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THERMODYNAMIC STUDY OF A SYSTEM FOR THE ENERGY RECOVERY OF MUNICIPAL SOLID WASTES

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Abstract. *The accelerated process of urbanization in addition to the increasing consumption of durable and/or disposable goods has caused substantial increase in the volume and diversification of solid waste generated by the population. Thus, the cost of managing this waste has become a task that demands differentiated and coordinated actions. The challenge is to find environmentally and efficiently solutions for waste generation problems in large quantities. One of the strategies for the waste management is its energy use. Since the 1980s, several countries in Europe, North America and Japan use energy from solid waste for various purposes, among which the generation of electricity. This transformation would have two beneficial effects: the first is to encourage the correct storage of waste, which become a raw material. The second is to use waste as a renewable energy source, which can generate carbon credits and help Brazil in the negotiations on climate change. The generation of credits is due to methane burning, natural product of organic decomposition. This work aims to study through thermodynamic analysis the energy use of municipal solid wastes. First, a physico-chemical study of the characteristics of MSW of two cities in the state of Minas Gerais will be performed. After, the calculation of the lower heating value and the use of MSW in incineration system using a mass burning boiler for the generation of electricity will be accomplished. The results show that the MSW can be a sustainable alternative for power generation in Brazil.*

Keywords: *Energy use, solid waste management, technical analysis, renewable resource.*

1. INTRODUCTION

According to the Brazilian law number 12305 of 08/02/2010, municipal solid waste (MSW) are defined as materials, substances, objects or goods discarded resulting from human activities in society, whose final destination is carried in solid or semi-solid and gases in containers and liquid whose characteristics make it impossible to launch the public sewage system or water bodies, or to require that technical or economically unviable solutions face the best available technology.

Generally, MSW are classified as organic (animal and plant origin) and inorganic (metals, glass, rubber and plastics). Its quantity and composition vary from population to population, according habits and customs. However, some studies allow an estimate of MSW generation per capita based on the number of inhabitants, as shown in Table 1.

Table 1. Average of municipal solid waste generation per capita in Brazil (ABRELPE, 2011).

Size of the City	Urban Population	*Per Capita* Generation
Small	Until 30 thousand	0.50
Medium	30 thousand to 500 thousand	0.50 to 0.80
Large	500 to 5 millions	0.80 to 1.00
Metropolis	> 5 millions	> 1.00

With the civilization growth, the population from rural areas migrated to urban areas, creating new cities with urban characteristics, which resulted in an increase in the amount of solid waste generated in these regions. In 1950, approximately 35% of the population was located in urban territory, while about 65% were located in rural areas. This scenario has been reversed since the middle of 1960 decade.

As in all parts of the world, Brazil also faces problems with the generation and consequent allocation of MSW, being necessary to analyze the current situation of the country in order to find solutions which minimize such impacts. In this scenario, the Brazilian law number 12305, the National Policy on Solid Waste (NPSW) was created. The NPSW join together the principles, objectives, instruments, policies, goals and actions taken by the Federal Government by itself or in cooperation arrangements with states, Federal District, municipalities or individuals, aimed to the integrated management and appropriate environmentally management of solid waste. Among its significant points, it can be highlighted the closing of dumps and the final disposal of solid waste by 2014; the elaboration of municipal plans of solid waste in order to guide municipalities and citizens on the proper management of waste; and the preparation of sectorial agreements involving the entire chain of generation and consumption, for the implementation of the shared responsibility for the product lifecycle (ANEEL, 2012).

NPSW directly influences the development of new opportunities for the deployment of biogas capture projects in landfills, with the consequent generation of energy and reducing emissions of greenhouse gases (GHG), offering great opportunities.

One of the alternatives for disposal of such waste is the landfill, which in addition to proper waste disposal, aimed at the use of the biogas produced, which allows greater efficiency in the production and collection of methane generated during the degradation of organic matter present in the waste.

As alternatives that enable the use of biogas in landfills, it can be mentioned the biogas use in Otto cycle engines and microturbines; as vehicle fuel; as fuel in steam cycles (Rankine) and manure treatment; and gas lighting.

