27th INTERNATIONAL CONGRESS OF MECHANICAL ENGENEERING
COBEM 2023
ABCM
Brazilian Society of Mechanical Sciences and Engineering
27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

COBEM-2023-0520
ENERGY RECOVERY FROM BIOGAS IN LANDFILLS: POTENTIAL ANALYSIS IN A CITY IN THE MIDWEST OF MINAS GERAIS

Vinícius Fonseca da Silva
vinicius.fonseca@ifmg.edu.br
Luis Fellipe Camargos
luis.camargos@ifmg.edu.br
Ricardo Carrasco Carpio
IFMG - Arcos, Av. Juscelino Kubitscheck, 485 - Distrito Industrial II, Arcos - MG, 35588-000, Brasil
ricardo.carpio@ifmg.edu.br

Same format for other authors, if any

Abstract. *The aim of this study is to analyze the potential for electricity generation from the biogas produced by the landfill in a city in the Midwest of Minas Gerais, which has a population of* $40,000$ *inhabitants. The study seeks to determine the appropriate methodology for analyzing biogas and methane production, as well as to determine the potential for energy production to minimize the operational costs of the landfill. To achieve this goal, a technical analysis was conducted to assess the potential for biogas production for electricity generation. It was necessary to estimate the growth curve of municipal solid waste (MSW) collection from* 2001 *to* 2019*. Additionally, it was necessary to estimate the population growth of the city during the studied period since the quantity of MSW produced is proportional, among other factors, to population growth, and this growth was based on the decreasing growth rate model. Among the existing methodologies, the LandGEM© methodology developed by the United States Environmental Protection Agency was chosen to estimate biogas production from the landfill. The method developed by the Environmental Company of the State of São Paulo (CETESP) was adopted to estimate the potential for electricity production. The results obtained indicated that the landfill in the city in the Midwest of Minas Gerais presents favorable conditions to produce sufficient biogas for electricity generation, estimated at around* $974\ kW$*. However, it is necessary to carry out a more precise characterization of the generated biogas and to control the volume of collected MSW. Although the proposed objectives have been achieved, there are still technical and economic challenges to overcome in order to implement an effective project for energy recovery from landfill biogas. Nevertheless, it is important to emphasize that this alternative can reduce the operational costs of landfills and contribute to reducing greenhouse gas emissions. In summary, the analysis conducted shows that energy recovery from biogas generated in landfills is a viable and promising option for electricity generation.*

Keywords: *Landfills; Biogas, LandGEM, Municipal solid waste*

1. INTRODUCTION

With the process of increasing urbanization and industrialization, the demand for energy has significantly risen. Consequently, there is also a substantial growth in the production of municipal solid waste (MSW). In this scenario, it becomes increasingly necessary to study technologies that allow for energy production and the reuse of MSW. One way to combine these two demands is through the utilization of landfill biogas for energy generation, establishing a connection between energy and environmental/sanitary solutions, resulting in a sustainable approach to the mentioned problems. However, despite not being a recent solution, the idea of harnessing landfill biogas lacks studies that encourage the creation of public policies to drive the implementation of this practice (SILVA, 2017) (ABRELPE, 2020).

The importance given to landfills in this study is due to the fact that they can generate gases with energy potential, with biogas being the main one. Biogas is mainly composed of methane (CH_4) and carbon dioxide (CO_2). However, it is important to emphasize that biogas, due to its high methane content, is a greenhouse gas. If released directly into the atmosphere, it can cause significant harm to the environment. Therefore, measures that reduce this impact are essential in landfills. A simple solution to minimize the environmental liabilities caused by improper methane disposal is its combustion. However, by using this method, the energy potential contained in biogas is lost.

In recent years, there has been a significant increase in the production of MSW (Municipal Solid Waste), both in total terms and per capita. According to the Associação Brasileira de Empresas de Limpeza Pública e Resíduos Especiais (ABRELPE), in the past decade alone, MSW production has grown by almost 20%. These numbers highlight the urgency of creating mechanisms for proper MSW disposal. In this context, Law 12,305/10, which established the Política Nacional de Resíduos Sólidos (PNRS), plays a fundamental role in establishing guidelines for integrated management and the handling of solid waste, including hazardous waste, as well as the responsibilities of waste generators and the government. However, even with this legislation, proper MSW disposal in Brazil remains a challenge, as evidenced by the fact that 40.50% of generated waste does not have appropriate disposal (ABRELPE, 2020).

As illustrated in Fig. 1, approximately 13% of all collected MSW in the country is still disposed of in open dumps, known as landfills. Proper disposal of MSW is crucial to transform it into a valuable asset for diversifying the energy matrix, as well as ensuring that environmental impact is minimized, making the entire process more sustainable.

