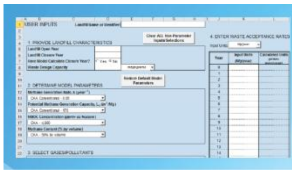

CHAPTER 6

Landfill Gas Modeling

When an SWD site owner or project developer wants to consider the technical and economic feasibility of an LFGE project, the first step is to estimate the volume of LFG (specifically methane) that can be collected. In many cases, no active collection system is installed and no LFG flow data exist to indicate an achievable collection rate. In cases where an active LFG collection system exists, flow and methane measurements provide historical LFG (and methane) volumes, but do not provide information on future LFG collection potential. For these reasons, a model to estimate LFG collection is an essential tool for planning an LFG flaring or energy project.

This chapter provides an understanding of selected publicly available LFG models, describes how these models are applied to estimate methane collection from SWD sites, and identifies considerations for their use. Topics covered include the following:

1. An overview of LFG generation, emissions and collection
2. Factors influencing LFG generation
3. Publicly available LFG models
4. Data needed to model LFG generation and collection
5. Estimating collection efficiency
6. LFG model uncertainty and performance.

Lessons Learned

Many LFGE projects in developing countries have failed to collect the volume of LFG anticipated at the beginning of the project. In many cases, the project design reflected inflated expectations based on inappropriate application of an LFG model.[1] For example, use of U.S.-based LFG models, which are designed for sanitary landfills in the United States, cannot accurately account for landfills in developing countries with vastly different waste characteristics and site conditions.

In the last several years, LFG models better suited for estimating the volume of LFG in developing countries have become publicly available; these models provide more realistic expectations of the potential for landfill methane recovery.

Costs associated with conducting LFG modeling are not presented because modeling depends on project-specific factors, which can vary significantly among countries.

6.1 LFG Generation, Emissions and Collection

An introduction to LFG generation models requires an understanding of the different pathways for generated LFG and how models have been used for estimating LFG generation and collection. A full accounting of the volume of LFG generated requires the identification of all of the terms on the right side of the following equation:

Generation = Collected LFG + Uncollected LFG Emitted through Cover + Methane Oxidation in Cover Soils + Lateral Migration + Change in LFG Storage

Collected LFG is the only term that can be accurately measured. The other terms are generally unknown. Therefore, LFG generation models cannot be fully validated with measured LFG collection data because the unmeasured parameters introduce potential error into the calculations.

[1] SCS Engineers. 2009. *Methane Emission Reductions Achieved by Landfill Gas Projects in Developing Countries*.

Evaluating Model Performance

Model performance can be evaluated at sites with active gas collection systems if data are available for LFG flow and methane concentration. However, these evaluations should be conducted at sites that have an extensive gas collection system and collect a high percentage of the generated LFG.

Modeling LFG Generation

LFG generation models were initially designed to estimate air emissions from landfills. The U.S. EPA's Landfill Gas Emissions Model (LandGEM)[2] was designed to serve as a tool for estimating emissions of various LFG constituents from U.S. landfills. Another landfill methane emissions model designed for worldwide applications is the Intergovernmental Panel on Climate Change (IPCC) Model.[3] These LFG generation models typically ignore lateral migration and change in storage, and either ignore methane oxidation in cover soils or assign it to a default value (for example, 10 percent), before subtracting recovery from modeled generation to calculate emissions. For example, LandGEM does not include an oxidation calculation, and the IPCC Model assigns default values for methane oxidation equal to 10 percent of uncollected LFG for managed sites with oxidizing soil covers and 0 percent for all other sites. Recent field studies have provided evidence of oxidation rates much higher than 10 percent at sites with good soil cover and efficiently operating gas collection systems. This recent research is reflected in a new landfill methane emissions model released in 2011 that provides a realistic accounting of methane oxidation, the California Landfill Methane Inventory Model (CALMIM).[4] CALMIM does not model LFG generation; instead, it models the processes that control emissions, including cover types and extent, the fraction of area with LFG collection, and the seasonal methane oxidation rate.

Additional Model Resources

Other models that estimate landfill methane emissions not discussed in this chapter include the U.S. EPA's Waste Reduction Model (WARM) and the British Environment Agency's GasSim2.5.

Modeling LFG Collection

LFG collection can be estimated using models by multiplying LFG generation projections by the percent "collection efficiency," a measure of the actual or expected ability of the gas collection system to collect generated LFG. For sites without an operating gas collection system, collection efficiency can be assigned an assumed default value (for example, 75 percent for U.S. landfills planning a comprehensive collection system), or a value estimated based on site characteristics and proposed gas collection system design (if available). Collection efficiency at sites with operating gas collection systems can be assigned a value that is back-calculated by dividing actual measured LFG collection by modeled LFG generation. Otherwise, it can be estimated independently of models based on an evaluation of site characteristics and gas collection system coverage and operations.[5] The U.S. EPA GHG Reporting Program methodology for estimating landfill methane emissions provides instructions for estimating collection efficiency based

[2] U.S. EPA. May 2005. *Landfill Gas Emissions Model (LandGEM), Version 3.02.* EPA 600-R-05-047. http://www.epa.gov/ttn/catc/dir1/landgem-v302-guide.pdf and http://www.epa.gov/ttn/catc/products.html#software.