Another process developed for the MSW treatment that stands out is incineration. This is a process of burning at high temperature that can reduce the volume by approximately 95% of the initial weight and about 90%, taking advantage of the lower heating value of the fuel present in the waste to steam generation in a boiler. Among the types of boilers using MSW as the fuel are the fixed or movable grate and the fluidized bed boiler. Incineration is the most common Waste-to-energy (WtE) implementation. All new WtE plants in OECD countries incinerating waste (residual MSW, commercial, industrial or RDF) must meet strict emission standards, including those on nitrogen oxides (NO_x), sulphur dioxide (SO_2), heavy metals and dioxins (Europe Union, 2011, 2000). Hence, modern incineration plants are vastly different from old types, some of which neither recovered energy nor materials.

Waste-to-energy (WtE) is the process of generating energy in the form of electricity and/or heat from the incineration of waste. Most WtE processes produce electricity and/or heat directly through combustion, or produce a combustible fuel commodity, such as methane, methanol, ethanol or synthetic fuels.

The method of using incineration to convert municipal solid waste (MSW) to energy is a relatively old method of WtE production. Incineration generally entails burning waste (residual MSW, commercial, industrial and RDF) to boil water which powers steam generators that make electric energy and heat to be used in homes, businesses, institutions and industries. One problem associated with incinerating MSW to make electrical energy, is the potential for acidic pollutants to enter the atmosphere with the flue gases from the boiler. Since 1980, the industry has removed this problem by the use of lime scrubbers and electro-static precipitators on smokestacks. Many other devices such as fabric filters, reactors and catalysts destroy or capture other regulated pollutants. According to Rosenthal (2010), modern incineration plants are so clean that “many times more dioxin is now released from home fireplaces and backyard barbecues than from incineration.” According to the German Environmental Ministry (2005), “because of stringent regulations, waste incineration plants are no longer significant in terms of emissions of dioxins, dust, and heavy metals”.

In addition, another widely used process is gasification. Gasification is a process that can convert any carbon based raw material to the fuel gas, also known as synthesis gas. Gasification is actually a partial oxidation process. The gasification typically uses only 25 to 40% of the oxidizing gases (air or pure oxygen) to generate enough heat to gasify the fuel remaining unoxidized, producing the syngas.

2. MSW LOWER HEATING VALUE

The lower heating value (LHV) of each component can be found in the laboratory or in the literature using statistical data. According to literature provided by The World Bank (1999), LHV can be calculated by Eq. (1):

$$LHV = LHV_{LAC} \times M_{AC} - 2445 \times W \ (kJ/kg) \quad (1)$$

Where: LHV is the lower heating value to be calculated; LHV_{LAC} is the lower heating value of the fuel fraction (free of water and ash); M_{AC} is the weight of condensed water per kg of sample, W is the moisture content. LHV_{LAC} value is calculated by using an elemental analyzer or by Eq. (2):

$$LHV_{LAC} = LHV_{AS} / ((1-A) \times M_{AC} \times 2445)(kJ/kg) \quad (2)$$

Where: LHV_{AS} is the lower heating value of the dry sample; A is the ash content per kg of dry sample. LHV_{AS} value is calculated through an adiabatic calorimetry pump.

The MSW composition was used to calculate the lower heating value. These data are from ABRELPE (2013) and RMBH Agency and Minas Gerais State Government (2013). The results of the lower heating values (LHV) of two cities in Minas Gerais state (Betim and Belo Horizonte), are presented in Table 2.

Table 2. Results of the lower heating values of two cities in Minas Gerais state.

City of Betim					
MSW Collected	**% of waste**	**% of carbon**	**% of moisture**	**LHV_{LAC} [kJ/kg]**	**LHV [kJ/kg]**
Organic	54	48.0	10	17,000	3482.19
Metals and Other	12	4.5	2	0	-5.87
Plastics	16	60.0	0.2	33,000	3167.22
Paper and cardboard	13	44.0	10.2	16,000	882.78
Textiles	4	55.0	10	20,000	430.22
Rubber	1	10.0	10	23,000	20.56
				LHV Total	**7977.09**
City of Belo Horizonte					
Organic	52	48	70	17,000	3353.22
Metals and Other	16.6	4.5	2	0	-8.12
Plastic	16	60	0.2	33,000	3167.22
Paper	10	43.5	10.2	16,000	671.06
Wood	3	6	1.5	17,000	29.50
Textiles	2	55	10	20,000	215.11
Rubber	0.4	10	10	23,000	8.22
				LHV Total	**7436.21**

3. METHANE GENERATION

According to CETESB (2003) there are several methods to calculate the amount of methane generated from cruder methods to methods that take important parameters into account, such as weather conditions, concentration of nutrients in the soil and waste composition.

