Estimate of Biogas and Electricity Generation in Landfills: A Study for the State of Minas Gerais, Brazil

Priscila S. Maradini¹, Lucas de L. C. Santos², Elisa C. Berg³, André P. Rosa⁴

Abstract

In the state of Minas Gerais, Brazil, a significant part of the urban population has their waste sent to inappropriate locations, as open dumps or controlled tipping. This form of disposal, besides causing environmental damage, does not consider possible benefits from the biogas recovery. Thereby, this work aimed to estimate the production of methane and the potential energy from the anaerobic degradation of municipal solid waste, considering the implementation of landfills in the municipalities of the state of Minas Gerais that do not have a proper disposal for their waste. The software LandGEM® developed by the United States Environmental Protection Agency, was used to model the biogas potential. The results were presented in terms of mesoregions for a total of 419 municipalities under study. The georeferencing of the information was performed using the software ArcGIS® (version 10.5). In 2030 and 2040, the mesoregion “Metropolitana de Belo Horizonte” was the one that reached the highest values for methane and electricity production; while the mesoregion “Campos das Vertentes” was the one that presented the lowest values for the same parameters. In addition, even after the end of landfills’ activities, they continue producing methane until the estimated year of 2120. Thus, it can be concluded that the use of biogas from landfills represents a positive externality of the proper disposal of municipal solid waste and can contribute to the increase of the Brazilian renewable energy matrix.

Keywords: biogas; electricity generation; landfill; municipal solid waste.

1. INTRODUCTION

In 2017, in the state of Minas Gerais (Brazil), about 60.1% of the urban population had their municipal solid waste (MSW) sent to appropriate locations, such as landfills, small landfills and/or waste sorting and composting plants, with the environmental regularization process completed [1]. Concerning the remaining, 10.5% of the population had their waste sent to appropriate locations, but with the environmental regularization process still underway; and 29.4% of the population had their waste sent to irregular units, such as open dumps or controlled tipping [1]. Thereby, the State Foundation for the Environment (Fundação Estadual do Meio Ambiente)
Ambiente – FEAM) of Minas Gerais created, in 2003, the Program “Minas sem Lixões” (Minas without Open Dumps – loose translation), in order to support the municipalities to attend the standards of proper MSW management by sending their waste to landfills [2].

The landfills provide greater environmental control with the collect and use of the biogas, generated by the anaerobic decomposition of MSW. This can bring environmental benefits, such as: (i) reduction of greenhouse gas emissions; (ii) electrical and/or thermal energy generation from the recovery of the biogas; (iii) income generation; and (iv) improvement of the energy sustainability. Many studies indicate the interest and the technical and economic feasibility of the biogas recovering in Brazil, mainly regarding the search for alternative energy sources and the sustainable management of MSW [3], [4].

In Brazil, the main categories of biogas production are: wastewater treatment, agriculture, co-digestion, industry and landfills; with 43% of the total production (about 705,190 m³.day⁻¹), coming from landfills [5]. However, this amount corresponds to only 7% of the units that recovery biogas for energy production [5]. In addition, a study from dos Santos et al. [6] showed that 41% of the landfills’ potential energy is concentrated in the southeast region of Brazil, once it is the most populous region in the country and, therefore, the region with the highest generation of MSW.

A study regarding biogas collection from landfills in Brazil shows that, between 2003 and 2016, there were registered just eight projects of biogas’s burning in flares [7]. In addition, between 2004 and 2015, only nine thermoelectric plants that recover biogas were installed in landfills, which together generated 86.3 MW of electricity [7]. Thereby, there are few projects about biogas recovery for energy production, mainly considering the Brazilian potential.

Given this scenario, this work aimed to estimate the production of methane and the potential energy from the anaerobic degradation of municipal solid waste, considering the implementation of landfills in the municipalities of the state of Minas Gerais that do not have a proper disposal for their waste.

2. MATERIALS AND METHODS

The study was developed in the state of Minas Gerais (Brazil), which had an estimated population of approximately 21 million inhabitants in 2019 [8]. The Brazilian Institute of Geography and Statistics (Instituto Brasileiro de Geografia e Estatística – IBGE) delimits the state in 12 mesoregions. This configuration was used in the methodology’s development and in the presentation of the results.

