The effect of climate change on the potential for landfill gas generation at the Vinča landfill site

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Abstract. Climate change projections indicate that Republic of Serbia and the Western Balkans will face a high probability of continuing temperature increases, climatic extremes are projected to become more common, including a significant increase in the number of extreme heat events. Heavier precipitation events are expected in the winter months, whilst summers are projected to become even drier. This paper aims to analyse effect of precipitation changes on landfill gas generation on the Vinča landfill, the biggest landfill in Serbia. Quantities of generated landfill gas and methane have been estimated by using LandGem model. Site specific methane generation rate has been calculated according to GMI methodology for Central Eastern Europe. Sensitivity analyses is performed to determine influence of a precipitation regimes on the methane generation rate on the site. Any increase in precipitation (in range 10-30%) may increase landfill gas production for 4.3%. The paper shows the difference in gas emissions, with the same composition of waste, and different precipitation regimes. Changes in precipitation regimes due to climate change can affect the dynamics of landfill gas emissions. This information is significant for the possible re-circulation of leachate from the landfill which could result in an increased production of landfill gas.

1 Introduction

Landfill gas is a renewable energy source. At the same time, it can be a significant source of anthropogenic methane emissions. Average composition of LFG is 50% CO_2 and 50% CH_4. Some studies have shown that methane produced in landfills accounts for between 5 and 10% of global methane emissions [1].

The Republic of Serbia generates about 2.5 million tonnes of municipal waste. To manage this waste effectively, the country sets the following priorities: prevention and reduction of waste generation, reuse of products for their original or alternative purposes, recycling of waste to obtain raw materials for new products, treatment of waste to use its value through methods such as composting or energy-generating incineration, and waste disposal [2]. As over 2 tonnes of waste are landfilled in Serbia annually, there is a great potential for landfill gas production [3]. However, conducted research shows that many modern landfills in Serbia do not meet environmental protection requirement [4]. Therefore, gas collection measures should be accompanied by legal policies the relies on country-specific circumstances [5].

1.1 Landfill gas

Landfill gas (LFG) is produced by the microbiological decomposition of waste. The amount of LFG produced depends on several important factors, such as the composition of the waste, its compactness, i.e., its fragmentation. The age of the deposited waste, as well as the height of the waste in the landfill, weather conditions, moisture content, acidic or basic environment, temperature, presence of nutrients to feed the bacteria, etc., also significantly affect the emissions [6]. The generation of landfill gas begins almost immediately after the waste is deposited and lasts for up to 100 years. The process of LFG production takes place in four stages. The first stage is hydrolysis, where complex organic substances are broken down into simpler products, releasing CO_2 as a by-product. The second stage begins when all oxygen has been consumed. In this phase, anaerobic bacteria break down the simpler organic molecules into acetic, formic and lactic acid alcohols in the absence of oxygen. This changes the pH, the landfill becomes acidic and soluble components of the waste dissolve. Hydrogen and carbon dioxide are the gaseous products of this stage. The third stage is called acidogenesis because acetate compounds are formed. The last stage is metagenesis, in which methane is formed from the products of the previous conversion stages. More carbon dioxide is produced in the aerobic phase of decomposition, while methane is produced in the anaerobic phase [7].

Methane formation in landfills is influenced by several factors, such as the quality of the landfilled waste, moisture content, temperature and oxygen content. The rate of methane formation is directly influenced by the amount of rapidly degradable and crushed municipal

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waste, the temperature and moisture content of the landfill, and the presence of nutrients [8]. It is also indirectly influenced by factors such as organic content, compaction rate and microbial population. The potential for methane formation is directly influenced by the organic content in the waste, the temperature of the landfill and the microbial population.

1.2 Emissions quantification

The rate of LFG emissions from landfill depends on the mechanisms of gas formation and transfer. Mechanisms include emissions of substances formed during reduction and evaporation processes, biodegradation, or chemical reactions. Transfer mechanisms include the transfer of unstable constituents in the vapour phase at the surface of the landfill, through the boundary layer of air above the landfill, and into the atmosphere. The three main mass transfer mechanisms that allow the transfer of volatiles to the vapour phase are diffusion, convection, and evaporation [9]. Liquefied gas is lighter than air and leaves the landfill naturally with the atmosphere. It is therefore very important to comply with all professional, national and European regulations when planning and carrying out work on new landfills and remediating existing landfills.

The literature search has shown that there are a number of models for predicting the amounts of generated landfill gas [10]. Most of these estimates are based on first-order kinetics, also known as first-order decay models. These models assume a linear relationship between the maximum gas generation potential per unit weight of waste and an exponential relationship between waste decay rate and time.

