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A STUDY ON ESTIMATING OF THE LANDFILL GAS POTENTIAL FROM SOLID WASTE STORAGE AREA IN SIVAS, TURKEY

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ABSTRACT

The objective of this study was to investigate the amount of landfill gas obtained from the domestic solid waste stored regularly at the Sivas city solid waste landfill site and its usability for electricity generation. In this research, the actual data acquired from field studies were utilized for the calculation of the parameters. The total landfill gas, methane, and carbon dioxide emission amounts generated at the urban solid waste landfill site in Sivas city were determined by employing the LandGEM model. In the study, electricity generation via methane harnessing at the landfill site located in Sivas city, Turkey, was examined. The results obtained by examining the current situation of electricity generation from landfill gas power plant located in Sivas province were compared with the electricity generation capacities calculated according to the LandGEM estimation model version 3.02. The L0 value calculated for the Sivas landfill was 116.7 m³/Mg. The maximum quantities of total gas and methane emissions from the Sivas sanitary landfill were 7.976E+06 m³/year and 4.068E+06 m³/year, respectively. The outcomes of the LandGEM model as a mathematical model showed that the total gas and methane production rates in the first five years of landfilling were considerable. The constituents of the solid waste stream affected the gas emission rate at highest. The highest amount of energy to be generated was calculated to be 2947 kWh in 2030. The operational life of the Sivas Landfill Gas Power Plant will nearly end in an economic sense after 2060. It was observed that the actual data obtained from the power plant and the estimated data calculated using the LandGEM model were close to each other and the model made accurate predictions. It is possible to use the method and results of the current study to design and execute of methane gas collection systems and control the emission of greenhouse gases for landfills.

1. INTRODUCTION

Due to problems such as energy needs increasing depending on today's technology, limited fossil fuels, and foreign dependency of countries in energy supply, the search for new energy resources continues all over the world. An increase of approximately 150% was observed in energy demand in the previous forty years [1], which said increase in energy demand caused air pollution to increase by 60% during the same period [2]. This has also increased the trend toward clean energy sources. In this process, in addition to the ability to generate electricity from renewable energy sources, including solar, wind, geothermal energy, etc., energy generation from landfill gas that occurs due to the anaerobic decomposition of urban solid wastes emerges as a significant option.

Landfill gas (LFG) represents primarily greenhouse gas (GHG) consisting mainly of methane and carbon dioxide generated as a result of the anaerobic biodegradation of municipal solid waste (MSW) in landfills. LFG is composed of methane (CH_4) (50%), carbon dioxide (CO_2) (45%), and other insignificant elements, such as nitrogen (N_2), hydrogen sulfide (H_2S), and nonmethane organic compounds (NMOCs) (5%) [3]. The increase in GHG emissions has changed the global pattern of temperature and posed a threat to the environment and human health. Methane that landfills emit is among the most significant contributors to GHGs. Methane represents the second most frequently observed greenhouse gas. It has a global warming potential that exceeds that of carbon dioxide (CO2) by a minimum of 28 times and creates 20% of the global greenhouse gas impact [4]. The CH4 increase rate in the previous few decades has been 1–2% annually [5]. In the United

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States of America, municipal solid waste landfills represent the third most significant source of human-made methane emissions that created 18% of the total anthropogenic methane emissions in 2011 [4].

The most dangerous greenhouse gases are methane and carbon dioxide. Therefore, the release of these gases into the atmosphere must be prevented or restricted as much as possible. Gas collection systems are used for this purpose. Even if a methane collection system is not economically efficient, methane must be collected or burned in a controlled manner for the purpose of preventing its direct release into the atmosphere. Gas collection systems contribute significantly to reducing the emissions of carbon dioxide and other greenhouse gases. Furthermore, these systems are also very effective in determining the amount and content of landfill gas that will be formed at landfill sites.

A system that consists of a few wells that are drilled into the landfill and connected by a piping system is utilized for the collection of landfill gas. The calorific power of LFG is significant enough to allow its usage as a fuel in combustion [6]. Thus, the capturing and positive usage of biogas is not only advantageous in environmental terms but also attractive in economic terms [7]. It is possible to use LFG for various energy projects, such as the generation of electricity, combined heat and power. It can also be burned directly in a boiler as a heat-energy source and utilized as an alternative vehicle fuel [4, 8]. The usage of LFG as a cleaner fuel source will minimize the effect of fossil fuels emitting polluting materials that damage the ozone layer, flora, and fauna [9]. Landfill gas is specified as "clean renewable energy sources" in the EU directive 2009/28/EC [2].

At active landfill sites, it is possible to identify LFG emissions as a result of field measurements (in other words, the measurement of LFG flows and composition in test wells at the site). Whereas field measurements allow obtaining more precise results about the production of LFG, they take a lot of time, and their expenditures are high. Therefore, mathematical modeling approaches have been introduced for the purpose of predicting LFG production and recovery based on previous and/or future waste amounts. The mentioned models are utilized to predict the amount of landfill gas formed as a result of the anaerobic decomposition of waste. Due to the complex structure of landfill gas formation, many models have been developed for different climatic zones or using different approaches. However, to make accurate predictions, it is very important to select the most suitable model for the field and to determine the parameters that are required for the model in landfill gas energy recovery projects [10].

