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EVALUATION OF THE TECHNICAL FEASIBILITY OF THE USE OF BIOGAS OF LANDFILL FOR GENERATION OF ELECTRICAL ENERGY ACCORDING TO DIFFERENT ENERGY CONVERSION TECHNOLOGIES

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Abstract. *It is verified that urbanization processes have occurred in a disorderly way, especially in developing countries, and are characterized as among the most aggressive forms of human interaction with the environment, requiring more services of energy and of infrastructure. In Minas Gerais, the majority of the population lives in cities, making clear the need for proper management of resources, especially energy resources, and adequate disposal of municipal solid wastes (MSW), since the patterns and levels of consumption tend to increase. In this context, a real possibility is the use of landfill biogas, that brings together solutions for both MSW management and electric power generation, providing an increase in the variety of renewable energy sources in the electrical matrix. In this way, this work presents the state of the art of the production of landfill biogas in the State of Minas Gerais and performs a projection of the state total potential of electric power generation from this source, considering four technological routes for energy conversion: internal combustion engines of "Otto cycle", diesel engines, gas turbines and microturbines. The results obtained will demonstrate that the use of engines as energy conversion technology presents the greatest feasibility for the implementation of projects of this type, reaching theoretical values of generation of up to 2,163.74 TWh/year in 2050.*

Keywords: *Municipal Solid Waste, Landfill Biogas, Electrical Energy, Energy Conversion Efficiency.*

1. INTRODUCTION

The cities are growing in a disorderly way and their structure limits have been exceeded, eventually leading to economic, social and environmental problems. According to Avaci *et al*. (2013), for the next decades, regarding the energy sector, the expectations are of crisis, mainly due to the population growth and the barriers found in guaranteeing an energy supply that accompanies the growth and expansion of the world's Gross Domestic Product (GDP). Thus, EPE (2008) expresses that energy consumption has a very close relation with GDP growth, which becomes more pronounced as the share of the industrial sector increases, whether in the economy or the consumption of electric energy. Within this context, Avaci, *et al*. (2013) and Deublein (2008) discuss the strong trend in increasing the search for alternative sources of renewable energy, due to higher costs for conventional energy sources, especially those of fossil origin, as well as Governments preoccupation with the issue of Energy Security. This scenario is a window of opportunity for the development and effective implementation of alternative sources of energy, with emphasis on renewable sources, which puts in evidence the energy potential of biomass, including residual biomass, as is the case with municipal solid waste.

Data from the United Nations Environment Program (UNEP) estimate that around 11.2 billion tons of waste are collected annually worldwide, and that the degradation of the organic matter contained in this waste amounts to up to 5% of world emissions of greenhouse gases (UNEP, 2011). The technical literature on MSW presents the demographic aspects as one of the determinants of the quantity and composition of the waste. Thus, according to Zveibil (2001), "the larger the urban population, the higher the generation per capita". Another problem is the question of meeting the energy demand, with regard to energy resources, several discussions have arisen on the need to diversify the energy matrix, which can be achieved through new technologies for the use of energy resources, especially known as renewable. According to the thinking of Bley Jr., *et al.* (2010), biogas is a form of energy storage of residual biomass, and can be later transformed into electrical, thermal or vehicular energy. Reinforcing this idea, Lucas Jr. and Santos (2000) say that, in the case of distributed generation, biogas can be used for heating, cooling, lighting, electric power generators, among others, and can replace the use of energy sources such as firewood, gasoline, diesel, alcohol and grid electricity (Gaspar, 2003). Souza, *et al.* (2005), says that, under an approach from the point of view of the raw material used for the generation of renewable energies, the biogas can become an income generating asset, while the solid waste is characterized as an environmental liability. Thus, the selection and choice of the energy conversion process to be applied to a biogas plant depends on the purpose of the use, the required temperature range, the amount of energy replaced and even the expected yield, which may vary according to the quality of the gas, the method of burning, the operating regime and the substituted fuel (CIBIOGÁS, 2014, apud Scarpetta, *et al.*, 2014).

The objective of this work is to present a proposed alternative generation of electricity through the recovery and energy utilization of the biogas generated in the decomposition of municipal solid waste (MSW) that are disposed in landfills. In this way, an overview of the situation of landfills in the State of Minas Gerais is presented and a preliminary and purely theoretical study of the power generation capacity of the same through different technological routes of energy conversion. As hypotheses of this study, were considered: a geometric growth of the population of the state of Minas Gerais; two fixed annual per-capita generation rates; the energy conversion efficiencies of biogas in electricity without variation in the proposed period; the rates of collection and grounding of the MSW as predicted by the competent bodies and the legislation in force in 2017.

