CLIMATE LEADERS GREENHOUSE GAS INVENTORY PROTOCOL

CORE MODULE GUIDANCE

Direct Emissions from Municipal Solid Waste Landfilling

CLIMATE LEADERS

U.S. Environmental Protection Agency

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The Climate Leaders Greenhouse Gas Inventory Protocol is based on the Greenhouse Gas Protocol (GHG Protocol) developed by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). The GHG Protocol consists of a corporate accounting and reporting standard and separate calculation tools. The Climate Leaders Greenhouse Gas Inventory Protocol is an effort by EPA to enhance the GHG Protocol to fit more precisely what is needed for Climate Leaders. The Climate Leaders Greenhouse Gas Protocol consists of the following components:

- Design Principles Guidance
- Core Modules Guidance
- Optional Modules Guidance

All changes and additions to the GHG Protocol made by Climate Leaders are summarized in the Climate Leaders Greenhouse Gas Inventory Protocol Design Principles Guidance.

For more information regarding the Climate Leaders Program, visit us on the web at www.epa.gov/climateleaders

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Introduction

This document presents guidance for estimating direct greenhouse gas (GHG) emissions from owned/operated municipal solid waste landfill sites. This guidance applies to any company whose operations involve municipal solid waste landfilling.

Sanitary landfilling is one of the primary methods of disposing of municipal solid waste (MSW) and has been an accepted solid waste management practice for many decades. In 2000, an estimated 128.3 million tons (or 116 million metric tonnes), representing approximately 55.3 percent of the reported 231.9 million tons (or 210.5 million metric tonnes) of MSW generated within the United States was managed through landfilling[1]. A direct result of solid waste landfilling is the generation of a natural by-product known as landfill gas (LFG) which is formed through the biodegradation of the decomposable organic fraction of the MSW landfilled. The gas is generally composed of 30 to 60 percent methane (CH_4) depending on a number of factors with the balance primarily carbon dioxide (CO_2). Other minor constituents present in the gas can include oxygen and nitrogen, trace amounts of hydrogen, hydrogen sulfide, volatile organic compounds (VOCs), and moisture. Depending on site characteristics, the LFG generation process can create internal positive pressure within the waste mass allowing for the fugitive emission of produced gas through permeable areas or pathways of least resistance within the final and temporary cover systems, leachate collection system and risers, landfill side slopes, etc.

Sources of GHG emissions from municipal solid waste landfilling include the fugitive release of landfill gas as well as stationary combustion sources, such as LFG flares and LFG energy (LFGE) facilities. Additional sources of GHG emissions include; fleet vehicles, landfill compactors, earthmovers and other equipment or machinery that is a necessary or typical part of the landfill operation that uses fossil fuels.

1.1. Gases Included

Although CH_4, CO_2, and minor trace gases are all emitted from fugitive landfill gas release, methane accounts for the majority of GHG emissions from MSW landfills[2]. MSW landfills are the largest human-made source of CH_4 emissions in the U.S. Landfill gas is made up of approximately equal amounts (on a volumetric basis) of CH_4 and CO_2 gas, however, only CH_4 is addressed within this protocol. The CO_2 produced through the anaerobic biodegradation of MSW (CO_2 fraction of LFG) is not reported. It is assumed that waste decomposition does not contribute to the net addition of CO_2 to the atmosphere. This exclusion is consistent with Intergovernmental Panel on Climate Change (IPCC) guidance[3].

1 U.S. EPA. *Municipal Solid Waste in The United States: 2000 Facts and Figures.* 2000 Update; EPA530-R-02-001.

2 In landfills, some carbon from waste can remain stored for long periods of time. The removal of carbon from the natural cycling of carbon between the atmosphere and biogenic materials – which occurs when wastes of biogenic origin are deposited in landfills – sequesters carbon. (Wastes of biogenic origin include paper, wood products, and yard trimmings, but do not include plastics or other synthetic organics) When wastes of sustainable, biogenic origin are landfilled, and do not completely decompose, the carbon that remains is effectively removed from the global carbon cycle. While EPA is continuing to study methodologies to measure this type of carbon storage, currently considerable uncertainty remains and thus Climate Leaders does not include this process in its GHG accounting.

