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Original Research

Potential use of methane gas from the Villavicencio sanitary landfill, Colombia

Potencial de aprovechamiento del gas metano generado en el relleno sanitario del municipio de Villavicencio, Colombia

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Abstract

The study evaluates the generation and recovery capacity of methane at the Villavicencio Landfill in Colombia, using the LandGEM model. It shows a significant increase in methane generation, rising from about 1.5 million cubic meters in 2010 to over 8.5 million in 2020, indicating a growing urgency to implement effective mitigation measures. It was estimated that by the year 2042, the electrical energy production from methane could be 248.067 kW/day, capable of supplying about 43.705 homes monthly. Additionally, thermal energy generation would be 468.572 kWh/day, useful for industrial processes. Management scenarios were proposed, where, for example, operational optimization could increase electric production to 342.333 kW/day, benefiting more than 60.000 homes monthly. The conclusions highlight the direct correlation between the amount of waste and methane generation, and the significant potential for converting these emissions into energy, pointing towards regional energy self-sufficiency and sustainability. Methane recovery represents a valuable alternative to the dependence on fossil fuels and for the development of a circular economy.

Resumen

El estudio evalúa la generación y capacidad de recuperación de metano en el Relleno Sanitario de Villavicencio, Colombia, mediante el modelo LandGEM. En donde se observa un aumento significativo en la generación de metano, pasando de alrededor de 1,5 millones de metros cúbicos en 2010 a más de 8,5 millones en 2020, lo que indica una creciente urgencia por implementar medidas de mitigación efectivas. Se estimó que, para el año 2042, la producción de energía eléctrica del metano podría ser de 248.067 kW/día, capaz de abastecer a unos 43.705 hogares mensualmente. Asimismo, se generaría energía térmica de 468.572 kWh/día, útil para procesos industriales. Se plantearon escenarios de gestión, donde, por ejemplo, la optimización operacional podría aumentar la producción eléctrica a 342.333 kW/día, beneficiando a más de 60.000 hogares mensualmente. Las conclusiones resaltan la correlación directa entre la cantidad de residuos y la generación de metano, y el significativo potencial de convertir estas emisiones en energía, apuntando hacia la autosuficiencia y sostenibilidad energética regional. El aprovechamiento del metano representa una alternativa valiosa frente a la dependencia de combustibles fósiles y para el desarrollo de una economía circular.

Keywords: air quality, Landfill gas, Greenhouse gas, Municipal solid waste, LandGEM.

Palabras clave: calidad del aire, Gases de vertedero, Gases de efecto invernadero, Residuos sólidos urbanos, LandGEM.

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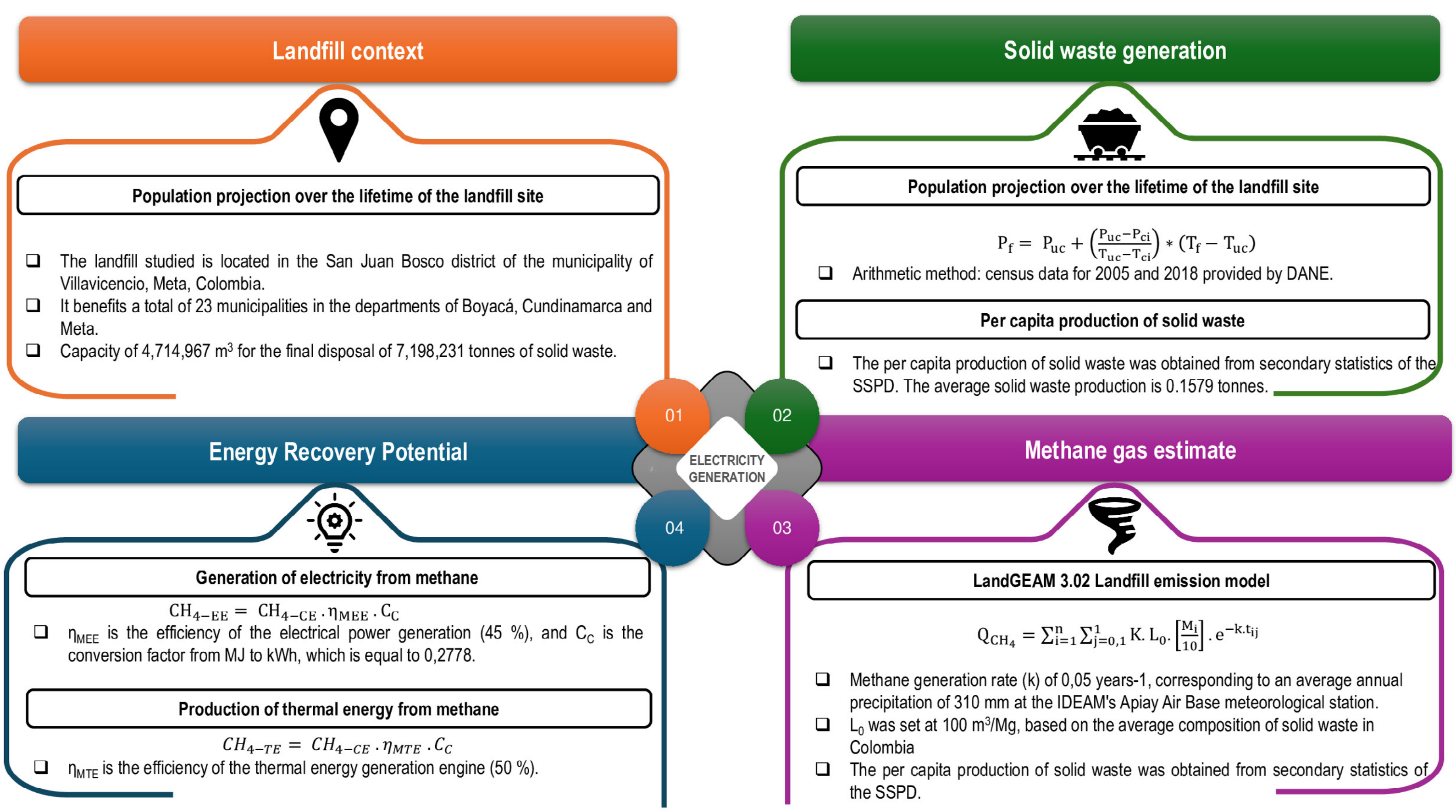
Why was it conducted?:
The study was conducted to assess the generation and energy recovery potential of methane produced at the Villavicencio Landfill, with the aim of implementing mitigation measures and utilizing this gas to produce electrical and thermal energy.

