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# Using biogas produced in landfill for electricity generation in a Brazilian state to a horizon of 2050

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**Abstract.** Generally, urbanization processes occur in a disorderly way, especially in developing countries, and are characterized as one of the most aggressive human interaction with the environment. In the State of Minas Gerais, which consists of 853 municipalities organized in 17 Development Territories, approximately 85.3% of the population live in urban areas, evidencing the need for a good management of energy resources and an adequate disposal of Municipal Solid Waste (MSW). In this context, one feasible possibility is the use of biogas from landfills, which aggregates solutions for both MSW management and electricity generation, as it is being analysed in this work. The methodology proposed by the Intergovernmental Panel on Climate Change was used, which is generally based on population expansion in urban areas, as well as the rate of MSW per capita, considering the different arrangements of gravimetric composition. Next, the potential of electricity generation was presented considering the energy conversion efficiencies of four technological routes. The results showed that the use of motors as energy conversion technology presents the greatest technical feasibility for the implementation of such projects, reaching theoretical values of generation of up to 2,237.06 MWh / day in 2050.

## 1. Introduction

The fast population growth and the high rates of urbanizations around the world have altered the patterns of consumption of goods and services, increasing the generation of Municipal Solid Waste (MSW). Thus, these issues have demanded greater access to energy services and solid waste management.

As expressed by [1], one of the factors contributing to the reinforcement of present urban difficulties is the “inability to anticipate, accept and plan in advance the massive and inevitable urban growth”. Such inability is reflected in the difficulties of planners in meeting the demands for quality energy services, as well as in urban infrastructure services, such as collection, treatment and adequate final destination for MSW, under a focus of increasing demand as predicted by population growth and urbanization rates for municipalities.

Thus, for the 2050 horizon, proposed for this study, there will be a considerable increase in demand for electricity throughout Brazil, a fact linked to the increase in population and economic growth expected for the country in this period, according to data of official studies, such as those presented by [2]. The purpose of this study is to stimulate the use of renewable energy sources and the development



of municipal solid waste energetic recovery, contributing to the advancement of sustainable development in the State of Minas Gerais, as well as for the mitigation of the imminent climate changes. This study is in progress and part of the results has been presented by the authors in previous works [3,4].

## 2. Methodology

For the determination of the potential of biogas generation in landfills, the Intergovernmental Panel on Climate Change (IPCC) presents a methodology widely accepted and used in many countries [5]. It consists of the application of some mathematical equations, as it is being presented in this section and in previous works [3,4]. This model makes possible the estimation of CH<sub>4</sub> generation in different geographic regions, since it predicts characteristic parameters of each region [6].

To define the theoretical estimate of the methane flow from MSW deposited in sanitary landfills, the IPCC proposes the calculation by means of equation (1) [5]. This model is discrete and demonstrates the theoretical annual generation of methane.

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

Where  $Q_{CH_4}$  is generated methane [kg of CH<sub>4</sub>/year],  $Pop_{urb}$  is urban population [individuals],  $Rate_{MSW}$  is rate of solid household waste generation per individuals per year [kg of MSW/individuals.year],  $MSW_f$  is Fraction of household solid waste deposited in solid waste disposal sites [%],  $L_0$  is methane generation potential of waste [kg of CH<sub>4</sub>/kg of MSW],  $R$  is recovered methane [kg of CH<sub>4</sub>/year] and  $OX$  is oxidation factor.

The methodology for population projections is based on the application of the geometric progression method, which consists of a numerical sequence that grows (or decreases) in according with a constant rate ( $k$ ), as it is expressed by equation (2).

$$P_2 = P_1 \cdot (1 + k)^{(t_2 - t_1)} \quad (2)$$

Where  $P_2$  is population in year 2,  $P_1$  is population in year 1,  $k$  is average annual growth rate,  $t_2$  is year 2 and  $t_1$  is year 1.

The population growth rate (%/year) corresponds to the percentage variation of the population in a given period, in the annual case. For this study, the methodology presented by [7] was used, where equation (3) is used to obtain the average annual population growth rate.

$$k = \left[ \left( \frac{P_2}{P_1} \right)^{\left( \frac{1}{t_2 - t_1} \right)} - 1 \right] \quad (3)$$

To calculate the per capita production rate of MSW, it was necessary to classify each municipality according to the population extracts presented in [8]. It is important to note that this classification was performed for each annual population along the municipal projections. That is, municipalities may have different rates as they move within the ranges proposed by the municipal population extracts, which gives more dynamicity to the projections.