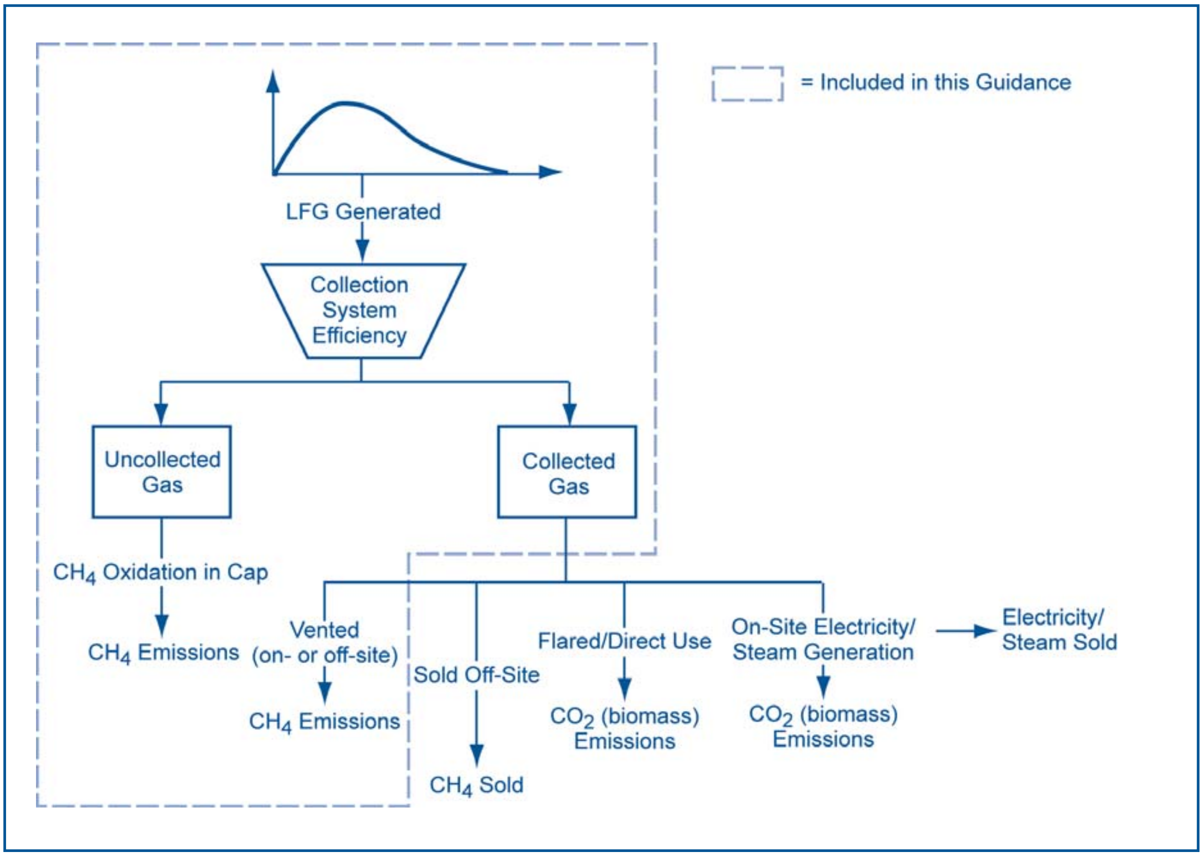
3 "Decomposition of organic material derived from biomass sources (e.g., crops, forests) which are regrown on an annual basis is the primary source of CO_2 released from waste. Hence, these CO_2 emissions are not treated as net emissions from waste in the IPCC Methodology." Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual, Chapter 6. Waste, Section 6.1 Overview, pg. 6.1.

CO_2 can also be produced from the combustion of CH_4 in captured LFG, this is considered biomass CO_2. As with emissions from other biofuels combustion, Climate Leaders considers that biomass CO_2 emissions do not contribute to CO_2-equivalent emissions as reported in a Climate Leaders Partner's entity-wide inventory[4]. Therefore, the biomass CO_2 emitted through the combustion of captured LFG are reported but only as a memo item in the Partner's inventory. Climate Leaders Partners are required to account for emissions of methane from MSW landfill sites.

1.2. Sources Included

This guidance covers emissions associated with LFG. When considering LFG emissions there are different factors to be taken into account including; production of the LFG, recovery of the gas, and treatment of the gas as shown in Figure 1.

Figure 1: Scope of Emissions Covered in This Guidance



4 This assumes no net loss of biomass-based carbon associated with the land use practices used to produce these fuels. This approach is consistent with that used by the U.S. EPA in conducting the National Inventory, U.S. EPA 2004 *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2002,* EPA430-R-04-003, April 2004. Also,"CO_2 emissions from landfill gas recovery combustion are of biogeneic origin and should not be included in National Totals." IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories, Chapter 5. Waste, Section 5.1.1.2, Methane Recovery pg. 5.10.

As mentioned in Section 1.1, projects using LFG as a fuel in stationary or mobile sources report the biomass CO_2 emissions from the combustion of LFG (oxidation of carbon in the LFG) as a memo item in the inventory[5]. Methods for estimating emissions from combustion of LFG are covered under additional Climate Leaders guidance. Carbon dioxide emissions resulting from a flare or an LFG (or LFG supplemented) electrical power generation station are calculated according to the Climate Leaders guidance for *Direct Emissions from Stationary Combustion Sources*. Emissions resulting from liquid or compressed fuels derived from LFG used in a Climate Leaders Partner's truck or vehicle fleet are calculated according to the Climate Leaders guidance for *Direct Emissions from Mobile Combustion Sources.* Furthermore, any additional sources of emissions from landfill operations, for example, combustion of fossil fuel in mobile sources or purchases of electricity, are also reported separately using the appropriate Climate Leaders guidance. Climate Leaders Partners are only responsible for direct emissions at their facilities. If carbon is sold and leaves the facility stored in a product it should not be counted as a release even if the product is subsequently burned or otherwise releases
the stored carbon.

In addition to reporting of direct emissions, there is also the potential that landfills can report savings due to collection and treatment of CH_4 that would otherwise have been released to the atmosphere. Guidance for reporting these reductions is currently under development.

5 This assumes carbon in LFG is of biogeneic origin and that there is no net loss of biomass-based carbon associated with land use practices surrounding the biomass that ultimately decomposes in the landfill to produce the LFG.

Methods for Estimating CH_4 Emissions

In general, there are two approaches used to estimate CH_4 emissions from MSW landfills, depending on the presence or absence of a gas recovery and control system.

- MSW landfill sites in which gas collection systems are absent: use mathematical models and apply appropriate default factors (see Section 2.1).
- MSW landfill sites with landfill gas recovery and control systems: monitor recovered landfill gas and apply gas system collection efficiency data (see Section 2.2).

2.1. Estimating Landfill Methane Emissions at MSW Landfills without Active Gas Collection Systems

Through the Control Technology Center, the U.S. EPA has developed an emissions model known as the "Landfill Gas Emissions Model" or LandGEM. The model is a tool used to estimate annual emission rates over a user-specified interval for methane as well as carbon dioxide, non-methane organic compounds (NMOC), and a list of other air pollutants. The LandGEM model has been implemented within a stand-alone software application distributed and supported by the U.S. EPA.