Zero-order models, on the other hand, assume that the gas generation rate is constant over time. This assumption leads to considerable inaccuracies in the results of these models. More complex mathematical models consider the carbon mass balance in the CH_4 production chain, including solid carbon, aqueous carbon, carbon in acidogenic and methanogenic biomass, carbon in acetate, carbon in CO_2 and carbon in CH_4. Numerical models have also proven to be effective tools for estimating CH_4 emissions [11].

2 Methodology

2.1 LandGEM

The United States Environmental Protection Agency (US EPA) has developed a model to predict uncontrolled emissions from landfills. The model is a software application typically used in industry for regulatory and non-regulatory applications and was also used in this study [12].

The LandGEM model is based on a simple first-order decomposition rate equation. The model determines the mass of methane produced as a function of the capacity of methane production and the mass of waste disposed of. It is based on input parameters: landfill waste volume, landfill waste types, landfill design, methane generation rate constant (k), methane generation potential (Lo), concentration of non-methane compounds, volume fraction of methane and carbon dioxide in landfill gas. LandGEM version 3.02, Equation 1, was used for the calculations.

$$Q_{CH4} = \sum \sum k\, L_0\, (M_i/10)\, (e^{-kt}ij) \qquad (1)$$

Where:
Q_{CH4} - estimated methane generation flow rate (in cubic meters [m^3] per year or average cubic feet per minute [cfm])
i = 1-year time increment
n = (year of the calculation) – (initial year of waste acceptance)
j = 0.1-year time increment
k = methane generation rate constant (1/year)
L_0 = potential methane generation capacity (m3 per megagram [Mg] or cubic feet per ton)
M_i = mass of solid waste disposed in the i^{th} year (Mg or ton)
t_{ij} = age of the j^{th} section of waste mass disposed in the i^{th} year (decimal years)

According to the methodology used, the methane formation constant depends directly on two parameters: the composition of the waste and the precipitation regime. In this work, the possible influence of the change of precipitation regime and waste composition on the change of the value of the constant k was investigated using real information from the regional landfill Vinča, Belgrade.

Historical data of the landfill should be entered into the LandGem worksheet shown in Figure 1. Information on possible contaminants, their properties and quantities should be entered in the pollutants window, Figure 2.

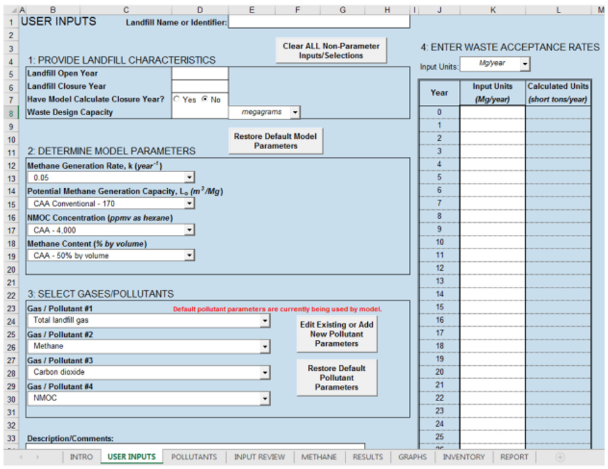
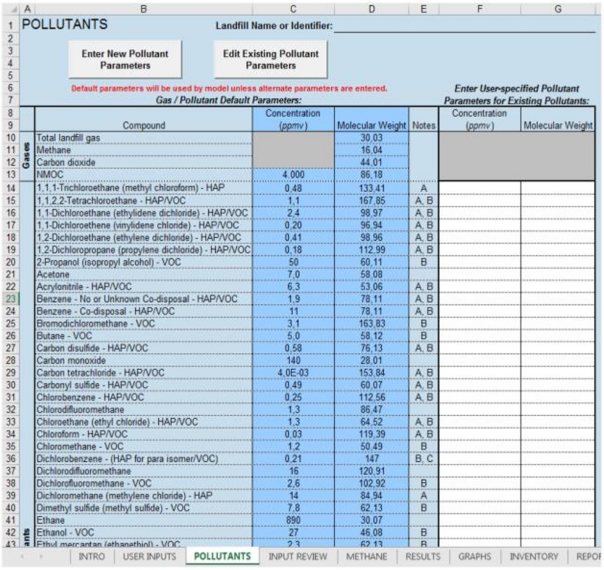


Fig. 1. LandGem User Inputs window (sheet).



