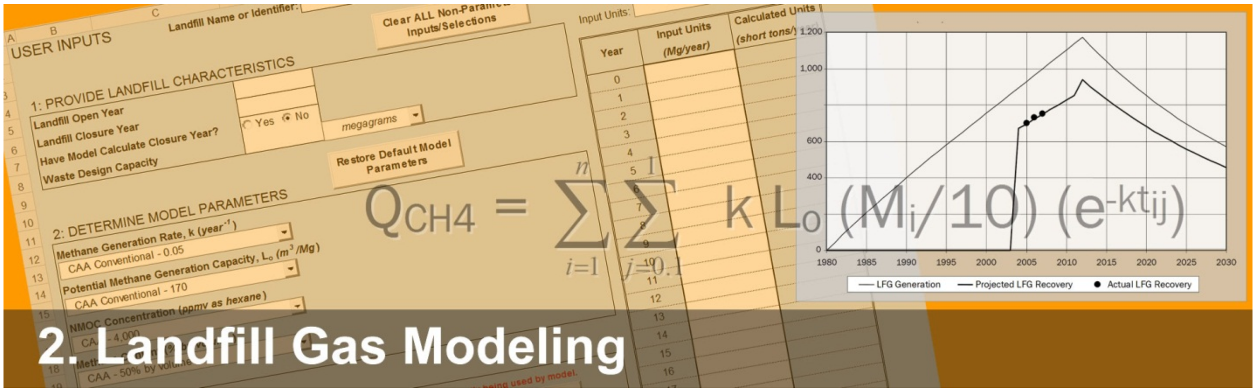


2. Landfill Gas Modeling

LFG modeling is the practice of forecasting gas generation and recovery based on past and future waste disposal histories and estimates of collection system efficiency. It is an important step in the project development process because it provides an estimate of the amount of recoverable LFG that will be generated over time. LFG modeling is performed for regulatory and non-regulatory purposes. Regulatory applications of LFG models are conducted for landfills in the United States to establish the requirements for installation and operation of the gas collection and control system. Non-regulatory applications of LFG models typically include any of the following:

- Evaluating the feasibility of an LFG energy project
- Determining gas collection and control system design requirements
- Performing due diligence evaluations of potential or actual project performance

This chapter covers non-regulatory LFG modeling applications only. EPA does not intend for the material presented in this handbook to supersede or replace required procedures for preparing LFG models for regulatory purposes. Federal regulations such as the NSPS require modeling to evaluate the applicability of and compliance with the rule. For regulatory applications, the modeler must use the specific procedures, default values and test methods prescribed in the rule.

ⓘ Refer to the appropriate regulations (such as the NSPS [40 CFR part 60, subpart XXX] and related documentation) for details.

2.1 Introduction to LandGEM

EPA's LandGEM is a Microsoft Excel-based software application that uses a first-order decay rate equation to calculate estimates for methane and LFG generation. LandGEM is the most widely used LFG model and is the industry standard for regulatory and non-regulatory applications in the United States.

The first-order decay rate equation produces an estimate for the amount of methane that will be generated at a specific time.

ⓘ The latest version of LandGEM (v. 3.02) was released in May 2005 and can be downloaded from EPA on the Clean Air Technology Center's Products page.

The First-Order Decay Equation

LandGEM uses the first-order decay equation below to estimate methane generation. LFG generation estimates are based on the methane content of the LFG. The default methane content of LFG is 50 percent, which is both the industry standard value and LMOP's recommended default value.

$$Q_{CH4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} k\, L_0\, (M_i/10)\, (e^{-kt_{ij}})$$

Where:

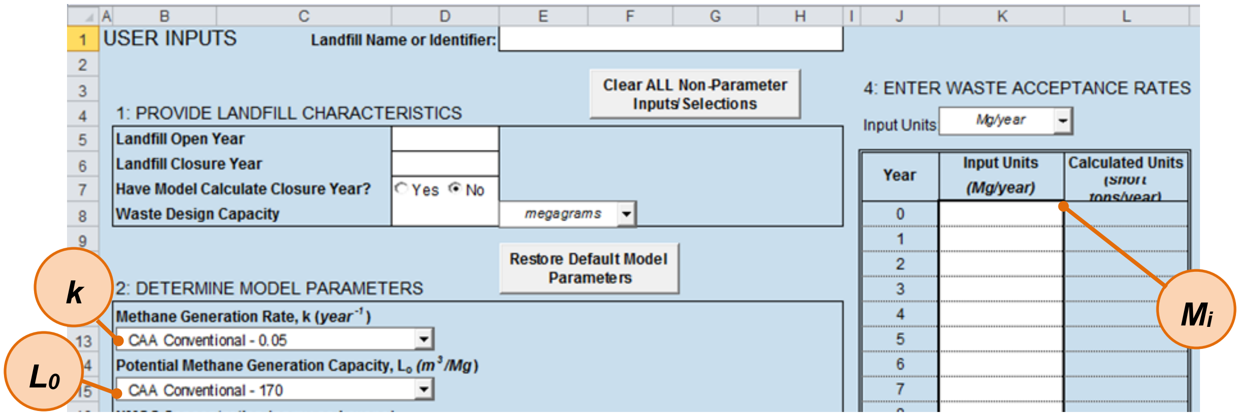
Q_{CH4} = estimated methane generation flow rate (in cubic meters [m^3] per year or average cfm)
i = 1-year time increment
n = (year of the calculation) – (initial year of waste acceptance)
j = 0.1-year time increment
k = methane generation rate (1/year)
L_0 = potential methane generation capacity (m^3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

LandGEM assumes that methane generation is at its peak shortly after initial waste placement (after a short time lag when anaerobic conditions are established in the landfill). The model also assumes that the rate of landfill methane generation then decreases exponentially (first-order decay) as organic material is consumed by bacteria.

Model Inputs

Only three of the variables in the first-order decay equation require user inputs (M_i, L_0 and k). Inputs are entered on the "USER INPUTS" worksheet in LandGEM (see Figure 2-1).

Figure 2-1. LandGEM User Inputs Worksheet



USER INPUTS
Landfill Name or Identifier:

1: PROVIDE LANDFILL CHARACTERISTICS
Landfill Open Year
Landfill Closure Year
Have Model Calculate Closure Year? ○ Yes ● No
Waste Design Capacity: megagrams

2: DETERMINE MODEL PARAMETERS
Methane Generation Rate, k (year^{-1}): CAA Conventional - 0.05
Potential Methane Generation Capacity, L_0 (m^3/Mg): CAA Conventional - 170

4: ENTER WASTE ACCEPTANCE RATES
Input Units: Mg/year

Year	Input Units (Mg/year)	Calculated Units (short tons/year)
0		
1		
2		
3		
4		
5		
6		
7		

***k (Methane Generation Rate Constant*)**: The methane generation rate constant, k, describes the rate at which waste placed in a landfill decays and produces LFG. The k value is expressed in units of 1/year or yr^{-1}. At higher values of k, the methane generation at a landfill increases more rapidly (as long as the landfill is still receiving waste), and then declines more quickly after the landfill closes. The value of k is a function of (1) waste moisture content, (2) availability of nutrients for methane-generating bacteria, (3) pH, and (4) temperature.

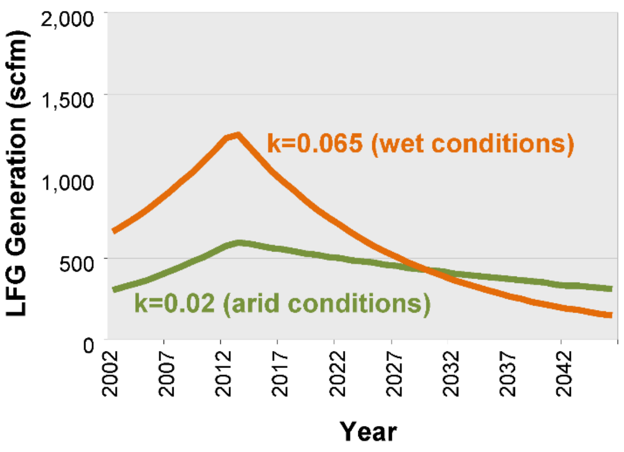
Moisture conditions within a landfill strongly influence k values and waste decay rates. Waste decay rates and k values are very low at desert sites, tend to be higher at sites in wetter climates, and reach maximum levels under moisture-enhanced conditions. Annual precipitation is often used as a surrogate for waste moisture because of the lack of information on moisture conditions within a landfill. Air temperature can also affect k values, but to a lesser extent. Internal landfill temperatures are relatively independent of outside temperatures and typically range from approximately 30 to 60°C (85 to 140°F) except at shallow, unmanaged landfills in very cold climates (as in landfills located in areas above 50 degrees latitude). For these landfills, waste decay rates and k values tend to be lower.