2. LITERATURE REVIEW

For a theoretical basis regarding the theme developed in this paper, it was necessary to carry out a review of the related literature on the energy recovery of landfill biogas and its state of the art, as well as the current and more usual technological conversion routes of the biogas in electricity.

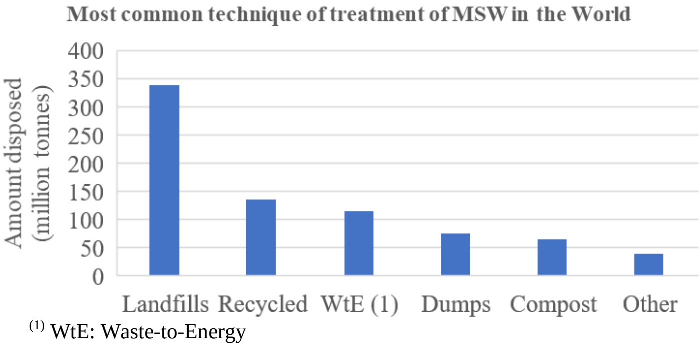
2.1 The energy recovery of biogas for power generation

In a number of societal spheres around the world, questions have been raised about the security of future energy supply, opening promising prospects for renewable energy sources, such as solar, wind, tidal, geothermal and biomass. It is known that about 81% of the world's primary energy demand is currently served by fossil fuels (IEA, 2016) and the consumption of such fuels corresponds to about 56.6% of the total anthropogenic emissions of GHG (greenhouse gases) (IPCC, 2011). However, the current context reveals that these sources are in a process of permanent decline, and in the case of oil and natural gas in theoretical terms, their exhaustion is expected to occur around the year 2070. Such forecasts require a change of behavior in social, political and economic that aims at a more prudent consumption of the fossil fuels as well as their complementarity through the use of alternative sources of energy (Boeriu, *et al.*, 2005).

The MSW are considered as biomass, within the concept applied by Schuch (2012), which expresses that biomass are all materials that decompose by means of biological actions of different types of bacteria. This concept is complemented by the *Agência Nacional de Energia Elétrica* - ANEEL, which considers as biomass any natural resource originating from organic matter that has potential of use for the production of energy (ANEEL, 2008). With respect to the growth rates in the production of garbage, it is known that there is a close relation between the generation of garbage and the GDP of each region, as can be proven by a study presented by the World Energy Concil - WEC, that shows this interdependence, being understood that the bigger the GDP, the greater the consumption of non-durable products and, consequently, the greater the production of waste (WEC, 2017).

It is estimated that global waste generation will double by 2025 to more than 6 million tonnes of waste per day and rates should not grow before the end of this century. As long as the OECD countries reach the "peak of waste" by 2050, and the countries of East Asia and the Pacific by 2075, waste will continue to grow in sub-Saharan Africa. By 2100, global waste generation will reach 11 million tonnes per day (WEC, 2017). Regarding the forms of treatment of municipal solid waste, the WEC presents data that demonstrate that the most common technique used in the world is the use of landfills, as it can be observed in Fig. 1.

In this context, Brazil has followed a pattern similar to world behavior. Data from the IBGE (2008) show that from 1989 to 2008 there was a reduction in the allocation of MSW to dumps, while the destination of waste to landfills increased, as can be seen in Tab. 1.



(1) WtE: Waste-to-Energy

Figure 1. Amount of waste disposed in 2012, by technique
Source: WEC (2017).

Table 1. Final destination of solid waste in Brazil, per type of destination in the period from 1989 to 2008.

Year	Final destiny of the solid waste (%) in Brazil		
	Dumps	Controlled Landfill	Landfills
1989	88.2	9.6	1.1
2000	72.3	22.3	17.3
2008	50.8	22.5	27.7

Source: IBGE (2008).

According to Serôa da Motta and Chermont (1996), the technological routes of waste treatment should be prioritized in the following order: recycling, composting, energy recovery and landfill. The data of the typology of MSW destination in the State of Minas Gerais, provided by the *Fundação Estadual do Meio Ambiente* – FEAM, are one of the main input data for this study. As can be seen from Fig. 2, in the period of 2008 for 2016 the number of dumping grounds has decreased, while the number of landfills has increased, even gradually.

