ISSN2344-8652

Assessing biogas energy generated by municipal solid waste from landfills using the LandGEM

Evaluación energética de la formación de biogás obtenido de residuos sólidos urbanos del relleno sanitario mediante el modelo LandGEM

Steven Javier Sofán Germán **Alejandro Ruiz Garcés**

Miguel Emigdio Doria Oviedo

Universidad del Sinú – Elías Bechara Zainúm, Colombia

Jose David Arrieta Torres

Universidad de Córdoba, Colombia

Received: 04/12/2023
Accepted: 06/14/2023
Published: 07/31/2023

Author Correspondence:
stivensofan@unisinú.edu.co

Abstract

Objective: Herein, using the Landfill Gas Emissions Model (LandGEM), adapted to the local conditions of Montería, Colombia, estimation of the energy available for electricity production from biogas obtained from landfill waste was conducted.
Methodology: For this purpose, information on the Loma Grande landfill in Montería was obtained from databases and studies, including waste volume, climate, and waste composition, from 2016 to 2028. This dataset was then applied to the LandGEM for biogas energy production.
Results: The findings of this study reveal that only for 2022, the calculated methane quantity was 9,984,000 m^3/year and the total estimated energy was 268,496.8 MWh, which could meet the requirements of the Loma Grande landfill.
Conclusions: This study suggests that assessment models, such as the LandGEM, can be used to estimate energy production from landfill gas, thereby utilizing the potential of unproductive lands that would typically be used as landfills for nondestructive contaminating materials.

Keywords: Biogas, LandGEM, Landfill, Municipal solid waste, Methane

Resumen

Objetivo: Estimar la energía disponible para generar electricidad a partir de biogás de vertedero utilizando el modelo LandGEM adaptado a las condiciones locales de Montería, Colombia.
Metodología: Para ello se obtiene de base de datos y estudios la información del relleno sanitario de residuos Loma Grande ubicado en la ciudad de Montería, volumen de residuos, clima y composición de residuos para el periodo 2016-2028, para aplicar el modelo LandGEM a la producción de energía de biogás.
Resultados: se observó que solo para el año 2022 la cantidad de metano calculada es de 9.984.000 m3/año y con esto la energía estimada total es de 268.4968 MWh, que podría suministrar los requerimientos del relleno sanitario Loma grande.
Conclusión: El estudio predice que estos modelos de evaluación se pueden utilizar para planificar la producción de energía a partir de gas de vertedero, y así, aprovechar la propiedad de terrenos improductivos que normalmente se utilizarían como vertedero y que se crearon previamente para materiales contaminantes no destructivos.

Palabras clave: Biogás, LandGEM, vertedero, residuos sólidos urbanos, metano

How to Cite (IEEE): S. J. S. Germán, A. R. Garcés, M. E. D. Oviedo, and J. D. A. Torres, "Assessing biogas energy generated by municipal solid

waste from landfills using the LandGEM," Investigación e Innovación en Ingenierías, vol. 11, no. 2, pp. 16–27, 2023, https://doi.org/10.17081/invinno.11.2.6373