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 softwares developed for the estimation of methane generated in landfills. Thus,  $L_0$  is calculated by equation (4) [5].

$$L_0 = MCF \cdot DOC \cdot DOC_f \cdot F \cdot \frac{16}{12} \quad (4)$$

Where  $MCF$  is methane correction factor [%],  $DOC$  is degradable organic carbon [kg of C/kg of MSW],  $DOC_f$  is fraction of DOC dissimilated,  $F$  is fraction by volume of CH<sub>4</sub> in landfill gas [%] and  $16/12$  is conversion factor of carbon (C) in methane (CH<sub>4</sub>) [kg of CH<sub>4</sub>/kg of C].

The DOC is the organic carbon that is accessible to biochemical decomposition. It is based on the

composition of the waste and can be calculated from a weighted average of the carbon content of various MSW components. This variable considers the gravimetric composition of urban solid waste and the amount of carbon present in each component of the MSW. Equation (5) estimates DOC using standard values of carbon by content [5].

$$DOC = (0.4 \cdot A) + (0.17 \cdot B) + (0.15 \cdot C) + (0.4 \cdot D) + (0.3 \cdot E) \quad (5)$$

Where  $A$  is percentage of paper and paperboard in the composition of MSW,  $B$  is percentage of pruning residues, gardening and other non-food organic materials (waste from parks and gardens) in the composition of MSW,  $C$  is percentage of organic food residues in the MSW composition,  $D$  is percentage of textiles in the MSW composition and  $E$  is percentage of timber and forest residues in the composition of MSW.

For this study, an adjustment was made to the DOC calculation, since the available data were not discriminated in the same way as the IPCC model [5]. Thus, the factors  $B$  and  $C$  were joined, considering  $0.16 (B+C)$ . According to data presented by [9], the average composition of MSW produced in Brazil is 60.0% organic matter, 15.0% paper and paperboard, 5.0% textiles, 1.0% wood and 20% other non-methane-producing materials (plastics, glass, metals, etc.). As presented by [10], the dissociated fraction of degradable organic carbon ( $DOC_f$ ) corresponds to the fraction of carbon that is available for the biochemical decomposition and can vary as a function of the temperature in the anaerobic zone of the landfill. If this temperature remains constant around 35 °C, despite the ambient temperature, the  $DOC_f$  can be calculated by equation (6).

$$DOC_f = (0.014 \cdot T) + 0.28 \quad (6)$$

Where  $T$  is Temperature (in °C) in the anaerobic zone of the landfill.

For the theoretical estimation of the landfill biogas production, one scenario was based on the goals established by the government program "Minas sem Lixão" (Minas Gerais without Dumping Ground), that is, it was considered for this work the MSWf value of 0.65 [11]. It was assumed that the MCF for the landfill case is 1.0, as reported in the [5]. The value of 50% was considered for the volume fraction of  $CH_4$  in landfill biogas, as a typical value [6,11]. The standard value for the  $CH_4$  (R) recovery is zero, according to the IPCC [5], in the same way as the oxidation factor (OX) [5]. For the conversion of  $L_0$  to  $m^3CH_4/kg$  of MSW, the methane density is  $0.0007168 t/m^3$  [12].

For the energy recovery of the methane gas produced in landfills there is still an environmental issue to be evaluated: Greenhouse Gas (GHG) emissions. Although its permanence in the atmosphere is much lower than that of carbon dioxide,  $CH_4$  is responsible for a substantial part of the man-made greenhouse effect, since its Global Warming Potential (GWP) is 28 times greater than that of  $CO_2$  for the same period of a hundred years, according to data updated by the IPCC in its Fifth Assessment Report (AR5) [13] and the USEPA in 2018 [14]. By definition, 1 kg of  $CO_2$  is equivalent to 0.2727 kg of carbon equivalent ( $CO_{2-e}$ ), since only is considered the mass of carbon (C) present in carbon dioxide ( $CO_2$ ) molecules. Thus, to calculate the amount of carbon equivalent present in other GHGs, one should consider the relative GWP of each gas, according to equation (7).