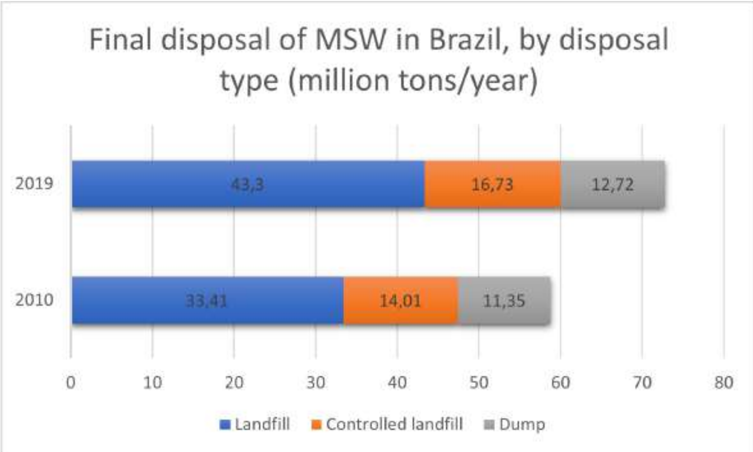

Figure 1: Final disposal of MSW in Brazil
Source: Adapted from ABRELPE (2020)

According to Brasil (2019), it is estimated that 50% of the methane released from landfills in Brazil can be utilized as biogas. This potential can be harnessed through thermal machines such as turbines and cogenerators, which convert the energy contained in biogas into electricity. Furthermore, the use of landfill biogas offers a range of benefits, including reducing greenhouse gas emissions, decreasing reliance on fossil fuels, and diversifying the energy matrix, thus contributing to energy security and environmental sustainability.

In this context, the analysis of the potential for biogas and electricity production from landfills becomes relevant as it allows for the assessment of the feasibility of implementing this sustainable technology in a specific scenario. It is crucial to consider the existing infrastructure, the quantity of available solid waste, and the energy demand of the region in order to establish appropriate and efficient planning for the implementation of landfill biogas utilization as an energy source.

In conclusion, the utilization of landfill biogas as a sustainable solution for electricity generation from solid urban waste is a promising approach that combines energy demands with proper solid waste management. The implementation of this technology requires further in-depth studies as well as the establishment of public policies that incentivize and facilitate its widespread adoption. By harnessing the energy potential of landfills, it is possible to contribute to the diversification of Brazil's energy matrix, reduce greenhouse gas emissions, and promote more sustainable development.

2. URBAN SOLID WASTE AND BIOGAS

2.1 Urban solid waste

According to the definition found in NBR 10004:2004, solid waste refers to materials, substances, objects, or discarded goods resulting from human activities in society. These waste materials can be in solid or semi-solid state and are generated by various activities, such as industrial, domestic, hospital, commercial, agricultural, service, and sweeping activities (Brasil, 2019) (ABNT, 2004).

The generation of solid waste is directly related to factors such as economic development and the purchasing power of the population. More developed countries with higher per capita income tend to generate a larger quantity of solid waste due to higher consumption of industrial products and packaging materials. However, in lower-income countries, there is lower consumption of industrial products and often a higher rate of source separation and recycling of waste (Kabir, 2015).

Characterizing solid waste is an important step in studying the theoretical potential for biogas production from landfills. This characterization involves physical, chemical, and biological analyses of the waste, considering factors such as calorific value, chemical composition, carbon-to-nitrogen ratio, *pH*, total and volatile solids content, gravimetric composition, particle size distribution, moisture content, among others (Ferreira, 2018) (Santos *et al.*, 2013).

The treatment of solid waste aims to reduce the quantity of waste generated and its potential for pollution. The most effective form of treatment is the adoption of sustainable practices by the population, such as waste reduction, material reuse, and source separation of recyclables. Additionally, there are physical and biological treatment processes, such as composting, incineration, recycling, biological treatment, and pyrolysis or gasification. The final disposal of waste can occur in sanitary landfills, controlled landfills, or open dumps, with open dumps being the most inappropriate form of disposal (IBAM, 2001).

Therefore, it is important to reconsider how we deal with urban solid waste, seeking more sustainable practices and valuing the reuse of discarded materials, in order to reduce environmental impact and promote a circular economy.

2.2 Landfill biogas

Biogas is formed through the anaerobic decomposition of organic matter, primarily composed of methane (CH_4) and carbon dioxide (CO_2), along with other gases in smaller concentrations. It is generated through processes of hydrolysis, fermentation/acidogenesis, and methanogenesis, as seen in Fig. 2. The presence of water is essential for the decomposition process, and factors such as the physical and chemical composition of USW, moisture, temperature, and *pH* influence biogas production (Alves, 2020) (Tarazona, 2010).