[3] IPCC. 2006. *IPCC Guidelines for National Greenhouse Gas Inventories.* Volume 5, Chapter 3. http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_3_Ch3_SWDS.pdf.

[4] See for example, Bogner et al. 2010. *Improved Understanding of Seasonal Methane Oxidation In Landfill Cover Soils: An Important Component of a New IPCC Tier IV Greenhouse Gas (GHG) Inventory Methodology*. SWANA 33rd Annual LFG Symposium. 8-11 March 2011, San Diego, CA.

[5] SCS Engineers. January 2009. *Current MSW Industry Position and State-of-the-Practice on LFG Collection Efficiency, Methane Oxidation, and Carbon Sequestration in Landfills*. http://www.scsengineers.com/Papers/Sullivan_SWICS_White_Paper_Version_2.2_Final.pdf.

on cover type and fraction of waste area with wells.[6] Country-specific LFG models developed by GMI include methods for estimating collection efficiency and are discussed in more detail in a later section. Figure 6-1 illustrates an example of calculating the collection efficiency for an LFG project that installed a gas collection system in 2003 and that will stop accepting waste in 2011.[7]

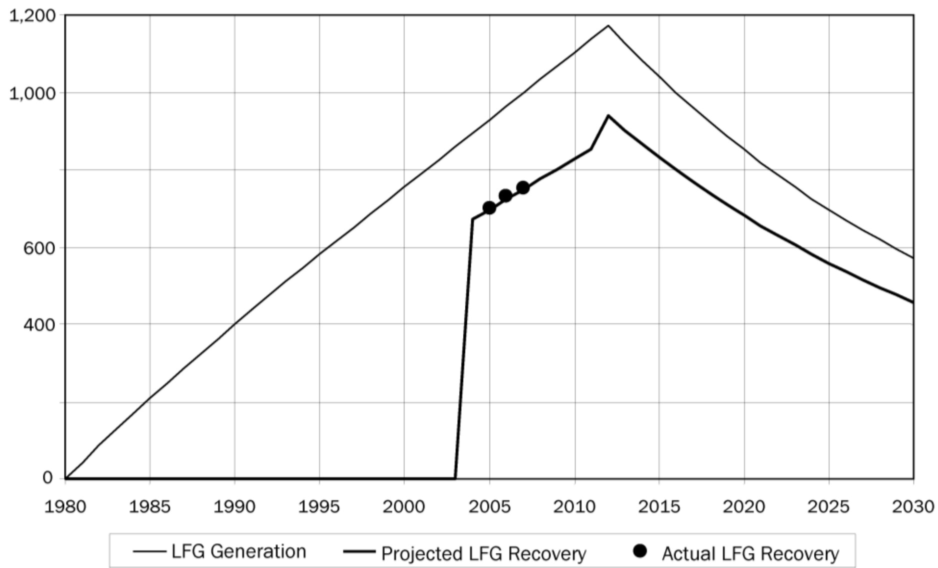

Figure 6-1. Example LFG Generation and Recovery Graph

When LFG generation models are used to estimate LFG collection instead of air emissions, their assumptions can be tested using measured collection data and estimates of collection efficiency. However, collection efficiency estimates can introduce significant error. Collection efficiency is especially difficult to estimate accurately at open dumps or poorly managed SWD sites where site conditions, site management practices, waste composition, and climate can exhibit significant variation and may be distinctly different than at well-operated sanitary landfills.

LFG models need to incorporate the likely impacts of differences in site conditions and these other factors when estimating LFG collection. For example, country-specific LFG models may incorporate in-country data and site characteristics, including waste composition, climate and measured LFG collection from operating projects. These models also may automatically calculate collection efficiency or provide instructions on estimating collection efficiency based on soil cover types and extent, extent of collection system coverage of disposal cells, and other influencing factors.

Estimating LFG collection using LFG models is a critical component of project assessments to evaluate the technical and economic feasibility of a proposed LFG project. The LFG collection projections are used to estimate project design requirements, capital and operating costs, the size of the project that can be supported, and the expected revenues from the sale of emission reduction credits and or energy. In particular, the design parameters of a gas collection system depend heavily on model estimates of LFG collection for the project design and implementation phases, as well as for pre-project planning (project feasibility assessment). A detailed evaluation of future LFG collection by an experienced LFG modeler can indicate system design requirements throughout various phases of the project as it expands into new waste disposal areas.

[6] U.S. EPA Greenhouse Gas Reporting Program. 40 CFR Part 98, subpart HH- Municipal Solid Waste Landfills, http://www.epa.gov/climatechange/emissions/subpart/hh.html.

[7] U.S. EPA. 2010. *LFG Energy Project Development Handbook*. http://www.epa.gov/lmop/publications-tools/handbook.html.

Modeling Requirements for Registering LFG Projects

If an LFG project is being implemented under a certified emissions reduction revenue stream, such as CDM or a JI mechanism, then LFG modeling is required as part of the registration process using a prescribed calculation method or "tool."[8] The project proponent (SWD site owner or project developer) is required to complete a project design document (PDD) for the planned project and the PDD includes projections of CERs achieved through combustion of methane (in the case of LFG flaring projects) and the sale of electricity or thermal energy from LFG (in the case of LFG utilization projects).