What were the most relevant results?
TThe increase in methane generation over the years and the projection that, by 2042, methane could generate enough electrical energy to supply more than 43,705 homes and thermal energy for industrial processes, highlights the efficiency and sustainability that could be achieved.

What do these results contribute?
The potential to transform an environmental problem into an energy opportunity, emphasizing the feasibility of producing renewable energy and reducing the dependence on fossil fuels, thus supporting the sustainable development of the region and the transition towards a circular economy.

Graphical Abstract



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Introduction

In the global effort for sustainable development, the investigation of renewable energy alternatives is fundamental (1) . Proper management of urban solid waste and mitigation of greenhouse gases are critical issues in this context (2). This study addresses these needs by exploring the potential for methane recovery at the Villavicencio Landfill, following the sustainability approach of the United Nations Sustainable Development Goals (3) .

Methane, a potent greenhouse gas, is generated in landfills through the anaerobic decomposition of organic waste (4). Capturing and utilizing this gas not only reduces greenhouse gas emissions but also provides a viable source of renewable energy (5). Various studies have highlighted the importance of strategies for greenhouse gas mitigation and the conversion of waste into energy resources (6)(7)(8)(9).

This study is based on the methodology of the LandGEM model (10) (11), adapted and validated by several researchers to estimate methane generation in different contexts (12) (13) (14) (15). By analyzing methane emissions and their energy potential, it seeks to fill the existing gap in the literature regarding the application of these techniques in Colombia, where specific research on methane recovery in landfills is still limited. This research not only examines methane generation but also explores its conversion into usable energy, aligning with previous studies that emphasize the conversion of waste into energy resources as a practical solution to the growing problem of urban solid waste (16) (17) (18).

Finally, the results of this research demonstrate a commitment to environmental sustainability and energy efficiency, providing perspectives based on empirical data for waste management and energy policy in Colombia. Methane recovery is expected to contribute significantly to local energy matrices, expanding on the premise of previous studies(19) (20) (21) (22), and presenting optimized scenarios for energy recovery in the Colombian context.

Methodology

Methane Emissions Estimation

For the calculation of methane emissions at the Villavicencio Municipal Landfill in Colombia, the LandGEM version 3.02 model was used. This model, developed by the Control Technology Center of the United States Environmental Protection Agency (EPA), has been widely used for estimating gas emissions at landfills in the United States (23) (24), Asia (25) (26) (27), South America (1) (16) (28), and Africa (19) (29) (30).

This automated estimation model is designed to calculate the emission rates of total landfill gases, methane, carbon dioxide, and non-methane organic compounds from municipal solid waste landfills (10). LandGEM is based on a first-order kinetic decomposition model of organic matter, where the default values are derived from empirical data collected from various landfills in the US (11).

The followed methodology applied the first-order decomposition equation (Eq. 1), which estimates the annual methane emissions of the year in question (31).

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0,1}^{1} K.\, L_0 . \left[\frac{M_i}{10}\right] . \, e^{-k.t_{ij}} \qquad \text{(Eq. 1)}$$

In this equation, QC_{H4} represents the annual methane generation in m^3/year, k is the methane generation rate ($year^{-1}$), L_0 is the methane generation potential per unit mass of waste deposited (m^3/Mg), Mi is the mass of waste deposited in year i (Mg), and tij is the age of section j of the waste mass i.