The model uses a first-order decay rate equation and operator-entered data for annual reported MSW tonnage, methane generation potential (L_o), and the methane generation rate constant (k) to estimate potential annual emission rates from landfill sites. The LandGEM is based on Equation 1.

Equation 1: Waste Decomposition Model

$$Q_{CH_4} = k\, L_o\, M_i\, (e^{-kt_i})$$

where:

Q_{CH_4}	=	methane emission rate, m^3/yr
k	=	methane generation rate constant, $year^{-1}$
L_o	=	methane generation potential, m^3 of CH_4/Mg of refuse
M_i	=	mass of the waste in the i^{th} section (annual increment), Megagrams (Mg)
t_i	=	age of the i^{th} increment (or section), in years

This equation computes the methane emission rate from one annual increment of waste where M_i is the mass in Megagrams (Mg) (or metric tonnes) of the annual waste increment and t_i is the age of the i^{th} increment, in years. The mass of any non-MSW may be subtracted from the total waste mass in a particular section when calculating the value for the mass of waste in that section. The methane emission rates are summed over all past annual increments to estimate the total current methane emission rate, which is further represented in Equation 2.

Equation 2: Summation of Annual Emission Rates

$$Q_{CH_4} = \sum_{i=1}^{n} k\, L_o\, M_i\, (e^{-kt_i})$$

where:

Q_{CH_4} = methane emission rate, m^3/yr

k = methane generation rate constant, $year^{-1}$

L_o = methane generation potential, m^3 of CH_4/Mg of refuse

M_i = mass of the waste in the i^{th} section (annual increment), Megagrams (Mg)

t_i = age of the i^{th} increment (or section), in years

The estimates of landfill methane emissions from the model only consider methane generation and not landfill methane released to the atmosphere. As shown in Figure 1, not all LFG that is generated gets released to the atmosphere. A portion of the methane generated may be oxidized while passing through the landfill cover, through soils used for daily cover, and through alternative cover materials such as compost used for odor control in, or on, landfill covers. Landfill methane emissions from sites without active LFG recovery systems are equal to the methane generation less the amount of methane oxidized based on the above potential oxidizing sources.

Based on the site size and gas management practiced, some landfills may have installed passive controls (wells, horizontal collectors and/or trenches) which simply vent collected gas to the atmosphere. Passive controls rely on the gas generation and internal pressure created within the waste mass to move the gas through diffusion and/or convection to the atmosphere. To date, there are no industry standard accepted collection efficiencies for passive LFG venting systems. If the methane emissions resulting from a passive venting system are measured, the emissions are a fraction of the overall gas emission estimated using the gas generation model. Passive controls may reduce the potential for methane to be oxidized.

Equation 3 describes the calculation to convert methane generated into methane emissions, default values for factors used are provided in Section 4.2.

Equation 3: Estimating CH_4 Emissions Based on Generation

CH_4 Emissions = CH_4 generated x (1 – oxidation factor)

The methodology used to determine methane emissions from MSW landfills through the gas generation method is as follows and assumes no active or passive gas control is implemented:

Step 1: Determine the landfill methane generation rate. This is done using the LandGEM model as described above and following the user manual to enter required landfill and model data and step through the program. Input data include Mg (metric tonnes) per year of municipal solid waste accepted and buried, the year the landfill opened, the current year, landfill design capacity, landfill closure year, and waste in place. Input data includes the methane generation potential (L_o), the methane generation rate constant (k) and selected methane concentration. A Climate Leaders Partner may also make these calculations directly using the first-order decay equations that are the basis of the LandGEM model if so desired.

Step 2: Determine the fraction of methane oxidized. Landfill gas may pass through the landfill cover, intermediate cover soils or alternative cover materials (compost) before being released to the environment. There is the potential that microbes in the soil or cover material may oxidize some of the methane in the gas. This oxidation reduces the amount of methane released to the environment. The Climate Leaders approach is to use a default factor of 10% for the fraction of methane oxidized. Refer to Section 4.2 for discussion of default parameters.

Step 3: Calculate methane emissions. Once the above parameters are known Equation 3 can be used to determine amount of methane emissions. Methane emission rates have to be converted from volume to mass through a simple conversion calculation based on the assumed density of methane.

Note: If the Climate Leaders Partner proposes to use measured flow rates from a passive gas collection and venting system to determine the net methane emission based on the collection efficiency of the passive system, a methodology must be presented for determining the passive collection efficiency. There is no widely accepted method for doing so. Therefore this approach has not been considered in the above methodology or the example for estimating methane emission from MSW landfills without active LFG collection systems.

2.2. Estimating Landfill Methane Emissions at MSW Landfills with Active Gas Collection Systems

Methane generation at MSW landfills with active gas collection systems (that is, incorporating gas collection systems used to extract LFG under an induced vacuum applied to the recovery wells and collection system) could be estimated using data from the gas collection system, verified by a qualified third party using U.S. EPA verification methods, and applying a collection system efficiency suitable to the site specific nature of the landfill cover system and gas collection system installation. The difference between the methane gas generation calculated in this manner and the measured methane gas recovery from the gas collection system (less the amount of methane oxidized within the final cover system) plus any vented gas is the net methane emission to the atmosphere. Equation 4 describes the calculation to convert amount of collected methane into methane emissions.