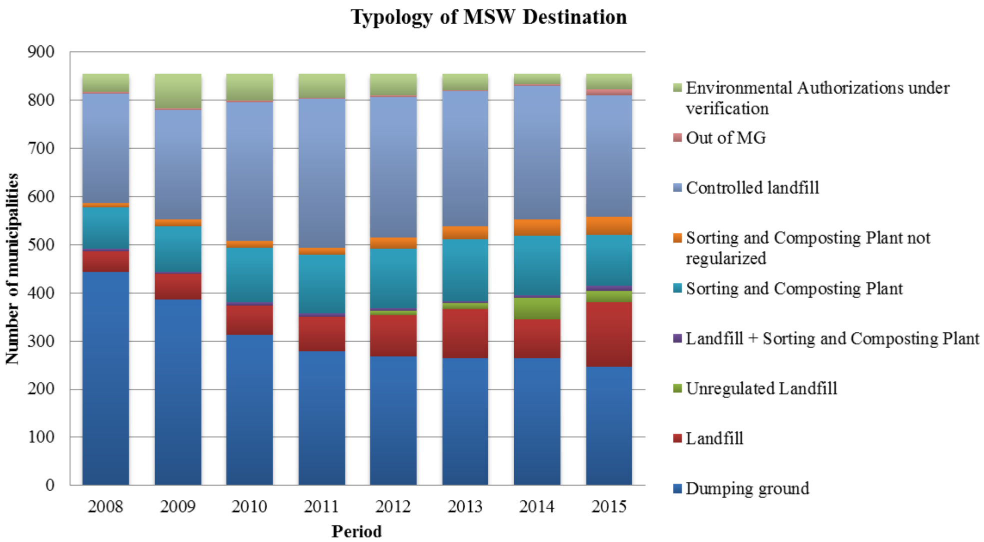


Figure 2. Historical stratification graph of the typologies of MSW destination in the municipalities of Minas Gerais.
Source: Adapted from FEAM (2016).

The use of biogas produced in landfills is the simplest technological route for the energetic use of urban solid waste. It is an alternative that can be applied in the short and medium term for the gases produced in most existing landfills, as it happens in hundreds of landfills in different countries. It consists of the recovery of biogas from the anaerobic decomposition of the organic fraction of MSW, by microorganisms that transform the residues into more stable substances, such as carbon dioxide (CO_2), water, methane gas (CH_4), hydrogen sulfide gas (H_2S), mercaptans and other mineral components. The energy utilization of the gas is a function of its production and recovery. Both depend on the confinement of the waste, and for the production this reflects in the absence of oxygen and for the recovery in fugitive emission. Thus, in addition to dumps that produce less gas than controlled landfills, and the controlled ones produce less than the landfill (IPCC, 2006), the rate of recovery of dumps is lower than that of controlled landfills, which in turn is lower than of landfills.

Biogas, according to the *Centro Nacional de Referência em Biomassa* - CENBIO, is considered as a source of renewable energy, which means that its recovery and use of energy have quite significant advantages in the environmental, social, technological and strategic spheres (CENBIO, 2001). Methane is the most important gas from waste treatment and can be transformed into energy, according to CETESB (2006). Thus, Barcelos (2009) emphasizes that the energetic use of methane from the biological degradation of residues can contribute to the mitigation of the greenhouse effect, allowing a greater sustainability to the energy matrix.

In the case of Brazil, Bronzatti and Larozinski Neto (2008) verify that the country is currently undergoing a period of development, going through changes both in energy production processes and in the economic structure itself. Thus, Bley Jr. (2014) expresses that the energy utilization of biogas is one of the alternatives available in Brazil to enable an increase in the supply of electric energy, reinforcing the guarantees of equilibrium of the national energy matrix. However, Fig. 3 shows the representativeness of the MSW biogas plants in Brazil, and only six federative states have this type of energy utilization in their matrixes.