6.2 Factors Influencing LFG Generation

A basic knowledge of environmental factors influencing LFG generation is important for understanding LFG modeling. LFG is generated through the action of microorganisms that begin decomposing organic waste within about 3 to 6 months after disposal, if the waste is in an anaerobic state. The rate of LFG generation caused by waste decomposition is sensitive to a number of environmental factors, including moisture, temperature, oxygen and refuse degradability. The effects of each of these variables can be summarized as follows:

- **Moisture** is one of the most important variables influencing LFG generation. LFG generation is known to increase with moisture because higher waste moisture content contributes to an increased rate of waste decay, but the total amount of LFG generated over time ("ultimate yield") may not increase with increases in moisture above a minimum threshold needed to support microorganisms that generate LFG. Moisture conditions can vary widely from desert to tropical sites or even within sites with liquids recirculation. Average annual precipitation is typically used as a surrogate for moisture because moisture within a waste mass is difficult to measure.
- **Temperature** increases generally cause LFG generation to increase up to approximately 57 degrees Celsius (^{o}C). At higher temperatures, the amount of LFG generation decreases, and the higher temperatures indicate aerobic rather than anaerobic decay, which can lead to subsurface fires. While cold air temperatures can penetrate the surface of the waste mass and decrease LFG generation, particularly in small, shallow sites, most of the waste mass of larger sites will be insulated from outside temperatures and warmed by microbial activity. Temperature effects on LFG generation are complex, and temperature profiles within a waste mass are too varied to characterize for LFG modeling, although some models do incorporate ambient air temperatures into their calculations.
- **Oxygen** in air can penetrate a waste mass and inhibit anaerobic microorganisms from producing LFG. A significant portion of the waste mass at shallow sites and sites with limited or no cover may be affected by air infiltration and reduced LFG generation. Gas collection systems also can contribute to enhanced air infiltration, particularly when operated aggressively.
- **Refuse degradability** has an important influence on the amounts and rates of LFG generation. Highly degradable organic materials, such as food waste, will produce LFG rapidly but will be consumed more quickly than less degradable organics, such as paper, which produce LFG slowly but over a longer time. Materials such as wood exhibit little degradation and produce minimal quantities of LFG. Inorganic materials do not produce LFG.[9]

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[8] United Nations Framework Convention on Climate Change (UNFCCC) Methodological Tool. "Emissions from solid waste disposal sites." http://cdm.unfccc.int/Reference/tools/index.html.

[9] Pierce, Jeffrey, Les LaFountain and Ray Huitric, SWANA. 2005. *Landfill Gas Generation and Modeling: Manual of Practice (Final Draft)*.

6.3 Publically Available LFG Models

The first and probably most important step in the modeling process is the selection of an appropriate model for LFG project evaluation. This section provides more details on publicly available LFG models, including LandGEM, IPCC and GMI country-specific LFG models. The discussion covers model variables, model calculation methods and considerations for their use in projecting LFG collection from SWD sites. Guidance or accompanying documents for each of these models provide a background on model assumptions and calculations, as well as instructions on model use.

When waste is placed in a site, the rate of waste decomposition and LFG generation are most rapid after waste disposal and gradually declines over decades as organic waste is depleted. Maximum LFG generation normally occurs within the first 2 years after the site stops accepting waste. This pattern of LFG generation over time is incorporated into LFG models typically by applying a first-order exponential decay equation, which assumes that LFG generation is at its peak following a time lag (period prior to methane generation), and then decreases exponentially as the organic fraction of waste is consumed.

LandGEM

LandGEM applies a first-order decay equation to calculate methane generation rates in units of flow (cubic meters [m^3]/year or average cubic feet [ft^3]/minute) or mass (Megagrams [Mg]/year). LandGEM was designed for U.S. regulatory applications but has been used for modeling LFG collection in the U.S. and worldwide. It applies the following first-order exponential equation to estimate methane generation:

$$Q = \sum_{t=1}^{n} \sum_{j=0.1}^{1} k L_0 \left[\frac{M_i}{10}\right] (e^{-kt_{ij}})$$

Where:

Q	=	maximum expected methane generation flow rate (m^3/yr)
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/yr)
L_0	=	potential methane generation capacity (m^3/Mg)
M_i	=	mass of solid waste disposed in the i^{th} year (Mg)
t_{ij}	=	age of the j^{th} section of waste mass M_i disposed in the i^{th} year (decimal years)

The LandGEM equation is used to estimate methane generation for a given year from cumulative waste disposed up through that year. Multi-year projections are developed by varying the projection year, and then re-applying the equation. Total LFG generation is equal to the methane generation rate divided by the volume fraction of methane assumed in the LFG. For example, two times the calculated methane generation if the LFG is assumed to contain 50 percent methane ($Q_{LFG} = Q/0.5 = 2Q$).