The methodology used to determine methane emission data from MSW landfills through the active gas collection method is as follows, default factors are provided in Section 4.2:

Step 1: Determine the amount of methane collected. Landfill gas collection and/or

Example CH_4 Emissions Calculation for MSW Landfills without Active LFG Collection

A Climate Leaders Partner owns a MSW Landfill Site which has been receiving primarily domestic waste for the past 20 years and is still active (year opened 1982). Under the NSPS regulations the Partner has not yet been required to install a LFG control mechanism. The landfill site has a permitted capacity of 3 million cubic meters and has annual waste acceptance records from the time of opening. Average waste compaction density is 0.8 tonnes/m^3 (1,350 lb/yd^3). The site is located in a very dry climate receiving less than 635 mm (25 inches) of precipitation per year. The Partner has not assessed methane emissions previously at the site.

The Partner uses the Landfill Gas Emissions Model (LandGEM Version 2.01) to calculate the methane emissions using the AP-42 default factors for the methane generation potential (L_o = 100 m^3 of CH_4/Mg of MSW landfilled) and methane generation rate constant (k = 0.02/yr). The final cover system is one meter of clay and topsoil and does not have a flexible membrane liner.

Step 1 – Estimate current methane generation rate using the LandGEM (Version 2.01):

Model Inputs:

Waste disposal	=	annual tonnage of MSW for each filling year (Mg)
L_o	=	AP-42 default (100 m^3/Mg)
k	=	AP-42 default (arid 0.02/yr)

Design capacity in Mg (or metric tonnes), year landfill opened and current year
Methane concentration = 50% by volume

LandGEM output yields a methane emission rate in both mass (Mg) and volume (m^3) on an annual basis. Conversion from the volumetric to a mass emission rate of methane is achieved through the use of the density of methane. The LandGEM Model assumes a density of methane at 1 atmosphere and 20°C, which is equal to 0.667 kilograms/cubic meter (0.0416 lb/ft^3). A sample report generated using LandGEM 2.01 is presented in Appendix A using the above parameters and an average annual waste acceptance of 80,000 Mg/yr.

Note: If the annual waste acceptance is unknown for any increment or interval, then the average annual waste acceptance should be used accordingly.

Step 2 – Determine the fraction of methane oxidized:

The methane oxidation factor is assumed to be 10% by volume (0.10). (see Section 4.2)

Step 3 – Calculate emissions:

This is done using the parameters specified above and Equation 3 outlined in Section 2.1

CH_4 Emissions = CH_4 generated x (1 – oxidation factor)

For the year 2003:

CH_4 generated = 1.85 x 10^3 tonnes (or Mg)/yr. (from the LandGem output shown in Appendix A)

CH_4 Emissions = 1.85 x 10^3 x (1 – 0.10) = 1.66 x 10^3 metric tonnes of CH_4 emitted in 2003.

Note: Emissions from any on-site combustion device are calculated using the Climate Leaders guidance for *Direct Emissions from Stationary Combustion Sources.* Emissions from these calculations, along with any other emissions sources, are added to the total emissions of the site.

Equation 4: Estimating CH_4 Emissions Based on Collection

$$CH_4 \text{ Emissions} = [(\frac{CH_4 \text{ Collected}}{Coll_{eff}} - CH_4 \text{ Collected}) \times (1 - OF)] + (CH_4 \text{ Collected} \times \text{Vent})$$

where:

CH_4 Collected	=	CH_4 Collected by active gas collection system
$Coll_{eff}$	=	collection system efficiency
OF	=	oxidation fraction
Vent	=	fraction vented

combustion systems generally are equipped with LFG composition and flow monitoring equipment which can be used to continually monitor methane capture from the landfill. In the event flow and composition data are not continuously monitored, routine gas sampling and flow measurement using portable monitoring equipment with data recording capability could be used, providing data can be supported through third party verification methods.

Step 2: Determine the collection system efficiency. With a gas collection system in place there may still be some fugitive gas that is not collected by the system. This could be due to spacing of gas collection wells, gas pressure, maintenance of the cover, etc. Refer to Section 4.2 for default selection of suitable collection system efficiency to be used.

Step 3: Determine the fraction oxidized. Landfill gas that is not collected passes through the landfill cover before being released to the environment. There is the potential that microbes in the soil of the landfill cover oxidize some of the methane in the gas. This oxidation reduces the amount of methane released to the environment. The Climate Leaders approach is to use a default factor of 10% for the fraction of methane oxidized. Refer to Section 4.2 for discussion of default parameters.

Step 4: Determine the fraction of gas vented. This is the amount of the collected gas that is vented directly to the atmosphere. It could either be through an active venting system, or in some cases gas may also be vented during scheduled start-up/shut down periods as well as from a malfunction of the primary LFG control device. Estimates should be made for LFG control device downtime if gas is vented during that period.

Step 5: Calculate methane emissions. Once all the parameters are known, Equation 4 can be used to determine the amount of methane emissions. Methane emission rates can be converted from volume to mass through a simple conversion calculation based on the density of

Example CH_4 Emissions Calculation based on Collection

A Climate Leaders Partner has a MSW Landfill Site which has been receiving waste for the past 15 years and is still active. Based on meeting criteria under the NSPS regulations, the Partner has installed a LFG collection and enclosed flaring system. The landfill site has been receiving 300,000 tonnes (Megagrams) of MSW per year and the site is located in a temperate climate receiving greater than 635 millimeters (25 inches) of precipitation per year. The partner has assessed methane and non-methane organic compound emissions previously at the site using the Landfill Gas Emissions Model with the required defaults for NSPS reporting. All LFG collected is flared at the site and the gas collection system is currently thermally destroying a consistent average of 1,000 standard cubic feet per minute (scfm) of LFG with a methane concentration of 53% by volume. The landfill is a currently active with 5 years of operation remaining and will be eventually closed with a low permeability clay cover.