In this work, a methodology for calculating the methane emission from solid waste in specific countries or regions, the methodology of IPCC (Intergovernmental Panel on Climate Change), is presented by Eq. (3). For this calculation, it is needed the statistical data of population and MSW. If there is no available data for the calculation, standardized data provided by the IPCC may be used; however, the quality of the result may be impaired.

$$Q_{CH4} = (Pop_{urb} \times Taxa_{RSD} \times RSD_f \times L_0) / \rho_{CH4} \quad (3)$$

Where: Q_{CH4} is the rate of methane generation [m³ CH_4/year]; Pop_{urb} is the number of inhabitants in an urban area [inhabitants]; $Taxa_{RSD}$ is the rate of solid waste generation per inhabitant per year [kg of MSW/inhabitant.year]; RSD_f is the fraction of household waste that is deposited in solid waste disposal sites [%]; ρ_{CH4} is the specific mass of methane [kg/m³], which for calculation purposes, it was used the value 0.740 kg/m³, for the temperature of 25°C and 1 atm. L_0 is the potential to waste generating methane [kg of CH_4/kg of MSW] and can be computed from Eq. (4):

$$L_0 = FCM \times COD \times COD_f \times F \times 16/12 \quad (4)$$

Where: FCM is the correction factor of methane; COD is the degradable organic carbon [kg of C/kg of MSW]; COD_f is the dissociated degradable carbon fraction [%]; and F is the volume fraction of methane in biogas [%].

According to CETESB, methane correction factor (MCF) varies depending on the type of place. IPCC (1996) defines four categories of places: inadequate landfill or dump (FCM of 0.4), controlled landfills (FCM of 0.8) suitable landfills or landfill (FCM of 1.0) and landfills unrated (FCM of 0.6). Since the calculation of the amount of degradable carbon (DOC) is based on the waste composition and the amount of carbon in each component of the waste mass. Table 2 shows the value of COD for some components of municipal solid waste.

Table 3. Values for the amount of degradable carbon (USEPA, 1997).

Component	COD (% mass)
A - Paper and cardboard	40
B - Waste of parks and gardens	17
C - Food Remains	15
D - Textiles	40
E - Wood	30

Equation (5) is used to calculate *COD*:

$$COD = (0,40 \times A) + (0,17 \times B) + (0,15 \times C) + (0,40 \times D) + (0,30 \times E) \quad (5)$$

Where: *COD* is the degradable organic carbon [kg de C/kg de RSD]; *A* is the paper and cardboard fraction in the waste; *B* is the fraction of parks and gardens; *C* is the food scraps fraction; *D* is the tissue fraction; *E* is the wood fraction in the municipal waste.

The fraction of dissociated *COD* (COD_f) denotes for the fraction of available carbon for biochemical decomposition, and can be obtained from Eq. (6):

$$COD_f = 0,014 \times T + 0,28 \quad (6)$$

Where: COD_f is the fraction of dissociated COD [%]; T is the temperature in the anaerobic zone [°C].

For a more detailed assessment of the methane generation in landfills, methods that take the generation of biogas over the years into account are recommended. The two methods used here are from IPCC and the USEPA (United States Environmental Protection Agency): method of design and theoretical first order decay methodology. Both methods use the methane generation rate constant (k). The methane generation rate constant is a function of factors such as nutrient availability, pH, temperature and especially humidity. The k values are shown in Table 4.

Table 4. Suggested values for the methane generation rate constant (IPCC, 1996).