Compound	Concentration (ppmv)	Molecular Weight	Notes	Concentration (ppmv)	Molecular Weight
Total landfill gas		30,03			
Methane		16,04			
Carbon dioxide		44,01			
NMOC	4.000	86,18			
1,1,1-Trichloroethane (methyl chloroform) - HAP	0,48	133,41	A		
1,1,2,2-Tetrachloroethane - HAP/VOC	1,1	167,85	A, B		
1,1-Dichloroethane (ethylidene dichloride) - HAP/VOC	2,4	98,97	A, B		
1,1-Dichloroethene (vinylidene chloride) - HAP/VOC	0,20	96,94	A, B		
1,2-Dichloroethane (ethylene dichloride) - HAP/VOC	0,41	98,96	A, B		
1,2-Dichloropropane (propylene dichloride) - HAP/VOC	0,18	112,99	A, B		
2-Propanol (isopropyl alcohol) - VOC	50	60,11	B		
Acetone	7,0	58,08			
Acrylonitrile - HAP/VOC	6,3	53,06	A, B		
Benzene - No or Unknown Co-disposal - HAP/VOC	1,9	78,11	A, B		
Benzene - Co-disposal - HAP/VOC	11	78,11	A, B		
Bromodichloromethane - VOC	3,1	163,83	B		
Butane - VOC	5,0	58,12	B		
Carbon disulfide - HAP/VOC	0,58	76,13	A, B		
Carbon monoxide	140	28,01			
Carbon tetrachloride - HAP/VOC	4,0E-03	153,84	A, B		
Carbonyl sulfide - HAP/VOC	0,49	60,07	A, B		
Chlorobenzene - HAP/VOC	0,25	112,56	A, B		
Chlorodifluoromethane	1,3	86,47			
Chloroethane (ethyl chloride) - HAP/VOC	1,3	64,52	A, B		
Chloroform - HAP/VOC	0,03	119,39	A, B		
Chloromethane - VOC	1,2	50,49	B		
Dichlorobenzene - (HAP for para isomer/VOC)	0,21	147	B, C		
Dichlorodifluoromethane	16	120,91			
Dichlorofluoromethane - VOC	2,6	102,92	B		
Dichloromethane (methylene chloride) - HAP	14	84,94	A		
Dimethyl sulfide (methyl sulfide) - VOC	7,8	62,13	B		
Ethane	890	30,07			
Ethanol - VOC	27	46,08	B		
Ethyl mercaptan (ethanethiol) - VOC	2,3	62,13	B		

Fig. 2. LandGem Pollutants window (sheet).

The value of the methane formation rate constant and the CH_4 formation potential depend on several factors. After a thorough review of the literature, default values for these factors were chosen for the model. The type and composition of the waste in the landfill affect the CH_4 formation potential. For example, MSW with a high cellulose to lignin ratio, such as food, degrades faster than waste with more lignin, such as cloth. The higher the cellulose content, the higher the value of L_0. The values of k and L_0 depend mainly on the amount of organic carbon in the waste and its availability. Food waste with medium and high carbon content is classified based on its organic carbon content of ≤50% and ≥65%, respectively. The k-value is given as a function of the annual rainfall and the temperature of the landfill, while L_o is a function of the annual rainfall rate.

In this paper, LFG and methane production have been estimated for Vinča landfill - the largest landfill in Serbia. Also, effects of precipitation levels, as consequence of climate change, on generated gas quantity were estimated using sensitivity analyses. According to climate change projections, the Republic of Serbia is likely to experience rising temperatures and more frequent extreme weather events. Winters are expected to become rainier, while summers will become drier. For this reason, a sensitivity analysis was carried out. LFG and methane production was estimated by LandGem model. Site specific methane generation rate has been calculated according to GMI (Global Methane Initiative) methodology for Central Eastern Europe [13].

Vinča is the site of Belgrade's municipal landfill. The biggest landfill in Serbia was one of Europe's largest uncontrolled landfills. In 2021. old uncontrolled landfill is closed and new sanitary landfill (capacity of 5.500.000 tons of waste) started with operations. New landfill is built in compliance with the regulations of Republic of Serbia and EU landfill Directive. Beside new landfill, on site is built Energy-from-Waste plant, that will treat 66% of MSW that Belgrade currently generates.

In a first two years, 510.000 tons/year of waste will be disposed of on the landfill. Next year amount of disposed waste will be 368.333 tons. In fourth year, Energy-from-Waste plant will be operational, so quantity of disposed waste will drop to 170.000 tons/year. The closing year for the Vinča landfill is 2041. In estimations, the k value used for the calculations is 0.065 and L_0 is 170.

