Methane Emissions from Landfills

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January, 2019

Submitted in partial fulfillment of the requirements for
M.S. in Earth and Environmental Engineering

Research co-sponsored by

COLUMBIA UNIVERSITY
EARTH ENGINEERING CENTER

Executive Summary

Methane, one of the main greenhouse gases (GHGs), has been assessed to have 28 times the global warming potential (GWP) of carbon dioxide over a 100-year time horizon in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). In municipal solid waste (MSW) landfills, methane is generated as a product of the anaerobic degradation of organic waste. United States Environmental Protection Agency (U.S. EPA) estimated that, in 2016, landfill methane emissions in the U.S. were approximately 107.7 million tons carbon dioxide equivalent (Mt CO_2 e). And globally, it was estimated that methane emissions from landfilling of solid waste were 794.0 million tons of CO_2 e in 2005. At both the U.S. and the global levels, landfilling was the third largest source of methane emissions, after enteric fermentation and natural gas & oil systems.

A broad range of topics about methane emissions from landfill are covered in this report, including the gas-generating processes in landfill, the theories about modeling landfill gas generation and emission, the developed models and the current estimates of landfill emissions, as well as the calculation and analysis on several aspects: 1) theoretical maximum methane generation per ton of MSW and actual methane emission per ton of MSW; 2) climate zone statistics about landfill gas generation model parameter, landfill methane generation, emission and recovery; 3) the time series of global landfill methane emissions with regional analysis and per capita analysis. The findings provide both theoretical information and empirical data on landfill methane emissions.

Currently, the most widely used model could be the 2006 IPCC Guidelines First-Order Decay (FOD) Method, which has been used by many countries to develop their national greenhouse gas inventories. In recent years, new methods based on direct measurements have been developed, such as the Back-Calculation Method used in the Greenhouse Gas Reporting Program (GHGRP).

The empirical formula of dry degradable organic waste in the U.S. is estimated as $C_6H_{9.21}O_{3.73}$ when ignoring nitrogen (N) and sulfur (S). Methane generation per ton of MSW in the U.S. has been calculated to be 0.135 *ton* (or 189 Nm^3) at maximum, which is 9% less than the previous estimation.

The actual landfill methane emissions per ton of MSW in the U.S. are much lower than this theoretical maximum generation value. The reason of the gap could be: 1) landfill gas collection systems, landfill gas destruction (flaring) and utilization projects reduce the methane emissions, 2) the intrusion of air at some parts of the landfill diverts the anaerobic degradation to aerobic degradation, 3) the biodegradable components in MSW cannot fully biodegrade due to their intrinsic properties and other limiting factors such as water content, temperature and pH.

Under dry basis, the degree of the biodegradation of the biodegradable components in U.S. MSW has been estimated to be 53.6%. At this degree, the expected methane generation would be 0.072 ton CH_4 / ton MSW. Besides, the excessive underestimation of the quantity of landfilled MSW in the U.S. in EPA’s annual summary figures and tables of waste management has also been detected.

The GHGRP landfill facility-level data and the Köppen-Geiger climate classification GIS data are used to derive climate zone statistics.

For methane generation rate *k*, the order of main climate types, from in which the *k* value of bulk waste is high to in which that is low, would be warm temperate (C), equatorial (A), snow (D), and arid (B), or ACDB under another calculation option. This indicates precipitation/water may play a more important role than temperature in the generation of landfill gas.

For methane generation ratio (tons CH_4 / ton MSW), those based on model estimation show the pattern that, in equatorial (A) climate, the generation ratio is the highest, followed by that in warm temperate (C) climate, snow climate (D) and arid (B) climate. While for those based on measurement, a different pattern has been shown that, the typical generation ratio in warm temperate (C) and snow (D) climate are very close and are higher than that in equatorial (A) climate, the lowest typical generation ratio is still in arid (B) climate. The lack of sufficient samples in equatorial (A) climate can be a possible reason, while this needs to be further analyzed.

Besides, the methane generation ratios based on measurement are all significantly less than the corresponding ratios based on model estimation, this implies there may exist systematical overestimation in the landfill gas generation model used, which is the 2006 IPCC Guidelines FOD Method.

The typical values of estimated collection efficiency are all relatively high (around 70%) and show small variations in different main climates. An interesting finding is that, the typical values of methane emission ratio show little difference in different main climates. To better understand this, more knowledge about how the landfill operators determine which emission value to report is needed.

The United Nations Framework Convention on Climate Change (UNFCCC) database and the Emissions Database for Global Atmospheric Research (EDGAR) are two separate sources of landfill methane emissions in different countries. Generally, there are varying degrees of difference between the two data sets in most countries because of the different methodologies used to develop them.

After comparison, the EDGAR data are selected as the basis to construct a complete time series of landfill methane emissions at the global level. It is estimated that the global methane emissions from landfills are 727.3 $Mt\ CO_2\ e$ in 2012. If there is no significant implementation of landfill methane mitigation measures in the world, the rapid growth of landfill methane emissions in the near future should be expected.

The per capita landfill methane emissions have been calculated for almost all countries covering a time period from 1970 to 2017. It is estimated that, in 2012, every person on the planet emits 4.10 *kg* of landfill methane (102.50 $kg\ CO_2\ e$) on average annually.

By world region, the per capita landfill methane emissions in North America and in Europe & Central Asia are significantly higher than those in other regions, among which South Asia region has the lowest per capita emissions.

By income group, it has been shown that, for both total emissions and per capita emissions, higher income group emits more than lower income group.