Other than waste disposal rates, the main variables in the first order decay equation are the methane generation rate constant (k), and the potential methane generation capacity (L_0), which are described below:

- **The methane generation rate constant (k)** describes the rate at which refuse decays and produces methane and is related to the half-life of waste based on the following equation: half-life = ln(2)/k. At low k values, methane generation is limited because a relatively small fraction of the deposited waste decays each year and produces LFG. At higher k values, a greater percentage of waste decays and produces LFG each year, resulting in higher methane generation rates. High k values result in rapid increases in LFG generation over time while the site is still receiving waste, but also rapid declines after the site closes because the waste continues decaying rapidly without being replenished. LFG generation can be visualized by a steeply rising curve followed by a steeply declining curve.[10] While several factors influence the k value, it is primarily controlled by waste type (organic waste degradability) and moisture content (estimated based on average annual precipitation).

- **The potential methane generation capacity (L_0)** describes the total amount of methane gas potentially produced by a metric tonne (Mg) of waste as it decays. It depends almost exclusively on the waste composition. A higher cellulose content in refuse results in a higher value of L_0. Although the potential methane generation capacity may never be reached at sites in very dry climates, the L_0 is viewed as being independent of moisture above a certain minimum threshold.

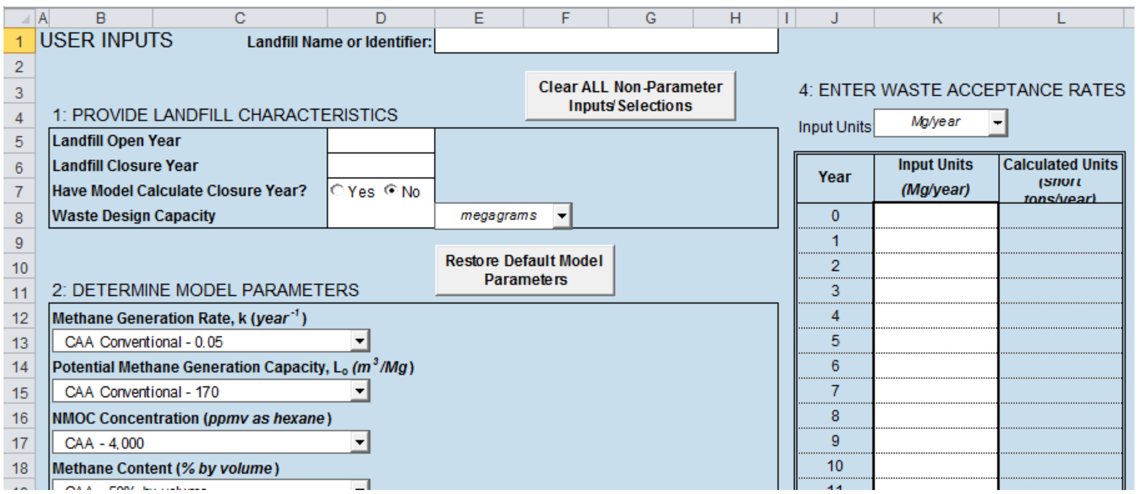

Figure 6-2. LandGEM User Input Sheet

LandGEM Limitations for Modeling Sites Outside of the U.S. In LandGEM's input sheet, model users are provided with alternative default values for the input variables k and L_0, depending on whether the model is being used for U.S. Clean Air Act compliance or other ("inventory") applications, whether the site is in an arid or non-arid ("conventional") climate, and whether the site is designed and managed for accelerated waste decay through liquids recirculation (bioreactor or "wet" conditions) (see Figure 6-2). The default k and L_0 values may be appropriate for modeling LFG generation from U.S. landfills that are characterized by these conditions, but they often are not appropriate when applied to SWD sites that may exhibit very different site conditions and waste composition, which cause dramatically different rates of LFG generation. Because LandGEM was based on data from SWD sites in the U.S., it assumes that the site being modeled is an engineered sanitary landfill. Therefore, it may not be appropriate for unmanaged dump sites where limited soil cover, poor waste compaction, high leachate levels, and other conditions can significantly limit LFG generation and collection. Additionally, LandGEM may not be appropriate for countries with significantly different climates or a different mix of waste types. As discussed below, international LFG models are designed to include adjustments to account for limits to LFG generation and collection caused by conditions at dump sites.

[10] See for example Figure 2-1 in U.S. EPA, 2010, *LFG Energy Project Development Handbook* (http://www.epa.gov/lmop/publications-tools/handbook.html), which shows different LFG generation curves produced by k values of 0.02 and 0.065.

SWD sites in many developing countries not only experience very different climates than in the U.S., but they also receive a very different mix of waste types. For example, typical municipal solid waste (MSW) in the U.S. contains approximately 18 percent food and 22 percent paper.[11] In developing countries, MSW often contains more than 50 percent food waste and less than 15 percent paper. With its higher food waste content, MSW will degrade and produce LFG much more rapidly than U.S. MSW. Therefore, a higher k value than would be used for U.S. SWD sites would be needed to accurately account for the different waste profile, even before any accounting for climate differences. Such higher k values are not provided in LandGEM unless specified by the user.

Example: LandGEM Limitations for Moisture Conditions

The range of default k values in LandGEM for non-bioreactor (arid and conventional) landfills is limited to 0.02 for sites that experience less than 25 inches (635 millimeters [mm]) of precipitation per year and 0.04 or 0.05 for sites that experience higher rainfall amounts. This range of values may reflect the typical range of moisture conditions found in most landfills in the U.S., but most tropical countries have regions where rainfall commonly exceeds 2,000 mm/year and can exceed 4,000 mm/year. LandGEM does not provide any guidance on appropriate k values for such rainy climates.