$$CO_{2-e} = GWP \cdot 0.2727 \quad (7)$$

To get an idea, according to [15], the company *Biogás Energia Ambiental* energetically recovers about 60% of  $CH_4$  collected at the *CTL* landfill in *São Paulo*, converting it into electricity. On the other hand, the company *Termoverde Caieiras*, located in the municipality of *Caieiras*, generates an average of 26 MW/hour, considering possible foreseen losses, being that this production was equivalent to the consumption of a municipality of approximately 300 thousand inhabitants, according to [16]. Yet on the aspect of the energy utilization of the landfill biogas for electricity generation, *Calculadora Brasil 2050* shows as the worst scenario using only 7% of the total biogas recovered for the generation of electricity [17]. However, [18] provides that at least 60% of the biogas recovered may be used for electricity generation. Thus, for the generation of electric energy, it was considered that 60% of total biogas potential to be produced will be used for electricity generation.

For the determination of the available energy potential, equations (8) and (9) are used.

$$P_x = (Q_x \cdot 0.6) \cdot \eta \cdot LCV_D \quad (8)$$

Where  $P_x$  is available electrical energy [kWh/day],  $Q_x$  is average daily flow of biogas generated [ $\text{m}^3/\text{day}$ ], 0.6 is percentage of biogas used to generate electricity,  $\eta$  is electric conversion efficiency [%] and  $LCV_D$  is available lower calorific value [ $\text{kWh}/\text{m}^3$ ].

$$LCV_D = \gamma_{CH_4} \cdot LCV_{CH_4} \cdot k \quad (9)$$

Where  $\gamma_{CH_4}$  is specific gravity of methane [ $\text{kg}/\text{m}^3$ ],  $LCV_{CH_4}$  is lower calorific value of methane [kcal/kg] and  $k$  is conversion factor of kcal in kWh [4.19/3,600].

The lower calorific value considered for  $\text{CH}_4$  was 3,281.92 kcal/kg and the specific gravity of 1.3372  $\text{kg}/\text{m}^3$ , both for a concentration of 50%  $\text{CH}_4$  in biogas [18].

Four technologies of conversion of biogas into electricity were considered, each with its different conversion efficiency. Although the differences between the efficiencies can be close to each other, when applied over large volumes of energy they present considerable distinctions. The efficiency to be considered was the following, according to the technological routes of energetic conversion of biogas to electricity [18]: gas engines (Otto cycle) 34%, diesel engines (Biogas + Diesel) 35%, gas turbines 30% and microturbines 28%.

The internal combustion engines (Otto cycle) correspond to the most commonly used conversion technology in biogas projects to generate electricity, corresponding to about 70% of the total of this type of project. This is mainly due to its relative low cost, high efficiency, compared to other technologies available in the market, and its dimensions of easy accommodation in landfills [19].

### 3. Results and discussions

Based on the data provided by the demographic censuses of the years 1980, 1991, 2000 and 2010, as well as the population counts, all performed by the Geography and Statistical Brazilian Institute (*Instituto Brasileiro de Geografia e Estatística, IBGE*), the urban population of each of the 853 municipalities in the State of *Minas Gerais* was projected, for geometric progression, as it was described in section 2. Thus, all the municipalities were grouped according to their respective Territories of Development.

Based on the data on the generation of MSW, applying the methodology to estimate the theoretical potential of annual biogas generation, the annual methane generation projections were obtained for each municipality in the State of *Minas Gerais*, from 2010 to 2050. Comparatively, in the table 1 are presented the results for the initial year (2010) and the final year (2050) of the study period, grouping the values by Development Territory, as well as the value that corresponds to the totality of the State.

**Table 1.** Comparison of Methane production at the beginning (2010) and at the end (2050) of the study period by Development Territory.