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1. Introduction

Methane, one of the main greenhouse gases (GHGs), has been assessed to have 28 times the global warming potential (GWP) of carbon dioxide over a 100-year time horizon in the IPCC Fifth Assessment Report; its GWP over a 20-year course is 84 times that of carbon dioxide [1]. Table 1-1 shows the 100-Year GWP values of methane assessed in the successive IPCC assessment reports.

Table 1-1 Comparison of the 100-Year GWP Values of Methane [2]

Gas	*SAR*	*AR4*	*AR5*	*AR5 with feedbacks*
CO_2	1	1	1	1
CH_4	21	25	28	34

SAR – IPCC Second Assessment Report, AR4 – IPCC Fourth Assessment Report, AR5 – IPCC Fifth Assessment Report.

In municipal solid waste (MSW) landfills, methane is generated as a product of the anaerobic degradation of organic waste. U.S. EPA estimated [2] that, in 2016, landfill methane emissions in the U.S. were approximately 107.7 million tons carbon dioxide equivalent (Mt CO_2 e), accounting for approximately 16.4 percent of total U.S. anthropogenic methane emissions in 2016, and were the third largest source of methane emission, after enteric fermentation (the largest) and natural gas systems. At the global level, it was estimated that methane emissions from landfilling of solid waste were 794.0 million tons of CO_2 e in 2005 [3], again, landfilling was the third largest source of methane emissions, after enteric fermentation and natural gas & oil systems.

A broad range of topics about methane emissions from landfills are covered in this report, including the gas-generating processes in landfill, the theories about modeling landfill gas generation and emission, the developed models and the current estimates of landfill emissions, as well as the calculation and analysis on several aspects. The findings provide both theoretical information and empirical data on landfill methane emissions.

Since the United Nations Framework Convention on Climate Change (UNFCCC) [4] requires Annex I Parties (see Section 5.3.1) to use GWP values from the IPCC Fourth Assessment Report (AR4), many of the data referred to in this report were calculated under this requirement. Therefore, when converting units between carbon dioxide equivalent and actual methane emissions, the GWP value of methane used in this report is 25, unless it is stated otherwise.

2. Gas-Generating Processes in Landfill

2.1 Main Processes

In landfills receiving organic waste, the dominating gas-generating process is the microbial conversion of organic carbon to CH_4 and CO_2, which are the main components of landfill gas; there are very small concentrations of other components.

The gas-generating processes in landfills are classified into aerobic composting, in the presence of ample oxygen and anaerobic degradation, which consists of three phases [5-7]. The most important interactions between the bacterial groups involved, the substrates involved, and the intermediate products in an anaerobic landfill are illustrated in Figure 2-1.

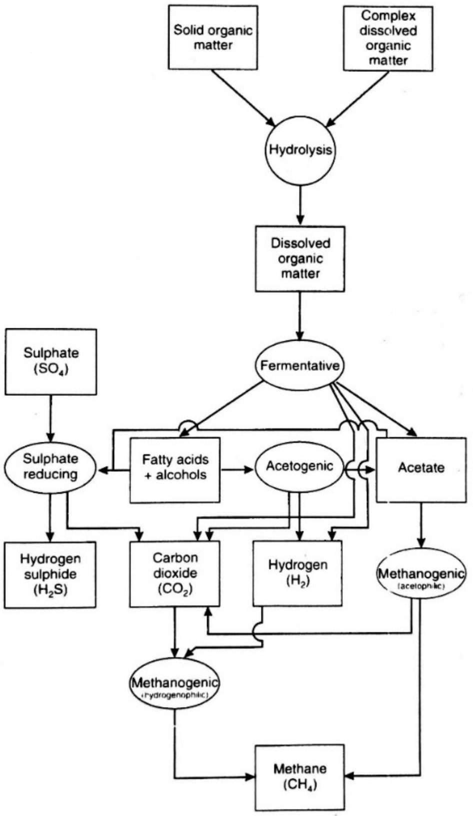


Figure 2-1 Substrates and Major Bacterial Groups in Methane-Generating Ecosystems [8]

2.1.1 Aerobic degradation

Shortly after the deposition of MSW, the readily degradable organic compounds at the outer surface of the landfill (to a depth of about 1 – 1.5m [7]) are oxidized aerobically. The aerobic reaction requires oxygen in atmospheric air to degrade organic matter, and it is similar to combustion since the reaction generates CO_2, H_2O, and heat as end products [6]. Themelis and Kim [9] have shown that the C, H, O composition of U.S. MSW can be simulated by the formula $C_6H_{10}O_4$. Accordingly, the aerobic composting reaction can be expressed as follows:

$$C_6H_{10}O_4 + 6.5O_2 \rightarrow 6CO_2 + 5H_2O \tag{2-1}$$

Generally, the aerobic process lasts only for days or a few weeks [5]; after this period, the landfilled materials are covered with newly deposited wastes and further reaction proceed anaerobically. Both the aerobic and anaerobic reactions are biochemical and require the presence of different types of bacteria.