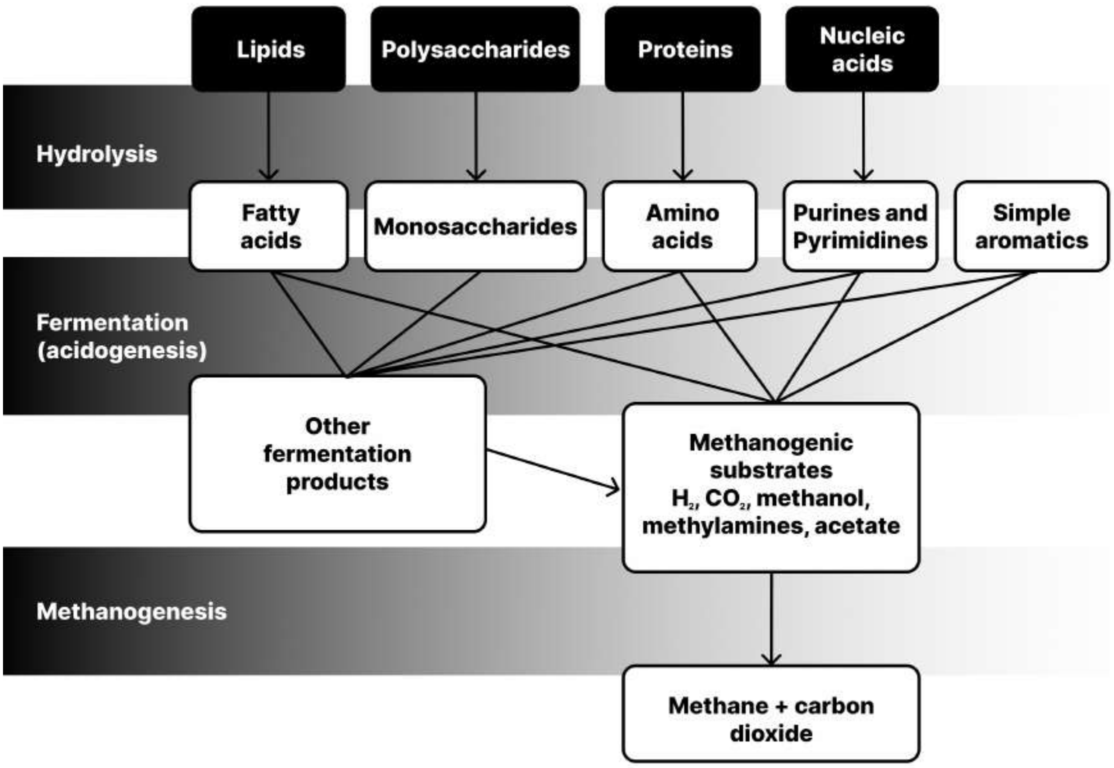

Figure 2: Sequence of processes in anaerobic decomposition
Source: Adapted from (Alves, 2020)

The ideal temperature for biogas production ranges from $30°C$ to $50°C$, while the appropriate *pH* level is between 6.6 and 7.6. Biogas exhibits similar characteristics to natural gas, but with lower calorific value and the presence of hydrogen sulfide and moisture. Its energy potential can be utilized in various ways, such as electricity generation, thermal use, vehicle fuel (biomethane), and gas lighting (Gonçalves, 2018).

The calorific value of biogas is directly related to the methane concentration, and the variation in this concentration influences its energy potential. In general, the lower heating value (LHV) of biogas varies according to the methane concentration (Ferreira, 2018).

According to Moura *et al.* (2017), biogas has a calorific value ranging from 5,000 to $7,000$ $kcal/m^3$, and when purified, it can reach up to $12,000$ $kcal/m^3$.

2.3 Biogas production estimation

To estimate the amount of biogas generated by organic matter during its anaerobic decomposition, algebraic or biochemical equations have been used, often requiring the use of software tools Alves (2020).

Various mathematical models are used to predict the biogas production capacity in a specific landfill. These models rely on data such as the type of waste, the quantity and disposal period of the waste. Some more complex models require more specific information, including temperature, Alves (2020), moisture content, carbon-to-waste ratio, volatile solids content in the organic matter, and waste degradation Alves (2020).

In this study, the LandGem 3.03 (Landfill Gas Emission Model) method will be utilized.

2.3.1 The LandGem 3.03

According to (Alves, 2020), the LandGem 3.03 is a free software developed within the Microsoft Excel environment and produced by the United States Environmental Protection Agency (EPA). Its purpose is to estimate the quantity and percentages of components present in the biogas generated from the landfill under study. The initial page of the LandGem 3.03 can be seen in Fig. 3.