Step 1 – Determine the amount of methane collected:

$$CH_4 \text{ collected/year} = \frac{1{,}000 \text{ ft}^3\text{/min x } 0.53}{35.31 \text{ ft}^3\text{/m}^3} \text{ x } 525{,}600 \text{ minutes/year}$$

$$= 7.89 \text{ x } 10^6 \text{ m}^3\text{/yr}$$

Step 2 – Determine the collection system efficiency:

The collection system efficiency is assumed to be 75% by volume (0.75). (see Section 4.2)

Step 3 – Determine the fraction of methane oxidized:

The fraction oxidized is assumed to be 10% by volume (0.10). (see Section 4.2)

Step 4 – Determine the fraction of methane gas vented:

Flare station records indicate that approximately 1% (0.01) of the recovered gas is vented during routine and unscheduled maintenance annually. These estimates should be made for flare system downtime if gas is vented during that period.

Step 5 – Calculate methane emissions:

CH_4 emissions = [((CH_4 collected/collection system efficiency) – CH_4 collected) x (1-oxidation factor)] + [CH_4 collected x fraction vented]

$$CH_4 \text{ emissions} = [((7.89 \text{ x } 10^6 \text{ m}^3\text{/yr}/0.75) - 7.89 \text{ x } 10^6 \text{ m}^3\text{/yr}) \text{ x } (1 - 0.10)] + [7.89 \text{ x } 10^6 \text{ m}^3\text{/yr x } 0.01]$$

$$= [2.63 \text{ x } 10^6 \text{ m}^3\text{/yr x } 0.90] + 7.89 \text{ x } 10^4 \text{ m}^3\text{/yr}$$

$$= 2.45 \text{ x } 10^6 \text{ m}^3\text{/yr}$$

Note: Conversion from the volumetric to a mass emission rate of methane is achieved through the use of the density of methane. The density of methane is equal to 0.667 kilograms/cubic meter (0.0416 lb/ft^3) at 1 atmosphere and 20°C.

$$Q_{CH_4} \text{ tonnes/yr.} = 2.45 \text{ x } 10^6 \text{ m}^3\text{/yr. x } 0.667 \text{ kg/m}^3 \text{ x 1 tonne/1000 kg} = 1{,}634 \text{ tonnes/yr.}$$

Note: The latest version of LandGEM as described in the previous section and sample calculation is used to estimate the methane emission rate in the area not served by the landfill gas collection system, as applicable. Also, emissions from any on-site combustion device would be calculated using the Climate Leaders guidance for *Direct Emissions from Stationary Combustion Sources.* Emissions from these calculations, along with any other emissions sources, are added to the total emissions of the site.

methane at standard temperature and pressure conditions.

The method of estimating landfill methane emissions at MSW sites incorporating LFG collection systems described in this section should be used only for landfill cells or landfill areas being served by the gas collection system. Estimation of landfill methane emissions for cells or landfill areas not being served or equipped with active gas recovery systems should be calculated using LandGEM (Version 2.01), as described in Section 2.1.

2.3. Estimating Methane Emissions from a Continuous Emissions Monitoring System (CEMS)

Neither the New Source Performance Standards (NSPS) nor the U.S. Clean Air Act require continuous monitoring systems for methane emissions on MSW landfills. However, the new National Emission Standards for Hazardous Air Pollutants (NESHAP) for MSW Landfills require procedures for operating and maintaining the collection and control system, including the continuous monitoring system during periods of start-up, shut-down and malfunction for LFG active collection systems on NSPS landfill sites[6].

The landfill gas combustion systems generally are equipped with LFG composition and flow monitoring equipment which can be used to continually monitor methane capture from the landfill. This equipment could potentially be used to monitor other GHG emissions such as CO_2 (biomass), CH_4, and nitrous oxide (N_2O) from stationary combustion sources (see Climate Leaders guidance for *Direct Emissions from Stationary Combustion Sources*).

2.4. Bioreactor Landfills

Bioreactor landfills enhance the microbiological process involved within the landfill to speed up the rate of waste decomposition. This enhancement can occur through several means. If the decomposition process is anaerobic, methane gas is produced. Estimating emissions from bioreactor landfills can be done using one of the methods outlined in this guidance. The recommended choice of method is discussed in Section 3. If emissions are to be estimated based on the Landfill Gas Emissions Model (described in Section 2.1 Estimating Landfill Methane Emissions at MSW Landfills without Active Gas Collection Systems) the parameters of the model, and potentially the model itself, are different than for a standard MSW landfill. Currently there is no good data on appropriate default factors that could be used to represent bioreactor landfills in this approach. More work is needed on this area, therefore, it is recommended that emissions from bioreactor landfills be estimated based on an active collection system approach (described in Section 2.2) or through CEMS (described in Section 2.3).

6 40 CFR 63 National Emission Standards for Hazardous Air Pollutants: Municipal Solid Waste Landfills, Final Rule.

Choice of Methods

The preferred choice of method used to estimate emissions depends on the type of information available. If the site has a gas collection system in place and has good data on the amount of gas collected and the methane concentration in the gas, then the emission calculation method based on gas collected is preferred. Using the data gathered from the LFG collection system is likely to provide a more precise estimate of net gas emissions than gas modeling, even if the estimate of collection efficiency is itself relatively imprecise.

However, if there is no collection system in place then the modeling approach is the preferred method for calculating emissions. The approaches for measuring or recording the estimated landfill methane emissions in order of preference are therefore:

1. Partner has LFG quantity (volume) and quality (composition) of LFG captured within the gas collection system at the site.

2. Partner has landfill parameters, waste composition data and annual waste acceptance figures for the site and uses LandGEM.

