

## 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.

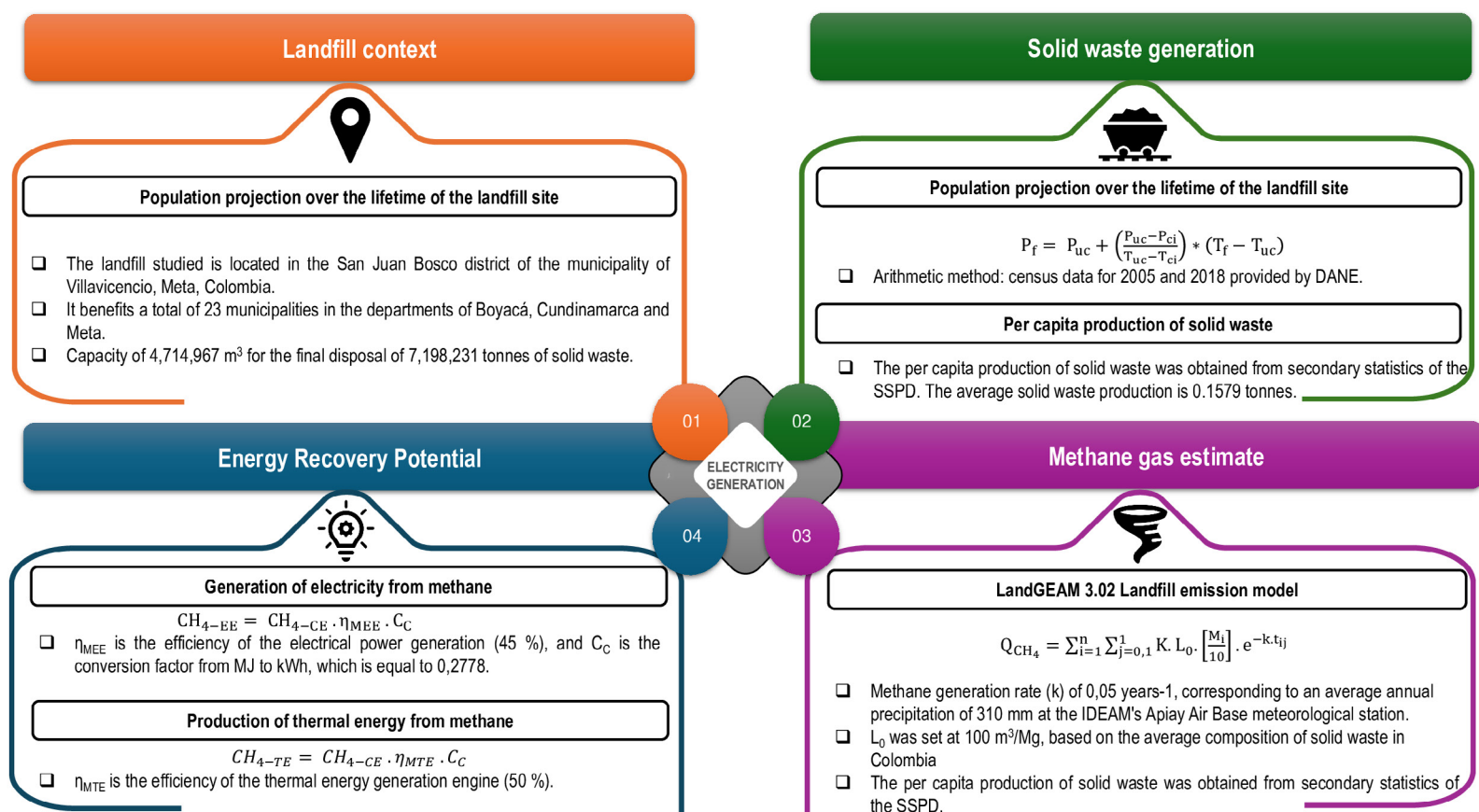
### What were the most relevant results?

The 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



## 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).

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

In this equation,  $Q_{CH_4}$  represents the annual methane generation in  $m^3/\text{year}$ ,  $k$  is the methane generation rate ( $\text{year}^{-1}$ ),  $L_0$  is the methane generation potential per unit mass of waste deposited ( $m^3/\text{Mg}$ ),  $M_i$  is the mass of waste deposited in year  $i$  (Mg), and  $t_{ij}$  is the age of section  $j$  of the waste mass  $i$ .

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 ( $M_i$ ), 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).

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

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).

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

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

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

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

With  $CH_{4-EE}$  representing the daily production of electricity from methane in  $kW/\text{day}$ ,  $\eta_{MEE}$  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).

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

Where  $CH_{4-TE}$  is the production of thermal energy from methane in  $kWh/\text{day}$ , and  $\eta_{MTE}$  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

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<sup>3</sup> (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<sup>-1</sup> (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<sup>3</sup>/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).