L_0 (Potential Methane Generation Capacity): The potential methane generation capacity, or L_0, describes the total amount of methane gas potentially produced by a metric ton of waste as it decays. EPA determined that the appropriate values for L_0 range from 56.6 to 198.2 m^3 per metric ton or megagram (m^3/Mg) of waste.[1] Except in dry climates where lack of moisture can limit methane generation, the value for the L_0 depends almost entirely on the type of waste present in the landfill. The higher the organic content of the waste, the higher the value of L_0. Note that the dry organic content of the waste determines the L_0 value, and not the wet weight measured and recorded at landfill scalehouses, as water does not generate LFG. LandGEM sets L_0 to a default value of 170 m^3/Mg to represent a conventional landfill.[2]

M_i (Annual Waste Disposal Rates): Estimated waste disposal rates are the primary determinant of LFG generation in any first-order decay-based model. LandGEM does not adjust annual waste disposal estimates to account for waste composition. Adjustments to account for waste composition are typically handled by adjustments to the L_0 value.

Figure 2-2 shows an example gas curve for a landfill with approximately 2 million tons waste-in-place expected at closure. The potential gas generation was modeled in two scenarios, using identical landfill parameters, except that k was varied between a value for arid conditions (0.02 yr^{-1}) and a value for wet conditions (0.065 yr^{-1}). The graph demonstrates the significant difference in gas generation that can occur based on moisture conditions at the site.

Figure 2-2. LFG Generation Variance by k Value



Model Outputs

After the model inputs are entered, emission estimates can be viewed in tabular format on the "RESULTS" worksheet. The results include annual data for waste inputs, waste-in-place amounts, and estimates of total LFG generation, methane, carbon dioxide and non-methane organic compounds (NMOCs). The results also may be viewed graphically on the "GRAPHS" worksheet, which plots emission estimates by year. LFG and methane generation estimates are the output parameters used for non-regulatory LFG predictions.

For additional details about the LandGEM model, see the LandGEM User's Guide.

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[1] U.S. EPA. 1995. *Air Emissions from Municipal Solid Waste Landfills — Background Information for Final Standards and Guidelines*. EPA-453/R-94-021. p. 2-60.

[2] U.S. EPA. 2005. Landfill Gas Emissions Model (LandGEM) Version 3.02 User's Guide. EPA-60/R-05/047. p. 17.

2.2 Estimating LFG Collection

Once the LFG and methane generation amounts are estimated, the next step is to estimate the amount of LFG that can be collected.

Developing accurate estimates for the amount of available LFG is critical to evaluating the technical and economic feasibility of an LFG energy project.

Estimating Collection Efficiency

Collection efficiency is a measure of the ability of a gas collection system to capture LFG generated at the landfill. The LFG generation estimate produced by the model is multiplied by the collection efficiency to estimate the volume of LFG that can be recovered for flaring or use in an LFG energy project. Considerable uncertainty exists regarding collection efficiencies achieved at landfills because the total LFG generated is always estimated.

To help address this uncertainty, EPA has published estimates of reasonable collection efficiencies for landfills in the United States that meet U.S. design standards[3] and have “comprehensive” LFG collection systems. A “comprehensive” LFG collection system is made up of vertical wells and or horizontal collectors that cover 100 percent of all waste areas within 1 year after the waste is deposited. Reported collection efficiencies at such landfills typically range from 50 to 95 percent, with an average of 75 percent most commonly assumed.[4] Since most landfills, particularly those that are still receiving wastes, have less than 100 percent collection system coverage, LFG modelers commonly use a “coverage factor” to adjust the estimated collection efficiency. The coverage factor adjustment is applied by multiplying the collection efficiency by the estimated percentage of the fill areas covered with wells. This adjustment also can be applied to account for areas where wells are not fully functioning.

The modeler typically assumes that a comprehensive system will be installed for sites without collection systems, and that future collection efficiency estimates may reflect planned collection system enhancements. Collection efficiency usually increases after site closure when disposal operations no longer interfere with LFG system operations and a final cover is installed.