Solid Waste Input Activity Data and Emission Calculation Factors

This section discusses choices of activity data and factors used for calculating landfill methane emissions. This guidance has been structured to accommodate Partners with varying levels of available information. Whenever possible, the preferred approach described within this document for estimating emissions from MSW landfills with or without gas collection systems should be the option employed to allow for the greatest level of accuracy in the landfill methane emission estimates.

4.1. Solid Waste Input Activity Data

When calculating landfill methane emissions using the LandGEM model, the initial information required is the type of waste (historical/current) accepted by the landfill site and the annual tonnage records, if available over the life of the landfill. Generally, depending on the landfill size and age, older sites will have only minimal filling records available for the late 1960's up to the early 1980's. In this case, annual tonnage and waste stream data can be taken as averages over the years required. If inert material has been accepted in known quantities and landfilled, these tonnage data should be subtracted from the overall annual MSW figures used in the calculation of the landfill methane emissions. The next source of data required is the climatic condition of the site (i.e., arid with less than 635 millimeters or 25 inches of annual precipitation, or non-arid with greater than 635 millimeters of annual site precipitation), this determines what default factor is selected for the methane generation rate constant. If input parameters other than defaults are used, site specific data obtained by gas recovery testing is the next data source. The minimum site data which must be reported to conduct a methane emission estimate is 1) the type of waste and, 2) annual tonnage figures.

When calculating landfill methane emissions based on gas collected, the main initial source data required is the volume of LFG annually captured and measured methane concentration by volume. This is the preferred method of estimating landfill methane emissions based on assumed or calculated gas collection system efficiency. In the case where a collection system covers only a portion of the site, a percent coverage must be used and reflect the overall area of influence for the gas collection system. The landfill methane emissions from large portions of the site and cells not containing LFG recovery systems and equipment are estimated separately using measured waste tonnage data and emission model calculations.

Landfill gas is metered in terms of physical and chemical units (i.e., mass or volume and percent methane by volume) and it is recommended that Partners track landfill methane generation, recovery (including composition by volume) and emissions to the atmosphere in terms of these physical and chemical units. Partners with MSW landfills incorporating gas collection should be continuously measuring gas recovered through gas collection monitoring systems. However, depending on the consistency of the sustainable volumes of LFG recovered, Partners may choose to monitor methane concentration periodically throughout the year. Quantity of landfill gas for recovery and methane composition may vary due to changes in site conditions, gas line blockages, damage to LFG system from site activities, system down time and fluctuations in anaerobic conditions (resulting from possible air ingression). For these reasons, it is recommended that continuous metering and data computation of LFG volumetric flow rate and methane concentration is conducted, for emission reporting accuracy as well as for future emission reduction verification requirements.

4.2. Emission Factors Data

A factor that is required for the methane collected method of calculating emissions is the LFG collection system efficiency (if one is installed). Gas collection system efficiency factors can vary widely depending on the type of landfill gas collection system (horizontal versus vertical, or a combination of both), construction and condition of the landfill cover, the landfill site characteristics, differential settlement, moisture, or other factors.

If the landfill is completely served by a gas collection system, then the waste management industry assumption has been that a collection efficiency of 75 percent or greater is typically achieved.[7] This collection efficiency factor is used as a default by Climate Leaders. Data supporting more precise estimates is not available and this assumption is likely to provide estimates that are more precise than using the LandGEM model for the reasons discussed within this guidance document.

Over the past several years, many landfills subject to the New Source Performance Standards (NSPS) for MSW Landfills (40 CFR Part 60, Subparts WWW and CC) have been required to conduct surface sweep monitoring of landfill emissions. Sites with fully functional and well-maintained low permeability cover systems have been found (indeed are required) to demonstrate near-zero surface emissions. Therefore, it is reasonable to assume that sites subject to the NSPS have a higher collection efficiency than the above-mentioned waste management industry standard assumption. If the Climate Leaders Partner uses an active collection system efficiency which is greater than 75% the methodology and assumptions used to determine the site specific collection efficiency shall be reported. Closed NSPS landfills with impermeable geomembrane covers and active gas controls are expected to have a collection system efficiency greater than 90%, based on the consistent reporting of near-zero surface emission measurements.

Climate Leaders Partners may own or operate MSW landfill sites which simply vent small amounts of LFG to the atmosphere for safety reasons and/or to prevent lateral subsurface migration from the landfill. This is frequently done using passive venting systems such as final cover gas vent layers, vent wells, horizontal gas migration cut-off trenches, and under-slab venting systems for on-site buildings or structures. There are no standard

7 Compilation of Air Pollutant Emission Factors, AP-42, U.S. EPA, 1998. op.cit. p. 2.4 - 6.

collection system efficiencies for passive venting systems and each emission estimation using passive systems, and the recovery efficiency applied, are evaluated on a site specific basis. Effectiveness of passive venting is generally determined by monitoring methane concentrations in perimeter soils and at building or structure foundations.

Another factor to be considered for both methods of estimating emissions is for methane oxidized as a result of methane oxidizing bacteria found within the landfill cover system, intermediate soils and alternative daily cover systems. Studies have been conducted which support methane oxidation, however the rates can vary substantially based on the final cover composition, thickness and seasonal variations[8]. Average oxidation of methane (on a volumetric basis) in some laboratory and case studies on landfill covers have indicated ranges from 10 percent to over 25 percent with the lower portion of the range being found in clay soils and higher in topsoils[9]. A conservative approach is an assumption that 10% of the non-captured landfill methane passing through the final cover system or soils may potentially be oxidized. Methane oxidation factors can be much higher for intermediate cover materials such as compost applications.