Expectation of MSW's biogas generation potential								
Territory	2010				2050			
	Estimated Population [residents]	MSW generation potential [t/year]	Biogas production potential [ $\text{m}^3$ of $\text{CH}_4/\text{year}$ ]	GWP can be saved [ $\text{tCO}_2\text{e}/\text{year}$ ]	Estimated Population [residents]	MSW generation potential [t/year]	Biogas production potential [ $\text{m}^3$ of $\text{CH}_4/\text{year}$ ]	GWP can be saved [ $\text{tCO}_2\text{e}/\text{year}$ ]
High Jequitinhonha	183,718	30,919	3,963,552	13,983	425,648	85,927	11,014,988	38,860
Caparaó	1,244,876	81,384	10,432,703	36,805	2,543,291	151,001	19,356,911	68,289
Central	591,557	37,300	4,781,501	16,869	1,152,031	65,072	8,341,675	29,428

<i>Mata</i>	902,598	391,208	50,149,226	176,921	1,962,584	673,367	86,319,362	304,525
Medium and Low <i>Jequitinhonha</i>	832,959	48,182	6,176,461	21,790	1,948,357	77,306	9,909,951	34,961
<i>a</i> Metropolitan	819,350	1,901,252	243,722,545	859,825	1,655,686	3,562,979	456,740,360	1,611,327
<i>Mucuri</i>	287,638	57,584	7,381,699	26,042	594,824	164,742	21,118,409	74,503
Northwest	272,102	101,075	12,956,925	45,711	493,333	207,758	26,632,675	93,957
North	919,515	227,541	29,168,630	102,904	1,763,119	716,614	91,863,108	324,082
West	676,944	212,654	27,260,253	96,171	1,265,378	851,289	109,127,211	384,988
Southwest	514,732	89,437	11,464,982	40,447	862,152	148,644	19,054,819	67,223
South	1,794,251	319,684	40,980,460	144,574	3,724,652	741,533	95,057,592	335,352
North Triangle	931,729	377,370	48,375,314	170,662	1,569,830	692,094	88,719,893	312,993
South Triangle	288,762	144,200	18,485,118	65,213	524,654	497,882	63,823,714	225,163
Stell Valley	378,368	154,084	19,752,140	69,683	796,765	275,935	35,372,286	124,789
<i>Rio Doce</i> Valley	661,071	122,611	15,717,554	55,450	1,551,798	200,835	25,745,217	90,826
<i>Vertentes</i>	608,488	121,243	15,542,156	54,831	1,326,309	206,100	26,420,131	93,207
Total	11,908,658	4,417,729	566,311,219	1,997,880	24,160,411	9,319,081	1,194,618,302	4,214,473

Table 1 also shows the amount of GHG emissions avoided with the energy recovery of the landfill biogas. It is interesting to note that, in 2010 it could be recovered up to 1,997,880 tCO<sub>2-e</sub>, while in 2050 the forecast is that it can avoid the emission of 4,214,473 tCO<sub>2-e</sub> in the atmosphere, with the use of biogas for electricity generation, disregarding the characteristic emissions present in the exhaust gases of each technological route considered in this study.

The obtained results demonstrate that the territory with the highest MSW generation potential in the horizon year of this work (2050) was the Metropolitan, with 3,562,979 t/year; followed by the West, with 851,289 t/year; and the third place, with a large difference in the second, is the South, with 741,533 t/year. The territory with the least potential of MSW generation in 2050 was the Central, with 65,072 t/year, preceded by the territory of Medium and Low *Jequitinhonha*, with 77,306 t/year.

**Table 2.** Comparison of Electricity generation at the 2050 by technological route of energy conversion.

Electricity generation by Development Territory - energy conversion technologies [MWh/day]									
Territory	Otto Cycle Engine	Diesel engine	Gas turbine	Micro-turbine	Territory	Otto Cycle Engine	Diesel engine	Gas turbine	Micro-turbine
High <i>Jequitinhonha</i>	20.44	21.04	18.03	16.83	West	202.5	208.45	178.67	166.76
<i>Caparaó</i>	35.92	36.98	31.69	29.58	Southwest	35.36	36.4	31.2	29.12
Central	15.48	15.93	13.66	12.75	South	176.39	181.58	155.64	145.26
<i>Mata</i>	160.17	164.89	141.33	131.91	North Triangle	164.63	169.47	145.26	135.58
Medium and Low <i>Jequitinhonha</i>	18.39	18.93	16.23	15.14	South Triangle	118.43	121.91	104.5	97.53
Metropolitan	847.53	872.46	747.82	697.96	Stell Valley	65.64	67.57	57.91	54.05
<i>Mucuri</i>	39.19	40.34	34.58	32.27	<i>Rio Doce</i> Valley	47.77	49.18	42.15	39.34
Northwest	49.42	50.87	43.61	40.7	<i>Vertentes</i>	49.03	50.47	43.26	40.37