Boreal and temperate climate zone				Tropical climate zone			
Average annual temperature ≤ 20°C				Average annual temperature ≥ 20°C			
Dry		Wet		Dry		Wet	
Average annual rainfall < 1 mm		Average annual rainfall > 1 mm		Average annual rainfall < 1000 mm		Average annual rainfall ≥ 1000 mm	
Default	Range	Default	Range	Default	Range	Default	Range
0,05	0,05 – 0,06	0,09	0,08 – 1,0	0,065	0,05 – 0,08	0,17	0,15 – 0,2

The design method is recommended for landfills in the design phase, because it is unknown what will be the annual flow of waste. This method is divided into two stages, the part where the landfill receives waste materials and after its closure. While the landfill is opened, the kinetic term ($e^{-k.c}$) will be equals 1. After the landfill is closed, this term should be considered.

Equation (7) calculates the methane generation during the time of receiving waste.

$$Q = F \times R \times L_0 \times (1 - e^{-k \times t}) \quad (7)$$

Equation (8) calculates the methane generation after landfill closure.

$$Q = F \times R \times L_0 \times (e^{-k \times c} - e^{-k \times t}) \quad (8)$$

Where: *Q* is the methane generation rate [m^3 of CH_4/year]; *F* is the methane fraction in biogas [%]; *R* is the average annual waste acceptance rate during active life [ton/year]; L_0 is the methane generation potential [m^3/ton of refuse]; *k* is the methane generation rate constant [$year^{-1}$]; c is the time since solid waste disposal sites (SWDS) closure [years]; t is the time since SWDS opened [years].

The theoretical first order decay methodology considers the methane generation of an amount of waste deposited in year "*x*" during the next years. As every year, new quantities of waste are deposited, the amount of methane generated in a given year is equal to the generation of waste deposited in the year "T" plus the generation of waste landfilled in previous years, the year referenced "T" as shown in Eq. (9):

$$Q_T = F \times R_x \times k \times L_0 \times e^{-k \times (T - x)} \quad (9)$$

Where: Q_T is the total emissions in year *T* from waste disposed of in previous years (including year *T*) [m^3/year]; *F* is the methane fraction in landfill gas [%]; R_x the amount of waste deposited in the year *x* [kg]; k is the methane generation rate constant [$year^{-1}$]; L_0 the methane generation potential [m^3/ton of refuse]; *T* is the current year; *x* is the year of waste input.

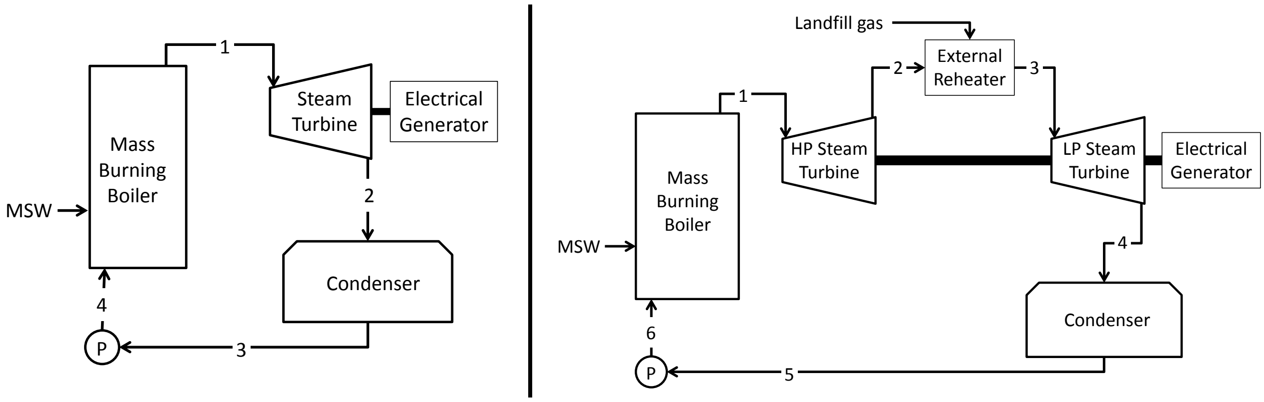
The waste disposed annually (R_x) is variable and depends on factors such as population growth rate, MSW rate produced per inhabitant per year and the percentage of waste that is collected and disposed in the landfill. Equation (10) estimates the sum of the corresponding methane flow quantities of waste deposited in the landfill every year.

$$\sum Q_T = F \times k \times L_0 \times \sum Rx \times e^{-k \times (T - x)} \quad (10)$$

Therefore, using this estimate, the methane emissions from landfill is obtained every year throughout its useful life and after its closure.