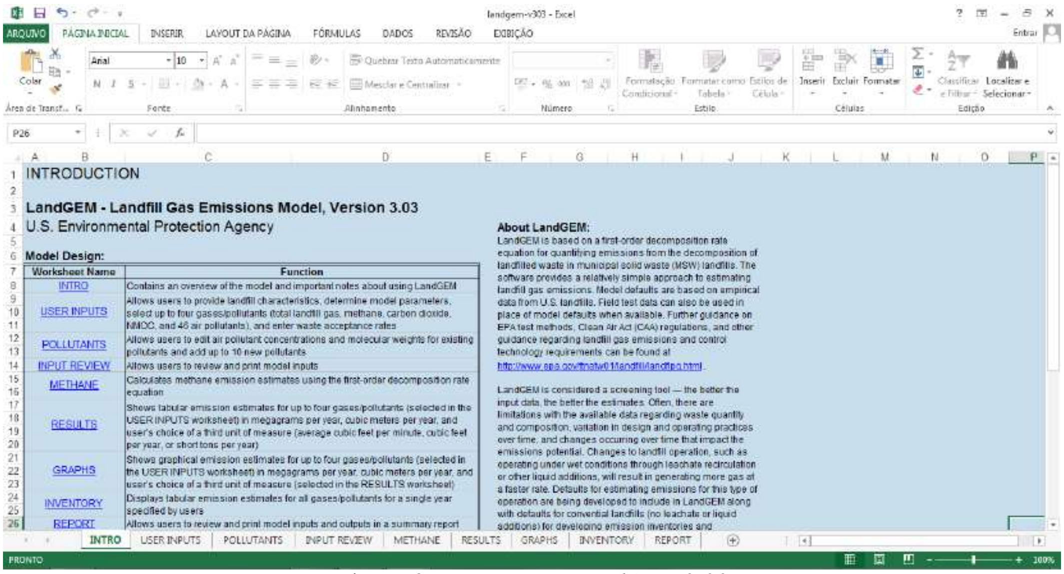

Figure 3: Home page *LandGem 3.03*
Source: Authors

To estimate biogas production, the software relies on a first-order decomposition equation. This allows for quantifying the annual methane production based on the Eq. 1.

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0,1}^{1} k \cdot L_o \left(\frac{M_i}{10} \right) e^{-k \cdot t_{ij}} \tag{1}$$

Where Q_{CH_4} is the quantity of methane generated in $[m^3/year]$, i is the time increment in $[year]$, n is the difference between the calculation year and the year when the landfill started operating, j is the time increment in $[year]$, k is the methane generation rate in $[year^{-1}]$, L_0 is the methane generation potential in $[m^3/Mg]$, M_i is the quantity of waste deposited in the year in $[Mg]$, and t_{ij} is the age of section j of the waste mass M_i deposited in year i.

The method used in the LandGem software follows a simpler approach, with predetermined parameters (k, L_0, concentration of non-methane organic compounds, and methane content) to determine biogas emissions levels from a landfill. The input data required for the calculation are the start and end years of landfill operation and the quantity of MSW deposited in the landfill per year. (Alves, 2020) recommends replacing the default values provided by the software with measured values from the study object to obtain results closer to reality.

2.4 Electrical potential

Having the methane flow generated per year, the power of the biogas power plant to be built can be determined using Eq. 2. It is necessary to consider the efficiency of the engine-generator set (in this study, Otto cycle engine with a efficiency of 25%), the biogas capture rate (60%), and the calorific value of methane CETESB (2020).

$$P = Q_{CH_4} \cdot E \cdot E_c \cdot PC_{CH_4} \cdot \left(\frac{1}{31.536.000} \cdot \frac{1}{1.000} \right) \tag{2}$$

Where Q_{CH_4} is the annual methane flow in m^3_{CH4} per year, E is the conversion efficiency of the engine-generator set (assumed as 25% for this study), E_c is the biogas collection efficiency (assumed as 100%), PC_{CH_4} is the calorific value of methane (equal to $35.53 \times 10^6 J/m^3_{CH_4}$), the number of seconds in a year $(31, 536, 000)$, and the unit conversion from J/s to kW $(1/1000)$.

3. CENTRAL WEST MINEIRO CITY AND THE MUNICIPAL SANITARY LANDFILL

The study site is located in the city of Arcos, a municipality in the Alto São Francisco region of Minas Gerais, Brazil. It covers an area of $510.048\ km^2$ is situated approximately 210 kilometers from the capital, Belo Horizonte. The estimated population according to the Brazilian Institute of Geography and Statistics (IBGE) in 2021 is $40,658$ inhabitants, with a population density of 79.74 inhabitants per square kilometer.

According to IBGE, the city's per capita Gross Domestic Product (GDP) in 2018 was $R\$31,945.72$. The city ranks $42nd$ in Minas Gerais in terms of the Human Development Index (HDI), with a percentage of 0.749.

According to the environmental licensing protocol number $0019428/2019$ from the Government of the state of Minas Gerais, the landfill has been in operation since November 2003 under certification LO number $579/2003$, which expired on November 7, 2009. On March 18, 2011, a Term of Conduct Adjustment (TAC) was signed between the Municipality of Arcos and the SUPRAM/ASF (Regional Superintendence of the Environment of Alto São Francisco) (Minas Gerais, 2018).