Additionally, a high percentage of food waste also creates a different pattern of waste decay over time. Because food waste decays more rapidly than other organic materials, it also is depleted more rapidly once waste disposal stops. A waste stream high in food waste will experience a rapid decline in LFG generation after disposal ends because food waste has a very short half-life (as reflected by a high k value). After a few years when the food waste has mostly degraded, only the slower decaying organic materials (such as paper) remain. These materials are less productive at generating LFG and also degrade at a slower rate. Changes in the mix of waste materials that are the primary generators of methane in an SWD site over time that result from varying degradation rates are not accommodated in LandGEM, which assigns a single k value for all wastes. Therefore, the LandGEM model reflects an unchanging "average" waste decay rate. While this limitation may not create a large error for modeling U.S. SWD sites, it can overestimate long-term LFG generation after site closure at sites with high food waste disposal rates. Not only are the default k values assigned in LandGEM not appropriate for modeling the climate and waste conditions experienced in many countries, but the use of a single k value for all wastes is flawed for sites with a high percentage of food waste where average waste degradability (and LFG generation) varies significantly over time.

The IPCC Model

The IPCC Model was released in 2006 and has several features that make it more suitable than LandGEM for assessing SWD sites worldwide, including applying separate first-order decay calculations for different organic waste categories with varying decay rates. The model was developed for countries to estimate methane emissions from waste disposal using regional per capita waste generation rates and population estimates, with deductions for LFG collection and oxidation. Although it was designed for estimating methane generation from entire countries, the IPCC Model can be modified to estimate generation from individual SWD sites. The standard GHG emissions reduction methodology for LFG projects seeking registration under the CDM is derived from the IPCC Model, and it uses the same variables and calculations.[12]

[11] U.S. EPA. November 2008. *Municipal Solid Waste in the United States: 2007 Facts and Figures.* http://www.epa.gov/osw/nonhaz/municipal/pubs/msw07-rpt.pdf.

[12] CDM. *Methodological Tool: Emissions from solid waste disposal sites, Version 06.0.0.* http://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-04-v6.0.0.pdf.

Like LandGEM, the IPCC Model uses a first-order decay equation that applies annual waste disposal rates and a waste decay rate variable (k value). The first-order calculations do not include the LandGEM variable L_0, but include other variables that, when combined together, constitute an L_0 equivalent variable, including the fraction of degradable organic carbon (DOC), the fraction of degradable organic carbon that decomposes (DOC_f) and a methane correction factor (MCF).

Unlike LandGEM, the IPCC model includes features that make it appropriate for modeling non-U.S. SWD sites, including the following:

- An allowance for the user to input waste composition data divided into the following categories: food waste, garden, paper, wood and straw, textiles, disposal diapers ("nappies"), sewage sludge, and industrial waste. If no waste composition data are available, the model provides regional default values. The model also assigns different DOC values for each waste type based on the amount of degradable organic carbon.
- The assignment of different k values for different waste types grouped into four categories based on their decay rates. For example, food waste and sewage sludge (category 1) have the highest k values, followed by garden waste, disposable diapers and industrial waste (category 2), paper and textiles (category 3), and finally by wood and straw (category 4), which have the slowest decay rates.
- The option of four different climates based on mean annual temperature, precipitation and (for temperate climates) potential evapotranspiration (PET). The climate categories are wet tropical, wet temperate, dry tropical and dry temperate. The model assigns k values for each of the waste categories based on climate as well as the waste decay rate.
- The inclusion of an MCF discount to account for aerobic (non-methane generating) waste decay at unmanaged disposal sites.

As a result of the features described above, the IPCC Model is currently the best available tool for estimating LFG generation from SWD sites in most countries. However, because it is a global model, it is not precise in its accounting for conditions in individual countries, particularly precipitation and its effects on LFG generation, since only two categories are used.

Limitations of the IPCC Model

While the IPCC Model's four climate categories represent an improvement over LandGEM's two climate category approach, limitations exist, including the following:

(1) Temperature has a smaller impact on LFG generation than precipitation and should not be assigned equal weight in assigning climate categories;

(2) PET data are usually not available for most locations and should not be a basis for assigning climate in temperate regions even if they are scientifically more valid;

(3) The 1,000 mm/year precipitation threshold for separating tropical climates into dry vs. wet categories is better than the LandGEM threshold of 635 mm/year (25 inches/year) but is likely too coarse to account for the effects of precipitation across the wide range of values encountered. For example, most areas in Colombia experience more than 1,000 mm/year of precipitation and many areas get more than 2,000 mm/year. Landfills in these areas would be treated the same (identical k values) in the IPCC Model, which implies that there are no noticeable effects from increasing precipitation above 1,000 mm/year.