4. RANKINE CYCLES

The studied cycle in this work is the steam cycle (Rankine cycle) using MSW as the fuel. A mass burning boiler is used along with a steam turbine, condenser and pump. Figure 1 shows the flow diagram of the two scenarios considered.



(a) Base scenario (b) Scenario 2

Figure 1. Rankine Cycle Scenarios studied: (a) base scenario and (b) scenario modified.

Two scenarios studied in this work were:

- ***Base Scenario*** which consists of a mass burning boiler (thermal efficiency of 90%, working pressure of 4.2 MPa and 420°C) associated to a condensing steam turbine (isentropic efficiency of 80%), condenser operating at 15 kPa. The MSW flow rate is set to 10 ton/h.

- ***Scenario 2*** which consists of a mass burning boiler (thermal efficiency of 90%, working at a higher pressure of the base scenario, 8.2 MPa and 420°C), an external reheater (which reheat the LP steam to 400°C using landfill gas as the fuel), a high pressure (isentropic efficiency of 82%) and low pressure (isentropic efficiency of 75%) turbines, condenser operating at 15 kPa and pump. The MSW flow rate is set to 10 ton/h.

According to Themelis (2003), the waste is fed into the mass burning boiler using a grate-fired system that is the most common technology of MSW incineration. The temperature of the superheated steam (420°C) is limited due to the possibility of corrosion caused by chlorine content of some materials found in the MSW. This limitation is the main cause of the low efficiency in the Rankine Cycle (Ma *et al.*, 2010). The superheated steam goes to the steam turbine (base scenario) or the high pressure steam turbine (scenario 2) where it undergoes an expansion to 0.015 MPa (base scenario) or an expansion to 2.3 MPa (scenario 2). In scenario 2, the reheater heats up the working fluid to 400°C using landfill gas as the fuel and then the fluid undergoes an expansion to 0.015 MPa in the lower pressure steam turbine.

5. RESULTS AND DISCUSSION

Figures 2 and 3 show the results of MSW generation and landfill gas for the cities of Belo Horizonte and Betim, respectively. In the figures, one can observe a global and usable methane generation in the landfill. The MSW generation in Belo Horizonte is higher than in Betim, which results in a higher global and usable methane generation. The data contained in figures 2 and 3 and in Table 2 are inputs for the electricity generation in the two scenarios studied. Figure 4 shows the results of electrical power generation and efficiency of the Rankine cycles proposed. In this figure, one can observe that, in the case of Belo Horizonte, a Rankine Cycle contained two steam turbines (HP and LP) and a reheater using landfill gas is more appropriated. In the case of Betim, because of the lower MSW generation, it is recommended a simple Rankine Cycle.