2.2 GMI methodology

GMI methodology is used to estimate k-values for different weather regimes. The inputs for the calculation of k-values are waste composition data and local weather conditions (average precipitation). All decaying waste is divided in four waste categories with corresponding k_x values [10]:

1. Very fast decaying waste (k_1) – food waste and other organics.
2. Medium fast decaying waste (k_2) – garden waste (green waste).
3. Medium slow decaying waste (k_3) – paper and cardboard, textiles.
4. Slowly decaying waste (k_4) – wood, rubber, leather, bones, straw, x_4.

GMI methodology differs 5 precipitation regimes shown in Table 1.

Table 1. Precipitation regimes in GMI methodology.

Regime	Precipitation level *[mm/m²/year]*
Wet	> 700
Moderately Wet	600-699
Moderate	500-599
Moderately Dry	400-499

The values of regional k-values for specific landfill are calculated as:

$$k = x_1k_1 + x_2k_2 + x_3k_3 + x_4k_4$$

where is k_n – waste fraction, x_n – waste type fraction.

3 Results and discussion

3.1 k-values estimation

GMI methodology is used for estimation of k-value on Vinča landfill. Sensitivity analyses is performed to determine influence of a precipitation regimes on the LFG and methane generation rate on the site.
Average composition of decaying waste is shown in Table 2.

Table 2. Composition of MSW on Vinča landfill.

Waste type fraction	%
x_1	27.0

x_2	18.0
x_3	18.3
x_4	12.4
Total	75.7

In table 3, precipitation levels and estimated k-values used in sensitivity analyses are shown. Precipitation levels are varied from -30% up to +30%.

Table 3. Precipitation regimes in GMI methodology.

Change in precipitation level, %	Precipitation level, mm/m^2/year	k (1/year)
-30	483	0.0491
-20	552	0.057
-10	621	0.065
0	690	
+10	759	0.074
+20	828	
+30	897	

3.2 LFG production on Vinča landfill

LFG and methane emissions generated on Vinča landfill are shown in Figure 3.

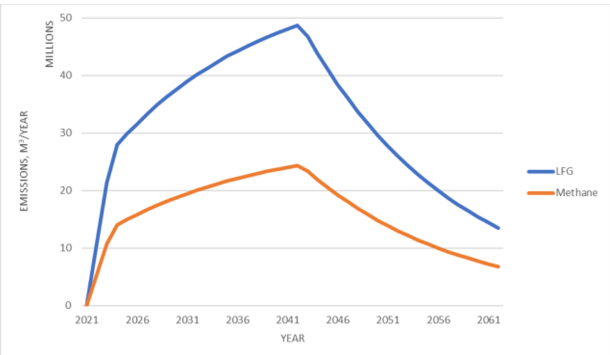


Fig. 3. LFG and methane emissions on Vinča landfill.

Results show that emissions will reach peak in 2042. In that year, landfill will produce 48 mil m^3 of landfill gas. In period of 30 years, Vinča landfill will produce 1.3 billion m^3 of landfill gas of which 668 million is methane.

3.3 Sensitivity analysis

3.2.1 LFG production

Results of sensitivity analyses for LFG production are shown in Figure 4.

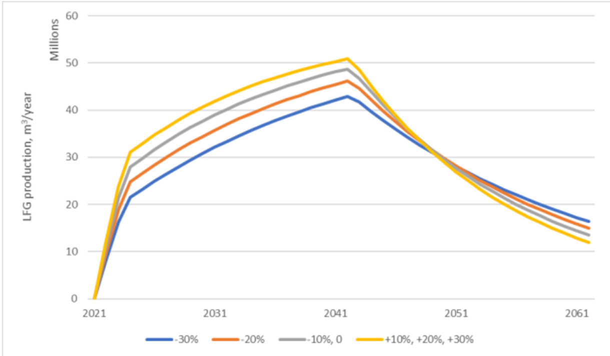


Fig. 4. LFG production on Vinča landfill in different weather regimes.

Results shows that all cases follow the same pattern. In drier climate, with less precipitation, generation of LFG is slower in a first 20 years. If level of precipitation drops for 30%, LFG production in peak year drops for 12.0 %. In regimes with higher level of precipitations, LFG production increases for 4.3%. After peak year, in drier climate LFG generation will decrease with slower pace compared to wetter climate. In 2061, 40 years after opening, the landfill in moderately dry climate will produce 19.5% more LFG compared to moderate climate. If precipitation levels rise, LFG production will decrease for 10.5% compared to moderate climate.