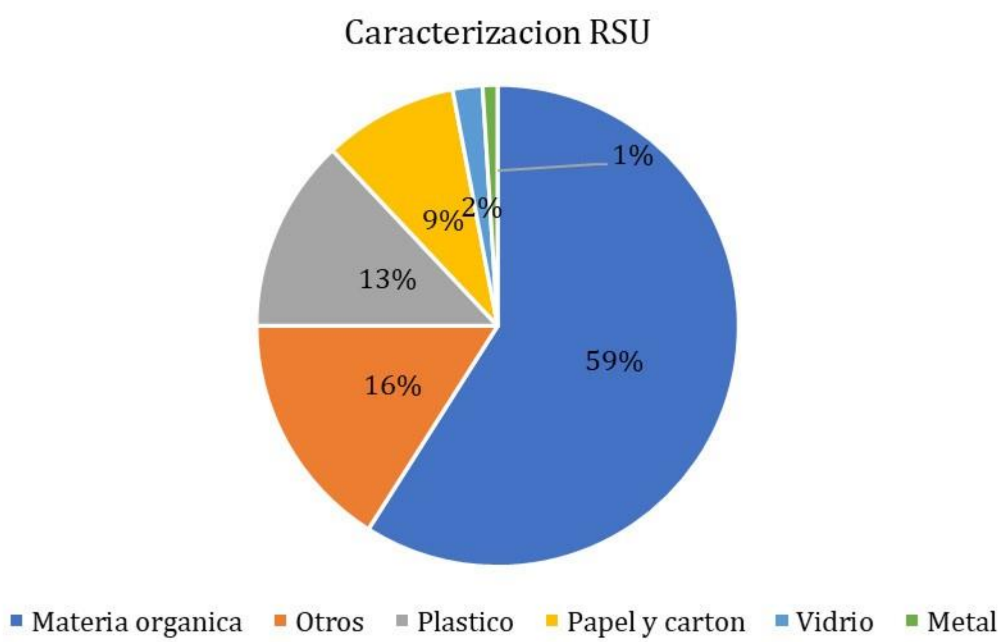
Introduction

Currently, landfills represent a substantial energy source, offering considerable potential for harnessing energy from waste, particularly in the form of biomass and, in certain cases, biogas. To generate biogas within landfills, the deposited waste should contain organic materials and be conducive to anaerobic decomposition. Furthermore, biogas production in landfills is not time-dependent; it increases during the initial year (the primary biogas production phase) and gradually diminishes after the third year [1]. In 2014, Latin America and the Caribbean generated 541,000 t of waste per day (of which 145,000 t per day went to landfills), and these figures are expected to reach 671,000 t per day by 2050. Today, the Latin American and Caribbean regions produce an average of 1.04 kg per day, with ~40 million people unable to collect their waste, and more than 50% of generated municipal solid waste (MSW) is organic [2].

For biogas production within a landfill, the stored waste should contain organic matter and meet the necessary conditions for anaerobic decomposition [3]. Municipal waste landfills represent a considerable source of greenhouse gas (GHG) emissions, primarily methane (CH_4) and carbon dioxide (CO_2), released into the atmosphere. While emissions in developed countries have largely stabilized, those in developing countries continue to rise [4].

MSW in Colombia typically includes organic matter and trimmings, as illustrated in Figure 1.

Figure 1. MSW characteristics - Colombia



Source: [5]

In Colombia, there are established policies for waste management that outline the composition of MSW [6, 7].

Research has been conducted in Colombia to assess and quantify greenhouse gas emissions from landfills. The conditions in certain regions of the country, often characterized by high temperatures and humidity, promote anaerobic waste decomposition, leading to considerable CH_4 emissions—the second-largest contributor toward Colombia's total emissions [8].

To provide more insights into electricity generation using landfill gas, it is crucial to identify the individual variables included in the process, including plant efficiency, methane content of biogas, and storage temperature. These variables help determine the amount of electricity produced by a specific amount of biogas. The gas production datasets were derived from [9], indicating methane quantity per volume of landfill gas, utilizing information from the thermodynamic properties table of methane [10].

Given that methane is a natural gas with superior characteristics compared to conventional petroleum-based energy sources, its use as a substitute makes energy-consuming activities, where methane is involved, more environment friendly [11].

Additionally, Novotny [12] assessed three integrated systems for water and MSW management in terms of energy use, production, and CO_2eq emissions. An aerobic treatment based on wastewater biogas and solid waste disposal through landfilling involved sludge codigestion with MSW and landfill gas capture to generate electricity using a turbine and generator. Wastewater treatment based on biogas with sludge codigestion and biodegradable solids was combined with the incineration of combustible sludge and other solids. Furthermore, a hydrogen-based system replaced landfilling through indirect gasification of organic solids, followed by hydrogen fuel cells.

There are notable variations in CO_2eq emissions between biogas and hydrogen-based systems. The initial two systems emit CO_2 and methane positively, making it improbable to achieve net-zero carbon emissions. On the contrary, the H_2-based system is entirely decarbonized and, in addition to providing clean water and energy as well as exhibiting negative CO_2 emissions, it yields valuable byproducts such as energy, concentrated hydrogen, fertilizers, oxygen/ozone, and concentrated CO_2.