Country-Specific Models Developed by the Global Methane Initiative

GMI has developed country-specific models that apply the structure of either LandGEM or the IPCC Model, but combine it with detailed information from each country to produce models that more realistically reflect local conditions which impact LFG generation and collection. These models were designed for non-expert users and may be advantageous for estimating LFG collection in each of the specific countries for the following reasons:

Country-Specific Models

- Landfill Gas Emissions Model (LandGEM)
- Central America LFG Model
- China LFG Model
- Colombia LFG Model
- Ecuador LFG Model
- Mexico LFG Model 2.0
- Philippines LFG Model
- Thailand LFG Model
- Ukraine LFG Model

- All eight of the GMI country-specific LFG models were developed after a study of the regional climates and automatically assign k and L_0 variables appropriate for the climate where the SWD site is located.
- Most of the models automatically calculate collection efficiency based on answers to the following factors: overall site conditions (dump site or managed landfill); waste depth; waste compaction practices; size of the tipping area; bottom liner type; percent of disposal area with operating extraction wells; percent of disposal area with daily, intermediate and final cover; and evidence of elevated leachate levels. Models that do not automatically calculate collection efficiency provide guidance on how to estimate collection efficiency.
- GMI models developed for Colombia, Mexico and Ukraine have the following additional features:
  - Default waste composition values based on detailed analysis of waste composition in these countries so that the user is not required to obtain these data. (The Central America Model also has this feature.)
  - Assignment of k values appropriate for the local climates based on a detailed analysis of average precipitation across all regions of these countries and the division of each country into four climate zones that reflect the range of climate conditions.
  - Automatic calculation of waste disposal rates based on the minimum required information (opening and closing years, recent year's annual disposal or waste in place, and growth rate).
  - Adjustments to account for aerobic waste decay (MCF) and past fires, both of which are common at unmanaged SWD sites and can significantly reduce LFG generation. (The models for China, the Philippines and Thailand also have this feature.)
  - Use of the IPCC Model structure and assignment of separate k and L_0 values to four waste groups based on waste degradability. This "multi-phased" first-order decay model approach avoids the single k model problem described previously and recognizes that significant differences in the types of waste disposed require changes to the model structure as well as to the values of the input variables.
  - Allows the user to override the automatic selection of model variables (other than k and L_0 values) with site-specific data. This feature includes methods for adjusting collection efficiency based on measured flow data at sites with operating collection systems.

6.4 Data Needed to Model LFG Generation and Collection

Data Collection Methods Vary

Because data collection methods and data quality can vary widely from country to country, there is no single standardized method that would apply to all cases.

Regardless of the type of LFG model that is used, the validity of the model results will be largely determined by the quality of the data used in the model. As the mathematical modeling saying goes, "garbage in, garbage out." Therefore, care should be taken in scrutinizing the data used to conduct LFG modeling. This section provides general guidance on obtaining and applying data needed for running the GMI and IPCC models, but does not provide detailed instructions on modeling procedures or explanations of model calculations that are covered in their supporting documents. A "best practices" approach to gathering all needed data is discussed, including the general procedure of using multiple data sources to accomplish a single task, such as double-checking historical waste disposal rates against estimated volume of waste in place (see below).

Historical Waste Disposal Estimates

Annual waste disposal rates are critically important model inputs that strongly influence projected LFG generation. When historical disposal records provided for a site are considered, a modeler needs to know their source and reliability. Are the disposal rates based on truck scale records? If so, when were the truck scales installed and how were tonnages for prior years estimated? For periods without actual historical waste tonnage data, past disposal rates can be estimated based on the following information:

- **Waste volume estimates based on records of incoming waste delivery vehicle counts and capacities.** The incoming waste volume estimates require conversion to weights based on the estimate of "as received" waste density. Different waste loads will have significantly varying densities, depending on the waste category (so, for example, construction waste will have a higher density than regular MSW), so some records of the sources of waste also may be required.
- **Site opening year and annual growth in disposal.** The models require assigning a start year, so the actual or estimated site opening date is an essential data item that must be obtained. Because disposal growth rates are related to population growth, they can be estimated or checked using population growth data. At a minimum, the opening year and growth rates need to be coupled with one more piece of information — either the amount of waste in place, or at least one year's disposal estimate — to develop a disposal history.
- **Estimated amount of waste in place.** Waste in place can be roughly calculated using a scaled site drawing showing the size of the waste disposal area and an estimate of the average waste depth. Topographic maps of the site can be used to develop more detailed estimates of waste depth and volume, but a drawing showing base contours is needed to yield a precise estimate since only the surface contours are shown on the map. Once a waste volume is calculated, it needs to be converted to mass using an appropriate "in-place" density factor. This conversion can create error because densities can vary widely depending on site conditions and waste composition, as well as on soil cover volumes (and whether soil is included in the density calculations). Typical in-place waste density for sites in developing countries is about 0.6 to 0.8 Mg/m^3, but densities outside of this range commonly occur based on varying site conditions.

Checking historical waste disposal estimates against the estimated volume and mass of waste in place is a good practice, especially at older sites where disposal records may be uncertain or have missing data.

Future Waste Disposal Estimates

Future waste disposal estimates require, at a minimum, an estimated growth rate and either a site closure date or a total (or remaining) site capacity with a density conversion factor. Completing independent calculations to project the year that the site reaches capacity to validate a site closure date is also recommended. However, a closure year may be set by a permit expiration date or some other reason that can prevent the site from being filled to capacity.