According to the environmental licensing, the study site has been classified as Class 3 (medium-sized) in terms of its capacity and is capable of receiving and disposing of approximately 40 tons of MSW per day.

The operation is located in the rural area, with no specific address provided, on the Arcos-Prata Road, approximately 5.8 kilometers from the urban center of the municipality, at coordinates $20°17'33.87"\ S\ /\ 045°30'03.56"\ W$. The sanitary landfill carries out activities such as sorting, treatment, and final disposal of MSW generated by the municipality, as depicted in the panorama presented in Fig. 4 (Minas Gerais, 2018).

Figure 4: General view of the municipal landfill in the city of Arcos, Minas Gerais
Source: Google Earth, 2022

According to the project presented in 2001, the property covers 22.69 hectares. The first platform was sealed with a compacted clay layer of 300 mm and a high-density polyethylene (HDPE) geomembrane with a thickness of $1.5\ mm$ was applied. For the collection and treatment of leachate, a main drain was installed on the sealing system base, to which secondary drains are connected. The collected leachate is directed to an on-site wastewater treatment plant (WWTP) at the landfill. The WWTP consists of three treatment ponds, one of which is anaerobic and the other two are facultative, each with a capacity of $462m\ ^3$ (Minas Gerais, 2018).

According to the environmental licensing, the solid waste found in the landfill has a gravimetric composition as specified in Tab. 1.

O aterro sanitário recebe em média de $940.595\ ton/ms$ de resíduo, conforme visto na Tab. 2 e deste valor em torno de $2,5\%$ são reciclados pela cooperativa de reciclagem instalada no aterro, segundo dados colhidos pela secretária de obras do município de Arcos-MG.

4. Population and MSW Estimation

For the analysis of biogas production generated by the landfill, it is essential to know the population projection in order to estimate the amount of waste generated during the study period and for greenhouse gas emission simulations.

Thus, the population of the city was estimated based on data obtained from the demographic censuses conducted by IBGE for the years 2000 and 2010, as well as the projection made by the same institution for the year 2021. This allows us to have a population projection between the years 2000 and 2028 (the estimated year for the closure of the current landfill) (Minas Gerais, 2018).

To estimate population growth, a model of decreasing growth rate was used, described by Eq. 3, where the variables

Table 1: Gravimetric composition of solid waste in the landfill of the city of Arcos-MG

Component	$\%$
Organic matter	$66,0$
Cardboard	$4,39$
Paper	$2,45$
Plastic	$5,42$
Wood	$0,50$
Metals	$3,13$
Glass	$1,14$
Rubber	$0,37$
Rejects	$14,31$
Others (rags and fabrics)	$1,72$

Source: Authors

Table 2: Collection of MSW Arcos-MG in the years 2019 and 2020

Month	2019 (ton/month)	2020 (ton/month)
Jan	1,841,250	1,119,690
Feb	977,590	1,019,440
Mar	927,380	998,750
Apr	925,770	878,980
May	946,340	841,570
Jun	807,080	903,350
Jul	822,090	889,100
Aug	921,600	864,831
Sep	822,910	873,960
Oct	897,810	967,450
Nov	931,340	956,090
Dec	1,028,370	973,930

Source: Authors

are determined by Eq. 4 and 5 (Barros *et al.*, 2014).

$$P_t = P_0 + (P_s - P_0)\left[1 - e^{-k_d(t-t_0)}\right] \tag{3}$$

$$P_s = \frac{(2 \cdot P_0 \cdot P_1 \cdot P_2) - P_1^2(P_0 + P_2)}{(P_0 \cdot P_2) - P_1^2} \tag{4}$$

$$k_d = \frac{\ln\left[(P_s - P_2)/(P_s - P_0)\right]}{t_2 - t_0} \tag{5}$$

Where P_t is the estimated population in year t, P_0, P_1, and P_2 are the populations in years t_0, t_1, and t_2 according to the demographic censuses, P_s is the saturation population, and k_d is the coefficient.

5. RESULTS AND DISCUSSION

5.1 Population and MSW Projection

Due to the lack of data on the quantity of waste deposited in the landfill between the years 2003 and 2019, it was defined for the study that the average annual waste production would be the average of the years 2019 and 2020.

Table **??** presents the population projection and the generation of MSW in Arcos (MG) from 2001 to 2028. According to the growth projection based on the decreasing growth rate, the population increased from $32,687$ inhabitants in 2000 to $43,072$ inhabitants in 2028.

As shown in Tab. 3, in the year 2001, an estimated MSW collection of $9,432.70$ $tons/year$ was projected, increasing to $12,277.45$ $tons/year$ in 2028. This corresponds to an average rate of 0.7804 $tons/(inhabitantyear)$, which is the average collected in the years 2019 and 2020. The total accumulated amount of MSW over the study period is $305,113.45$ $tons$. The population growth rate and MSW collection are directly proportional, and the projection of MSW collection growth is presented in Fig. 5.