Padilha and Mesquita [13] conducted a succinct review of recent literature on waste-to-energy technologies and operational projects in Brazil as well as introduced an innovative approach to assess the financial viability of established routes (technological routes) for MSW management. These routes incorporated waste-to-energy practices and considered income supplementation for small cities with populations ranging from 30,000 to 250,000 through the application of a contribution optimization algorithm. They employed a structured algorithm concentrating on estimating the minimum value of contributors' contribution (RPC) to ensure the viability of these routes for most cities considered in the project. The economic metrics employed included net present value (NPV), internal rate of return, discounted payback period, and levelized cost of electricity. A sensitivity analysis of the two most favorable routes (based on the lowest RPC values) was conducted with a focus on the NPV. The results confirmed solutions that could garner approval not only from the government but also from the business sector. The most promising routes involved landfill and landfill gas as well as recycling and anaerobic digestion, considering the sale of digestate and landfill. The sensitivity analysis highlighted a more considerable impact on landfill gas investment costs for the first route, whereas the second route was more influenced by urban collection and cleaning services.

Further, Moutushi et al. [14] studied the abiotic decomposition of simulated MSW to elucidate thermal reactions impacting landfill gas components such as methane, carbon dioxide, and hydrogen. The regulation of gas composition and temperature was based on the heating rate and time. Gas composition trends indicated that for heat inputs surpassing 46 W, the CH_4/CO_2 ratio deviated from the initial value of 1.0–0.2, which correlated with a reduction in CH_4 concentration. The key study findings revealed that the primary gas composition ratio (CH_4/CO_2) begins to decline from the reference value of 1.0 as the heating rate escalates from 30 to 51 W and it continues to decrease at considerably higher rates beyond 51 W. Their study shed light on operational conditions, such as available heat and moisture, contributing to alterations in landfill gas ratios.

The global impact of various waste types has been a major concern, and recent advancements have enabled intelligent waste management. In Australia, artificial intelligence has emerged as a potent technology gaining traction and applications across diverse fields, including waste management [15].

The integration of technological tools for production, classification, collection, vehicle routing, handling, disposal, and management planning has streamlined these processes in Australia. Building upon work conducted from 2005 to 2021 on MSW using several databases has allowed for the increasingly precise implementation of artificial intelligence in resource management. By comparing the performance of artificial intelligence applications, exploring its benefits, and addressing its potential issues, recommendations have been proposed to optimize the efficiency of this environmental and social process [16].

Ultimately, it was that the application of these processes has a more positive impact than using conventional systems. The intelligent processing of data leads to improvements in predictions crucial for early decision-making, providing substantial benefits to Australia by offering a more environmentally sound approach and transforming existing problems into sustainable solutions. This approach applies to other locations worldwide [16].

Methodology

Municipal Solid Waste Collection in Montería

The waste collection company serves the 250 neighborhoods in Montería, with 83% of them falling within the urban area [6]. Consequently, Urbaser manages ~13,700 t of monthly waste, which is subsequently directed to the Loma Grande landfill.

Biogas Composition

Anaerobic decomposition occurs in the absence of air when organic matter containing cellulose, such as manure, bird droppings, and decomposing plants, is involved. This lack of exposure to oxygen during decomposition leads to the production of combustible gas.

Gases obtainable from landfills include ammonia (NH_3), carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H_2), hydrogen sulfide (H_2S), methane (CH_4), nitrogen (N_2), and oxygen (O_2) [1]. Methane and carbon dioxide are the primary gases generated during the anaerobic digestion of biodegradable organic waste components in MSW.

Given that methane, with a concentration ranging between 5% and 15% in air, is explosive, it plays a critical role in this assessment. As landfills have limited oxygen, the risk of explosions within them is low when methane concentrations reach critical levels. However, if landfill gas migrates off-site and mixes with air, it can form a methane–air mixture within the explosive range.

Table 1. Typical constituents of MSW gases

Component	Symbol	Dry volume basis [%]
Methane	CH_4	50–70
Carbon dioxide	CO_2	35–55
Nitrogen	N_2	2–5
Sulfurs, disulfides, mercaptans, etc.	-	0–1.0
Oxygen	O_2	0.1–1
Ammonia	NH_3	0.1–1
Hydrogen	H_2	0–0.2
Carbon monoxide	CO	0–0.2

Source: [1]

Table 1 displays the percentage distribution of common gases present in MSW landfills. This distribution varies based on the landfill's age and the characteristics of the waste. Hence, it is essential to conduct periodic waste inspections to assess the amount of biogas that can be utilized within a specific time period.