Waste Composition Data

Waste composition strongly influences the amount and timing of waste generation by setting the amounts and relative decay rates of the various degradable organic waste categories. Waste composition studies are relatively common in many countries and are conducted by municipalities or universities to help in developing solid waste planning programs. While waste composition data may not be available for the specific site being modeled, studies providing data from other cities or sites in the country often are available. In such cases, the waste composition data source and the modeling study site should be compared to evaluate whether the data are representative, although in many cases there may be no alternative data.

Another consideration is the need for the waste disposal estimates and composition data to be consistent. For example, a site may receive a high percentage of construction and demolition (C&D) waste that is included in the disposal estimates but not in the waste composition data. (Only regular MSW may have been evaluated in the study.) In such cases, the extra C&D waste tonnages not reflected in the waste composition percentages should be subtracted from the inputs to the model.

Finally, any significant changes to waste composition that are expected in the future should be considered. For example, waste composition could be significantly affected if a large new industrial waste contract is expected or a major organic waste recycling program is planned. Future changes in waste composition can be incorporated directly into the IPCC Model, but the LMOP models require separate model runs to reflect conditions before and after the expected change.

Climate Data

The IPCC and GMI models assign k values according to climate and waste composition. The best source of reliable climate data worldwide is World Climate, which presents processed surface station observations of temperature, precipitation and pressure data from the Global Historical Climatology Network (GHCN). Data are listed by the name of the closest municipality and organized by grouping all climate stations within the same 1 degree longitude by 1 degree latitude on the same web page. Data coverage is not available for many remote regions of the world. Other websites with worldwide climate data include the World Meteorological Organization's World Weather Information Service and Weather Base. Select the closest station to the site being modeled that has the longest climate record. Some sites record on-site precipitation, although the reliability of these data will be unknown and should not be used if they show values that are significantly different from the closest public station.

> **GHCN Climate Data Set**
>
> Produced jointly by the National Climatic Data Center and Carbon Dioxide Information Analysis Center at Oak Ridge National Laboratory in the United States, the GHCN is a comprehensive global surface baseline climate data set designed to be used to monitor and detect climate change.

Site Management, the Methane Correction Factor and Fire Impacts

The IPCC Model and several of the GMI models apply a methane correction factor (MCF) in the calculation of LFG generation at unmanaged disposal sites to account for aerobic waste decay that does not produce methane.[13] The IPCC Model introduced this adjustment and assigns an MCF of 0.8 (20 percent reduction) for unmanaged sites greater than 5 meters deep and an MCF of 0.4 for unmanaged sites less than 5 meters deep.

The GMI models for China, Thailand, Philippines, Colombia, Mexico and Ukraine apply a “fire adjustment factor” to account for the consumption of organic material in fires that would otherwise have been available for LFG generation. Application of a fire adjustment factor requires obtaining information on the volume or surface area of waste areas affected and the severity of the fire (ranked as low, medium, or severe impacts).

6.5 Estimating Collection Efficiency

Site Conditions and Management Practices

Several of the GMI models automatically calculate collection efficiency based on user inputs in response to questions about site conditions and site management practices. To answer these questions, the model user should gather information on the following:

- **Site management practices**. Properly managed SWD sites will have characteristics (cover soils, waste compaction and leveling, control of waste placement, control of scavenging, control of fires, and leachate management systems) that allow achieving higher collection efficiencies than unmanaged dump sites.
- **Waste depth**. Shallow sites require shallow wells, which are less efficient because they are more prone to air infiltration. The GMI models apply discounts to collection efficiency when average waste depth is less than 10 meters.
- **Cover type and extent**. Collection efficiencies will be highest at sites with a low-permeable soil cover over all areas with waste, which limits the release of LFG into the atmosphere, air infiltration into the collection system, and rainfall infiltration into the waste. Information on the percentage of disposal area with daily, intermediate and final cover is needed for the GMI models to run collection efficiency calculations.
- **Base liner**. SWD sites with clay or synthetic liners will have lower rates of LFG migration into surrounding soils, resulting in higher collection efficiencies. Information on the percentage of the site lined with a synthetic or clay liner is needed for the GMI models to run collection efficiency calculations.
- **Waste compaction**. Uncompacted waste will have higher air infiltration and lower gas quality, and thus lower collection efficiency. The GMI models require information on whether waste is compacted on a regular basis.
- **Size of the active disposal (“working face”) area**. Unmanaged SWD sites with large waste placement areas will tend to have lower collection efficiencies than managed sites where disposal occurs in smaller waste placement areas.
- **Leachate management**. High leachate levels can dramatically limit collection efficiencies, particularly at sites with high rainfall, poor drainage and limited soil cover. Evidence of high leachate levels includes leachate seeps, surface ponding and runoff channels. Severity of leachate impacts is calculated in the GMI models based on precipitation rates and whether the evidence of high leachate levels occurs only after rainstorms.

[13] Unmanaged disposal sites do not meet IPCC’s definition of managed solid waste disposal sites, which “must have controlled placement of waste (i.e., waste directed to specific deposition areas, a degree of control of scavenging and a degree of control of fires) and will include at least one of the following: (i) cover material; (ii) mechanical compacting; or (iii) leveling of the waste.” (IPCC, 2006. Table 3.1). Sites where management practices are unknown are assumed to be unmanaged.