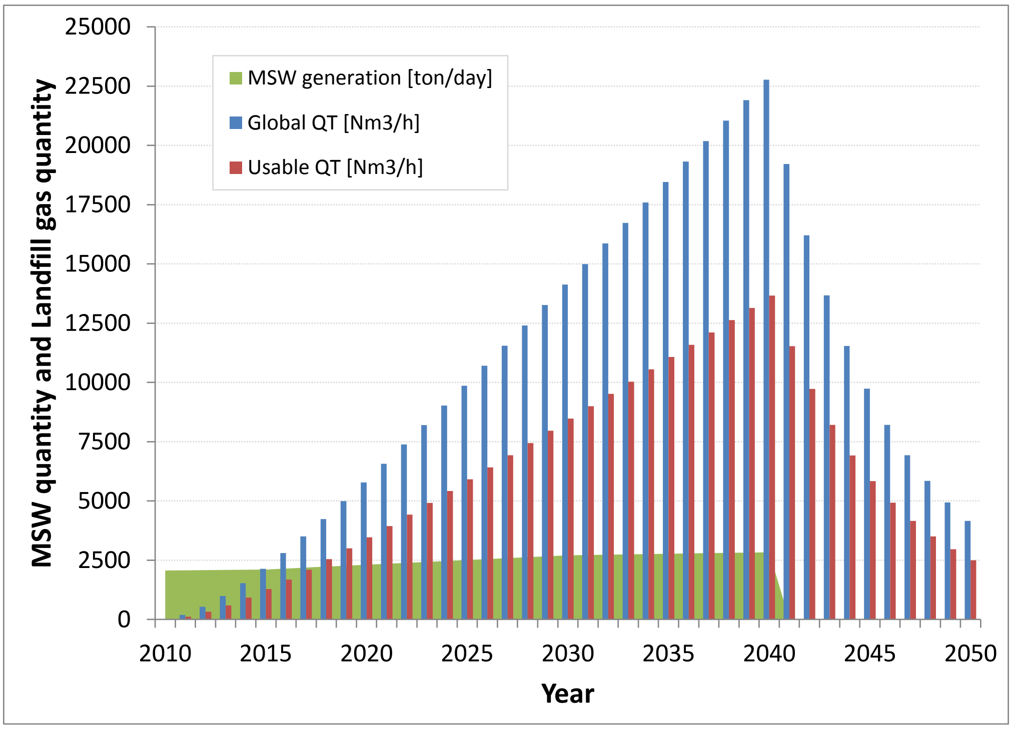


Figure 2 – Results of MSW generation and Landfill gas for Belo Horizonte city.

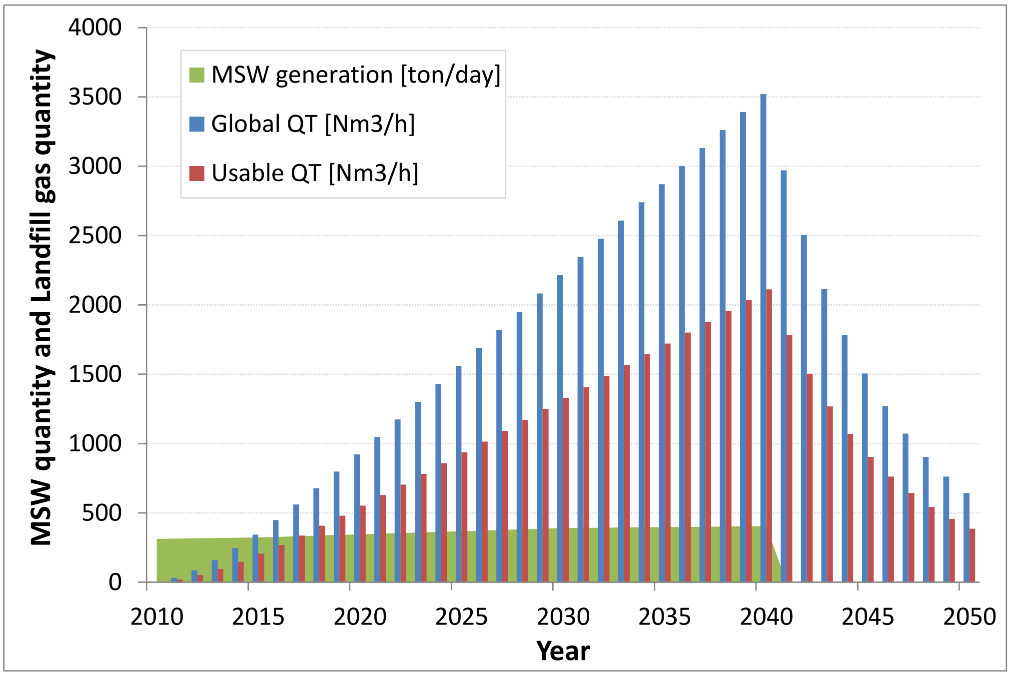


Figure 3 – Results of MSW generation and Landfill gas for Betim city.