The International Panel on Climate Change (IPCC) Model and Landfill Gas Emissions Model (LandGEM) are the most common tools for estimating landfill methane emissions. Moreover, the IPCC and LandGEM methodologies have higher flexibility and are easier to use in comparison with models, such as the Belgium, TNO, Scholl Canyon, and German EPER models [3]. Among the above-mentioned integrated models, LandGEM modeling software has been introduced for the environmental evaluation of municipal solid waste landfills. LandGEM predicts the volume and composition of the gas produced over time as a result of the degradation of organic matter in the landfill [11, 12].

This study was carried out in Sivas, Turkey, in 2020. This study's goal is to present the LandGEM model prepared for gas emission in the municipal solid waste landfill located in Sivas, Turkey, along with the prediction results of methane and carbon dioxide production based on input data. Using the selected LandGEM model, it was tried to determine the amount of landfill gas that would be formed at the Sivas sanitary landfill site and its energy equivalent. The study area and the content of the research differ from other studies because most of similar studies are based only on predictions made using the LandGEM model [5, 12–15].

Cakir et al., [13] investigated with prediction models the use of the landfill gas as potential energy and electricity obtained from the municipal solid waste stored regularly in the Harmandali solid waste landfill area in İzmir, Turkey. Singh et al., [5] at their study aimed to estimate the potential emissions of CH_4 from landfills at the national scale. Potential energy and electricity production from CH_4 emissions was not estimated. This study observed that the net annual emission of CH_4 from landfills in India was 1084 Gg in 2015. Kalantarifard et al., [12] estimated the methane emission by using LandGem model for Tanjulangsat Malaysia, solid waste disposal sites. Methane emission rate and total greenhouse gases from a landfill site located in Hamedan, Iran were determined in a 20-years period from 2011 to 2030 using LandGEM model by Hosseini et al., [14]. Based on the results, 4.371×10^8 m^3 methane will be produced after 20 years, mostly (4.053×10^6 m^3) in the first year. Fallahizadeh et al., [15] aimed to estimate the amounts of methane emissions from the municipal solid waste landfill in Yasuj city using LandGEM software. Methane gas production for 2012 year was obtained to be 330 m^3/h. The method and results of their research can be used for design and execute of methane gas collection systems and also, control of greenhouse gases emission for the landfills.

However, in this study, it was tried to prove the accuracy of the model predictions by examining the closeness of the model predictions to actual values as a result of the comparison of the LandGEM model results and the real facility data. Using the selected LandGEM model, it was tried to determine the amount of landfill gas that would be formed at the Sivas sanitary landfill site and its energy equivalent. In this respect, the study was different and innovative than the other studies mentioned above. This study was carried out in Sivas, Turkey, in 2019-2020. This study's objective was to present the LandGEM model prepared for gas emission in the municipal solid waste landfill located in Sivas, Turkey, along with the prediction results of methane and carbon dioxide production based on input data.

2. MATERIALS AND METHODS

2.1. Description of the study area and context

The landfill site in question is situated in Sivas city, in the Central Anatolia Region, Turkey. The landfill site is situated at a distance of 15 km from Sivas city center. The area of the landfill is 89 hectares, and its elevation above sea level is 1323 m. The distance between the main road and the landfill site is 1.5 km. The solid wastes collected from Sivas city center were disposed in this landfill. In this area, waste was collected at the Sivas Seyfebeli open dumpsite between 1999-2013. After open dumping has been given up since 2014, the waste storage process has been continued at the newly established Sivas sanitary landfill facility in the same region. The sanitary landfill was divided into three levels (1st level 73722 m^2, 2nd level 66300 m^2, and 3rd level 71000 m^2), and the 1st level is expected to be filled at the end of 2020. By assuming that each level would be filled in 5 years, 15-year planning was done. The sanitary landfill will be closed completely in 2029, and the total storage capacity of the site is 3.018.046 m^3.

2.2. Measurement and collection of landfill gas

For the implementation of to implement the model, two different calculations were made for the Sivas Seyfebeli open dumpsite operating that operated between 1999-2013 and the first part of the Sivas sanitary landfill operating that operated between 2014-2020. The Seyfebeli open dumpsite, which was in use between 1999-2013, is currently not used. However, landfill gas emission still continues from this area. Therefore, since the gas emitted from the open dumping dumpsite between 2015-2019 was drawn with gas collection pipes, combined with the gas emitted from the sanitary landfill, and sent to the measurement station with gas collection pipes. The gases formed at the landfill site were drawn with gas collection pipes, and gas measurements were made twice a week at nine measurement stations where gases were collected.

The isolation of the orientation of all gases to the measurement device with the flue gas from the atmosphere was carried out isolated. Thus, an appropriate cap was placed on the top of the chimney stack in the field research. The specimens were obtained from the top of the cap for the flow rate and gas components. The landfill gas components of study area (CH_4, H_2S, CO_2, and O_2) was measured using a Geotech Biogas 5000 gas analyzer.

2.3. Municipal solid waste characterization studies

Municipal solid waste characterization studies for wastes going to the Sivas sanitary landfill were carried out twice a year, in summer and winter, in 2017, 2018, and 2019. The composition of solid waste was obtained from the Sivas Municipality Waste Unit. The composition of solid waste for every year was found to be the mean of seasonal measurements made in summer and winter.