Mathematical Model

The Landfill Gas Emissions Model (LandGEM), based on the first-order equations developed by the US Environmental Protection Agency (EPA) [17], is an automated Microsoft Excel–based tool that can be used to estimate emission factors for biogas, methane, carbon dioxide, and other compounds. The LandGEM [18] uses the first-order reduction equation (Equation (1)) to estimate annual emissions over a period of time.

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} kL_0 \cdot \left(\frac{M_i}{10}\right) e^{-kt_{ij}} \quad , (1)$$

where:

Q_{CH_4}: Annual methane production calculated during year n [$\frac{m^3}{year}$];

i : A 1-year time increase;

n: The difference between the calculation year and the year waste collection begins;

j: A 0.1-year time increase;

k: Methane production rate [$\frac{1}{year}$];

L_0: Methane production potential [$\frac{m^3 CH_4}{year}$;
M_t: Amount of waste collected annually i [t];
$t_{ij:}$ Year of the "*j*" section of waste accumulated during the "*i*" year.

The values of k and L_0 vary depending on the annual rainfall recorded in the city where the landfill is located, as denoted in Table 2.

Table 2. Methane generation rates: *k* and *L₀*

Annual rainfall (mm/year)	*k* (year $^{-1}$)	L_0 (m³/t)
0–249	0.040	60
250–499	0.050	80
500–999	0.065	84
≥1000	0.080	84

Source: [1]

The Loma Grande landfill is located on the outskirts of the city center of Montería, with an average temperature of 26°C and average precipitation of 1262 mm/year. This creates a favorable environment for the development of anaerobic digestion and enhances the extraction of landfill biogas.

The quality of the model's output depends on the input data, which necessitates certain assumptions to estimate the quantity and composition of waste. These parameters can be easily assigned based on field conditions.

Determination of Electricity Generation Potential

CH_4 from MSW was used to determine the electricity generation potential. Equation (2) shows how to forecast the magnitude of energy generation from a landfill biogas recovery system.

$$EAG = \frac{Q_{CH4} * 37.2 \frac{Mj}{m^3} * EGE * ER * 0.9 * C}{\emptyset} \quad , (2)$$

where:
Q_{CH_4}: Methane generated;
37.2 ($\frac{mj}{m^3}$): Minimum warming for methane [17, 18];
EGE: Energy production efficiency of the conversion device. According to [18], an acceptable value is 35%;
ER: Methane recovery efficiency and it is assumed to be 75%, as stated in [18, 19];
0.9: Landfill oxidation factor [17];
C: Capacity factor, considered as 85% [18, 19];
Ø: Conversion factor from MJ to MWh.

Raw data was collected from the solid waste deposited in the landfill managed by Montería Loma Grande. The specific landfill data are presented in Table 3 as a reference for the Colombia case study.

Table 3. Elemental MSW composition - Colombia

Waste	%H_2O	%C	%H	%O	%N	%S	%Ash
Food	70,0	48.0	6.4	37.6	2.6	0.4	5.0
Paper	6.0	43.5	6.0	44.0	0.3	0.2	6.0
Plastic	2.0	60.0	7.2	22.8	0.0	0.0	10.0
Textiles	10.0	55.0	6.6	31.2	4.6	0.2	2.5
Wood	20.0	49.5	6.0	42.7	0.2	0.1	1.5
Pruning	60.0	47.8	6.0	38.0	3.4	0.3	4.5

Source: [20, 21].

Results

Primary and secondary solid waste data were collected from the Loma Grande landfill located in Montería. According to [22], the available data and projections of the amount of solid waste entering the landfill in this study, and the characterization of residential solid waste from the Loma Grande landfill in the municipality of Montería is shown in Table 4.

Table 4. Characterization of residential solid waste from the Loma Grande landfill

Waste	Waste %
Paper	1.87
Cardboard	3.34
Plastic	18.06
Textiles	5.35
Rubber	0.33
Wood	0.2
Metal	0.33
Gardening products	0.6
Ceramics, rubble, ashes, and rocks	0.33
Organic waste	60.87
Hygiene and sanitary items	4.01
Other	4.71

Source: [22]

The waste entering the Loma Grande landfill is predominantly composed of organic or food waste, followed by plastic, textiles, hygiene and sanitary items, cardboard, and paper, as indicated in Table 4.