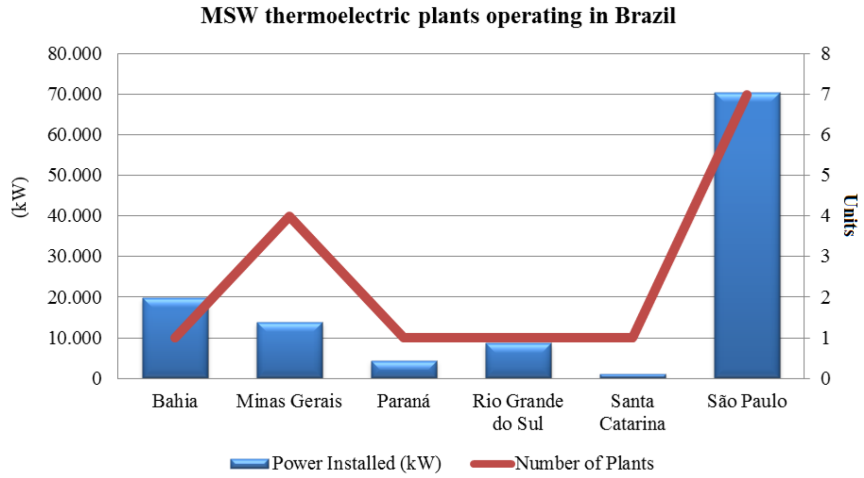


Figure 3. Total MSW thermoelectric plants operating in Brazil in January 2017.
Source: Adapted from ANEEL (2017).

As an advantage of the recovery and energetic utilization of landfill biogas, it is possible to mention the avoided emissions of greenhouse gases (through the use of a renewable source) and the efficiency of the conversion systems (CENBIO, 2005), as well as the additional revenue for existing landfills (energy + carbon credits) and reducing the (remote) possibility of occurrence of autoignition and / or explosion by high concentrations of methane. However, there are also some drawbacks, such as the partial recovery of the gas in landfills (mainly those whose construction was not designed for this purpose, where maximum recovery is often limited to 50%), the decay of fuel availability over of the useful life from enterprises and the high cost of the gas recovery plant (due to the necessary treatments) (EPE, 2014).

2.2 Biogas energy conversion technologies in electricity

The sizing of power plants for the use and energy recovery of landfill biogas for electricity generation is not simple; on the contrary, it requires strong technical and economic commitment due to the declining supply curve of the primary energy throughout the lifetime of the landfill. Unlike other processes of energy recovery of waste, such as anaerobic digestion and incineration, the use of landfill biogas does not bring a significant reduction in the volume of accumulated waste, so that the continuous deposition of residues results in saturation of the landfill accumulation capacity. However, the use of biogas for the generation of electric energy promotes the reduction of pollution in the environment, since it is a gas composed basically of methane gas (CH_4), which is about 21 times more polluting than carbon dioxide (CO_2), considering the greenhouse effect (EPE, 2014). Because it is highly combustible, biogas needs to be continuously drained to avoid landfill explosions. According to ICLEI (2009), in Brazil, most landfills use the open drainage system, where a flame is kept lit for immediate burning of the biogas that is naturally drained. However, this system has low efficiency and it is estimated that only 20% of the biogas drained is effectively destroyed by burning, with the remainder emitted directly into the atmosphere.

There are several technologies for the energetic conversion of biogas. Energy conversion is the process that transforms one type of energy into another (Coelho *et al.*, 2001). In the case of biogas the chemical energy contained in its molecules is converted into mechanical energy by means of a controlled combustion process. This mechanical energy activates a generator that converts it into electrical energy (Pecora, 2006). It is also worth mentioning the use of direct biogas burning in cogeneration boilers as well as the advent of remnant but non-commercial technologies that are currently under development and improvement, such as the fuel cell, which can be considered a promising technological route (Figueiredo, 2007). The energy conversion of biogas into electricity can be realized in various ways due to current technological advances. The most common technological routes currently used for this type of energy conversion are gas turbines and micro turbines and "Cycle - Otto" type internal combustion engines. The use of microturbines still presents high costs and their life time operating with biogas is still low (Souza, *et al*., 2004; CENBIO, 2005). Otto cycle internal combustion engines, however, require smaller modifications to use biogas as fuel and their efficiency depends only on the compression ratio (Van Wylen, 2003). However, Otto cycle engines are not the most suitable for electricity generation. The most appropriate is the Diesel cycle engine, due to its greater robustness and lower cost for the same power, compared to the Otto cycle. The introduction of biogas into diesel cycle engines can be achieved by two technologies: ottolization and diesel/gas bi-fuel conversion (Pereira, 2005).