2.4. Description of the LandGEM model

Different mathematical models are used for the prediction of landfill gas formed at landfill sites. In this study, the LandGEM landfill gas estimation model version 3.02 was preferred. First-order models are linearly correlated with the maximum potential of methane generation per unit weight of waste and are exponentially correlated with decay rate and time [10,16]. LandGEM finds the mass of methane produced by utilizing the methane generation capacity and the mass of waste deposited. The mathematical formulation of the LandGEM model as a first-order model is presented in Eq. 1 [11]:

$$Q_{CH4} = \sum_{i=1}^{n} \sum_{J=0.1}^{1} kL_0 \left[\frac{M_i}{10}\right] e^{-k\,t_{ij}} \tag{1}$$

Where Q_{CH4} denotes the methane gas amount (m^3/year), L_0 represents the potential of methane generation (m^3 CH_4/Mg waste), Mi refers to the amount of the stored waste in the i^{th} year (Mg), k refers to the rate constant of methane gas generation (year^{-1}), n represents the calculation year [(year of the calculation) - (initial year of waste acceptance)], i denotes the one-year time increment, j denotes the 0.1-year time increment, and t_{ij} refers to the age of the j^{th} section of the waste mass, Mi, accepted in the i^{th} year (decimal years, e.g., 3.2 years) [13,15].

The methane production rate constant, k (year^{-1}), and the methane production potential, L_0 (m^3/Mg), represent two significant parameters utilized while modeling LFG production based on a first-order equation [15].

3. RESULTS AND DISCUSSION

3.1. Solid waste composition in the study area

Table 1. Waste Composition at the Sivas Landfill Site (2017-2019)

Waste type	Weight average of summer (%)	Weight average of winter (%)	Three-year average value (%)
Kitchen	39.51	32.45	35.98
Paper	4.61	0.53	2.57
Cardboard	4.33	0.42	2.37
Voluminous carton	7.74	9.38	8.56
Plastics	12.21	11.48	11.85
Glass	11.55	11.32	11.43
Metal	6.17	0.26	3.21
Bulky metal	2.11	0.76	1.43
WEEE	-	-	-
Hazardous waste	-	-	-
Park and garden wastes	3.04	-	3.04
Other non-combustible waste (ash)	-	7.36	7.36
Other combustible waste	3.57	12.58	8.08
Other combustible bulky waste	3.66	10.08	6.87
Other non-combustible bulky waste	1.79	2.46	2.13

The solid waste composition significantly influences the rate of landfill gas generation. A high amount of organic and food waste can cause an acceleration in gas emission from a landfill [14]. Table 1 shows the results regarding the composition of solid waste in the research area. Of the household waste, 52.52% (paper, kitchen, cardboard, voluminous carton, garden, and park waste, etc.) comprised degradable organic waste in accordance with the data acquired from the waste characterization studies conducted in 2017 and 2019.

3.2. Determination of the solid waste weight in the study area

The MSW generation amount at the particular site and population growth are correlated. Therefore, the amount of MSW generated increases along with the population increasing. The Iller Bankasi geometric increase method is utilized for the calculation of population projection for the next years [17, 18].

It is a geometric increase method but calculation of Kg is different. In this method $K_g=C$

$C = \left(\sqrt[a]{\frac{P_2}{P_1}} - 1\right) x100$ where; $a=t_2-t_1$

If $C<1$ then $C=1$ If $1<C<3$ then $C=C_i$ If $C>3$ then $C=3$

To calculate C average

$\bar{C} = \frac{\sum_{i=1}^{x} C_i}{x} = \frac{C_1 + C_2 + C_3 + \dots\dots\dots + C_x}{x}$ where; x= number of past record interval

The future population is calculated as

$P_{future} = P_{past}\,(1+\frac{\bar{C}}{100})^n$ where $n = t_{future} - t_{past}$

The Turkish Statistical Institute provided the population values for 1999-2019. The population projections for 2020-2029 were calculated by employing the Iller Bankasi geometric increase method taking 2019 as a base year. The central population of Sivas for 2019 year is approximately 381 325 [19].

The solid waste amounts produced between 1999-2013 when the Sivas Seyfebeli open dumpsite was in operation and between 2014-2029 when the Sivas sanitary landfill facility would be in operation were determined and presented in Table 2. The results in Table 2 demonstrate that the amount of annual solid waste generation at the Sivas Seyfebeli open dumpsite varied from 108589 Mg to 127247 Mg from the opening of the landfill (1999) to its closure (2013). The unit volume weights of solid wastes coming to the sanitary landfill are usually in the range of 0.3-0.7 Mg/m^3. This value for Turkey may vary in the range of 0.75-1 Mg/m^3 after the compression procedures required at sanitary landfills are performed. The unit volume weights of solid wastes stored at the Sivas sanitary landfill site were determined to be 0.8 Mg/m^3 after the compression procedure.

Accordingly, the estimated amount of waste to be deposited at the Sivas sanitary landfill site is presented in Table 3. The total solid waste amount is 2722400 Mg/year, disposed between 1999-2020 at the Sivas landfill facility (open dumpsite (1999-2013) and sanitary landfill (2014-2020), which represents a single regular solid waste storage facility in Sivas.