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For the selection of parameters, the study began with the range of values suggested in the LandGEM user's manual, with a methane generation rate (k) varying between 0,02 and 1,7 per year (10). The values of the methane generation potential (L_0) were estimated in a range of 96 to 170 m^3/Mg of waste (10). To calculate the annual solid waste disposal data (Mi), the population projection year after year during the estimated useful life of the landfill was used, multiplied by the per capita production of solid waste for the area under study. To project the population, the arithmetic method (Ec. 2) was adopted, after verifying that it showed the highest correspondence for the study area with the census data from 2005 and 2018 provided by the National Administrative Department of Statistics (DANE), as established by the Technical Regulation of the Drinking Water and Basic Sanitation Sector (32). The per capita production of solid waste was obtained from secondary statistics of the Superintendency of Public Home Services (33) (34).

$$P_f = P_{uc} + \left(\frac{P_{uc}-P_{ci}}{T_{uc}-T_{ci}}\right) * \left(T_f - T_{uc}\right) \quad \text{(Eq. 2)}$$

Where P_f is the population (inhabitants) corresponding to the year for which the population is to be projected, P_{uc} is the population corresponding to the last census year with information, P_{ci} is the population corresponding to the initial census year with information, T_{uc} is the year corresponding to the last census with information, T_{ci} is the year corresponding to the initial census with information, and T_f is the year to which the information is to be projected.

Energy Recovery Potential

To evaluate the potential energy generation, the chemical energy production from CH_4 was initially estimated using Eq. 3 (35).

$$CH_{4-CE} = \bar{Q}_{CH_4} \,.\, LHV_{CH_4} \quad \text{(Eq. 3)}$$

Where $CH_{4\text{-}CE}$ is the chemical energy production from methane in MJ/day, $\bar{Q}_{CH_4}$ is the average methane flow in m³/day, and LHV_{CH4} is the lower heating value of methane in MJ/m³ (35 MJ/m^3) (27).

To calculate the generation of electricity from methane, Eq. 4 was applied (35).

$$CH_{4-EE} = CH_{4-CE} \,.\, \eta_{MEE} \,.\, C_C \quad \text{(Eq. 4)}$$

With $CH_{4\text{-}EE}$ representing the daily production of electricity from methane in kW/day, η_{MEE} is the efficiency of the electrical power generation engine in percentage (45 %), and C_C is the conversion factor from MJ to kWh, which is equal to 0,2778. The efficiency for methane electricity generation is within the typical range for CHP systems using internal combustion engines or gas turbines (36).

Furthermore, the production of thermal energy through CH_4 was determined using Eq. 5 (35).

$$CH_{4-TE} = CH_{4-CE} \,.\, \eta_{MTE} \,.\, C_C \quad \text{(Eq. 5)}$$

Where $CH_{4\text{-}TE}$ is the production of thermal energy from methane in kWh/day, and η_{MTE} is the efficiency of the thermal energy generation engine (50 %). The thermal efficiency of 50 % for CHP systems utilizing methane is supported by existing literature on cogeneration technologies. According to the United States Environmental Protection Agency (36) (EPA, 2017), CHP systems using natural gas or biogas can achieve thermal efficiencies of up to 50 % under optimal conditions. Finally, the potential evolution in methane generation and utilization was considered, reflected in two prospective scenarios that consider recycling practices and operational changes in

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the landfill: 1) Maximization of Recycling and Composting, and 2) Operational Optimization of the Landfill.

Results and discussion

Study area

The landfill studied is located in the San Juan Bosco district of the municipality of Villavicencio, Meta, Colombia, managed by a public services company that provides urban sanitation services (street sweeping and cleaning of public spaces, and collection and transportation of residential and commercial solid waste). As of 2012, this landfill had used only 9,38 % of its capacity, maintaining a reserve of 5.435.530 m^3 (33).

It benefits a total of 23 municipalities across the departments of Boyacá (Almeida, Chivor, Garagoa, and San Luis de Gaceno), Cundinamarca (Guayabetal, Medina, Paratebueno, and Quetame), and Meta (Acacías, Barranca de Upía, Cabuyaro, Castilla La Nueva, Cubarral, Cumaral, El Castillo, Granada, Guamal, Puerto Gaitán, Puerto López, Restrepo, San Carlos De Guaroa, Villavicencio, and Monterrey) (37).

Methane Emissions Estimation

Methane emissions from the landfill were calculated using a methane generation rate (k) of 0,05 $years^{-1}$ (14), corresponding to an average annual precipitation of 310 mm at the IDEAM's Apiay Air Base meteorological station between September 2013 and January 2016 (38). L_0 was set at 100 m^3/Mg (14), based on the average composition of solid waste in Colombia; consisting of organic waste such as food and garden waste (59 %), plastics (13 %), paper and cardboard (9 %), and glass and metals at 2% and 1% respectively. Other wastes constitute 16% (16) (39).