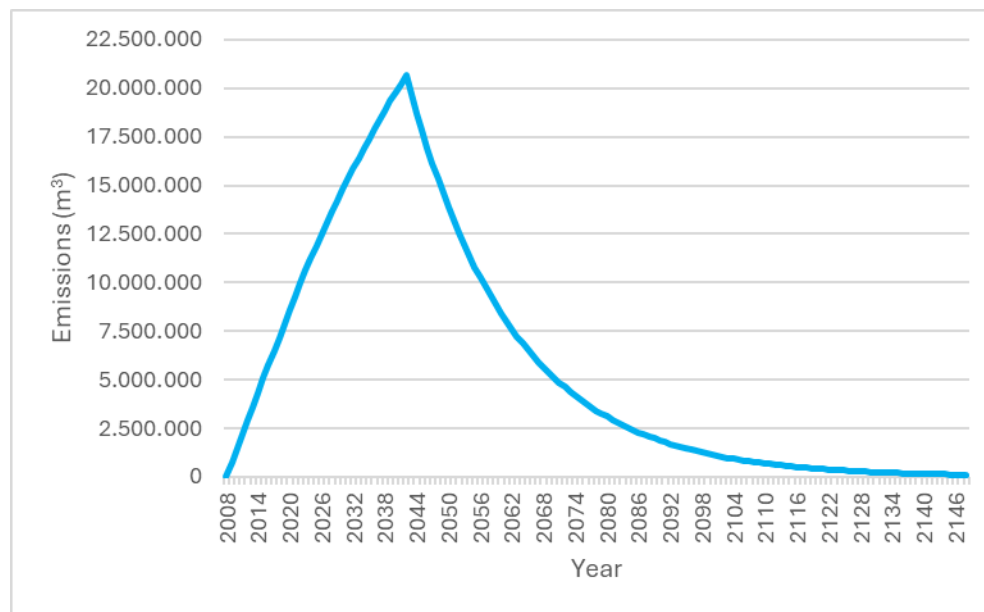
Using these values, the population year by year, the total solid waste disposed of in the landfill, and the annual methane emissions were estimated. Table 1 presents these results for the operating period of the landfill from 2008 to 2041 (Annex 1 presents results for even years after the closure of 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.



**Table 1** Methane Generation at the Villavicencio Municipal Landfill

| Year | Population | MSW generated (Mg/year) | Methane generated (Mg/year) | Methane generated (m <sup>3</sup> /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



**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 m<sup>3</sup> in 2042 (equivalent to 13.806 Mg), and a total accumulated volume of 796.367.807 m<sup>3</sup> 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<sub>4</sub> 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 m<sup>3</sup> 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 m<sup>3</sup>. 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<sub>2</sub> 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).

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 presents the results for the even years after the closure of the disposal site and the total accumulated for the year 2148).



**Table 2** Energy Generation Potential at the Villavicencio Municipal Landfill

| Year | CURRENT CONDITIONS                |                                   |                                    | SCENARIO 1                        |                                   |                                    | SCENARIO 2                        |                                   |                                    |
|------|-----------------------------------|-----------------------------------|------------------------------------|-----------------------------------|-----------------------------------|------------------------------------|-----------------------------------|-----------------------------------|------------------------------------|
|      | [CH <sub>4</sub> -CE]<br>(MJ/día) | [CH <sub>4</sub> -EE]<br>(kW/day) | [CH <sub>4</sub> -TE]<br>(kWh/day) | [CH <sub>4</sub> -CE]<br>(MJ/día) | [CH <sub>4</sub> -EE]<br>(kW/day) | [CH <sub>4</sub> -TE]<br>(kWh/day) | [CH <sub>4</sub> -CE]<br>(MJ/día) | [CH <sub>4</sub> -EE]<br>(kW/day) | [CH <sub>4</sub> -TE]<br>(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

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 m<sup>3</sup> in 2010 to almost 8.596.308 m<sup>3</sup> 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.

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



### Methane Generation after the Closure of the Villavicencio Municipal Landfill

| Year | Methane generated (Mg/year) | Methane generated (m <sup>3</sup> /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                                  |

| Year    | Methane generated (Mg/year) | Methane generated (m <sup>3</sup> /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

| Year | CURRENT CONDITIONS                          |                                             |                                              | SCENARIO 1                                  |                                             |                                              | SCENARIO 2                                  |                                             |                                              |
|------|---------------------------------------------|---------------------------------------------|----------------------------------------------|---------------------------------------------|---------------------------------------------|----------------------------------------------|---------------------------------------------|---------------------------------------------|----------------------------------------------|
|      | Energy<br>[CH <sub>4</sub> -CE]<br>(MJ/día) | Energy<br>[CH <sub>4</sub> -EE]<br>(kW/day) | Energy<br>[CH <sub>4</sub> -TE]<br>(kWh/day) | Energy<br>[CH <sub>4</sub> -CE]<br>(MJ/día) | Energy<br>[CH <sub>4</sub> -EE]<br>(kW/day) | Energy<br>[CH <sub>4</sub> -TE]<br>(kWh/day) | Energy<br>[CH <sub>4</sub> -CE]<br>(MJ/día) | Energy<br>[CH <sub>4</sub> -EE]<br>(kW/day) | Energy<br>[CH <sub>4</sub> -TE]<br>(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                                      |



|      |         |        |        |         |        |        |         |         |         |
|------|---------|--------|--------|---------|--------|--------|---------|---------|---------|
| 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   |

|         |            |           |            |            |           |           |             |            |            |
|---------|------------|-----------|------------|------------|-----------|-----------|-------------|------------|------------|
| 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    |