Due to the uncertainty involved and the lack of a standard method to determine oxidation rate, EPA recommends the default factor of 10% by volume methane oxidation for landfills with low permeability cover systems. Landfill cover systems incorporating a flexible membrane liner (FML) within the final cover system have negligible methane oxidation and the default oxidation rate for these types of covers is equal to zero.

Use of the methane generation method of calculating emissions requires use of a first order decay model, which is the basis of the U.S. EPA LandGEM computer software. The model has input parameters used to represent characteristics of the waste as described in Section 2.1. The variables k and L_o that determine the rate of gas production are functions of site-specific conditions. A set of default values for k and L_o are listed in the U.S. EPA's Compilation of Air Pollutant Emission Factors, Document No. AP-42, (1998)[10]. The L_o factor is a function of the waste composition and a single default is provided for typical municipal solid waste.

The k factor is a rate constant that is a function primarily of the refuse moisture content. Two default values are listed for this factor, one for arid regions (less than 635 mm or 25 inches of precipitation per year) and another for non-arid regions. The AP-42 default values are listed below.

Parameter	AP-42 Default Value
L_o	100 m^3/t
k	0.04/yr (non-arid area) 0.02/yr (arid area)

8 *"Quantifying the Effect of Oxidation on Landfill Methane Emissions".* P. Czepiel, B. Mosher, P.M. Crill, and R.C. Harriss. 1996. Journal of Geophysical Research, Volume 101: 16712-16729.

9 *"Isotopic signatures of atmospheric methane at NIGEC tower sites and of anthropogenic sources of methane to the atmosphere".* Annual Progress Report for FY 97/98, National Institute of Global Environmental Change.

10 Compilation of Air Pollutant Emission Factors, AP-42, 5th Edition, Volume 1: *Stationary Point and Area Sources* Chapter 2: Solid Waste Disposal, Section 2.4, U.S. EPA Supplement E, November 1998. p. 2.4 - 4.

These default parameters are based on average moisture conditions and generally reflect "dry-tomb" style landfill applications for various climates. For "bioreactor" type landfills the methane generation rate constant is generally high due to the amount of moisture added to the waste, resulting in a higher production rate of LFG over a shorter interval of time. Gas generation rates for bioreactor type landfills are generally in the order of two to three times that of dry tomb landfill operations.

It is suggested that Climate Leaders Partners having MSW landfill sites without gas collection systems use the LandGEM computer model (LandGEM Version 2.01) with AP-42 default factors or site specific determined values for parameters L_o and k. LandGEM 2.01 can be obtained through the U.S. EPA's Technology Transfer Network (TTN) at:

> http://www.epa.gov/ttn/catc/products.html#software

Partners who are landfill owners may have collected data to establish site-specific values of k and L_o for this widely used model of landfill gas emissions. These values may be used if they were derived using methods approved by U.S. EPA for this purpose. Partners should make available the data, data collection procedures, and calculations they used in deriving these site-specific factors for verification if they are used for estimating landfill methane emissions.

Completeness

In order for a Partner's GHG corporate inventory to be complete it must include all emission sources within the company's chosen inventory boundaries. See Chapter 3 of the *Climate Leaders Design Principles* for detailed guidance on setting organizational boundaries and Chapter 4 of the *Climate Leaders Design Principles* for detailed guidance on setting operational boundaries of the corporate inventory.

On an organizational level the inventory should include emissions from all applicable facilities. Completeness of corporate wide emissions can be checked by comparing the list of facilities included in the GHG emissions inventory with those included in other emission's inventories/environmental reporting, financial reporting, etc.

At the operational level, a Partner should include all emission sources from the facilities included in their corporate inventory. For a Partner who's operations include MSW landfilling, possible emissions sources are stationary fuel combustion, combustion of fuels in mobile sources, purchases of electricity, HFC emissions from air conditioning equipment and methane emissions from MSW decomposition. Partners should refer to this guidance document for calculating methane emissions from MSW decomposition and to the Climate Leaders Core Guidance documents for calculating emissions from other sources.

Partners should be aware when using this guidance that any losses in methane collected based on fugitive emissions through piping systems should be accounted for. Landfill gas could be lost due to fugitive releases of LFG from collection system valves and piping as well as through the leachate collection system (LCS). It should be noted that the leachate collection system can be a significant pathway for landfill methane emissions. Generally most LFG collection systems installed incorporate provisions for recovery of gas from the LCS piping and storage network.

As described in Chapter 1 of the *Climate Leaders Design Principles*, there is no materiality threshold set for reporting emissions. The materiality of a source can only be established after it has been assessed. This does not necessarily require a rigorous quantification of all sources, but at a minimum, an estimate based on available data should be developed for all sources.

The inventory should also accurately reflect the timeframe of the report. In the case of Climate Leaders, the emissions inventory is reported annually and should represent a full year of emissions data.

Uncertainty Assessment

Uncertainties in estimating methane emissions from MSW landfill sites without gas collection systems is high based on the fact the landfill is not a homogeneous mass of waste deposited under fully controlled conditions.

The emission estimates using the first-order decay equation with standard default factors could have a +/- error of 200% or more depending on actual site conditions[11]. There is always a level of uncertainty in the accuracy of measurements or estimates of the annual landfilled waste mass, including the variability in the waste composition. A very important factor in modeling landfill gas emissions is the underlying assumption that the waste composition is typical (which is generally not the case).

Gas generation and subsequent emission of that gas to the atmosphere is based on many factors as discussed throughout this document. Also, the first-order decay equation does not take into account a lag period from initial placement of waste and assumes gas generation commences within the first year of waste placement. Experience with gas collection from landfills in arid locations shows that they can exhibit extremely long lag times from the initial placement of waste until the onset of significant anaerobic gas production.