2.1.2 Anaerobic degradation

After the oxygen supply ends, anaerobic digestion comes into being and this is the principal bioreaction in landfills. The reaction takes place in three phases, during which, organic substances are converted to CH_4 and CO_2 as well as small amounts of biomass and energy. The three steps in the anaerobic process are as follows [6, 7]:

1. ***Hydrolysis***: fermentative bacteria hydrolyze the complex organic matter (proteins, fats, carbohydrates, etc.) into simple soluble organic substances such as amino acids, glucose, etc.
2. ***Acetogenesis***: the end products of hydrolysis are converted by acid forming bacteria to volatile fatty acids, CO_2, and H_2. Acetogenic bacteria then convert volatile fatty acids to acetic acid, CO_2, and H_2. The principal acids produced are acetic acid, propionic acid, butyric acid and ethanol. A representative reaction is shown below:

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 \tag{2-2}$$

3. ***Methanogenesis***: at this phase, methane is formed by methanogenic bacteria, either by breaking down the acids to methane and carbon dioxide, or by reducing carbon dioxide with hydrogen. A representative reaction is shown below:

$$CH_3COOH \rightarrow CH_4 + CO_2 \tag{2-3}$$

$$CO_2 + 4H_2 \rightarrow CH_4 + H_2O \tag{2-4}$$

In the second and the third phases, acetogenic bacteria and methanogenic bacteria are extremely sensitive, strictly anaerobic, and substrate-specific.

The overall process of converting organic compounds to methane and carbon dioxide may stoichiometrically be expressed by [10]:

$$\mathrm{C}_n\mathrm{H}_a\mathrm{O}_b + \left(n - \frac{a}{4} - \frac{b}{2}\right)\mathrm{H_2O} \rightarrow \left(n - \frac{n}{2} - \frac{a}{8} + \frac{b}{4}\right)\mathrm{CO_2} + (\frac{n}{2} + \frac{a}{8} - \frac{b}{4})\mathrm{CH_4} \qquad (2\text{-}5)$$

2.2 Landfill Gas Composition Change During the Processes

The actual microbial degradation processes in landfills are complex. Christensen et al. [5] classified the gas composition change during the processes into eight distinct phases according to the progress of the waste degradation, as shown in Table 2-1:

Table 2-1 Gas Composition Change in Eight Phases of Waste Degradation [5], modified by the author

Phase	*Description*	*Gas (Vol.% decreased)*	*Gas (Vol.% increased)*
I	A short aerobic phase depleting O_2 by composting of easily degradable organic matter to CO_2.	O_2	CO_2
II	Fermentative and acidogenic bacteria produce under anaerobic conditions volatile fatty acids, CO_2 and H_2. The presence of these gases reduces the content of N_2.	N_2	CO_2, H_2
III	In a second anaerobic phase, methanogenic bacteria start to grow producing CH_4, while CO_2 and H_2 decrease.	CO_2, H_2	CH_4
IV	The stable methanogenic phase is characterized by 50-60% CH_4 and low concentrations of H_2. The latter being oxidized by CO_2 to CH_4.	CO_2	CH_4
V	Air starts to intrude into the outer part of landfill body reducing the formation of CH_4. The lower rates lead to a relatively more significant washout of CO_2 and a relative increase in CH_4 content of the gas.	CO_2, CH_4	N_2
VI	Methane produced in the center of the waste is oxidized to CO_2 as it migrates through the outer part of the landfill body. N_2 is now present in significant concentrations in the gas.	CH_4	CO_2, N_2
VII	Methane formation is now negligible and intruding air now oxidizes solid organic carbon (and reduced inorganic species) yielding CO_2.	CH_4, CO_2	O_2, N_2
VIII	The rates of the processes now approach the rates found in an active soil and the landfill gas starts to resemble soil air.	CO_2	O_2

Figure 2-2 illustrates the overall influence of these microbial degradation processes on the main composition of the landfill gas for a homogeneous landfill cell.

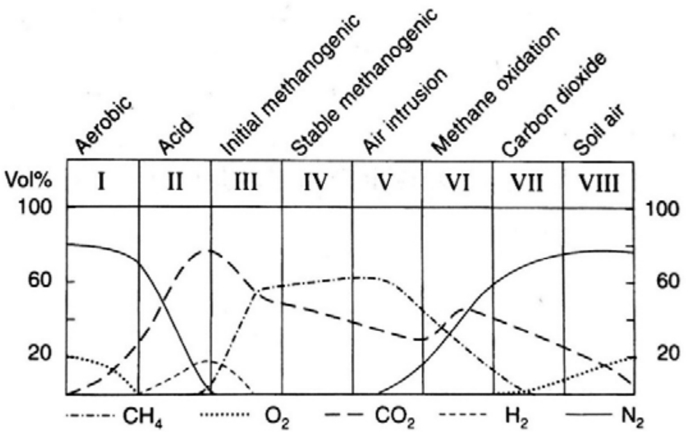


Figure 2-2 Illustration of Developments in Gas Composition in a Landfill Cell [5]

The gas composition sequence in Figure 2-2 is idealized, and there are no estimates of the length of the phases involved, due to their dependence on abiotic factors and local conditions such as waste composition and landfilling procedure. The initial aerobic phase lasts only for days or a few weeks, whereas the other phases may last for months, years and decades. [5]

2.3 Composition of Landfill Gas

2.3.1 Main Components

After relatively short times after disposal (weeks to months), landfill gas mainly consists of 55 (±5)% of CH_4 and 45 (±5)% of CO_2 [11]. This composition indicates the molecular structure of the digested organics must be close to that assumed by Themelis and Kim [9]; they approximated the anaerobic decomposition as Equation (2-6), in which the product gas contains about 54% CH_4 and 46% CO_2.