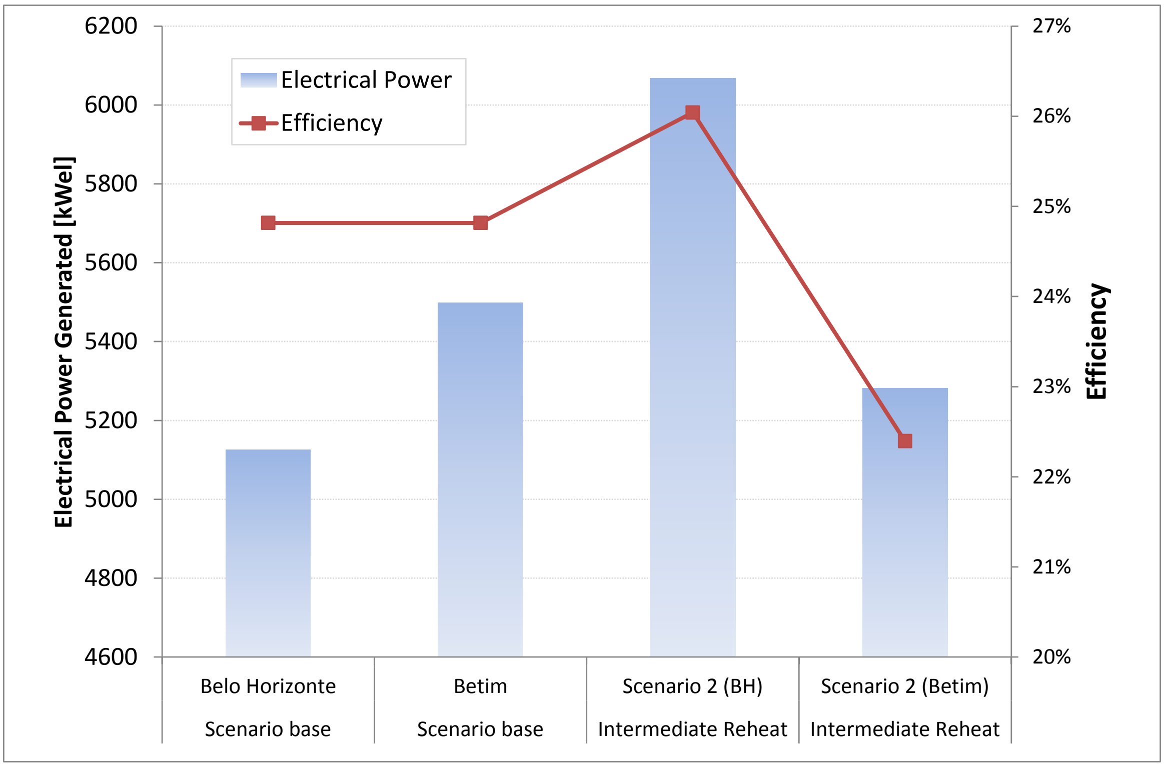


Figure 4 – Results of electrical power generation and efficiency for the base scenario and scenario 2.

6. CONCLUSIONS

Waste-to-Energy technologies are able to convert the energy content of different types of waste into various forms of valuable energy. Power can be produced and distributed through local and national grid systems. Heat can be generated both at high and low temperatures and then distributed for district heating purposes or utilized for specific thermodynamic processes. Several types of biofuels can be extracted from the organic fractions of waste, in order to be then refined and sold on the market. As of today, the most common and well-developed technology is in the form of Combined Heat and Power plants, which treat Municipal Solid Waste - and possibly a combination of industrial, clinical and hazardous waste, depending on the system settings - through an incineration process.

By definition, waste incineration is carried out with surplus of air. This process releases energy and produces solid residues as well as a flue gas emitted into the atmosphere (Hulgaard and Vehlow, 2011). Because of emission and safety concerns, there is a certain temperature range that is demanded for this type of process.

In this paper, a study of the MSW incineration and the electricity generation through steam cycles taking into account the influence of MSW composition adopting two scenarios was accomplished. First, the data of the amount and composition of waste of two cities in the state of Minas Gerais (Belo Horizonte and Betim) were collected for the calculation of the lower heating value of the waste. Through the model presented by IPCC and USEPA, a usable and total methane generation was calculated. These data were used in an energy analysis of a power generation system using a mass burning boiler and a steam turbine. Two scenarios were studied: one containing a simple Rankine cycle and the other containing a Rankine cycle with intermediate reheating. The results showed that the use of MSW in a WtE plant can be a technically viable alternative for the production of electricity.

7. ACKNOWLEDGEMENTS

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9. RESPONSIBILITY NOTICE