The municipalities with an irregular destination of MSW (controlled tipping or open dumps) were inventoried from the report “Classificação e Panorama de Destinação dos Resíduos Sólidos Urbanos em Minas Gerais” (Classification and Panorama of Municipal Solid Waste’s Disposal in Minas Gerais – loose translation), totalizing 419 cities of the state under study (49.12%) (Table 1; Figure 1) [9]. The georeferencing of the information was performed using the software ArcGIS® (version 10.5).

Table 1. Quantification of municipalities in the state of Minas Gerais with irregular waste disposal for each mesoregion

<table>
<thead>
<tr>
<th>Mesoregions</th>
<th>Municipalities total</th>
<th>Municipalities with irregular destination</th>
<th>Controlled tipping</th>
<th>Open dumps</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Noroeste de Minas</td>
<td>19</td>
<td>11</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>2 - Norte de Minas</td>
<td>89</td>
<td>71</td>
<td>24</td>
<td>47</td>
</tr>
<tr>
<td>3 - Jequitinhonha</td>
<td>51</td>
<td>44</td>
<td>21</td>
<td>23</td>
</tr>
<tr>
<td>4 - Vale do Mucuri</td>
<td>23</td>
<td>22</td>
<td>6</td>
<td>16</td>
</tr>
<tr>
<td>5 - Triângulo Mineiro / Alto Paranaiba</td>
<td>66</td>
<td>31</td>
<td>15</td>
<td>16</td>
</tr>
<tr>
<td>6 - Central Mineira</td>
<td>30</td>
<td>26</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>7 - Metropolitana de BH</td>
<td>105</td>
<td>31</td>
<td>19</td>
<td>12</td>
</tr>
<tr>
<td>8 - Vale do Rio Doce</td>
<td>102</td>
<td>53</td>
<td>23</td>
<td>30</td>
</tr>
<tr>
<td>9 - Oeste de Minas</td>
<td>44</td>
<td>28</td>
<td>19</td>
<td>9</td>
</tr>
<tr>
<td>10 - Sul / Sudoeste de Minas</td>
<td>146</td>
<td>55</td>
<td>27</td>
<td>28</td>
</tr>
<tr>
<td>11 - Campo das Vertentes</td>
<td>36</td>
<td>11</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>12 - Zona da Mata</td>
<td>142</td>
<td>36</td>
<td>15</td>
<td>21</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>853</strong></td>
<td><strong>419</strong></td>
<td><strong>196</strong></td>
<td><strong>223</strong></td>
</tr>
</tbody>
</table>
It was proposed six steps to estimate the methane production and the energy generation from the use of the biogas in the municipalities that would have implemented landfills to dispose their MSW: (1) Calculation of population projection; (2) Estimative of per capita generation; (3) Modeling of biogas potential; (4) Study of electricity generation from biogas recovery; (5) Calculation of equivalent population index; and (6) Projection of final methane and energy production.

Step 1 was carried out using the geometric projection method for the period from 2020 to 2040 (Equation 1). The methodology was based on historical data from the Atlas of Human Development in Brazil (Atlas do Desenvolvimento Humano do Brasil) and the years 2000 and 2010 were used as base years \[ T_0 \].

\[
P = P_0 \cdot e^{k(T-T_0)} \tag{1}
\]

In what: P: expected population; P₀: initial population; T: expected year; T₀: initial year; k: exponential coefficient.

The estimative of per capita generation (step 2) was determined from the data of the National Information System on Sanitation (Sistema Nacional de Informações sobre Saneamento - SNIS) for the year of 2017 [11]. In this regard, it was obtained an average value of 0.7194 kg.inh⁻¹.day⁻¹ for the state of Minas Gerais from the MSW total collected and the population attended by the household collection.

The software LandGEM® (version 3.02), developed by the United States Environmental Protection Agency, was used to model the biogas potential (step 3) [12]. The methane generation rate (k) was considered to be 0.05 year⁻¹ for the mesoregion “Norte de Minas” and 0.06 year⁻¹ for the others mesoregions, based on the average annual rainfall of each region [13]. The considered potential methane generation capacity (L₀) was 170 m³ methane.ton⁻¹ of waste (Equation 2) [13], [14].

\[
Q_{CH4} = \sum_{i=1}^{n} \sum_{j=0}^{n} \sum_{k=0.1}^{M} k \cdot L_0 \cdot \left( \frac{M}{15} \right) \cdot e^{-kt_{ij}} \tag{2}
\]
In what: $Q_{\text{CH}_4}$: annual methane production ($\text{m}^3\text{.year}^{-1}$); $i$: 1 year time increase; $n$: year of calculation; $j$: 0.1 year time increase; $k$: methane generation rate ($\text{year}^{-1}$); $L_0$: potential methane generation capacity ($\text{m}^3\cdot\text{ton}^{-1}$); $M_i$: mass of residues in the $i$-th year (mg); $t_{ij}$: age of the $j$-th section of the waste mass in the $i$-th year.