Table 3: Population and Municipal Solid Waste (MSW) Production Projection between the years 2000 and 2028

Years	Population	MSW (mg/years)	Years	Population	MSW (mg/years)
2001	33,092	9,432.70	2015	38,495	10,972.80
2002	33,495	9,547.58	2016	38,861	11,077.13
2003	33,896	9,661.88	2017	39,225	11,180.88
2004	34,294	9,775.33	2018	39,587	11,284.07
2005	34,689	9,887.92	2019	39,946	11,386.40
2006	35,081	9,999.66	2020	40,303	11,488.16
2007	35,471	10,110.83	2021	40,658	11,589.35
2008	35,858	10,221.14	2022	41,009	11,689.40
2009	36,242	10,330.60	2023	41,359	11,789.17
2010	36,624	10,439.48	2024	41,706	11,888.08
2011	37,003	10,547.52	2025	42,051	11,986.42
2012	37,380	10,654.98	2026	42,394	12,084.19
2013	37,754	10,761.58	2027	42,734	12,181.11
2014	38,126	10,867.62	2028	43,072	12,277.45

Source: Authors

Como apresentado na Tab. 3 no ano de 2001 foi estimado uma coleta de $9.432,70\ mg/ano$ de RSU e $12.277,45\ mg/ano$ no ano de 2028. O que equivale a um índice de $0,7804\ mg \cdot hab^{-1} \cdot ano^{-1}$ que é a média coletada nos anos de 2019 e 2020. Totalizando uma quantidade acumulada de $305.113,45\ mg$ de RSU ao longo do período estudado. A taxa de crescimento da população e da coleta de RSU são diretamente proporcionais e a projeção do crescimento da coleta de RSU é apresentado nas Fig. 5.

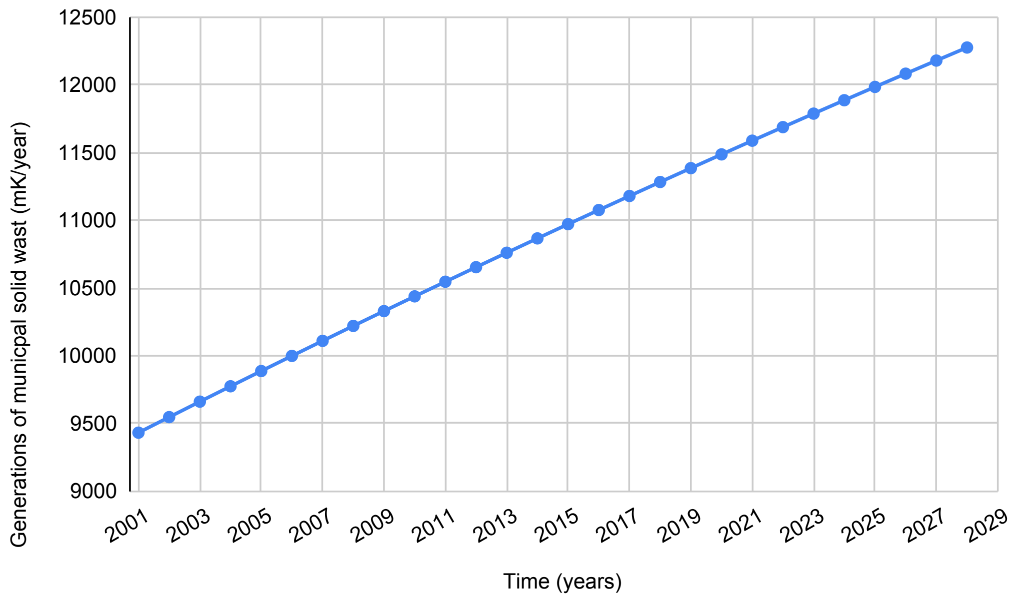

Figure 5: Projection of MSW generation in Arcos (MG) between the years 2001 and 2028
Source: Authors

5.2 Biogas estimation

With the use of the LandGEM software, the generation or emission of gases was estimated, with methane being the main gas emitted, as it has the highest calorific value and the necessary capacity for energy generation. The landfill gas generated is composed of approximately 60% methane, approximately 40% carbon dioxide, and the remainder consists of non-methane organic compounds.

Figure 6 presents the fractions of gas emitted by the landfill, which result from anaerobic digestion. It can be observed that the last year of landfill operation, 2028, is the year with the highest biogas production - $144\ km^3$ of methane per year and $961\ km^3$ of carbon dioxide per year.