Table 2. The daily waste acceptance rates for the landfill examined in the current research

Seyfebeli open dumpsite			**Sivas sanitary landfill**		
Years	**Population**	**Total waste (Mg/year)**	**Years**	**Population**	**Total waste (Mg/year)**
1999	297504	108589	2014	351431	108589
2000	299935	109476	2015	359219	109476
2001	303144	110648	2016	365135	110648
2002	306387	111831	2017	372300	111831
2003	309665	113028	2018	377561	113028
2004	312987	114240	2019	381325	114240
2005	316327	115459	2020	386600	115459
2006	319712	116695	2021	391200	116695
2007	335002	122276	2022	395855	122276
2008	329011	120089	2023	400566	120089
2009	338728	123636	2024	405333	123636
2010	354913	129543	2025	410156	129543
2011	345762	126203	2026	415037	126203
2012	346629	126520	2027	419976	126520
2013	348623	127247	2028	424974	127247
-	-	-	2029	430031	108589

* The amount of waste generated per person at the facility is determined as 1 kg/day. 1 ton=1 Mg

Table 3. Estimated solid waste amounts to be stored at the Sivas sanitary landfill between 2014-2029

Year	**Amount of solid waste stored, Mg/year**	**Amount of solid waste stored, m^3/year**
2014	128272	160340
2015	131115	163894
2016	133274	166593
2017	135890	169863
2018	137810	172263
2019	139184	174313
2020	141109	176386
2021	142788	178485
2022	144487	180609
2023	146207	182759
2024	147947	184934
2025	149707	187134
2026	151489	189361
2027	153291	191614
2028	155116	193895
2029	156961	196201
Total	2294645	2868644

3.3. Modelling of methane generation

It is crucial to predict landfill methane emissions precisely to quantify greenhouse gas emissions of a landfill and biogas-to-energy projects [20]. The most reliable way to calculate the current LFG generation is to open test wells and measure the LFG collected in the said wells. Nevertheless, this method is expensive. Furthermore, the main obstacle of this method is the ability to apply it only in the presence of sufficient waste in the storage area to generate LFG in high amounts. The establishment of realistic models solves this problem. The models such as the Belgium, TNO, Scholl Canyon, LandGEM and German EPER commonly need data, such as storage time, the amount of waste stored, and the properties of waste. One of these models is LandGEM software, developed by the US Environmental Protection Agency (USEPA) [21]. As a first-order decomposition rate model, LandGEM was introduced for the estimation of landfill gas emissions produced in the course of the decomposition of municipal solid waste. The software in question can perform the automatic modeling of the gas emission rate from municipal landfill sites [14].

The separation level, biodegradable waste quantity, volatile solids, microbial usage rates, and climatic conditions such as temperature and humidity determine the methane potential of waste. The model was established on the basis of climatic conditions and waste specifications of the USA. Several assumptions or real data were taken into account while determining the mentioned parameters. In this research, the actual data acquired from field studies were utilized for the calculation of specific k and L_0 values related to the storage area.

There is a need for information, such as the input data of open landfill year, land closure year, potential methane production capacity (L_0), methane production rate (k), and waste acceptance rate, to run the LandGEM model. To this end, the waste projections given in Tables 2 and 3 were first created. In this way, the potential methane production capacity, L_0 can be calculated. Then, the storage starts and end dates were entered into the model. These dates are 1999-2013 for the Seyfebeli open dumpsite and 2014-2020 for the Sivas sanitary landfill, when its first level will be used.

According to the results of the gas measurement carried out twice a week at the nine gas measurement stations located at the site, the composition of the landfill gas is shown in Table 4. The methane content of LFG produced was found to be about 51.4%.

Table 4. The composition of landfill gas (3-month average values)

Parameter	% (volume)
CH_4	51.4
CO_2	37.9
O_2	0.3
Other gases	10.4

The methane production rate constant (k) is a function of the nutrient content, moisture content, temperature, and pH value of waste, and the moisture content of waste is the main factor in determining the k value [22]. Garg et al., [23] state that precipitation is the most significant parameter for the estimation of the k value [22]. Therefore, it is possible to calculate the k value for a waste mass in accordance with Eq. 2, based on precipitation rates [11]:

$$k = (3.2\times10^{-5} \times \text{annual precipitation in mm}) + 0.01 \tag{2}$$

According to the data collected between 1930-2019, the average of the annual total precipitation rate of the central district in Sivas province is 432.0 mm [24].

Where,
$k = [3.2 \times 10^{-5} \times 432.0] + 0.01$
$k = 0.024 \text{ year}^{-1}$

There is a restriction of the range of default k values in LandGEM for conventional landfills to 0.02 year^{-1} for sites with the annual precipitation quantity below 635 mm and 0.04 or 0.05 for sites with higher precipitation quantities [20]. In this research, it was calculated to be 0.024 year^{-1} because the average annual precipitation for Sivas city is 432.0 mm. The type and composition of solid waste deposited at the landfill site determine the potential rate of methane production capacity at the Sivas landfill site. Following the IPCC standard described in 2006, it is possible to calculate the potential methane production capacity using Eq. 3 [14]. The IPCC [25] model utilizes the properties of waste (DOC and DOC_f) and the landfill site (MCF and F) to predict CH_4 production.

$$L_0 (m^3/Mg) = [(DOC \times DOC_f \times MCF) \times F \times 16/12)] / 0.714 \tag{3}$$

The average data on waste composition in 2017, 2018, and 2019 (Table 1) were utilized to determine the methane generation potential in the Sivas landfill. It is necessary to mention that DOC has a broad range because of the discrepancy in solid waste combination in various countries. Thus, it would be more beneficial to utilize actual data. It is possible to calculate the actual specific DOC value (DOC=Degradable organic carbon in waste (m^3/Mg)) for the landfill site using the data in Table 1, by means of Eq. 4:

$$DOC = 0.4\ A + 0.17\ B + 0.15\ C + 0.3\ D \qquad (4)$$

Where, A represents paper, cardboard, and rags, B denotes leaves, straw, and others, C refers to fruit and vegetable wastes, and D is the fraction of woods/leaves in MSW.
According to Equation 4, the specific DOC value for the study area was calculated.