In the Tab. 2 it is possible to see a comparison under the conversion technologies of the biogas in electric energy. As can be observed, although the engines have higher electric conversion efficiency, gas turbines can increase their overall conversion efficiency by approximately 70% by using the exhaust gas to generate steam (Alves, 2000), when operated in cogeneration systems (heat and electricity) (Figueiredo, 2007). The advantage of microturbines lies mainly in the expected environmental gain in their low NOx emission rates (CENBIO, 2006), as well as their modularity due to their small size, which is an attractive when it comes to distributed generation.

Table 2. Comparison of conversion technologies.

Conversion Technologies	Installed Power	Energy conversion efficiency	NOx emission in parts per million (ppm)
Gas Engines (Otto Cycle)	30 kW – 20 MW	30% - 34%	250 – 3000
Diesel Engines (Biogas + Diesel)	-	30% - 35%	Average 27
Gas Turbines (Medium Size)	500 kW – 150 MW	20% - 30%	35 – 50
Microturbines (Small Size)	30 kW – 100 MW	24% - 28%	< 9

Source: Adapted from Pecora (2006).

3. EXPERIMENTAL PROCEDURE

In order to determine the potential for methane generation from MSW Biogas in Minas Gerais, the Intergovernmental Panel on Climate Change (IPCC) methodology was used, following Eq. (1), which involves the estimation of the amount of degradable organic carbon present in MSW (IPCC, 1996).

$$Q_{CH_4} = \lfloor (Pop_{urb} \cdot Rate_{MSW} \cdot MSW_f \cdot L_0) - R \rfloor \cdot (1 - OX) \quad (1)$$

Where:
Q_{CH4}: Generated methane [10^3 kg of CH_4/year];
Pop_{urb}: Urban population [individuals];
$Rate_{MSW}$: Rate of solid household waste generation per individuals per year [kg of MSW/ individuals.year];
MSW_f: Fraction of household solid waste deposited in solid waste disposal sites [%];
L_0: Methane generation potential of waste [10^3 kg of CH_4/10^3 kg of MSW];
R: Recovered methane [10^3 kg of CH_4/year];
OX: Oxidation factor.

The methane generation potential of waste (L_0) is a data of great importance that, besides being used in the methodology developed by the IPCC, can also be used in other methodologies and even in software developed for the estimation of methane generated in landfills. Thus, L_0 is calculated by Eq. (2) (IPCC, 1996).

$$L_o = MCF \cdot DOC \cdot DOC_f \cdot F \cdot \frac{4}{3} \quad (2)$$

Where:
MCF: Methane correction factor;
DOC: Degradable organic carbon;
DOC_f: Fraction DOC dissimilated;
F: Fraction by volume of CH_4 in landfill gas;

4/3: Conversion factor of carbon in methane [10^3 kg of CH_4/10^3 kg of C].

The DOC is the organic carbon that is accessible to biochemical decomposition. It is based on the composition of waste and can be calculated from a weighted average of the carbon content of various components of the waste stream. The Equation (3) estimates DOC using default carbon content values (IPCC, 1996).

$$DOC = (0.4 \cdot A) + (0.17 \cdot B) + (0.15 \cdot C) + (0.3 \cdot D) \quad (3)$$

Where:
A: Fraction of MSW that is paper and textiles;
B: Fraction of MSW that is garden waste, park waste or other non-food organic putrescibles;
C: Fraction of MSW that is food waste;
D: Fraction of MSW that is wood or straw.

There are several mathematical models to perform the population projection. For this paper the chosen model was the one of geometric progression, given by Eq. (4) (MMA, 2016).

$$P_2 = P_1 \cdot (1+k)^{t_2 - t_1} \quad (4)$$

Where:
P_2: Final population of period;
P_1: Initial population of period;
t_2: Final year of period;
t_1: Initial year of period;
k: Average growth rate by period.

Since the growth rate is given by Eq. (5) (MMA, 2016).

$$k = \left[\left(\frac{P2}{P1} \right)^{\frac{1}{(t_2 - t_1)}} \right] - 1 \quad (5)$$

In order to estimate the potential of electrical energy generation from the use of landfill biogas, it is possible to use Eq. (6), which shows a relation between the quantity of methane gas captured by the extraction system, with the calorific power value of this gas and the energy conversion efficiency of the conversion technology.

$$P = Q_{CH_4} \cdot CP_i \cdot \eta \cdot CF \quad (6)$$

Where:
P : Electric power available every year (kW);
Q_{CH4} : Methane flow every year (m^3 of CH_4);
CP_i : Calorific power of methane (kWh/m^3);
η : Energy conversion efficiency (%);
CF : Capacity factor (%).