Meanwhile, Table 5 provides insights into the current waste generation patterns and the municipality's population, along with projections for the years 2016–2028 (the landfill's anticipated lifespan) [22]. Calculations for waste production were based on a per capita production of 0.911 kg/person/day, yielding an estimated total of 360,720 t of MSW in 2028. Presently, the municipality generates ~390,198 t of MSW.

Table 5. Waste production estimates - Municipal Capital, Montería

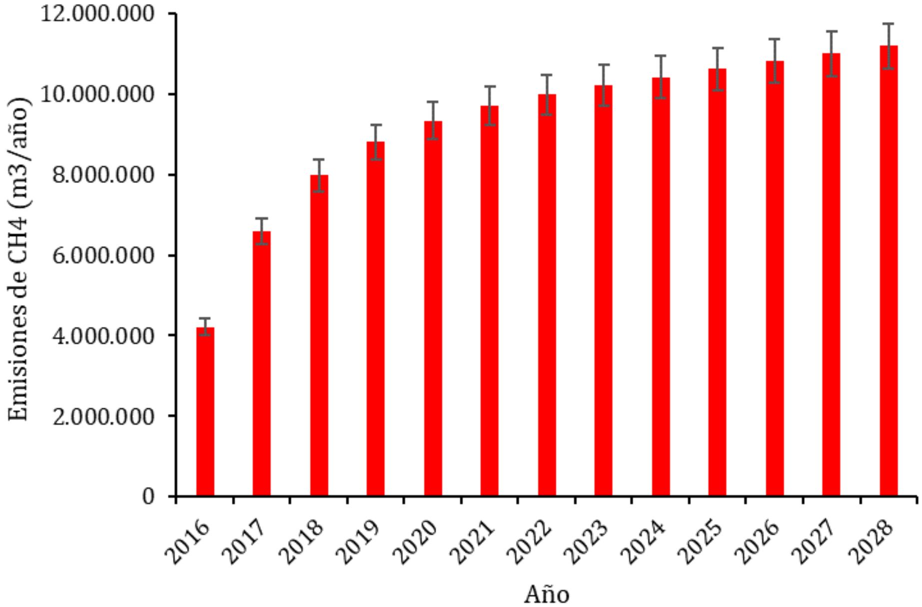
Year	Municipal capital population	MSW generated (kg/day)	MSW generated (t/day)	MSW generated (t/year)	Total MSW generated
2016	346,921	294,883	294.88	107,632.24	107,632.24
2017	352,796	299,877	299.88	109,455.05	217,087.29
2018	358,771	304,955	304.96	111,308.74	328,396.03
2019	364,847	310,120	310.12	113,193.81	441,589.84
2020	371,026	315,372	315.37	115,110.81	556,700.66
2021	377,310	320,713	320.71	117,060.28	673,760.94
2022	383,699	326,145	326.15	119,042.76	792,803.70
2023	390,198	331,668	331.67	121,058.82	913,862.52
2024	396,806	337,285	337.29	123,109.02	1,036,971.53
2025	403,526	342,997	342.99	125,193.94	1,162,165.47
2026	410,360	348,806	348.81	127,314.17	1,289,479.64
2027	417,310	354,713	354.71	129,470.31	1,418,949.95
2028	424,377	360,720	360.72	131,662.96	1,550,612.90

Source: [22]

CH_4 Production Calculation Using the LandGEM

Moreover, Table 5 shows the estimated composition of MSW reaching the Loma Grande landfill in Montería, considering the study period from 2016 to 2028. Urbaser, the waste collection company in the city, reports managing 16,500 t of waste per month across Montería's 250 neighborhoods. However, this study specifically examines MSW from the urban area, comprising 207 neighborhoods and corresponding to an approximate monthly waste generation of 13,700 t. The calculation of CH_4 production for a year in Colombia utilized the modified LandGEM. As depicted in Figure 2, the model estimates an annual average methane volume of 9,297,923 m^3/year.