The use of internal combustion engines was considered to obtain the electricity generation from the biogas recovery (step 4), considering the landfills’ operations starting and ending in 2020 and 2040, respectively. Thereby, it was adopted 10 kWh.Nm$^{-3}$ as the lower calorific value of methane (LCV) and an energy conversion efficiency ($\eta$) of 34% (Equation 3) [15], [16].

$$\text{PEP} = \frac{\text{LCV} \cdot Q_{\text{CH}_4} \cdot 365 \cdot \eta}{100} \quad (3)$$

In what: PEP: potential electricity production (kWh.year$^{-1}$); LCV: lower calorific value of methane (kWh.Nm$^{-3}$); $Q_{\text{CH}_4}$: annual methane production ($\text{m}^3\cdot\text{year}^{-1}$); $\eta$: energy conversion efficiency (%).

The equivalent population index (step 5) was proposed to estimate the number of inhabitants per mesoregion that could have their energy needs supplied from the recovery and use of the biogas generated in the units under study (Equation 4). For that, it was considered a per capita energy consumption (PCEC) of 2,586 kWh.inh$^{-1}$ [17].

$$\text{EP} = \frac{\text{PEP}}{\text{PCEC}} \quad (4)$$

In what: EP: equivalent population (inh.year$^{-1}$); PEP: potential electricity production (kWh.year$^{-1}$); PCEC: per capita energy consumption (kWh.inh$^{-1}$).

In step 6, the results of methane and electricity production in all mesoregions were grouped, obtaining a time series. It was considered the landfills’ operations starting and ending years (2020 and 2040, respectively) and the subsequent years until the final methane and energy generation.

3. RESULTS AND DISCUSSION

Figure 2 (a) and 2 (b) shows methane production and electricity generation for the 12 mesoregions in the years 2030 and 2040, respectively. In the landfills’ operations starting year (2020) there is no methane generation, as predicted by the model under study.

Figure 2. Potential for methane and electricity production from biogas recovery for the years 2030 (a) and 2040 (b)
In 2030, the mesoregion “Metropolitana de Belo Horizonte” was the mesoregion that reached the highest values for methane and electricity production: around 20.48 $10^6$ m³ and 69.63 $10^6$ kWh, respectively. While the mesoregion “Campos das Vertentes” exhibited the lowest values for methane and electricity production: around 3.55 $10^6$ m³ and 12.09 $10^6$ kWh, respectively. In addition, in 2040, the above-mentioned mesoregions remained at the same positions in terms of methane production and electricity generation. The mesoregion “Metropolitana de Belo Horizonte” registered around 35.49 $10^6$ m³ and 120.67 $10^6$ kWh, while the mesoregion “Campo das Vertentes” reached around 5.88 $10^6$ m³ and 19.99 $10^6$ kWh for methane production and electricity generation, respectively.

On the other hand, the mesoregion “Vale do Mucuri” presented the highest equivalent population index concerning the total population of the mesoregion, with a value of 2.39% and 3.45% in 2030 and 2040, respectively (Table 2). While the mesoregion “Metropolitana de Belo Horizonte” was the one which exhibited the lowest equivalent population index, with a value of 0.34% and 0.51% in 2030 and 2040, respectively (Table 1). However, these mesoregions were the fourth-lowest and the first potential for methane and electricity production in the same years, respectively (Figure 2).

Table 2. Percentage representation of the equivalent population index based on the total population of each mesoregion