Estimating LFG Recovery

The final step in the modeling process is to estimate annual LFG recovery, which is calculated as the product of LFG generation and collection efficiency. Table 2-1 shows a recommended format for estimating LFG recovery.

Table 2-1. LFG Generation and Recovery Projections

Year	Disposal Rate	Waste in-Place	LFG Generation		Collection Efficiency	LFG Recovery	
	(tons/year)	(tons)	(scfm)	(m^3/yr)	(%)	(scfm)	(m^3/yr)
Year 1							
Year 2							
Year X (final year)							

m^3/yr: cubic meters per year scfm: standard cubic feet per minute

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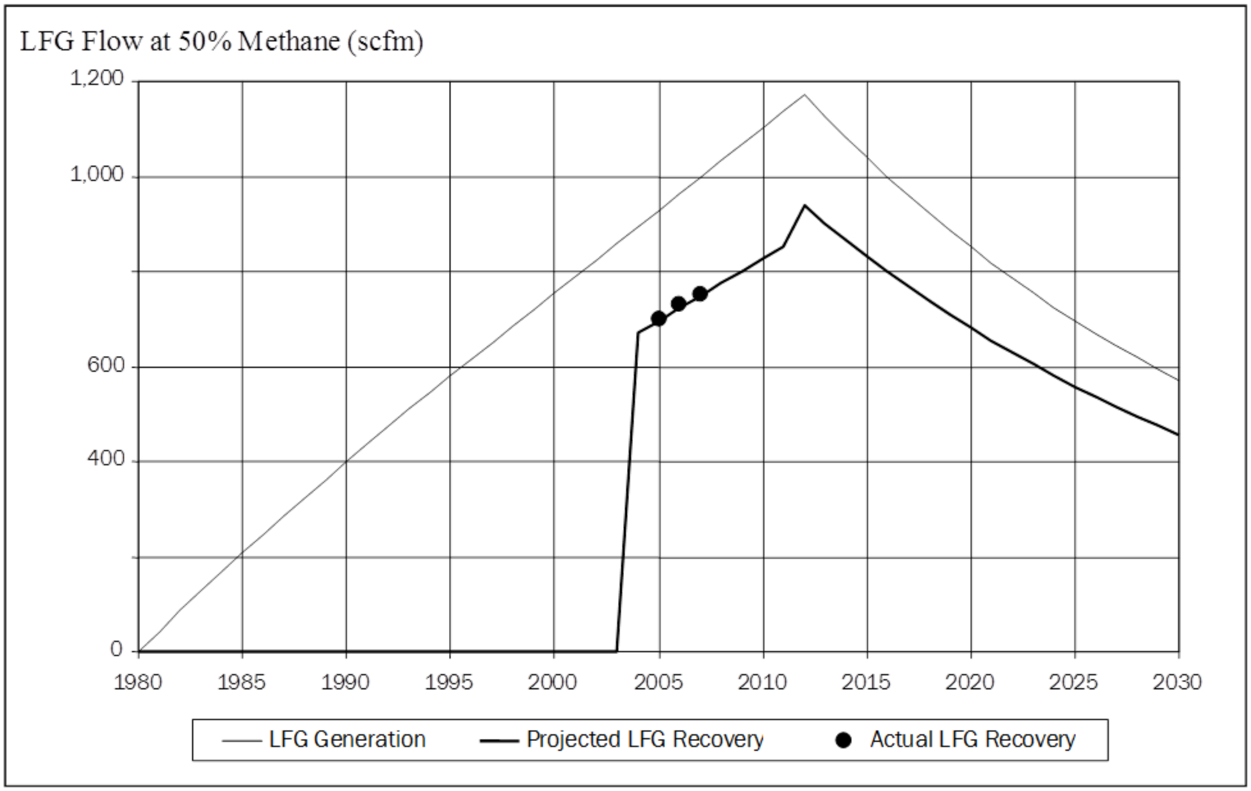
[3] Landfills that meet or exceed the requirements in the 40 CFR parts 257 and 258 RCRA Subtitle D criteria.

[4] U.S. EPA. 2008. Background Information Document for Updating AP42 Section 2.4 Municipal Solid Waste Landfills, EPA/600/R-08-116. https://www.epa.gov/ttn/chief/ap42/ch02/.