$DOC = 0.4\ (2.57+2.37+8.56) + 0.17\ (3.04) + 0.15\ (35.98) + 0.3\ (8.08+6.87)$
$DOC = 15.79\% = 0.1579$

Previous studies have indicated that DOC in MSW varies between 8% and 30% [22]. The DOC in MSW for the study area was found to be 15.79%.
DOC_f represents the fraction of DOC, which will degrade in the landfill. DOC_f represents a dissimilarity coefficient, depending on temperature, and it may be computed using Eq. 5 [14]:

$$DOC_f = 0.014\ T + 0.28 \qquad (5)$$

The previous study has shown that temperature values in the deep landfill and moderate water flux may achieve 45°C. Furthermore, it is predicted that the landfill temperature will remain higher than 30°C even in case of a decrease in the ambient air temperature to 0°C [5,26]. Based on this information and facility data, the temperature was taken as 35°C. Accordingly, Eq. 5 is as follows:

$DOC_f = 0.014 \times 35 + 0.28 = 0.77$

MCF represents the CH4 correction factor for anaerobic decomposition. F denotes the methane volumetric percentage in landfill gas (%), 16/12 represents the molecular weight ratio of CH_4 and C, and 0.714 refers to the CH_4 density (0°C, 1 atm) [22]. The default values (0.4–1.0) for MCF depend on MSW landfill practice types. In this study, the MCF parameter value was taken as 1, according to the IPCC 2006 guide. The parameter F denotes the fraction of CH_4 in LFG generated. The fraction of methane in landfill gas, F, is obtained as 51.4% (volumetric percentage) for the Sivas landfill, using Eq. 3.

$L_0 = [(DOC \times DOC_f \times MCF) \times F \times 16/12)] / 0.714$
$L_0 = [(0.1579 \times 0.77 \times 1) \times 0.514 \times 16/12)] / 0.714$
It was determined to be $L_0 = 116.7\ m^3/Mg$.

The USEPA presented the values for the potential methane production capacity, L_0 (1997, 2005, 2008), and they varied between 100 m^3/Mg (USEPA, 1997) and 170 m^3/Mg (Clean Air Act) for conventional landfills [6]. The L_0 value calculated for the Sivas landfill, according to Eq. 3, was 116.7 m^3/Mg. There was a good agreement between this value and values in the literature. The description of the given supplementary data is provided in Table 5.

Table 5. Description of the Supplementary Input Data for the Execution of LandGEM

Input Review		
Landfill properties		
Landfill opening-closure year	Seyfebeli open dumpsite	1999-2013
	Sivas sanitary landfill	2014-2029
Model parameters		
Methane production rate		0.024 $year^{-1}$
Potential methane production capacity		116.7 m^3/Mg
NMOC concentration		4 ppmv as hexane
Methane content		51.4% by volume

After running the LandGEM model with the data in Table 5, the possible rates of methane production and total landfill gas emission at the Sivas Seyfebeli open dumpsite were calculated. Fig. 1 demonstrates the model results. The predicted maximum quantities of total gas and methane emissions from Sivas city in 2014 were found to be 7.976E+06 m^3/year and 4.068E+06 m^3/year, respectively. The outcomes of the LandGEM model as a mathematical model showed that the total gas and methane production rates in the first five years of landfilling were considerable. The components of the solid waste stream affected the gas emission rate at the highest. Fig. 1 demonstrates a general decreasing tendency in total gases emissions for every year following the year of 2014. The findings of the present research demonstrated that the total gas and methane generation rates decreased because the open dumpsite was closed and regular storage was initiated since 2014. Sadeghi et al., [27] indicated that the methane generation rate in the first year of the landfill operation was 10 m^3/h and achieved 671 m^3/h during twenty years (2014–2033) [15]. A comparison of the current research with the findings obtained by Sadeghi et al., [27] demonstrated that the amount of methane generation in Sanandaj was lower because of the lower population and the amount of waste generated.