<table>
<thead>
<tr>
<th>Mesoregions</th>
<th>2030</th>
<th>2040</th>
</tr>
</thead>
<tbody>
<tr>
<td>01 - Noroeste de Minas</td>
<td>1.37%</td>
<td>1.98%</td>
</tr>
<tr>
<td>02 - Norte de Minas</td>
<td>1.11%</td>
<td>1.68%</td>
</tr>
<tr>
<td>03 - Jequitinhonha</td>
<td>2.25%</td>
<td>3.29%</td>
</tr>
<tr>
<td>04 - Vale do Mucuri</td>
<td>2.39%</td>
<td>3.45%</td>
</tr>
<tr>
<td>05 - Triângulo Mineiro/Alto Paranaiba</td>
<td>0.43%</td>
<td>0.64%</td>
</tr>
<tr>
<td>06 - Central Mineira</td>
<td>1.6%</td>
<td>2.37%</td>
</tr>
<tr>
<td>07 - Metropolitana de Belo Horizonte</td>
<td>0.34%</td>
<td>0.51%</td>
</tr>
<tr>
<td>08 - Vale do Rio Doce</td>
<td>0.57%</td>
<td>0.81%</td>
</tr>
<tr>
<td>09 - Oeste de Minas</td>
<td>1.52%</td>
<td>2.21%</td>
</tr>
<tr>
<td>10 - Sul/Sudoeste de Minas</td>
<td>1.01%</td>
<td>1.43%</td>
</tr>
<tr>
<td>11 - Campo das Vertentes</td>
<td>0.77%</td>
<td>1.12%</td>
</tr>
<tr>
<td>12 - Zona da Mata</td>
<td>0.43%</td>
<td>0.64%</td>
</tr>
</tbody>
</table>

In addition, Figure 3 shows the methane and electricity production’s potential of all mesorregions conjugated from 2020 until 2120. It can be observed that methane production would reach its maximum value in the year 2041, one year after the considered landfills’ operations ending year. However, it is still possible to extract electricity from the landfill, even after the end of its operation. According to Figure 3, 2120 is the final year of methane production, and consequently, electricity generation. Thereby, the implementation of landfills in the municipalities under study and the biogas recovery become even more attractive, since the methane and electricity production remain even after the final landfills’ activities.

Figure 3. Time series of methane and energy production
According to Figure 3, in 2041, the methane production and electricity generation in the state of Minas Gerais reached around 201.53 $10^6$ m³ and 0.685 TWh respectively.

Dos Santos et al. [6] estimated the biogas production potential from landfills for Brazil in three different scenarios (minimum, average and maximum). The authors obtained that the maximum biogas flow for these scenarios were, respectively, 4,418.94 $10^6$, 5,956.10 $10^6$ and 7,575.33 $10^6$ m³ year$^{-1}$; while the electricity generated were 6.9; 9.3 and 11.83 TWh year$^{-1}$, respectively [6].

Lima et al. [18] also measured the potential for biogas and electricity production in the Brazilian context from 2015 to 2045. Two scenarios were considered: (i) landfills already in operation in 2014; and (ii) a hypothetical scenario of municipality arrangements, with one landfill for each arrangement [18]. The highest value for biogas production in scenario 1 was 1,567 $10^6$ m³ year$^{-1}$ in the year of 2024; while the highest value in scenario 2 was 3,732 $10^6$ m³ year$^{-1}$ in 2045 [18].

The study of Lima et al. [18] also presented its results through a geographical distribution of biogas and electricity production among the states of Brazil. Analyzing specifically the state of Minas Gerais, the maximum installed capacity for scenario 1 was 47.97 MW in 2025; while for scenario 2 it was 106 MW in 2045 [18].

In this present work, on the other hand, the value of total electricity generation was 0.685 TWh year$^{-1}$, including the whole state of Minas Gerais (Figure 3). This amount corresponds to 78.22 MW, considering an uninterrupted electricity production throughout the year (365 days). Thereby, the maximum possible installed capacity obtained was among the values presented in the study of Lima et al. [18].

4. CONCLUSIONS

The treatment and proper disposal of municipal solid waste are an urgent need in the municipalities of Minas Gerais, mainly after the implementation of the Program “Minas sem Lixões” (Minas without Open Dumps - loose translation). Besides, the biogas is a by-product of waste anaerobic degradation in landfills, where it can be recovered and used to produce energy. In this way, the study proposed to estimate the production of methane and electricity from biogas recovery generated in landfills to be installed in the Minas Gerais municipalities with inappropriate disposal of MSW. The best value regarding the equivalent population was obtained for the mesorregion “Vale do Mucuri” in 2040, which is 3.41% of the total population of the mesorregion. Although the quantified percentage is small in terms of energy supply to big urban centers, the electricity generated could be used to supply small rural communities and population nucleus nearest the landfills areas. In addition, the results of this study can be used as a management tool to guide public investment policies in renewable energy sources, especially in locations that still dispose their waste inappropriately. In this way, it can be concluded that the use of biogas from landfills represents a positive externality of the proper disposal of municipal solid waste and can contribute to the increase of the Brazilian renewable energy matrix.

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