North	170.46	175.47	150.41	140.38	Total	2,216.73	2,281.93	1,955.94	1,825.55
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As the proposed methodology, after obtaining the methane generation data, the potential of electric energy generation was calculated by means of four technological routes of energetic conversion of biogas into electricity. The scenario presented is one in which the entire biogas generated would be used for electricity generation, considering as time limit the year 2050. It can be observed from the results presented in table 2 that the technological route of energy conversion of biogas in electricity that presents the best results is the diesel engine, considering only the conversion efficiency. However, considering the lower implementation costs, the best option nowadays would be the Otto Cycle engine, since it needs few adaptations for use with biogas and has wide use in the Brazilian market.

It is noted that, among the Development Territories with the greatest potential for CH<sub>4</sub> generation, the differences between the technological routes were more notable than among those with lower CH<sub>4</sub> generation potential. That is, the greater the availability of biogas for energy conversion, the greater the influence of the conversion efficiency of the available technologies.

According to data provided by [20], in October 2017 residential consumption of electricity in the Southeast region of Brazil, region where the state of *Minas Gerais* is located, was 5,315,363 MWh/month, with the number of consumers (households) equal to 31,887,052 residences. Thus, the ratio between these data shows that the average monthly consumption in the Southeast region was 166.69 kWh/month. Considering the worst case among the results of the scenarios proposed in this work, there is a potential of electric power generation of about 382.5 MWh/month (Central Territory by microturbine). Thus, with the use of biogas in this scenario, it would be possible to serve up to 2,294 residences. Considering an average of 3.2 residents per household, according to data from the Demographic Census 2010 for the State of *Minas Gerais*, it would be possible to attend about 7,342 people. That is, it would be possible to meet all the residential demand of any one of the 531 municipalities of the State of *Minas Gerais* that have between 527 and 7,2793 inhabitants residing in their urban areas, according to Demographic Census 2010. For the best scenario of 26,173.8 MWh/month (Metropolitan Territory by diesel engine), it would be possible to serve approximately 157,020 residences, corresponding to 502,466 inhabitants, that is, about 21.15% of the total population of the state's capital, *Belo Horizonte*, or 99.5% of any one of the other municipalities of *Minas Gerais*, according to Demographic Census 2010 data. According to [2] forecasts, it is expected that by 2050 average monthly electricity consumption per household will be around 198 kWh/month. That is, in the best scenario, it would be possible to supply monthly about 132,190 households; while in the worst-case scenario, the number of households served could be 1,931.

As for the cost of installing the megawatt from biogas from landfills, this is around 497.75 US\$/MW in the base-year 2010, according to data presented by the United Nations Development Program (UNDP) [19].

#### 4. Conclusions

The present study showed that, in 2050, the State of *Minas Gerais* could have a potential of electric generation of up to 2,281.93 MWh/day, through the technological route of diesel engines (adapted for diesel and biogas); and with a minimum of 1,825.55 MWh/day, through microturbines. The territorial analysis of the generation potential of MSW, biogas and electricity, contribute to the Government's current proposal to explore the potential of each Development Territory in order to systematize a more uniform and distributed development throughout the State. In this perspective, this paper shows that the Development Territory with the highest potential for biogas generation, by the year 2050, was the Metropolitan, with 456,740,360.27 m<sup>3</sup>CH<sub>4</sub>/year, followed by West (109,127,211.39 m<sup>3</sup>CH<sub>4</sub>/year). The data presented demonstrate that it is possible to reduce by up to 4,214,473 tCO<sub>2-e</sub>/year that would be released into the atmosphere due to the non-utilization and non-recovery of the methane gas produced in landfills, according to the scenario proposed for the year 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, but it is an important

step to be considered in future analysis because the work is in progress. Under a superficial analysis, it was presented that the cost of installing the megawatt from biogas from landfills, this is around 497.75 US\$/MW in the base-year 2010. 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. Thus, in the future, biogas may contribute in an increasingly significant way to the diversification of the State's energy matrix and to the increase of the renewable portion of this matrix.

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