$$C_6H_{10}O_4 + 1.5H_2O \rightarrow 3.25CH_4 + 2.75CO_2 \qquad (2\text{-}6)$$

These concentrations remain relatively constant, while higher methane concentrations can possibly have been observed in older landfills. Also, because landfill is not a closed system, the CH_4 value may decrease when air enters in the gas flow through the landfill. In addition, due to the non-homogeneity of waste composition and water content, different parts of the landfill may undergo different phases thus resulting in different landfill gas compositions. [7, 11]

2.3.2 Trace Components

As noted earlier, landfill gas also contains a certain amount of trace components (less than 1% [7]). These trace components can be characterized into non-methane organic compounds (NMOC) and volatile organic compounds (VOC) and may be either decomposition byproducts or due to volatilization of biodegradable wastes [2]. They can also be differentiated into two types according to their generation [11]:

1. trace components generated during anaerobic degradation in the landfill, which can be differentiated into three main groups:
    - oxygen compounds;
    - Sulphur compounds;
    - hydrocarbons.
2. trace components generated by man-made wastes (anthropogenic trace components), which can be differentiated into two main groups:
    - aromatic hydrocarbons;
    - chlorinated hydrocarbons.

These trace components may cause damage to the technical equipment used for gas extraction and utilization (gas engines, for example) and render the gas odorous, and have negative impacts on the atmospheric air, and on the health of human beings and animals [7, 11]. Their concentrations in mg/m^3 are presented in Annex A.

2.4 Factors Affecting Waste Generation, Composition & Landfill Gas Generation, Emission

The generation and emission of landfill gas are affected by many factors, which can be roughly characterized into four groups: waste generation, waste composition, waste management and environment factors.

2.4.1 Factors Affecting Waste Generation and Waste Composition

Solid waste generation and composition are essential basis for activity data to estimate emissions from landfilling, they vary from different countries and regions depending on factors such as economic development, the degree of industrialization, public habits, climate, waste management practices and energy sources. A summary of these factors is shown in Table 2-2.

Table 2-2 Factors Affecting Waste Generation and Waste Composition

	Source	
	Eggleston et al., 2006 [12][a]	*Hoornweg and Bhada-Tata, 2012 [13]*
Waste Generation	1) economic situation 2) industrial structure 3) waste management regulations 4) life style	1) economic development 2) the degree of industrialization 3) public habits 4) local climate
Waste Composition		1) culture 2) economic development 3) climate 4) energy sources

a. These factors affect both waste generation and waste composition

2.4.2 Factors Affecting Landfill Gas Generation and Emission

The major drivers of generation of landfill gas (LFG) are:

1) amount of organic material deposited in landfills,
2) degree (%) of anaerobic decomposition of organic matter in MSW,
3) thickness and physical and chemical properties of cover materials in the landfill,
4) seasonal variation in methane oxidation rates,
5) moisture and bacterial concentration in landfill.

The driving factors for the trends in material landfilled and landfill gas are [3]:

1) growing populations,
2) increases in personal incomes,
3) expanding industrialization.

The emissions of landfill methane to the atmosphere depend on:

1) the operation of landfill (e.g. thickness of daily deposition, provision of daily cover, etc.),
2) the effort made to capture landfill gas (e.g. placement and timing of gas collection piping; horizontal collection pipes are placed in early days of landfill, vertical pipes are placed after filling a landfill cell);
3) use of LFG to operate electricity generators and/or gas flaring systems.

Cernuschi and Giugliano [14] described a large number of factors that may affect the quantity of gas emitted to the atmosphere through the top cover of the landfill, they are summarized here in Table 2-3 as follows:

Table 2-3 Factors Affecting the Quantity of Gas Emitted to the Atmosphere through the Top Cover of the Landfill

Factors	*Sub-Factors*
1. gas production rate	1) organic matter content of waste and its biodegradability 2) moisture and the temperature inside the landfill
2. gas migration properties through the waste deposited and through the top layer of the landfill	1) pressure and concentration gradients of the gas inside the landfill 2) transport properties of the gas 3) permeability, moisture content and thickness of the cover
3. collection efficiency of the gas extraction system	
4. factors affecting the transfer of the gas from the exposed area to the atmosphere	1) wind speed 2) barometric pressure fluctuations 3) air temperature

3. Modeling Landfill Gas Generation and Emission

3.1 Classification of LFG Generation Models

The development of landfill gas generation models started in the 1970s as several authors analyzed their experimental data [15].

As shown in Figure 3-1, a general classification of models can be made according to the availability of data and the state of knowledge of the system:

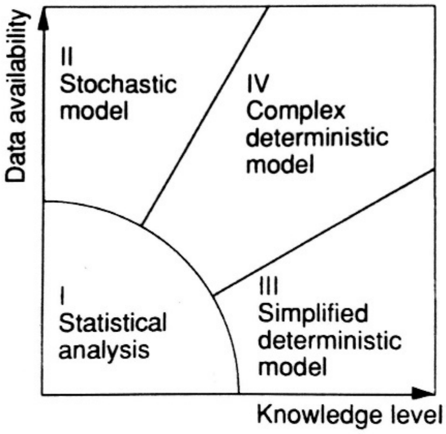


Figure 3-1 Classification of Models based on Knowledge Level and Data Availability [16]

Andreottola and Cossu [17] also categorized landfill gas generation models into four classes: empirical, stoichiometrical, biochemical and ecological models.

Because of overlaps or similarities between the definitions of model classes in the above two classification systems, the model classes have been synthesized in Table 3-1.

The majority of LFG models belong to the simplified deterministic model group, and the (simplified/complex) deterministic models can be subdivided into static and dynamic models [15]:

1. ***static model***, in which the relation between input and output is instantaneous, there is no time influence; it describes a system that has no memory of the past input and output and whose state is stationary.