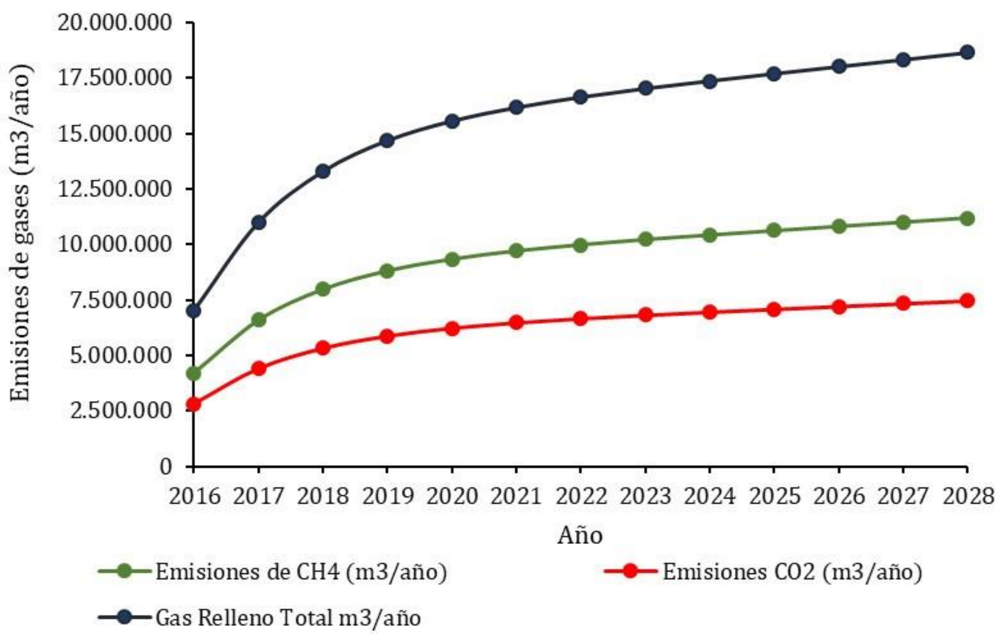
Figure 2. Annual methane production at the Loma Grande landfill from 2016 to 2028 (m^3/year)



Source: Prepared by the authors

However, Figure 3 illustrates the yearly trends in gas emissions (m^3/year) for all the calculated gases (total landfill gas, CH_4, and CO_2). As observed, the annual production increases because the population is growing, leading to a higher generation of MSW. Consequently, gas production increases over the years.

Figure 3. Annual gas emissions within the Loma Grande landfill from 2016 to 2028 based on the LandGEM (m^3/year)

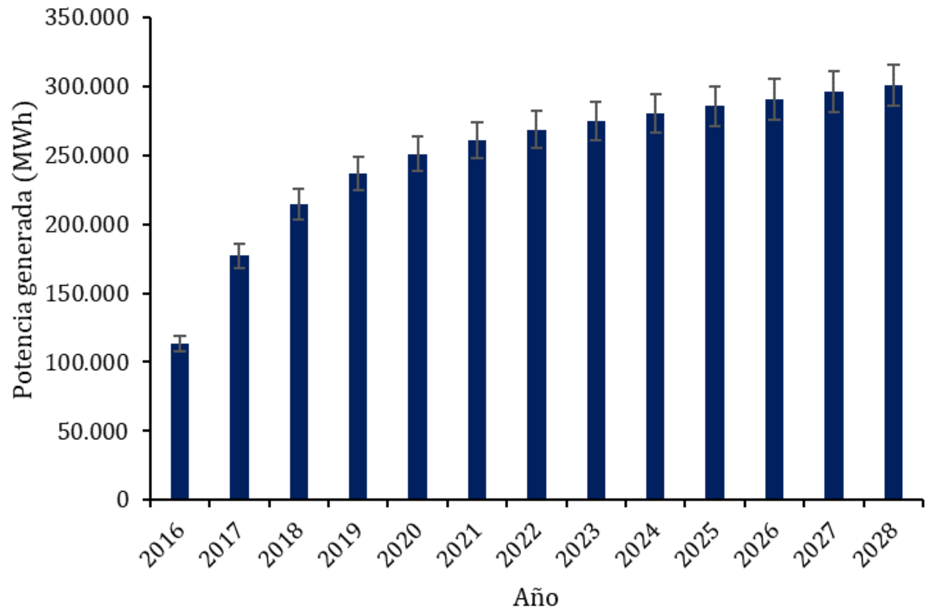


Source: Prepared by the authors

Calculation of Generated Power

The proportion of CH_4 produced from the accumulated and managed MSW at the Loma Grande landfill was assessed for the potential generation of electricity from biogas using Equation (2), which offers an estimate of the electricity generation potential at the Loma Grande landfill. Based on the assessment, it was observed that the landfill could have supplied 17,152 MWh in 2022 for the municipality of Montería. Furthermore, it was projected for the annual timeframe, with a net production of 3,250 GWh.