The per capita solid waste production was calculated by dividing the total volume of waste received at the landfill in the years 2005 and 2018 (33) (34) by the combined population of the 23 contributing municipalities (40) (41), resulting in an average value of 0,1579 tonnes per inhabitant. The arithmetic method was chosen for population projection until 2041, the projected year of landfill closure (42), based on census data from 2005 and 2018 provided by the DANE (40) (41).

Using these values, the population year by year, the total solid waste disposed of in the landfill, and the annual methane emissions were estimated. Table 1 presents these results for the operating period of the landfill from 2008 to 2041 (Annex 1 presents results for even years after the closure of the disposal site and the accumulated generation until 2148). Likewise, Figure 1 shows the generation of methane from the beginning of the landfill's operation until 2148, the year in which it is expected that all organic matter will have degraded, and gas production will cease.

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Table 1 Methane Generation at the Villavicencio Municipal Landfill

Year	Population	MSW generated (Mg/year)	Methane generated (Mg/year)	Methane generated (m^3/year)
2008	531.462	156.661	0	0
2009	539.884	158.997	511	765.956
2010	548.307	161.334	1.005	1.505.978
2011	556.730	163.670	1.482	2.221.335
2012	565.153	166.007	1.944	2.913.224
2013	689.711	190.601	2.390	3.582.796
2014	700.466	193.481	2.895	4.339.959
2015	711.221	196.361	3.385	5.074.275
2016	721.977	199.241	3.861	5.786.860
2017	732.732	202.121	4.322	6.478.773
2018	363.566	221.220	4.771	7.151.021
2019	370.507	224.358	5.260	7.883.864
2020	377.448	227.496	5.735	8.596.308
2021	384.389	230.634	6.197	9.289.349
2022	391.329	233.773	6.647	9.963.931
2023	398.270	236.911	7.086	10.620.962
2024	405.211	240.049	7.513	11.261.291
2025	412.152	243.187	7.930	11.885.733
2026	419.093	246.326	8.336	12.495.064
2027	426.034	249.464	8.733	13.090.024
2028	432.974	252.602	9.121	13.671.311
2029	439.915	255.740	9.500	14.239.590
2030	446.856	258.878	9.871	14.795.496
2031	453.797	262.017	10.234	15.339.634
2032	460.738	265.155	10.589	15.872.580
2033	467.679	268.293	10.938	16.394.877
2034	474.620	271.431	11.280	16.907.044
2035	481.560	274.570	11.615	17.409.574
2036	488.501	277.708	11.944	17.902.944
2037	495.442	280.846	12.267	18.387.593
2038	502.383	283.984	12.585	18.863.949
2039	509.324	287.123	12.898	19.332.415
2040	516.265	290.261	13.205	19.793.381
2041	523.204	293.399	13.508	20.247.208

Source: Adapted from LandGEM

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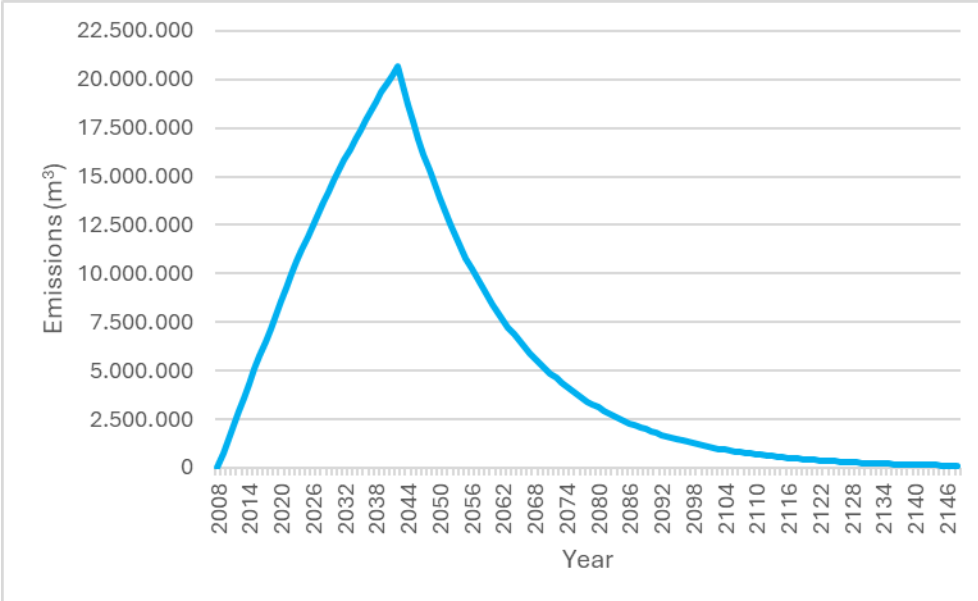

Figure 1 Methane Emission at the Villavicencio Landfill, Meta

The temporal analysis of methane generation at the landfill, presented in Table 1 and Figure 1, reveals a constant increase in the production of this greenhouse gas from its commencement in 2008 until the cessation of operations in 2041. It is observed that methane generation increases proportionally to the mass of waste at the site, reaching a maximum annual output of 20.694.244 m³ in 2042 (equivalent to 13.806 Mg), and a total accumulated volume of 796.367.807 m³ by the year 2148 when the production of this gas concludes (equivalent to 531.295 Mg).