To illustrate LFG recovery projections over time, both LFG generation and recovery can be displayed in a line graph. The x-axis (horizontal) shows the year, and the y-axis (vertical) shows the LFG flow at 50 percent methane (in standard cubic feet per minute [scfm]). The graph can be used to assess the model's accuracy by displaying actual recovery as dots for sites with operating collection systems and recovery data. Figure 2-3 shows a sample model output graph for a landfill that opened in 1980, installed a gas collection system in 2003,[5] and accepted waste through 2011. Measurements of recovered LFG are shown as dots.

LMOP recommends seeking the help of an experienced professional LFG modeler to perform model calibration, which involves adjusting model k and L_0 values so that the projected LFG recovery rates closely match actual recovery.

Figure 2-3. LFG Generation and Recovery Rates



Special Considerations for Bioreactor and Leachate Recirculation Landfills

Some landfills deliberately introduce liquids into the waste in a controlled manner to speed up the waste decay process and shorten the time period for LFG generation. Landfills that achieve 40 percent moisture content in the waste through the controlled introduction of liquids (other than leachate and condensate) are considered "bioreactor" landfills, according to EPA air regulations.[6] Landfills that introduce liquids (most commonly leachate and condensate) but achieve waste moisture content less than 40 percent are considered "leachate recirculation" landfills.

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[5] LFG recovery starts at known or projected date of the installation of the gas collection and control system.

[6] "Bioreactor" is defined in the municipal solid waste landfill National Emission Standards for Hazardous Air Pollutants, 40 CFR part 63, subpart AAAA.

The introduction of liquids into the landfill causes significant increases in waste decay rates and k values. LFG generation increases more rapidly while the landfill is receiving waste and decreases more rapidly once disposal stops, but the total LFG generation over the long term remains the same. L_0 values should not be affected by liquids introduction because only the rate of LFG generation is affected.

- k value for bioreactor landfills: LandGEM provides a default k value of 0.7 for modeling bioreactor landfills (the "inventory wet" value). LMOP, however, recommends assigning a k value of 0.3 for bioreactors based on a study conducted by the University of Florida.[7]
- k value for leachate recirculation landfills: No single k value is recommended or appropriate for leachate recirculation landfills because the impact of leachate recirculation on LFG generation varies depending on the amount of liquids added and the moisture content of waste achieved.

In some instances, only a portion of a landfill's total site is designed and operated as a bioreactor or leachate recirculation landfill. In such cases, the bioreactor or leachate recirculation portion should be modeled separately from the remainder of the site, using waste disposal inputs for these areas only.

Visit the EPA's website to learn more about bioreactors.

2.3 Model Limitations

Accurate estimates for LFG recovery are critical to the proper design and financial success of LFG energy projects. LFG modelers should be aware of factors that can produce error within a model and use appropriate inputs to avoid significantly overestimating the amount of recoverable LFG. Factors that can affect the accuracy of LFG recovery projections include:

- ***Inaccurate assumptions.*** Inaccurate assumptions about variables such as organic content, future disposal rates, site closure dates, wellfield buildout, expansion schedules or collection efficiencies can result in large errors in predicting future recovery.
- ***Limited or poor quality disposal data.*** Significant model error can be introduced if good disposal data are not available.
- ***Poor-quality flow data or inaccurate estimates of collection efficiency used for model calibration.*** Model calibration requires both accurate estimates of collection efficiency and good quality flow data that are representative of long-term average recovery.
- ***Atypical waste composition.*** Waste composition data are often not available to determine if unusual waste composition is a cause of model inaccuracy. However, the risk can be minimized by introducing sample collection procedures to better determine waste composition.
- ***Limitations because of the structure of LandGEM.*** For example, LandGEM cannot accommodate changes in k or L_0 values in the same model run. Changing landfill conditions that cannot be modeled as a result of this limitation include the following:
  - Application of liquids to existing waste
  - Variations in waste composition over time
  - Installation of a geomembrane cover

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[7] U.S. EPA. 2005. *First-Order Kinetic Gas Generation Model Parameters for Wet Landfills*. EPA-600/R-05/072. http://nepis.epa.gov/Adobe/PDF/P100ADRJ.pdf.