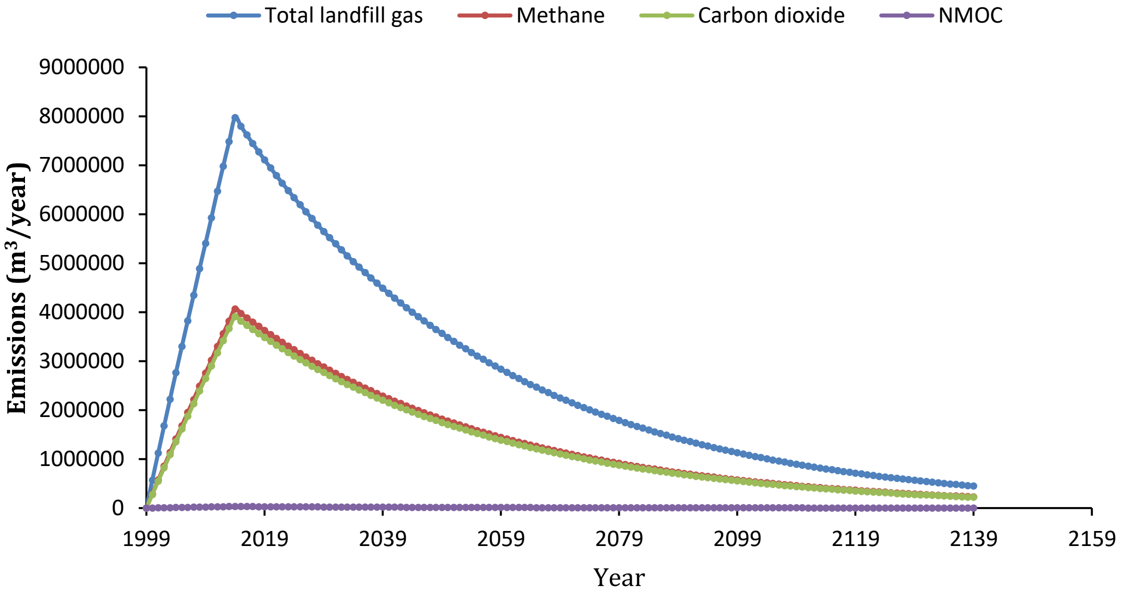

Fig 1. The amount of gas emission from the Sivas Seyfebeli open dumpsite

As the breakdown of compounds increases between the first and final years of waste accumulation, the amounts of methane gas and landfill gas increase. In Fig 1, it is observed that gas formation decreased gradually after 2014, when the maximum gas formation continued, especially from 2010 to 2014. The reason for this may be the decreased emission rate following the first five years since the degradation of the majority of the organic fractions of solid waste will occur during the mentioned time. Generally, it is possible to divide the organic fraction of MSW into rapidly degradable compounds and slowly degradable compounds. Rapidly degradable compounds decompose between three months to five years, while slowly degradable compounds decompose in a period reaching fifty years or more. Rapidly degradable compounds comprise putrescible (food waste), fines, sewage sludge, cardboard, newspaper, a part of garden waste, and incinerator ash. Slowly degradable compounds include rubber, textile, leather, and the woody parts of garden waste [14]. Therefore, methane generation in a landfill usually starts 6 to 12 months after placing the waste in the landfill, then it increases to the highest value shortly after the landfill is closed and finally decreases in a gradual way during 30-50 years [12].

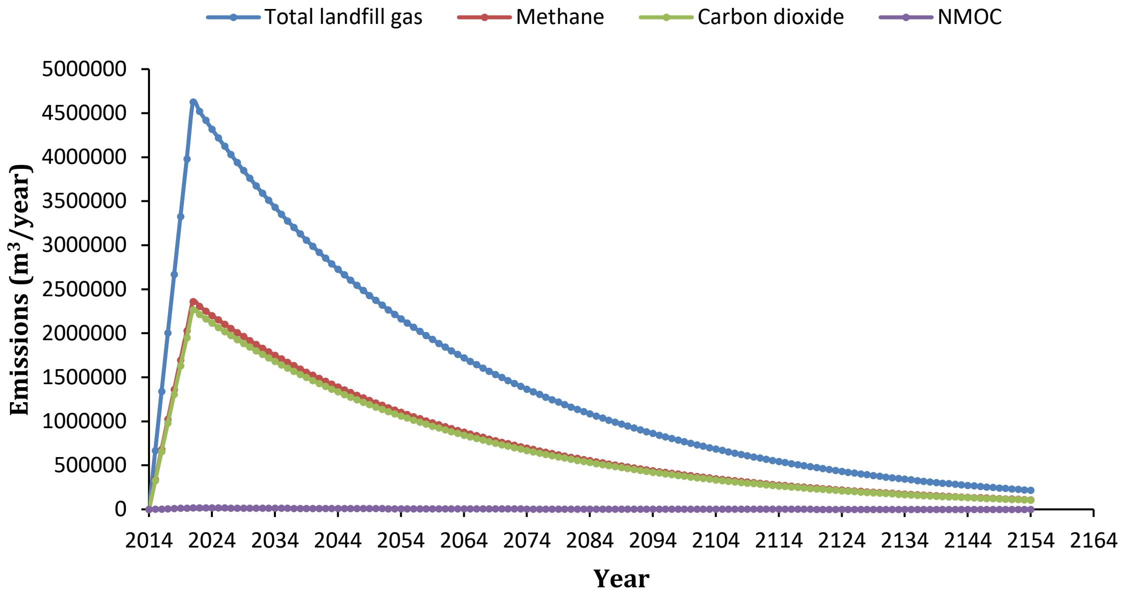

Fig 2. The amount of gas emission from the Sivas sanitary landfill

After running the LandGEM model with the data in Table 5, the possible rates of methane production and total landfill gas emission at the Sivas sanitary landfill site were calculated. Fig 2 demonstrates the model results. As is observed from Fig 2, 2014 was selected as a start year for disposing MSW at the Sivas sanitary landfill site. The mentioned landfill must be closed and caped by the end of 2029 when its maximum capacity will be achieved. Nevertheless, despite selecting 2029 as the final year, the generation of landfill gases will continue for a long period following this. Moreover, the possible rate of gas generation (carbon dioxide, methane, non-methane organic carbon (NMOC), and total gases) that will occur in the study area is shown in Figs. 1 and 2. 2.36E+06 m^3 methane (the highest amount) would be produced after seven years. According to the outcomes of the LandGEM model, a gradual decrease will occur in the methane emission rate following the first ten years. The main reason for this may be a change in the nutrient-microorganism ratio, in addition to the rate of the decomposition of compounds, as mentioned above. Furthermore, the type of solid waste components that will decompose may influence the methane production amount. The microbial type, solid waste components, and population represent three significant factors that determine the rate of gas emissions from landfill sites. It is necessary to indicate that a gradual increase up to 2024 and then a decrease will occur in all gas emissions. The reason for this may be the decreased food-to-microorganism ratio following 2024 [14]. Previous research has obtained similar findings [28,29]. The result mentioned above is quite significant for landfill management and gas collection. Thus, it is necessary to perform gas collection for long years in the research area. The LandGEM model makes calculations for 140-years. The data obtained as a result of modeling for 140 years are presented in Table 6.