Figure 4. Production of electrical energy (MWh) from MSW within the Loma Grande landfill from 2016 to 2028



Source: Prepared by the Authors

The models generating these landfill methane estimates are crucial for considering their potential environmental impacts and aiding in the preparation and tracking of greenhouse gas inventories.

Conclusions

The compiled background information on solid waste deposited in the Loma Grande landfill was used for estimating landfill gas emissions using the LandGEM. The average quantity of methane indicated in the MSW was 9,297,923 m^3/year. The total electricity consumption for 2016–2028 was expected to be between 113,273 and 300,931 MWh to meet the landfill's demand (water treatment systems and pumps), as well as additional household payments and other benefits. This estimation heavily relies on the quality of available data and the selection of appropriate factors. The calculated production volume using the model was strongly influenced by the amount of generated waste, suggesting that a higher waste generation rate will lead to an increase in methane production in the future [23].

The results are region-specific and depend on qualities strictly related to each area. Within the context of this study, the results are quite beneficial compared to those found in the rest of Colombia and worldwide. This is due to the abundance of elements necessary for biogas in the landfill of Montería and the quality of MSW available in this region due to diverse vegetation. Furthermore, the project contributes to the improved use of idle lands surrounding the area. In addition to reducing its impact by diverting materials for this project, it helps to organize the space more efficiently, resulting in an increase in recycling efficiency, which is also crucial in such locations. Therefore, this study makes a considerable contribution to the improvement of the environment in Córdoba, setting a good example for how MSW should be handled throughout the region.

References

1. F. Andrés, A. Juan, J. Juan, and del C. María, "Análisis del biogás captado en un relleno sanitario como combustible primario para la generación de energía eléctrica," [Analysis of biogas captured in a landfill as primary fuel for the generation of electrical energy], Sci. Tech., vol. XVII, pp. 23–28, 2011 [Online]. Available: https://www.redalyc.org/articulo.oa?id=84921327006.

2. United Nations Organization - Environment (UN Environment), Perspective of Waste Management in Latin America and the Caribbean Perspective of Waste Management in Latin America and the Caribbean. 2018.

3. FAO, MINENERGIA, PNUD, and GEF, "Manual del Biogás," Proy. CHI/00/G32, p. 120, 2011 [Online]. Available: http://www.fao.org/docrep/019/as400s/as400s.pdf.

4. I. Márquez, "Disposición Final de Residuos Sólidos," [Final Disposal of Solid Waste], Supt. Serv. Públicos Domic., vol. 2215, p. 97, 2019.

5. T. E. Pilar, E. M. Arce, D. Daza, M. S. Faure, and H. Terraza, "Evaluation on urban solid waste management in Latin America and the Caribbean - 2010 report," Inter-American Dev. Bank, vol. 4, no. 1, pp. 88–100, 2557.

6. Fabiana Meijon Fadul, "Estudios para la revisión del POT Monteria-Córdoba," [Studies for POT review Monteria-Córdoba], 2019.

7. K. M. Noguera and J. T. Olivero, "Los rellenos sanitarios en Latinoamérica: Caso Colombiano," [Landfills in Latin America: The Colombian Case], Rev. Acad. Colomb. Cienc, vol. 34, no. 132, pp. 347–356, 2010.

8. M. de A. Housing and territorial development Institute of Hydrology, Meteorology and Environmental Studies-IDEAM-, United Nations Development Program -UNDP-, "Waste Module," Inventar. Nac. Fuentes y Sumideros Gases Ef. Invernadero 2000-2004, pp. 295–320, 2009.

9. C. G. B. Perez, "Biogás: una alternativa energética para los rellenos sanitarios urbanos y un beneficio mitigador de cambio climático," [Biogas: an energy alternative for urban landfills and a climate change mitigating benefit], Univ. Mil. NUEVA GRANADA, vol. 7, no. 6, p. 14, 2016 [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/26849997%0Ahttp://doi.wiley.com/10.1111/jne.12374.