After the landfill's closure in 2041, the accumulated waste at the site amounts to 7.963.899 Mg, and although the acceptance of waste ceases, methane continues to be generated due to the anaerobic decomposition of the organic matter present (43). This is consistent with studies like those from India and China (20) (27), which simulated CH_4 emissions from landfills and also reported significant emissions post-closure, reflecting a common phenomenon in the management of urban solid waste.

The progressive decrease in methane generation after 2041 suggests that, although biological activity continues, the rate of decomposition reduces as the more readily biodegradable material is depleted. This behavior is akin to observations in a study from China (27), where the methane generation potential decreases over time in landfills.

In terms of environmental impact and climate change, the cumulative emissions are significant. For instance, in 2010, 161.334 Mg of waste was accepted, and approximately 1.505.978 m³ of methane was generated. Ten years later, in 2020, with 227.496 Mg of waste accepted, methane generation had almost sextupled to 8.596.308 m³. This increase highlights the compounding effect of growth in waste generation and the accumulation of methane over time. Considering that methane has a global warming potential 28 times greater than CO_2 over a 100-year horizon (44), these volumes represent a considerable contribution to the greenhouse effect and the need for effective mitigation strategies.

Comparatively, the dynamics of methane generation at the Villavicencio Landfill show similar patterns to those reported in other latitudes, such as Iran (13), Brazil (45), India (46), and Trinidad and Tobago (15), among others. Factors such as the composition of the waste, the climatic and management conditions of the landfill, as well as time, are consistent variables that influence methane generation, as reflected in global landfill emissions studies (47).

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It is pertinent to highlight that, when comparing the volumes of methane generated and the waste disposed of year after year, the correlation is direct and practically linear until the closure of the landfill, which is a constant in the literature, as indicated by various sources (43). This increase and subsequent gradual post-closure decrease is a behavior that must be considered for the design of waste management systems and environmental policies, where methane capture and treatment should not only be a strategy during the operational life of the landfill but also post-operation, as an effective mechanism for reducing the contribution of landfills to global climate change.

Energy Recovery Potential

Based on the projected methane emissions, the potential for methane energy generation under current management conditions was assessed. Additionally, this potential was calculated under two hypothetical management scenarios to estimate the future impact of possible political decisions on solid waste management in the region and the country.

The scenarios considered were: Scenario 1, a 30 % increase in composting that would reduce methane production by decreasing the amount of waste destined for the landfill by 15 %, considering an initial proportion of 59 % compostable waste (16) y (39). Scenario 2, a 15 % increase in methane capture efficiency and a 20 % increase in methane generation due to operational optimization of the landfill, resulting in 38 % more utilizable methane. Table 2 presents the results of the energy generation potential under the scenarios evaluated for the period 2008 – 2041 (Annex 1 and 2 presents the results for the even years after the closure of the disposal site and the total accumulated for the year 2148).

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Table 2 Energy Generation Potential at the Villavicencio Municipal Landfill