Table 6. Summary of the LandGEM model results

Landfill area	Total waste (Mg)	Total methane formation (m^3 CH_4)	Total gas formation (m^3)	Unit methane formation (m^3 CH_4 / Mg waste)
Sivas Seyfebeli open dumpsite (1999-2139)	1.775.480	198.105.300	388.438.300	111.6
Sivas sanitary landfill (2014-2154)	946.920	106.048.100	207.936.100	112.0

3.4. Electricity generation from landfill gas

The landfill gas occurring due to the anaerobic decomposition of wastes stored at the landfill site is used for electricity generation in the landfill gas power plant located in the same region. For the production of energy at the power generation facility that started operating in 2015, the landfill gas formed at the Sivas Seyfebeli open dumpsite and the Sivas sanitary landfill site between 2015-2019 was drawn simultaneously and used. As of 2020, electricity generation has been continued only with the landfill gas drawn from the Sivas sanitary landfill.

The energy equivalent of 1 m^3 of landfill gas is given in Eq. 6.

$$CH_4 + 2O_2 \leftrightarrow CO_2 + 2H_2O \quad \Delta H_{(298)} = -802.7\ kJ/mol \tag{6}$$

According to the equation, when 1 mole CH4 is burnt at constant pressure, it releases 802.7 kJ/mol (192 kcal) of energy [30,31]; Karakurt et al., 2010). The density of methane is 0.717 kg/m^3, and there is 0.514 m^3 of methane in 1 m^3 of gas. Accordingly, the weight of 1 m^3 of methane was determined to be 368 g from d=m/V.

When 1 mole of CH_4 (16 g/mol) is burned, it releases 192 kcal of energy,

When 368 g of methane is burned, it releases X = 4416 kcal of energy

Since 1 kWh = 860 kcal, the 4416 kcal energy released is equivalent to 5.13 kWh. In other words, the energy equivalent of 1 m^3 of landfill gas is 5.13 kWh. Accordingly, the energy equivalent of landfill gas in this study was taken as 5 kWh/m^3. It is not possible to recover all the landfill gas formed in solid waste storage areas [32]. Therefore, it is necessary to identify the gas collection efficiencies for the storage areas to be examined. The collection efficiency factors were obtained from frequently applied values in the literature concerning landfilling operating conditions and LFG collection methods (Table 7). According to Table 7, the average LFG collection efficiency was determined to be 67% for the Sivas Seyfebeli open dumpsite and 75% for the Sivas sanitary landfill.

Table 7. Mean LFG collection efficiency according to operation methods [32]

Description	Average collection efficiency
The absence of an LFG collection system	0%
Active landfill having an active LFG collection system of vertical wells and daily cover only	67%
Active landfill having an active LFG collection system of vertical wells and intermediate cover or an active LFG collection system of horizontal trenches and daily cover	75%
Active landfill having an active LFG collection system of vertical wells and engineered final soil cover or an active LFG collection system of vertical wells and horizontal trenches and intermediate cover	87%
Closed landfill having an active LFG collection system and geomembrane, subtitle D, or equivalent cover	95%

The facility has two gas engine and generator sets, each with a capacity of 1.4 MWe. Table 8 presents data on the technical properties of the gas engines examined [33]. According to the technical specification of the manufacturer, the electrical efficiency of engines is 41.9%. In the calculations, the electrical efficiency of engines was accepted to be 41%.

Table 8. The technical specifications of the investigated internal combustion engines [33].

Model	JMS 420 GS-B.L
Electrical output (kW el)	1415
Electrical output (kW)	1431
Electrical efficiency (%)	41.9
Thermal efficiency (%)	42.4

Standard conditions: Nominal operation conditions:
air pressure 1000 mbar; temperature 25°C; relative humidity 30%.

Based on this information, the electricity generation potential that can be obtained from landfill gas was calculated using Eq. 7 [34]. The electricity generation amounts for 2017, 2018, and 2019 were calculated in detail below.

E_{el} (kWs) = m_{dg} x LHV_{dg} x R x n_{el} (7)

Where,

M_{dg} = Total landfill gas flow rate (Nm^3/h)

LHV_{dg} = Energy equivalent of landfill gas (kWh/Nm^3)

R = Gas collection efficiency (%)

N_{el} = Electrical efficiency of the gas engine (%)

Electricity generation for 2017

Total landfill gas flow rate = Gas from open dumping x (67%) + Gas from sanitary landfills x (75%)

Total landfill gas flow rate = [7445000 (m^3/year) x 0.67] + [2005000 (m^3/year) x 0.75]

= 6491900 m^3/year

1 m^3 of free gas = 1.109 Nm^3. From here;

Total landfill gas flow rate = 822 Nm^3/h

The energy equivalent of 1 m^3 of landfill gas = 5 kWh/Nm^3

Electrical efficiency of engines = 0.41

Electricity generation for 2017 = $822 \frac{Nm3}{h} \text{ x } 5 \frac{kWh}{Nm3} \text{ x } 0.41 = 1685$ kWh

Electricity generation for 2018

Total landfill gas flow rate = [7275000 (m^3/year) x 0.67] + [2669000 (m^3/year) x 0.75]

= 6876000 m^3/year = 785 m^3/h = 870.5 Nm^3/h

Electricity generation for 2018 = $870.5 \frac{Nm3}{h} \text{ x } 5 \frac{kWh}{Nm3} \text{ x } 0.41 = 1784.53$ kWh

Electricity generation for 2019

Total landfill gas flow rate = [7110000 (m^3/year) x 0.67] + [3328000 (m^3/year) x 0.75]

= 7259700 m^3/year = 829 m^3/h = 919 Nm^3/h

Electricity generation for 2019 = $919 \frac{Nm3}{h} \text{ x } 5 \frac{kWh}{Nm3} \text{ x } 0.41 = 1885$ kWh

The energy potentials (kWh) calculated according to the data obtained from the LandGEM model for 2017, 2018, and 2019 and the energy data (kWh) obtained for these three years at the Sivas landfill gas power plant are presented in Table 9. The energy potentials calculated from the LandGEM model versus the amount of waste deposited are given in Fig 3.