2. ***dynamic model***, in which the relation between input and output is not instantaneous and the temporal evolution of the system is described by certain state variables.

Table 3-1 Classification of Landfill Gas Generation Models

Class	*Required Data / Knowledge*	*Characteristics*
1. statistics analysis	• a large number of data which are collected for different purposes • inadequate knowledge of the system	• no assumption of cause-effect relation • does not deal with the temporal dynamics of the system • presents the general characteristics of the data 'population' and provides correlations
2. stochastic model (empirical model)	• time series of experimental data	• simply generates output based on specific input with no explanation • useful for describing the behavior of a black-box system
3. stoichiometrical model	• a global stoichiometric reaction, where the waste is represented by an empirical formula	• generally this kind of model leads to the highest potential yield of biogas
4. simplified deterministic model (biochemical model)	• knowledge of the mechanisms governing the system, such as the biodegradability of the different components of waste, and each differs in terms of kinetic expression, number of substrata and parameters	• is able to describe the behavior of the system with simplified mathematical equations
5. complex deterministic model (ecological model)		• deals with the ecosystem on which the process is based • describes the relation between the system components • acts in a similar way to simplified deterministic model using more complex mathematical equations

3.2 Structure of LFG Generation Models

Cossu et al. [15] indicated that a complete landfill gas model should include three submodels: stoichiometric submodel, kinetic submodel and diffusion submodel. Descriptions of the submodels are provided in Table 3-2; their classes based on the classification discussed in the previous section are also provided:

Table 3-2 Structure of LFG Generation Models [15], modified by the author

Submodel	*Class*	*Characteristics*
1. Stoichiometric submodel	static	• gives the maximum theoretical yield of biogas from the anaerobic degradation of the organic waste fraction. • some provide as a result only information on LFG yields
2. Kinetic submodel	dynamic	• gives as a result the temporal evolution of LFG generation rates, can be either of three types of model below: 1) an empirical model, based on a more or less simple equation of a defined order 2) a deterministic model, based on a set of equations describing the degradation of the different biodegradable MSW fractions 3) an ecological model, which describes the dynamic of microbial populations and substrata within the landfill
3. Diffusion submodel	dynamic	• describes the time and space variation of pressure and gas composition within the landfill body • LFG emission rates can be obtained • the effectiveness of the gas extraction system can be verified

3.3 Estimation of Maximum LFG Yields

For the practical evaluation of the maximum theoretical LFG yield, the organic matter in solid waste that is converted to biomass, i.e. it is not converted to CH_4 and CO_2, can be neglected since that fraction is about only 4% when considering an infinite retention time in the system. Then, the overall digestion process for organics in solid waste can be represented by Equation (3-1) [15]:

$$\mathrm{C}_a\mathrm{H}_b\mathrm{O}_c\mathrm{N}_d + \frac{4a-b-2c+3d}{4}\cdot \mathrm{H_2O} \rightarrow \frac{4a+b-2c-3d}{8}\cdot \mathrm{CH_4} + \frac{4a-b+2c+3d}{8}\cdot \mathrm{CO_2} + d\mathrm{NH_3} \tag{3-1}$$

Where $\mathrm{C}_a\mathrm{H}_b\mathrm{O}_c\mathrm{N}_d$ is the empirical chemical formula for biodegradable organics in solid waste. The equation is similar to Equation (2-5), with additional consideration of the nitrogen concentration in solid waste. Once the empirical formula of the waste is deduced from the its composition, the theoretical yields of landfill gas can be obtained.

Equation (3-1) indicates that 1 mol of organic carbon is bioconverted to 1 mol of landfill gas. Therefore, under standard temperature and pressure, 1 mol C in organic matter will generate 22.4 l gas, and since the atomic weight of carbon is 12, 1 g C in organic matter will generate 1.867 l gas on a weight basis.

To take into account the effective biodegradability of organic matter in the waste, the following formula has been proposed to evaluate the content of biodegradable organic carbon [17]:

$$(\mathrm{OC_b})_i = \mathrm{OC}_i \cdot (f_\mathrm{b})_i \cdot (1 - u_i) \cdot p_i \tag{3-2}$$

- $(\mathrm{OC_b})_i$ biodegradable organic carbon in the *i*th component of waste (kg biodegradable carbon / kg wet MSW)
- OC_i organic carbon content in the dry *i*th component of waste (kg carbon / kg dry *i*th component)
- $(f_\mathrm{b})_i$ biodegradable fraction of OC_i (kg biodegradable carbon / kg carbon)
- u_i moisture content of the *i*th component of waste (kg water / kg wet *i*th component)
- p_i wet weight of the *i*th component of waste (kg *i*th component / kg MSW)

Table 3-3 provides values for some of the above parameters for the main constituents of MSW.

Table 3-3 Moisture Content (u_i), Organic Content (OC_i) and Biodegradable Organic Fraction $(f_b)_i$ in Various Constituents of MSW [15]

Waste component	u_i *(kg H_2O/kg wet component)*	OC_i *(kg C/kg dry component)*	$(f_b)_i$ *(kg biodeg. C/kg C)*
Food waste	0.6	0.48	0.8
Yard waste	0.5	0.48	0.7
Paper and cardboard	0.08	0.44	0.5
Plastics and rubber	0.02	0.7	0.0
Textiles	0.1	0.55	0.2
Wood	0.2	0.5	0.5
Glass	0.03	0.0	0.0
Metals	0.03	0.0	0.0

The lignin content of the MSW organic fraction can also be used to estimate the biodegradability of organic matter as follows [18]:

$$(f_\mathrm{b})_i = 0.83 - 0.028\ \mathrm{LC} \tag{3-3}$$

- $(f_\mathrm{b})_i$ biodegradable fraction expressed on a volatile solids (VS) basis
- LC lignin content of the volatile solids (VS) expressed as a percentage of dry weight

As indicated by Equation (3-3), high lignin content in waste will lead to significantly lower biodegradability.