Year	CURRENT CONDITIONS			SCENARIO 1			SCENARIO 2		
	[CH_4-CE] (MJ/día)	[CH_4-EE] (kW/day)	[CH_4-TE] (kWh/day)	[CH_4-CE] (MJ/día)	[CH_4-EE] (kW/day)	[CH_4-TE] (kWh/day)	[CH_4-CE] (MJ/día)	[CH_4-EE] (kW/day)	[CH_4-TE] (kWh/day)
2008	0	0	0	0	0	0	0	0	0
2009	73.448	9.182	10.202	62.431	7.804	8.672	101.358	12.671	14.079
2010	144.409	18.053	20.058	122.748	15.345	17.050	199.284	24.913	27.681
2011	213.005	26.628	29.586	181.054	22.634	25.148	293.946	36.746	40.829
2012	279.350	34.922	38.802	237.448	29.683	32.981	385.503	48.192	53.546
2013	343.556	42.948	47.720	292.022	36.506	40.562	474.107	59.268	65.853
2014	416.160	52.024	57.805	353.736	44.221	49.134	574.301	71.793	79.770
2015	486.574	60.827	67.585	413.588	51.703	57.447	671.473	83.941	93.268
2016	554.904	69.369	77.076	471.669	58.963	65.515	765.768	95.729	106.365
2017	621.252	77.663	86.292	528.064	66.013	73.348	857.328	107.175	119.083
2018	685.714	85.721	95.246	582.857	72.863	80.959	946.286	118.295	131.439
2019	755.987	94.506	105.007	642.589	80.330	89.256	1.043.262	130.418	144.909
2020	824.304	103.046	114.496	700.658	87.589	97.321	1.137.539	142.204	158.004
2021	890.759	111.354	123.726	757.146	94.651	105.168	1.229.248	153.668	170.743
2022	955.445	119.440	132.711	812.129	101.524	112.805	1.318.515	164.828	183.142
2023	1.018.448	127.316	141.462	865.681	108.219	120.243	1.405.459	175.696	195.218
2024	1.079.850	134.992	149.991	917.872	114.743	127.492	1.490.193	186.289	206.988
2025	1.139.728	142.477	158.308	968.769	121.106	134.562	1.572.824	196.619	218.465
2026	1.198.157	149.782	166.424	1.018.433	127.314	141.460	1.653.456	206.699	229.665
2027	1.255.208	156.914	174.348	1.066.927	133.376	148.196	1.732.187	216.541	240.601
2028	1.310.948	163.882	182.091	1.114.305	139.299	154.777	1.809.108	226.157	251.285
2029	1.365.440	170.694	189.660	1.160.624	145.090	161.211	1.884.307	235.557	261.730
2030	1.418.746	177.357	197.064	1.205.934	150.754	167.504	1.957.870	244.753	271.948
2031	1.470.924	183.880	204.311	1.250.285	156.298	173.665	2.029.875	253.755	281.950
2032	1.522.028	190.269	211.410	1.293.724	161.728	179.698	2.100.399	262.571	291.745
2033	1.572.111	196.530	218.366	1.336.295	167.050	185.611	2.169.514	271.211	301.345
2034	1.621.223	202.669	225.188	1.378.040	172.269	191.410	2.237.288	279.683	310.759
2035	1.669.411	208.693	231.881	1.419.000	177.389	197.099	2.303.788	287.996	319.996
2036	1.716.721	214.607	238.452	1.459.213	182.416	202.685	2.369.074	296.158	329.064
2037	1.763.194	220.417	244.908	1.498.715	187.354	208.171	2.433.208	304.175	337.973
2038	1.808.872	226.127	251.252	1.537.541	192.208	213.564	2.496.243	312.055	346.728
2039	1.853.793	231.743	257.492	1.575.724	196.981	218.868	2.558.235	319.805	355.339
2040	1.897.995	237.268	263.632	1.613.296	201.678	224.087	2.619.234	327.430	363.812
2041	1.941.513	242.709	269.676	1.650.286	206.302	229.225	2.679.288	334.938	372.153

Based on the results from Table 2 and using the potential energy generation under current conditions for the year 2042, with 248.067 kW/day of electricity, and considering the average subsistence consumption set at 173 kWh/month per household (48), it is established that the electricity generated could supply power to approximately 43.705 households per month in Villavicencio and surrounding municipalities.

Furthermore, the thermal energy generated, which amounts to 275.630 kWh/day, could be used for typical industrial processes in the region that require heat, such as pasteurization in the food industry, drying in agricultural processes, or steam generation for operations in manufacturing plants (49). This application would not only optimize the use of recovered methane but would also represent a source of renewable and sustainable energy that could reduce the dependence on fossil fuels and decrease the environmental impact of such industries. These results are consistent

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with those obtained by recent studies on the utilization of methane generated in landfills (12) (22) (26) (29) (50).

Under Scenario 1 for the year 2042, an electrical energy generation of 210.857 kW/day is estimated, which could supply approximately 37.293 homes monthly. In the case of Scenario 2, with electricity generation of 342.333 kW/day, the number of homes that could benefit increases to approximately 60.194 homes per month, highlighting the significant impact of operational optimization on the energy capacity of the landfill. This scenario reflects an even greater potential to support the growing energy demand of the region and contribute to local energy stability and development.

Existing policies in Latin America for the energy use of biogas demonstrate its feasibility. In Brazil, the PROINFA program has successfully integrated biogas into the energy matrix (51), while in Mexico, the Renewable Energy Program of the Secretary of Energy has supported numerous biogas projects (52). In Colombia, several regulations and strategic plans stand out, such as Law 1715 of 2014 (53), which regulates the integration of non-conventional renewable energies, including biogas and biomethane, into the National Energy System, and the National Energy Plan 2020-2050 (54), which promotes the use of renewable energies and low-emission gases. Additionally, Resolution 240 of 2016 (55) by the CREG establishes the regulatory framework for the use of biogas and biomethane in public gas services. Law 2128 of 2021 (56), in its Article 7, encourages the replacement of firewood, coal, and waste with transitional energy sources, and Law 2099 of 2021 (57), authorizes financing for generation and self-generation projects with Non-Conventional Renewable Energy Sources (FNCER). These policies and regulatory frameworks facilitate the integration of biogas into the energy matrix and offer economic and legal incentives that can be replicated in other regions.