Table 9. Comparison of energy potentials and facility data according to the LandGEM model

Year	Energy potential according to the model (kWh)	Power plant data (kWh)	Standard deviation
2017	1685	1572	±79.903
2018	1784	1717	±47.376
2019	1885	1992	±75.660

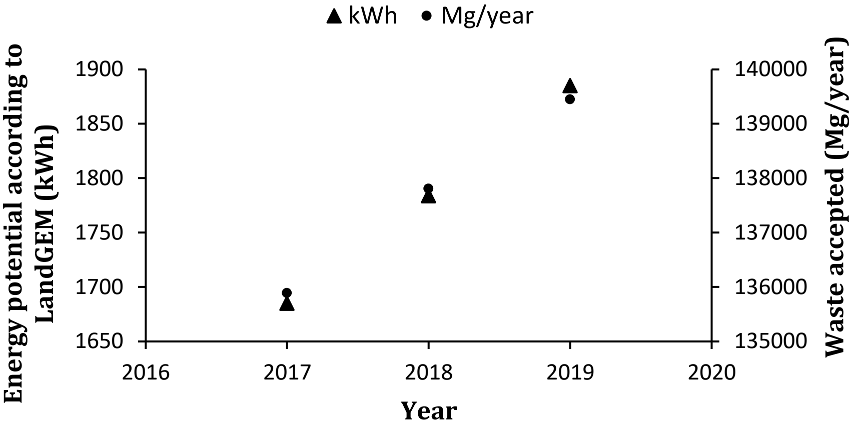

Fig 3. Energy potentials calculated from the LandGEM model versus the amount of waste deposited

The distribution of electricity generated from landfill gas that was calculated according to the LandGEM model by years is given in Fig 4. The highest amount of energy to be generated was calculated to be 2947 kWh in 2030. The reason for this can be the fact that a significant part of landfill gas at a closed landfill site is formed in the first few years following its closure and that lower gas formation occurs in the following years. In Fig 4, energy production increased, especially starting from 2021 until 2030. It was observed that electricity generation amounts decreased due to a decrease in landfill gas formation after 2030. It is understood that the operational life of the Sivas landfill gas power plant will nearly end in an economic sense after 2060.

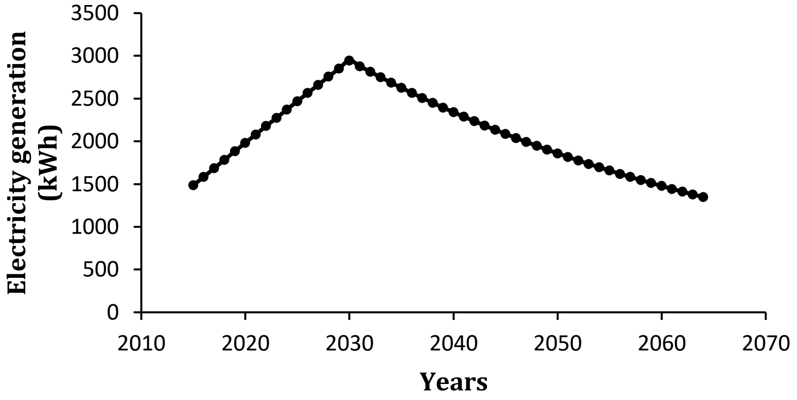

Fig 4. Distribution of electricity generation from landfill gas according to the LandGEM model by years

4. CONCLUSIONS

The study results can be used efficiently in other applications in landfill regions and planning for energy production. The methane emission rate and total greenhouse gases from a landfill site in Sivas, Turkey, were found during 140 years from 2014 to 2154 by employing the LandGEM model. The amount of methane generation from solid waste was calculated to be 3.416E +05 m^3/year in 2015, 2.360E+06 m^3/year in 2021, and 1.105 E+06 m^3/year in 2054. Afterward, according to the total landfill gas and methane amounts obtained from the LandGEM model, the electricity generation amounts that could be obtained from the facility were calculated. Unlike other studies, there is a landfill gas power plant in operation at the landfill site selected for this study since 2015. Thus, the accuracy of the model was also tested by comparing the electricity generation amounts to be produced from methane gas according to the LandGEM model and the actual electricity generation amounts generated at the facility. The energy potential calculated according to the LandGEM model for 2017, 2018, and 2019 is 1685, 1784, and 1885 kWh, respectively, while the data obtained from the facility are 1572, 1717, and 1992 kWh, respectively. Although there are differences by years, it is observed that electricity generation from landfill gas can be calculated using the LandGEM model. Municipalities should calculate the amounts of electricity generation from the landfill site and the useful life of the facility in this way with modeling predictions before landfill gas power plants are built. Modeling studies to be carried out in this way will also guide municipalities and investors.

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