Table 3-4 provides the biodegradability for several of the organic compounds found in MSW, based on lignin content.

Table 3-4 Biodegradability of Some Organic Compounds Found in MSW, Based on Lignin Content [18]

Component	*Volatile solids (VS) as percent of total solids (TS)*	*Lignin content (LC) as percent of VS*	*Biodegradable fraction (BF)*
Food waste	7-15	0.4	0.82
Paper			
Newsprint	94.0	21.9	0.22
Office paper	96.4	0.4	0.82
Cardboard	94.0	12.9	0.47
Yard wastes	50-90	4.1	0.72

Combining the above data, the specific yield of LFG (Y_{LFG}) can be evaluated as in Equation (3-4), which is the common basis for the majority LFG generation models [15]:

$$Y_{LFG} = 1.867 \cdot OC_i \cdot (f_b)_i \cdot (1 - u_i) \cdot p_i \text{ (l gas / kg MSW)} \tag{3-4}$$

where 1.867 (l) is the volume of landfill gas that will be generated from 1 g C in organic matter under standard temperature and pressure.

3.4 LFG Generation Rates

In addition to estimating the amount of LFG that will be generated, the generation rate and the generation duration are also necessary parameters for modeling landfill gas generation. Equation (3-5) is the general equation that rules landfill gas generation, which can express either the rate of substrate degradation or the rate of gas generation [15]:

$$\frac{dC}{dt} = f(t, C^n) \tag{3-5}$$

- t time
- C amount of methane or of biodegradable organics

In the majority of LFG generation models, Equation (3-5) is applied to a specific waste batch, such as the amount of MSW disposed either in a single year or in a single layer; then the overall generation rate of LFG is calculated as the sum of these single batch contributions. [15]

The order of the model (i.e. the kinetic order of reaction) is defined as the greatest absolute value of n, i.e., the exponent of the dependent variable C in Equation (3-5) [15]:

- ***Zero-Order Model***

  In a zero-order model, the rate of methane generation remains as a constant k and is independent of the amount of substrate left or of the amount of biogas already produced.

  Zero-order kinetics are mainly found during the periods of highly active gas generation: under this condition, the limiting factor for methane formation can be moisture, nutrients etc. [19]

- ***First-Order Model***

  In a first-order model, the rate of methane generation is dependent on the amount of substrate remaining or the amount or biogas already produced, either of which can be considered as the limiting factors.

  First-order kinetics are assumed by the majority of LFG generation models. It should be noted that other factors such as the water content, which plays a major role in the hydrolysis of organic matter, and temperature, availability of nutrients and presence of the necessary microorganism can also influence the biogas generation.

The rate constant k in models controls the rate at which substrate decays and gas is produced, and is usually estimated by model calibration, when time series of field data are available. The degradation rate of each biodegradable component of waste is different. Therefore, in many models the substrate is split into two classes (slowly and readily biodegradable) or three classes (slowly, moderately and readily biodegradable) each characterized by a proper decay rate constant k_i. [15]

- ***readily biodegradable fraction***: food waste,
- ***moderately biodegradable fraction***: yard waste,

- ***slowly biodegradable fraction***: paper, cardboard, wood and textiles.

In many models, to take into account other factors such as moisture content, particle size that may influence the decay rate constant, some appropriate corrective factors are introduced [15].

The default methane generation rate (*k*) values provided in the 2006 IPCC guidelines First-Order Decay (FOD) Tier 1 method [20] are shown in Table 3-5, organized by the biodegradability of waste and climate zone.

Table 3-5 Recommended Default Methane Generation Rate (*k*) Values under Tier 1 [20]

Type of Waste		*Climate Zone*							
		Boreal and Temperate (MAT ≤ 20 °C)				*Tropical (MAP > 20 °C)*			
		Dry (MAP/PET < 1)		*Wet (MAP/PET > 1)*		*Dry (MAP < 1000 mm)*		*Moist and Wet (MAP ≥ 1000 mm)*	
		Default	*Range*	*Default*	*Range*	*Default*	*Range*	*Default*	*Range*
Slowly degrading waste	Paper / textiles waste	0.04	0.03 – 0.05	0.06	0.05 – 0.07	0.045	0.04 – 0.06	0.07	0.06 – 0.085
	Wood / straw waste	0.02	0.01 – 0.03	0.03	0.02 – 0.04	0.025	0.02 – 0.04	0.035	0.03 – 0.05
Moderately degrading waste	Other (non-food) organic putrescible / Garden and park waste	0.05	0.04 – 0.06	0.1	0.06 – 0.1	0.065	0.05 – 0.08	0.17	0.15 – 0.2
Rapidly degrading waste	Food waste / Sewage sludge	0.06	0.05 – 0.08	0.185	0.1 – 0.2	0.085	0.07 – 0.1	0.4	0.17 – 0.7
Bulk waste		0.05	0.04 – 0.06	0.09	0.08 – 0.1	0.065	0.05 – 0.08	0.17	0.15 – 0.2

MAT – Mean annual temperature; MAP – Mean annual precipitation; PET – Potential evaporation.