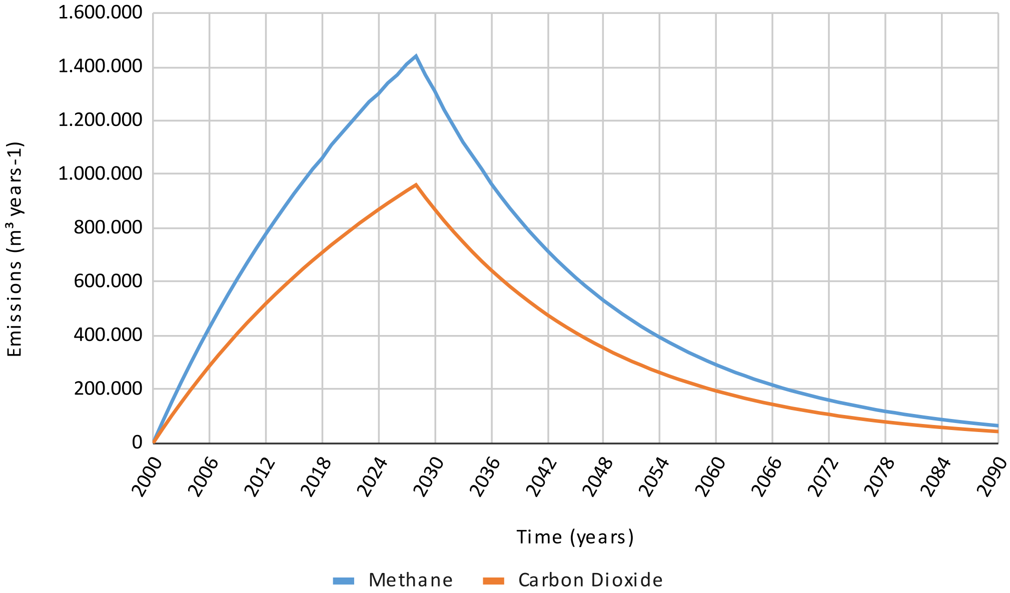

Figure 6: Estimate of landfill gas emissions using the LandGEM©software
Source: Authors

5.3 Estimate of the energy potential for converting biogas into electrical energy

Considering the adopted parameters throughout the study, the results of the energy production potential were calculated using Eq. 2 and are presented in Fig 7. As shown in Figure 7, the peak of the production potential occurs in the year 2028 with an electrical potential of $974.78\ kW$. All the biogas produced until the year of the plant's implementation cannot be utilized for electrical energy generation and is burned in flares or burners.

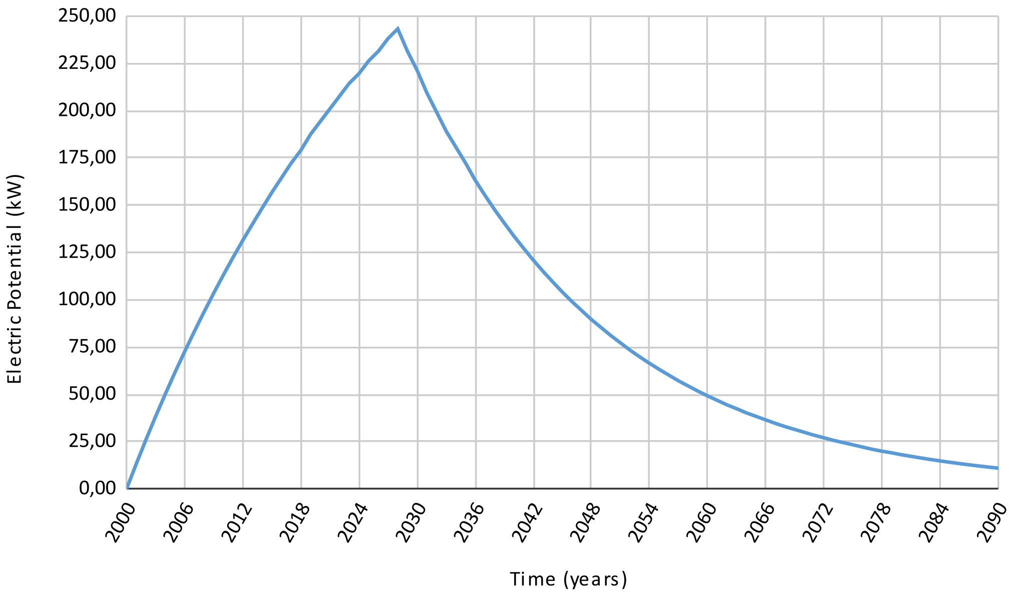

Figure 7: Estimation of the electric generation potential from landfill biogas
Source: Authors

According to Barros *et al.* (2014), the economic attractiveness of energy production projects using landfill biogas is only viable for landfills serving populations above $200,000$ inhabitants. Therefore, in order for energy utilization initiatives using landfill biogas to become financially attractive for smaller populations, it is necessary to create public policies that incentivize these energy sources, such as carbon offset policies.