10. Y. A. Çengel and M. A. Boles, Thermodynamics: an engineering approach. Sixth edition. Boston: McGraw-Hill Higher Education, 2008.

11. M. Markets, "La importancia del metano y las actividades de reducción de sus emisiones," [The importance of methane and emissions reduction activities], Methane to Mark., pp. 1–2, 2015 [Online]. Available: https://www.globalmethane.org/documents/methane_fs_ spa.pdf.

12. V. Novotny, "From biogas-to hydrogen – Based integrated urban water, energy and waste solids system - Quest towards decarbonization," Int. J. Hydrogen Energy, vol. 47, no. 19, pp. 10508–10530, 2022, https://doi.org/10.1016/j.ijhydene.2022.01.085.

13. J. L. Padilha and A. L. A. Mesquita, "Waste-to-energy effect in municipal solid waste treatment for small cities in Brazil," Energy Convers. Manag., vol. 265, p. 115743, 2022, https://doi.org/10.1016/j.enconman.2022.115743.

14. T. Moutushi, S. S. Tupsakhare, and M. J. Castaldi, "Abiotic decomposition of municipal solid waste under elevated temperature landfill conditions," Sci. Total Environ., vol. 823, p. 153685, 2022, https://doi.org/10.1016/j.scitotenv.2022.153685.

15. M. Regis, "Humans, not machines, create meaning: an interview of Miguel Benasayag by Regis Meyran," UNESCO Cour., vol. 3, pp. 15–17, 2018.

16. L. Andeobu, S. Wibowo, and S. Grandhi, "Artificial intelligence applications for sustainable solid waste management practices in Australia: A systematic review.," Sci. Total Environ., vol. 834, p. 155389, Aug. 2022, 10.1016/j.scitotenv.2022.155389.

17. T. R. Ayodele, A. S. O. Ogunjuyigbe, and M. A. Alao, "Economic and environmental assessment of electricity generation using biogas from organic fraction of municipal solid waste for the city of Ibadan, Nigeria," J. Clean. Prod., vol. 203, pp. 718–735, 2018, https://doi.org/10.1016/j.jclepro.2018.08.282.

18. D. Cudjoe, M. S. Han, and A. P. Nandiwardhana, "Electricity generation using biogas from organic fraction of municipal solid waste generated in provinces of China: Techno-economic and environmental impact analysis," Fuel Process. Technol., vol. 203, p. 106381, 2020, https://doi.org/10.1016/j.fuproc.2020.106381.

19. A. Alexander, C. Burklin, and A. Singleton, "Landfill gas emissions model. United States Environmental Protection Agency, Version 3.02 user's guide." U.S. Environ. Prot. Agency Off. Res. Dev., no. May, p. 48, 2005 [Online]. Available:

http://www3.epa.gov/ttncatc1/dir1/landgem-v302-guide.pdf.

20. A. Andrade, J. E. Tibaquirá, and A. Restrepo, “Estimación de biogás de relleno sanitario, caso de estudio: Colombia,” [Estimation of landfill biogas, case study: Colombia], Entre Cienc. Eng., vol. 12, no. 23, p. 40, 2018, https://doi.org/10.31908/19098367.3701.

21. S. Garcia-Freites, A. Welfle, A. Lea-Langton, P. Gilbert, and P. Thornley, “The potential of coffee stems gasification to provide bioenergy for coffee farms: a case study in the Colombian coffee sector,” Biomass Convers. Biorefinery, vol. 10, no. 4, pp. 1137–1152, 2020, https://doi.org/10.1007/s13399-019-00480-8.

22. A. de Montería, “Actualización del plan de gestión integral de residuos sólidos (PGIRS) del municipio de Montería dando cumplimiento a la resolución 0754 del 25 de noviembre del 2014,” [Updating the comprehensive solid waste management plan (PGIRS) of the municipality of Montería in compliance with resolution 0754 of November 25, 2014], 2017.

23. D. D. López Juvinao, L. M. Torres Ustate, and F. O. Moya Camacho, “Tecnologías, procesos y problemática ambiental en la Minería de arcilla” [Technologies, processes, and environmental problems in Clay Mining], Investigación e Innovación en Ingenierías, vol. 8, n. 2, pp. 20–43, 2020, https://doi.org/10.17081/invinno.8.2.385.