3.2.2 Methane production

Results of sensitivity analyses for methane production are shown in Figure 5.

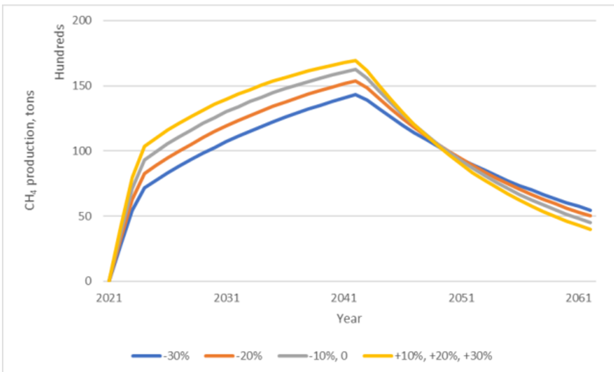


Fig. 5. Methane production on Vinča landfill in different weather regimes.

Quantity of produced methane is important because its global warming potential is very high. It can be observed that Vinča landfill will produce 397.491, 422.006, 440.927 and 455.948 tons of methane for precipitation levels changing in range -30% / +30%.

Study of Chi at al. [14] shows importance of moisture content in landfills. The highest methane yield is observed at moisture content of 60 %. Too low or too high-water content in landfill can significantly decrease methane production. Study of Wangyao et al. [15] shows difference in the methane emission for rainy and dry seasons. During rainy season methane emission was about 5-6 times higher than winter season and summer season.

4 Conclusion

Landfill gas and methane production on the biggest landfill in Serbia has been predicted using LandGem model. Specific k-values are calculated using GMI methodology. Depending of climate regime k-value are in a range 0.0491-0.074 1/year. Obtained results show that if the precipitation regime shifts from moderate to wet LFG production in peak year increases. In next years, production of LFG declines faster compared to moderate precipitation levels. If precipitation decrease, LFG production also decreases compared to moderate climate. This information can be used in planning recirculation of leachate on landfill. If LFG is collected and used as renewable source of energy effect on climate is greatly reduced.

The authors are grateful to the Ministry of Education, Science and Technological Development of the Republic of Serbia (Project No. 451-03-47/2023-01/200287 and 451-03-47/2023-01/200135) for its support.

References

1. USEPA, *Advancing Sustainable Materials Management: 2018 Fact Sheet* (2020)
2. A. Dajić, M. Mihajlović, M. Jovanović, M. Karanac, D. Stevanović, J. Jovanović, Clean Techn. Environ. Pol. **18**(3), 753-764 (2016)
3. N. Stanisavljević, D. Ubavin, B. Batinić, J. Fellner, G. Vujić, wmr. **30**(10), 1095-1103 (2012)
4. M. Mihajlović, R. Pešić, M. Jovanović, Greenhouse Gas Sci. Technol. **9**, 152–159 (2019)
5. M. Karanac, M. Jovanović, M. Mihajlović, A. Dajić, D. Stevanović, J. Jovanović, Recycl. Sustain. Dev. **8**(1), 27-37 (2015)
6. S.J. Mbazima, M.D. Masekameni, D. Mmereki, Energ Explor Exploit. **40**(4), 1287-1312 (2022)
7. H. Zhang, G. Liu, L. Xue, J. Zuo, T. Chen, A. Vuppaladadiyam, H. Duan, jclepro **277**, 123490 (2020)
8. A. Majdinasab, Z. Zhang, Q. Yuan, Rev. Environ. Sci. Biotechnol. **16**, 361–380 (2017)
9. D. Huang, Y. Du, Q. Xu, J.H. Ko, jenvman **302**(A), 114001 (2022)
10. S.C. Scheutz, K.P. Kjeldsen, J.E. Bogner, A. De Visscher, J. Gebert, H.A. Hilger, M. Huber-Humer, K. Spokas, Waste Manag. Res. **27**, 409 (2009)
11. A. Rafey, F.Z. Siddiqui, cles **5**, 100076 (2023)
12. LFG Energy Project Development Handbook (2016)
13. GMI, User's Manual Central-Eastern Europe Landfill Gas Model (2014)
14. C. Zi-fang, Y. Zhao, L. Wenjing, H. Wang., B.F Yang, Z. Mou, EPPHA (2011)
15. K. Wangyao, S. Towprayoon, C. Chiemchaisri, M. Yamada, K. Endo, T. Ishigaki, S.H. Gheewala, A. Nopharatana, JSWME (2008)