Data provided by the *Intituto Brasileiro de Geografia e Estatística* - IBGE, the *Fundação Estadual do Meio Ambiente* - FEAM, the *Agência Nacional de Energia Elétrica* - ANEEL and the Intergovernmental Panel on Climate Change - IPCC were also used.

4. RESULTS AND DISCUSSION

The urban population in Minas Gerais over the period 1980-2050 was projected based on the average ten-year growth rate of 2.09%, obtained by analyzing the data presented in the fourth people censuses conducted by IBGE in the years 1980, 1991, 2000 and 2010, and the model of projection of the population growth used was by a geometric progression, as can be seen in the graph of Fig. 4.

Based on data from the National Survey of Basic Sanitation - 2000 (IBGE, 2000), and according to the latest demographic census of 2010, the state had about 63% of its total population residing at 845 municipalities, all with a population of up to 200,000 inhabitants each, that is, only 8 municipalities in Minas Gerais had a total resident population of more than 200,000 inhabitants, two generic per capita MSW generation rates were chosen for this work:

450 g / inhabitant / day and the rate of 700 g / inhabitant / day; considering the lowest and the highest rate within the range presented by IBGE (2000) for municipalities with up to 200,000 inhabitants.

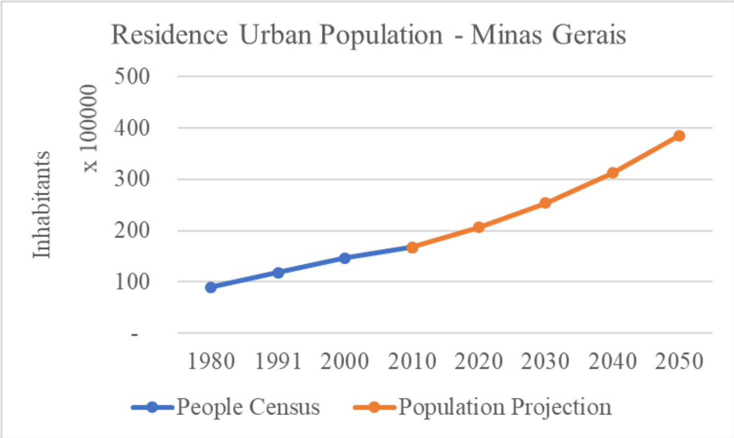


Figure 4. Urban population residing in Minas Gerais during the period from 1980 to 2010 and projections for 2050.
Source: Own elaboration of IBGE (2010).

The MCF for the landfill case is 1.0, as reported in IPCC (1996). At an estimated temperature 35 °C in the anaerobic zone of the waste, the DOC_f corresponds to a value of 0.77. A value of 50% was considered for the fraction by volume of CH_4 in landfill gas, as it is usually accepted, as expressed by (FEAM, 2012). Thus, the value obtained from L_0 is 0.0911 [10^3 kg of $CH_4/10^3$ kg of MSW], or 127.12 [m^3 of $CH_4/10^3$ kg of MSW].

The default value for CH_4 recovery (R) is zero, according to the IPCC (1996). According to the goals established by the "Minas sem Lixão" program (Minas Gerais without Dumping Ground), it was considered for this work the MSW_f value of 0.65 (FEAM, 2012). With all the data, applying the Eq. (1), (2), (3), (4) and (5), presented previously, and associating the default values suggested by the IPCC (1996), the results presented by the graph of the Fig. 5 were obtained.