MAP/PET is the ratio of MAP to PET. The average annual MAT, MAP and PET during the time series should be selected to estimate emissions and indicated by the nearest representative meteorological station.

3.5 LFG Generation Time

The period during which biogas is generated, usually called the generation time, is an important result of LFG generation models, however, its general definition is hard to provide. Cossu *et al.* [15] summarized some estimations of the generation time as follows:

Table 3-6 Estimations of Landfill Gas Generation Time [15]

Source	*Andreottola and Cossu [17]*	*Bridgewater and Lidgren [21]*	*Ham [19] and Richards [22]*
Generation Time (yr)	30	20	10 – 15

The half time ($t_{1/2}$), i.e., the time taken for degradable organic carbon in waste to decay to half its initial mass or the time over which the gas generation equals half of the estimated yield, can provide satisfactory information on generation time. In first-order kinetic models, the half time can be calculated by Equation (3-6). [15, 20]

$$t_{1/2,i} = \ln\frac{2}{k_i} \tag{3-6}$$

- k_i – the decay rate constant of the *i*th component of organic waste.

Table 3-7 Recommended Default Half-Life ($t_{1/2}$) Values (yr) under Tier 1 [20]

Type of Waste		*Climate Zone*							
		Boreal and Temperate (MAT ≤ 20 ^{o}C)				*Tropical (MAP > 20 ^{o}C)*			
		Dry (MAP/PET < 1)		*Wet (MAP/PET > 1)*		*Dry (MAP < 1000 mm)*		*Moist and Wet (MAP ≥ 1000 mm)*	
		Default	*Range*	*Default*	*Range*	*Default*	*Range*	*Default*	*Range*
Slowly degrading waste	Paper / textiles waste	17	14 – 23	12	10 – 14	15	12 – 17	10	8 – 12
	Wood / straw waste	35	23 – 69	23	17 – 35	28	17 – 35	20	14 – 23
Moderately degrading waste	Other (non-food) organic putrescible / Garden and park waste	14	12 – 17	7	6 – 9	11	9 – 14	4	3 – 5
Rapidly degrading waste	Food waste / Sewage sludge	12	9 – 14	4	3 – 6	8	6 – 10	2	1 – 4
Bulk waste		14	12 – 17	7	6 – 9	11	9 – 14	4	3 – 5

MAT – Mean annual temperature; MAP – Mean annual precipitation; PET – Potential evaporation.

MAP/PET is the ratio of MAP to PET. The average annual MAT, MAP and PET during the time series should be selected to estimate emissions and indicated by the nearest representative meteorological station.

The range of the estimated $t_{1/2}$ values is very wide. Under 2006 IPCC guidelines First-Order Decay (FOD) Tier 1 method [20], the recommended default half-life ($t_{1/2}$) values according to the biodegradability of waste and climate zone are shown in Table 3-7.

The lag time is another parameter useful to define the generation time; it is the time between the placement of waste in the landfill to the beginning of significant gas generation. Given a typical one-year placement period for batch units of waste, an average lag of six months is usually considered as the default lag time in landfill gas generation models. In practice, the lag time can vary from a few weeks, to one year and more. [15, 20]

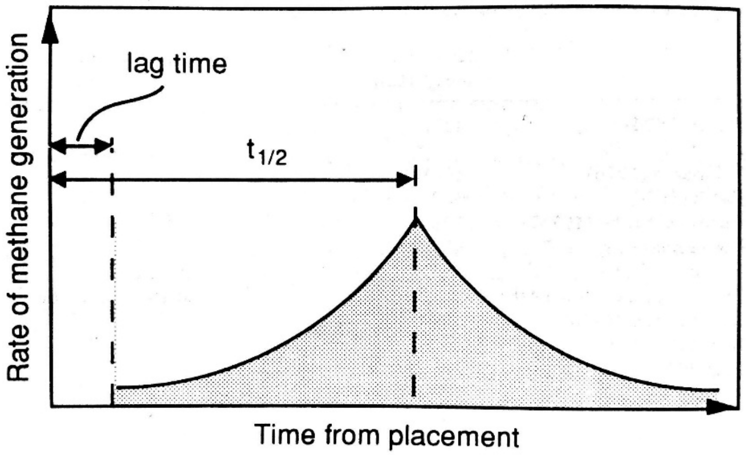


Figure 3-2 General Gas-Generation Curve with Lag Time and $t_{1/2}$ Shown [15]

3.6 Selection of Models and Parameters Values

The selection of parameter values plays an important role in the output of a model.

According to Zison [23], the order of the model is not very important. The explanation is that long-term curves are based on the contribution of multiple waste batches and not on the degradation of a single batch of waste, so the generation curves of each waste batch are mutually masked. Therefore, other factors could be considered, such as the choice of an appropriate value for the decay rate constant and the correct evaluation of the amount of degradable organic carbon in the waste. [15, 23]

The sensitivity of models to generation time and model parameters was investigated by Augenstein and Pacey [24]. Figure 3-3 shows the comparison between two models, the sensitivity to model parameters is detected in the short term, while is not very significant in the long term. They concluded that, as also supported by Zison [23], the shape proposed for a unit batch generation curve can be relatively important for many purposes, including prediction over the long term. [15]

