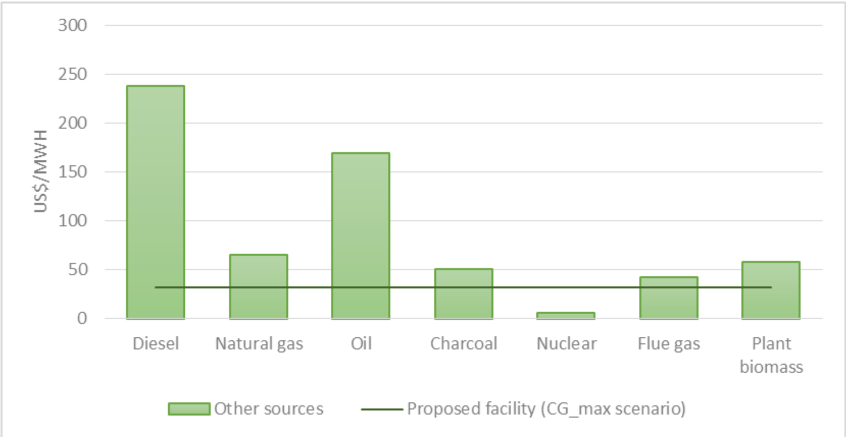

Figure 5. Unitary Variable Cost (CVU) [US$/MWh] of the proposed facility compared to other energy sources (July 2015)

It is also interesting to evaluate the relation between the electricity cost of the proposed facility and the natural gas price. As shown on Fig. 6, a raise of the costing fuel price results in a proportional increase of the electricity generation cost.

4. CONCLUSION

As observed from Fig. 4, the ICB of the proposed facility in the minimum scenario is smaller than all other sources, which may indicate that this scenario is underestimated. In the average scenario, the ICB is higher than the one presented by wind and hydroelectric sources but lower than all other sources. This result is expected since wind and water are free fuels and the WTE facility has around 50% of its fuel coming from a free source. The average and maximum ICBs show that the electricity produced in the proposed waste-to-energy facility is competitive with the energy produced in power plants fueled with biomass and natural gas. Finally, the CVU obtained in the maximum scenario is very competitive with all other sources, except nuclear. The cost of the electricity generated in the proposed facility is very dependent on the price of the natural gas (its single costing fuel), i.e., as observed from Fig. 6, tripling the natural gas price increases the CG 1.4 times and doubles the CVU of the proposed facility.

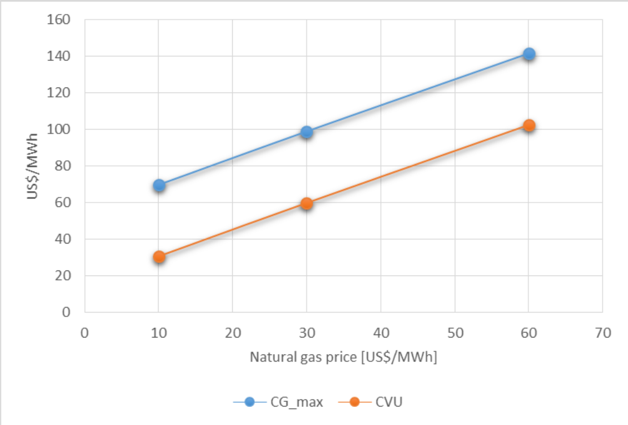

Figure 6. Unitary Variable Cost (CVU) and total generation cost (CG maximum scenario) [US$/MWh] variation with natural gas price

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5. RESPONSIBILITY NOTICE

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