Successful experiences in countries such as Argentina (58) and Brazil further demonstrate the potential of biogas utilization. In Argentina, the CEAMSE landfill has implemented a biogas capture and utilization system to generate electricity, supplying thousands of households and reducing greenhouse gas emissions. In Brazil, financial viability was achieved for the commercialization of excess electricity produced by landfills located in São Paulo, illustrating the use of biogas for electricity production.

Finally, the inclusion of thermal energy in the calculation of the overall energy potential underscores the versatility of methane utilization, allowing not only to cover the basic electricity needs of households but also to support local industries through a clean and renewable energy source (46) (26) (50), evidencing a positive step towards the integral sustainability of the Villavicencio region.

Conclusions

The implementation of the LandGEM model confirms the direct relationship between the tons of waste accepted and the generation of methane, which increased from approximately 1.505.978 m³ in 2010 to almost 8.596.308 m³ in 2020, illustrating the exponential nature of methane growth, even after the landfill's closure, and the urgent need for long-term mitigation measures.

The potential for electric energy generation from methane emissions could reach 248.067 kW/day by the year 2042, which could supply the monthly electric consumption of about 43.705 households, marking a significant contribution toward regional energy self-sufficiency and environmental sustainability.

The thermal energy derived from methane, estimated at 275.630 kWh/day, could support local industrial processes, demonstrating the versatility of methane as an energy resource and its potential to replace fossil fuels in the industry, contributing to the reduction of the regional carbon footprint.

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The hypothetical landfill management scenarios present a significant impact on the potential for methane utilization; for example, under the operational optimization scenario, the generation of electricity could be increased to 342.333 kW/day, underscoring the effectiveness of improved waste management policies and methane capture in driving towards a circular economy.

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Annex 1

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Methane Generation after the Closure of the Villavicencio Municipal Landfill

Year	Methane generated (Mg/year)	Methane generated (m^3/year)
2042	13,806	20,694,244
2044	12,492	18,724,927
2046	11,304	16,943,014
2048	10,228	15,330,673
2050	9,255	13,871,767
2052	8,374	12,551,694
2054	7,577	11,357,242
2056	6,856	10,276,458
2058	6,203	9,298,523
2060	5,613	8,413,652
2062	5,079	7,612,987
2064	4,596	6,888,516
2066	4,158	6,232,987
2068	3,763	5,639,840
2070	3,405	5,103,138
2072	3,081	4,617,510
2074	2,787	4,178,096
2076	2,522	3,780,497
2078	2,282	3,420,736
2080	2,065	3,095,210
2082	1,868	2,800,661
2084	1,691	2,534,143
2086	1,530	2,292,988
2088	1,384	2,074,781
2090	1,252	1,877,339
2092	1,133	1,698,687
2094	1,025	1,537,036
2096	928	1,390,767
2098	840	1,258,418
2100	760	1,138,664
2102	687	1,030,306
2104	622	932,259
2106	563	843,543
2108	509	763,269
2110	461	690,635
2112	417	624,912
2114	377	565,444
2116	341	511,635

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Year	Methane generated (Mg/year)	Methane generated (m^3/year)
2118	309	462,946
2120	279	418,891
2122	253	379,028
2124	229	342,959
2126	207	310,322
2128	187	280,791
2130	170	254,070
2132	153	229,892
2134	139	208,015
2136	126	188,220
2138	114	170,308
2140	103	154,101
2142	93	139,437
2144	84	126,168
2146	76	114,161
2148	69	103,297
TOTAL	531,295	796,367,807
AVERAGE	3,768	5,647,999

Source: Adapted from LanGEM

Annex 2

Energy Generation Potential After the Closure of the Villavicencio Municipal Landfill

	CURRENT CONDITIONS			SCENARIO 1			SCENARIO 2		
Year	Energy [CH_4-CE] (MJ/día)	Energy [CH_4-EE] (kW/day)	Energy [CH_4-TE] (kWh/day)	Energy [CH_4-CE] (MJ/día)	Energy [CH_4-EE] (kW/day)	Energy [CH_4-TE] (kWh/ day)	Energy [CH_4-CE] (MJ/día)	Energy [CH_4-EE] (kW/day)	Energy [CH_4-TE] (kWh/day)
2042	1.984.380	248.067	275.630	1.686.723	210.857	234.286	2.738.444	342.333	380.370
2044	1.795.541	224.461	249.401	1.526.210	190.791	211.991	2.477.846	309.756	344.173
2046	1.624.673	203.100	225.667	1.380.972	172.635	191.817	2.242.048	280.278	311.420
2048	1.470.065	183.773	204.192	1.249.555	156.207	173.563	2.028.689	253.606	281.785
2050	1.330.169	166.284	184.761	1.130.644	141.342	157.046	1.835.634	229.473	254.970
2052	1.203.587	150.460	167.178	1.023.049	127.891	142.102	1.660.950	207.635	230.706
2054	1.089.051	136.142	151.269	925.693	115.721	128.579	1.502.890	187.876	208.751
2056	985.414	123.187	136.874	837.602	104.709	116.343	1.359.871	169.997	188.886
2058	891.639	111.464	123.849	757.893	94.744	105.271	1.230.462	153.820	170.911
2060	806.789	100.857	112.063	685.770	85.728	95.253	1.113.368	139.182	154.647
2062	730.012	91.259	101.399	620.511	77.570	86.189	1.007.417	125.937	139.930