Uncertainties associated with estimating landfill methane emissions are lessened using recovery data available from MSW landfills incorporating a gas collection system. Assuming that a properly designed gas recovery system falls in a typical range for gas collection system efficiency, the confidence level is higher when back calculating the landfill methane emissions using default or site specific gas collection system efficiencies then the confidence level obtained using the first-order decay equation.

The area of methane oxidation is not fully defined and even using a 10 percent methane oxidation factor can lead to uncertainty in annual emission estimations calculated and subsequently reported.

11 Ibid, p. 2.4 - 4.

Reporting and Documentation

Partners are required to complete the Climate Leaders *Reporting Requirements* and report annual emissions. In order to ensure that emissions estimates are transparent and verifiable, the input data used to develop the emission estimates should be clearly documented and all sources listed in Table 1 should be maintained for each relevant year. These documentation sources should be collected to ensure the accuracy and transparency of the related emissions data, and should also be reported in the Partner's Inventory Management Plan (IMP).

Table 1: Documentation Sources for Solid Waste Landfill Methane Emissions

Data	Documentation Source
Total permitted landfill capacity	Operating Certificate or Permit
Year opened	Landfill site records
Year of closure	Operating Certificate or Permit, site records
Current area devoted to landfilling	Current contour maps and filling plans
Annual landfill acceptance rate for the site Tonnage figures including waste in place	Weigh scale records, volumetric calculations, aerial photographs, and landfill annual reports
MSW composition (% MSW, other organic wastes, C&D, Fill)	Waste categorization based on weigh scale records including reused and recycled material broken down by percent, mass or volume.
Average Waste moisture content	Waste records, climate data
Average Waste Depth	Up-to-date contour map, site records.
Meteorological data, primarily precipitation	Local weather authority or on-site meteorological station
LFG flow rate and composition	Site testing, Gas collection monitoring system, flow meter, in-line chromatograph or gas analyzer, third party laboratory analysis
Landfill area covered by gas collection system	LFG system record drawings
Emission factors and default input methane emission model parameters	All applicable sources, U.S. EPA with programs such as the Landfill Methane Outreach Program (LMOP), also SWANA technical documents
Landfill gas captured, flared and/or utilized	Gas collection monitoring system, flow meter, in-line chromatograph or gas analyzer, third party laboratory analysis

Inventory Quality Assurance and Quality Control

Chapter 7 of the *Climate Leaders Design Principles* provides general guidelines for implementing a QA/QC process for all emission estimates. For MSW landfill sources, a review of input data and emission factors should be verified for various approaches, specifically if customized defaults were developed based on site specific data. QA/QC may include, but not limited to:

- Landfill methane emissions calculated using Landfill Gas Emission Model compared with emissions calculated using proprietary gas generation models developed by industry experts or other agencies.
- Landfill methane emissions calculated by gas collection system efficiency in comparison to emissions estimated through gas modeling.
- Examining the quality assurance and quality control program associated with equipment used for facility level LFG flow rate and composition measurements and any equipment used to calculate site-specific emissions factors, or emissions.
- Performing back-checks and re-calculations for all equations used.
- Landfill gas sampling and third-party laboratory analysis using the applicable U.S. EPA test methods for determination of methane and total hydrocarbon content.
- Ensuring that measuring and monitoring equipment is maintained, operated and calibrated based on manufacturer's recommendation and calibration and maintenance records kept for audit purposes.

LandGEM Sample Output

The following is a sample text emission output report generated using LandGEM Version 2.01 and based on the example and model input parameters in Section 2.1.

LandGEM 2.01 Text Report

Source: Operating Parameters: .\LANDFILL.000

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Model Parameters

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Lo : 100.00 m^3/Mg ***** User Mode Selection *****

k : 0.0200 1/yr ***** User Mode Selection *****

NMOC : 4000.00 ppmv ***** User Mode Selection *****

Methane : 50.0000 % volume

Carbon Dioxide : 50.0000 % volume

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Landfill Parameters

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Landfill type : No Co-Disposal

Year Opened : 1982 Current Year : 2003 Closure Year: 2012

Capacity : 2400000 Mg

Average Acceptance Rate Required from Current Year to Closure Year : 80000.00 Mg/year

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Model Results

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		Methane Emission Rate				Methane Emission Rate	
Year	Refuse In Place (Mg)	(Mg/yr)	(Cubic m/yr)	Year	Refuse In Place (Mg)	(Mg/yr)	(Cubic m/yr)
1983	8.000E+04	1.067E+02	1.600E+05	1994	9.600E+05	1.150E+03	1.724E+06
1984	1.600E+05	2.114E+02	3.168E+05	1995	1.040E+06	1.234E+03	1.850E+06
1985	2.400E+05	3.139E+02	4.706E+05	1996	1.120E+06	1.317E+03	1.973E+06
1986	3.200E+05	4.145E+02	6.212E+05	1997	1.200E+06	1.397E+03	2.094E+06
1987	4.000E+05	5.130E+02	7.689E+05	1998	1.280E+06	1.476E+03	2.213E+06
1988	4.800E+05	6.096E+02	9.137E+05	1999	1.360E+06	1.554E+03	2.329E+06
1989	5.600E+05	7.043E+02	1.056E+06	2000	1.440E+06	1.630E+03	2.443E+06
1990	6.400E+05	7.971E+02	1.195E+06	2001	1.520E+06	1.704E+03	2.554E+06
1991	7.200E+05	8.880E+02	1.331E+06	2002	1.600E+06	1.777E+03	2.664E+06
1992	8.000E+05	9.772E+02	1.465E+06	2003	1.680E+06	1.849E+03	2.771E+06
1993	8.800E+05	1.065E+03	1.596E+06				

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