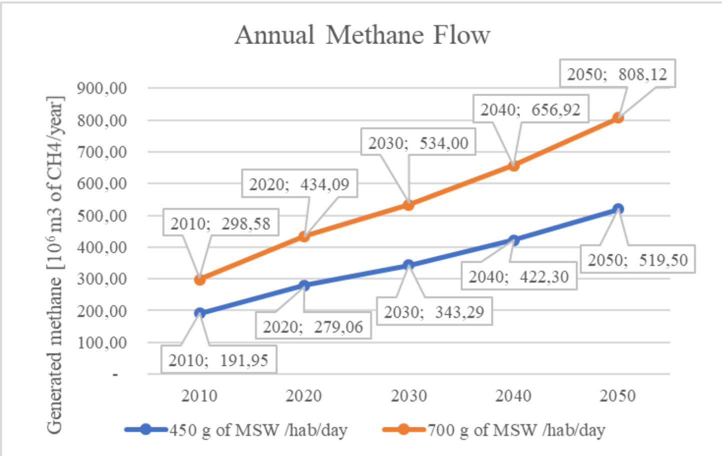
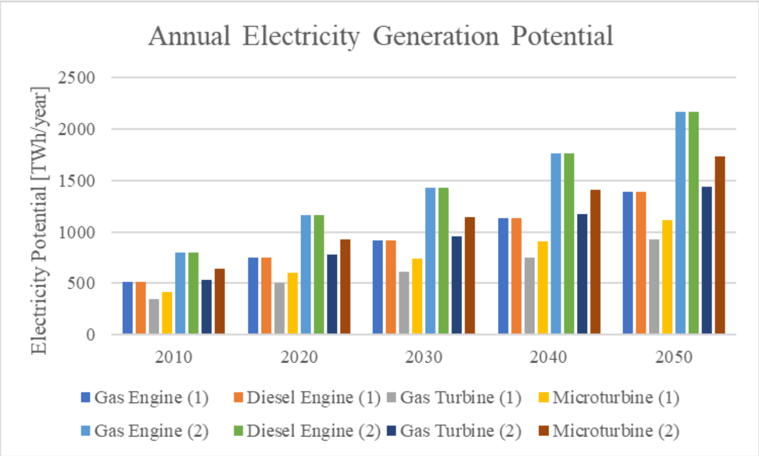


Figure 5. Estimated annual methane generation from landfill biogas recovery in two waste generation scenarios.
Source: Prepared by the author.

In order to estimate the annual electricity generation potential, it was used Eq. (6), whose parameters considered were: CP_i of 10.5 [kWh/m^3 of CH_4] (LMOP, 2011); 85% Capacity Factor (Muylaert, *et al.*, 2001); energy conversion efficiency of the technologies presented, according to Pecora (2006). The results are shown in the Fig. 6.

As can be seen, there is a natural growth potential of biogas generation and, consequently, of methane to be recovered energetically for electricity generation. The scenario that presents the lowest potential of electricity generation, within the hypotheses proposed in this paper, uses microturbines in a context in which the generation of RSU per capita is 450 g per year. The optimum scenario corresponds to that where the energy conversion technology applied is that of engines (Diesel or Otto Cycle), mainly in a per capita generation context of 700 g per year of urban solid waste. However, it should be remembered that the economic and environmental issues of the different energy conversion technology routes presented, were not taken into account in this work, but only the technical requirements, in order to present the potential of the state of Minas Gerais for the use of biogas from landfills.



(1) – 450 g of MSW/inhabitant/day; (2) – 700 g of MSW/inhabitant/day

Figure 6. Estimate of the annual electricity generation potential by energetic conversion technology in two waste generation scenarios.
Source: Prepared by the author.

5. CONCLUSIONS

The issue of the problems of disordered urbanization has led governments to some concern regarding the logistics of meeting the basic needs of municipal populations. This study therefore presented the energy potential that can be exploited, as well as the feasibility of the different technological routes of energy conversion of MSW biogas in electric energy, by means of an evaluation of the different conversion efficiencies.

As results, the present study showed that the state of Minas Gerais has a potential of electric generation of up to 799.46 TWh / year in base year of 2010, reaching 2,163.74 TWh / year in the year of the final horizon of the proposal of this paper, 2050. It is known, however, that the implantation of systems for generating electric energy from biogas generated in landfills has a high cost, a subject that was not the scope of this work. However, it is important to note that these systems can provide a viable solution to the problems caused by methane emissions into the atmosphere, contributing to the reduction of greenhouse gas emissions. Another favorable aspect of the investment in this technological route is the fact that the energy generated can be used in local service, with the surplus energy being commercialized in the market, according to the rules in force in Brazil for DG. It should be noted that engine technologies have high conversion efficiency for biogas operation, not to mention its favorable availability in the Brazilian market, consolidating this option as a safe option for deployment in the state of Minas Gerais.

The purpose this study is to stimulate the development of this type of renewable energy source, contributing to the advancement of sustainable development, as well as to mitigation of the imminent climate changes. Thus, in the future, biogas could contribute to the diversification of the energy matrices increasing their renewable parts.

6. ACKNOWLEDGMENTS

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