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2064	660.543	82.574	91.749	561.461	70.188	77.987	911.549	113.953	126.614
2066	597.684	74.716	83.018	508.031	63.509	70.566	824.803	103.109	114.565
2068	540.807	67.606	75.118	459.686	57.465	63.850	746.313	93.297	103.663
2070	489.342	61.173	67.970	415.941	51.997	57.774	675.292	84.418	93.798
2072	442.775	55.351	61.501	376.359	47.049	52.276	611.029	76.385	84.872
2074	400.639	50.084	55.649	340.543	42.571	47.301	552.882	69.116	76.795
2076	362.513	45.318	50.353	308.136	38.520	42.800	500.269	62.539	69.487
2078	328.016	41.005	45.561	278.813	34.854	38.727	452.662	56.587	62.875
2080	296.801	37.103	41.226	252.281	31.538	35.042	409.585	51.202	56.891
2082	268.557	33.572	37.303	228.273	28.536	31.707	370.608	46.330	51.477
2084	243.000	30.377	33.753	206.550	25.821	28.690	335.340	41.921	46.579
2086	219.876	27.487	30.541	186.894	23.364	25.960	303.428	37.932	42.146
2088	198.952	24.871	27.634	169.109	21.140	23.489	274.553	34.322	38.135
2090	180.019	22.504	25.005	153.016	19.129	21.254	248.426	31.056	34.506
2092	162.888	20.363	22.625	138.455	17.308	19.231	224.785	28.100	31.223
2094	147.387	18.425	20.472	125.279	15.661	17.401	203.394	25.426	28.251
2096	133.361	16.671	18.524	113.357	14.171	15.745	184.039	23.007	25.563
2098	120.670	15.085	16.761	102.570	12.822	14.247	166.525	20.817	23.130
2100	109.187	13.649	15.166	92.809	11.602	12.891	150.678	18.836	20.929
2102	98.796	12.351	13.723	83.977	10.498	11.664	136.339	17.044	18.937
2104	89.395	11.175	12.417	75.986	9.499	10.554	123.365	15.422	17.135
2106	80.888	10.112	11.235	68.755	8.595	9.550	111.625	13.954	15.505
2108	73.190	9.150	10.166	62.212	7.777	8.641	101.002	12.626	14.029
2110	66.225	8.279	9.199	56.291	7.037	7.819	91.391	11.425	12.694
2112	59.923	7.491	8.323	50.935	6.367	7.075	82.694	10.338	11.486
2114	54.221	6.778	7.531	46.088	5.761	6.402	74.824	9.354	10.393
2116	49.061	6.133	6.815	41.702	5.213	5.792	67.704	8.464	9.404
2118	44.392	5.549	6.166	37.733	4.717	5.241	61.261	7.658	8.509
2120	40.168	5.021	5.579	34.142	4.268	4.742	55.431	6.929	7.699
2122	36.345	4.544	5.048	30.893	3.862	4.291	50.156	6.270	6.967
2124	32.886	4.111	4.568	27.954	3.494	3.883	45.383	5.673	6.304
2126	29.757	3.720	4.133	25.293	3.162	3.513	41.065	5.133	5.704
2128	26.925	3.366	3.740	22.886	2.861	3.179	37.157	4.645	5.161
2130	24.363	3.046	3.384	20.708	2.589	2.876	33.621	4.203	4.670
2132	22.044	2.756	3.062	18.738	2.342	2.603	30.421	3.803	4.226
2134	19.947	2.494	2.771	16.955	2.120	2.355	27.526	3.441	3.823
2136	18.048	2.256	2.507	15.341	1.918	2.131	24.907	3.114	3.460
2138	16.331	2.042	2.268	13.881	1.735	1.928	22.537	2.817	3.130
2140	14.777	1.847	2.053	12.560	1.570	1.745	20.392	2.549	2.832
2142	13.371	1.671	1.857	11.365	1.421	1.579	18.451	2.307	2.563
2144	12.098	1.512	1.680	10.284	1.286	1.428	16.696	2.087	2.319
2146	10.947	1.368	1.521	9.305	1.163	1.292	15.107	1.889	2.098

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2148	9.905	1.238	1.376	8.419	1.053	1.169	13.669	1.709	1.899
TOTAL	76.364.036	9.546.268	10.606.965	64.909.431	8.114.328	9.015.920	105.382.370	13.173.850	14.637.611
AVERAGE	541.589	67.704	75.227	460.351	57.548	63.943	747.393	93.432	103.813

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