6. FINAL CONSIDERATIONS

The purpose of this study is to conduct a technical analysis for biogas production for electricity generation using the biogas from a landfill in a city in the Midwest region of Minas Gerais, Brazil.

Based on the presented information, it can be concluded that the objective has been achieved, as the landfill under study has the potential to produce sufficient biogas for electricity generation, estimated at around 974 kW. However, due to the lack of control over the volume of solid waste collected in the years prior to 2019, it is necessary to characterize the generated biogas and conduct more precise analyses of biogas production from the landfill.

In the absence of more accurate data, such as an updated census and better waste quantity control by the municipality, the projections made in this study align with the per capita daily waste production estimates from international and national organizations studying the subject.

The adopted methodology for estimating biogas production, LandGEM©, proved to be the most suitable, particularly in the absence of data. It is a simple methodology for assessing technical feasibility and can be easily employed.

Despite the lack of data from the Arcos-MG landfill and the unknown quantity of greenhouse gas emissions generated, this study estimated a production of $24,205,700$ cubic meters of biogas since the year 2001.

The energy generation potential of the landfill can also be utilized in other ways, such as converting biogas into green hydrogen.

7. REFERENCES

ABNT, 2004. *NBR 10004: Resíduos sólidos - Classificação*. Rio de Janeiro.

ABRELPE, 2020. *Panorama dos Resíduos Sólidos no Brasil 2020*. São Paulo. URL `https://abrelpe.org.br/panorama/. Accessed 11 Jun 2023.`

Alves, A.F.M., 2020. *Análise exergoeconomica e exergoambienal de um sistema de trigeração usando gás natural e extensão para o uso do biogás de aterro sanitário*. Ph.D. thesis, Universidade Federal da Paraíba, João Pessoa.

Barros, R.M., Tiago Filho, G.L. and da Silva, T.R., 2014. "The electric energy potential of landfill biogas in brazil". *Energy Policy*, Vol. 65, pp. 150–164.

Brasil, M.d.M.A., 2019. *Agenda Nacional de Qualidade Ambiental Urbana: Programa Nacional Lixão Zero*. Departamento de Qualidade Ambiental e Gestão de Resíduos, Brasília, DF. URL `https://www.gov.br/mma/pt-br/assuntos/agendaambientalurbana/lixao-zero. Accessed 25 Jun 2023.`

CETESB, 2020. *Biogás: Geração e uso energético - versão 1.0*. São Paulo. URL `https://cetesb.sp.gov.br/biogas/softwares/. Accessed 10 de out. 2022.`

Ferreira, W.R., 2018. *Análise do potencial energético territorial do biogás proveniente de aterros sanitários para inserção na matriz elétrica do Estado de Minas Gerais no horizonte de 2050*. Master's thesis, Universidade Federal de Minas Gerais, Belo Horizonte.

Gonçalves, M.N., 2018. *Os Efeitos da Temperatura na Produção de Biogás em Biodigestores*. Master's thesis, Universidade Federal de Uberlândia, Uberlândia.

IBAM, I.B.d.A.M., 2001. *Manual de gerenciamento integrado de resíduos sólidos*. Rio de Janeiro. URL `http://www.ibam.org.br/media/arquivos/estudos/manual`$_girs.pdf.Accessed15mar.$2021.

Kabir, M.R., 2015. "Municipal solid waste management system: a study on dhaka north and south city corporations". *Journal of Bangladesh Institute of Planners ISSN 2075-9363*, Vol. 8, pp. 35–48.

Minas Gerais, S.d.E.d.M.A.e.D.S., 2018. *Licenciamento Ambiental*. Belo Horizonte. URL `http://sistemas.meioambiente.mg.gov.br/licenciamento/site/view-externo?id=10298. Accessed 29 abr. 2021.`

Moura, R.S., Carpio, R.C., Macedo, C.F.d.C., Pinheiro, D.S., Figueiredo, L.S. and Freire Junior, L.C., 2017. "Análise da viabilidade do uso de biodigestores em propriedades rurais". *ForScience*, Vol. 5, No. 3.

Santos, A.d.A., Peixoto, K.L.G., Passos, A., Noguchi, H.S., Pessoa, J.O. and da Motta Sobrinho, M.A., 2013. "Caracterização quantitativa e qualitativa dos resíduos sólidos urbanos do município de apuí-am." *EDUCAmazônia*, Vol. 10, No. 1, pp. 49–58.

SILVA, G.A.d., 2017. *Produção de biogás a partir de resíduos orgânicos e lodo de esgoto*. Master's thesis, Universidade Federal de Pernambuco, Recife.

Tarazona, C.F., 2010. *Estimativa de produção de gás em aterros de resíduos sólidos urbanos*. Master's thesis, Universidade Federal do Rio de Janeiro, Rio de Janeiro.

8. RESPONSIBILITY NOTICE

The authors are solely responsible for the printed material included in this paper.