The GMI models, which automatically estimate collection efficiency, use the above information to calculate discounts to the maximum collection efficiency that is achievable with a comprehensive and efficiently operated GCCS. Other GMI models provide instructions in the user's manual on how to apply the discounts to calculate collection efficiency. IPCC Model users can refer to one of the GMI user's manuals (such as the Central America Model) for instructions on collection efficiency calculations.

Collection System Coverage

While site conditions and management practices set limits to achievable collection efficiency, the primary determinant of collection efficiency is the fraction of total waste that is under active LFG collection, known as "collection system coverage." Collection system coverage is calculated by dividing the surface area of waste that is within the influence of the existing or planned extraction wells by the total surface area of the site. "Collection system coverage" accounts for the extent to which wells are installed in all areas with waste and the extent to which the installed wells are effectively drawing LFG from the waste. Collection system coverage will be zero before system start-up date and will vary over time at active disposal sites as new disposal cells are developed and collection systems are expanded. Unmanaged SWD sites, and sites that are still receiving wastes and that have high food waste disposal rates and or wet climates, will have considerably less than 100 percent collection system coverage as a result of the following issues:

- Sites with security issues or large numbers of uncontrolled waste pickers will not be able to install equipment in unsecured areas and cannot achieve good collection system coverage.
- Extraction wells cannot operate without significant air intrusion in areas with uncovered waste, so well installation will be delayed until a cover is installed. When combined with security issues, this limitation often means that no wells can be installed in an area until it is closed, capped with a final cover and protected with security fencing.
- Extraction wells cannot be installed in areas with steep, unstable slopes, soil stockpiles or other locations where equipment access is restricted.
- While the GMI models include discounts to collection efficiency to account for shallow waste depths and high leachate levels, additional discounts may be required to account for limited collection system coverage in areas where shallow waste or elevated leachate levels prevent well installation or restrict it to shallow depths.
- If there is a long time lag (more than 1 to 2 years) between waste placement and well installation in the waste as a result of the issues described above, there can be an especially large decline in the amount of LFG available for collection at sites with high food waste disposal and rainy climates. This combination of highly degradable waste and high moisture results in high LFG generation rates and rapid consumption (short half-life) of much of the organic material during the time period before there is collection.
- Many countries lack experience and expertise in designing, installing, operating and maintaining LFG collection systems. These countries can seek outside help, but LFG experts from other countries may not be familiar with the different conditions encountered in developing countries, where their methods may not be successful. Programs such as the GMI help to build the LFG project capacity of developing countries.

Achievable Collection Efficiencies. Given that conditions at some sites often limit the achievable collection efficiencies, the following are recommended maximum collection efficiency values that should not be exceeded when applied to LFG generation projections to estimate LFG collection:

- At active dump sites: 50 percent in wet climates and 60 percent in dry climates.
- At closed dump sites: 70 percent.
- At active engineered landfills: 75 percent in wet climates and 80 percent in dry climates.
- At closed engineered landfills: 85 percent.

Note that these are maximum values that can be achieved only under the best conditions and most successful LFG project implementation efforts, given the limitations of each SWD site category. Actual collection efficiencies achieved will be lower in most cases where site conditions and available resources to address problems that arise limit LFG collection.

6.6 LFG Model Uncertainty and Performance

LFG model uncertainty has been addressed in discussions of the following topics:

- The inability to validate LFG generation models, particularly when used for emissions estimates, based on the lack of measured values for most parameters in the LFG generation equation.
- The inability to directly measure conditions inside the waste mass that influence LFG generation such as moisture (thus requiring the use of a surrogate, precipitation data, in the model).
- The long list of data required to run models, and the need to evaluate data and use alternative methods for calculating missing data caused by data problems or unavailability.
- The many issues encountered at unmanaged disposal sites, which are very different from managed landfills and have impacts on LFG generation and recovery that are difficult to quantify.

Instructions for the IPCC Model provide a thorough discussion of factors contributing to model uncertainties and divide them into uncertainties created by the first-order decay calculation method, model input parameters and data. Ultimately, model uncertainty or accuracy can be tested only by comparing model estimates of LFG recovery against future measurements of flow data. Because of this requirement, the list of potential sources of error includes the ability to accurately predict future conditions, as well as model methods, parameters and historical data inputs.

IPCC concludes that uncertainties posed by the calculation method are much less than uncertainties that result from parameter selection or data and provides a table assigning an estimate of uncertainty to each parameter or data category. Most of the estimates indicate significant uncertainty (ranging from 5 percent to 50 percent) which, when combined, indicate a very large potential for error. Although multiple errors can often offset each other, which may limit the accumulation of error, the overall potential for error is significant. Modelers need to be vigilant in their efforts to limit potential error at every step in the process.

Best Practices for Landfill Gas Modeling

Estimating the volume of LFG generation from a landfill is a critical component of a project assessment and conceptualization because the collection projections are used to estimate the size of the project, expected revenues, project design requirements and capital and operating costs. However, accurately projecting the total LFG and methane generation for a landfill can be difficult for many stakeholders. It requires selection and use of an appropriate LFG model among several options, consideration of local conditions that affect LFG generation, and an understanding of the uncertainty inherent with LFG modeling. The value of LFG estimates also depends on the quality of data used in the model; proper consideration of factors such as annual waste composition, disposal rates and estimated growth rates; and the participation of an experienced LFG modeler.