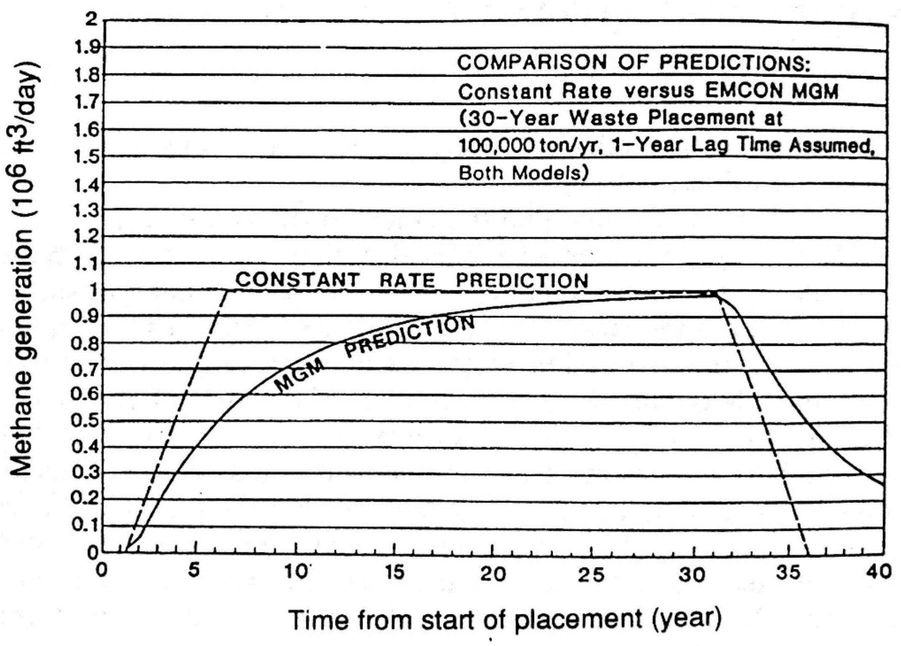


Figure 3-3 Long-Term Methane Generation Predictions Comparing a Constant-Rate Model and the EMCON MGM Model [24]

4. Developed Models and Current Estimations

4.1 General Models

4.1.1 Themelis & Ulloa Method

Themelis and Ulloa [6] used the empirical formula of MSW to estimate the maximum generation of methane per ton of MSW by Equation (4-1), which is consistent with Equation (2-4):

$$C_6H_{10}O_4 + 1.5H_2O = 3.25CH_4 + 2.75CO_2 \tag{4-1}$$

where $C_6H_{10}O_4$ is the approximate molecular composition of MSW. Then they combined the estimations of methane generation per ton of MSW from literatures with the amount of global landfilled MSW to obtain an estimate of global methane generation from landfilling. By assuming on the average the methane generation was at least 50 Nm^3 of methane per ton of MSW, they estimated the global generation of methane from landfilled MSW was in the order of 54 million tons of methane. This method requires small amount of data and is easy to apply, but can only provide a rough estimation because it assumes that all the biodegradables in MSW are reacted.

4.1.2 1996 IPCC Guidelines Default Method

In Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories [25], the default methodology for the calculation of CH_4 emission from land disposal of solid waste is based on:

1. the amount of waste deposited in different categories of solid waste disposal sites (SWDSs);
2. the fraction of degradable organic carbon and the amount which actually degrades; and,
3. the fraction of CH4 in landfill gas.

The model equation is as follows, the default values for some parameters are provided in the original document:

$$QCH_4 = (MSW_T \times MSW_F \times MCF \times DOC \times DOC_F \times F \times \frac{16}{12} - R) \times (1 - OX) \tag{4-2}$$

- QCH_4 annual CH_4 emission (Gg/yr)

MSW_T	total MSW generated (Gg/yr)
MSW_F	fraction of MSW disposed at SWDS
MCF	methane correction factor (fraction)
DOC	degradable organic carbon (fraction)
DOC_F	fraction DOC dissimilated
F	fraction by volume of CH_4 in landfill gas (default is 0.5)
16/12	molecular weight CH_4/C (ratio)
R	recovered CH_4 (Gg/yr)
OX	oxidation factor (fraction, default is 0)

The fraction of degradable organic carbon (DOC) can be calculated by Equation (4-3):

$$\mathrm{DOC} = 0.4\mathrm{A} + 0.17\mathrm{B} + 0.15\mathrm{C} + 0.30\mathrm{D} \tag{4-3}$$

A	per cent MSW that is paper and textiles
B	per cent MSW that is garden waste, park waste or other non-food organic putrescibles
C	per cent MSW that is food waste
D	per cent MSW that is wood or straw

where the multiplier numbers before A, B, C and D are default DOC values for the corresponding waste streams.

This is a simple method generating estimates of annual generation of LFG, based on mass balance equation. It assumes that all potential CH_4 is released in the first year after deposition of the MSW. The most suitable situation for this method is when the amount and composition of landfilled waste are constant or vary slowly over several decades. It will not provide a reliable estimate when the amount and composition of waste change significantly with time. [26]

4.1.3 U.S. EPA Landfill Gas Emissions Model (LandGEM)

The Landfill Gas Emissions Model (LandGEM) [27] was developed by U.S. EPA to estimate emission rates for total landfill gas, methane, carbon dioxide, nonmethane organic compounds, and individual air pollutants from municipal solid waste landfills. Equation (4-4) is used to estimate annual emissions over a time period specified by user, the default values for some parameters are provided in the original document.

$$QCH_4 = \sum_{i=1}^{n} \sum_{j=0.1}^{1} k \cdot L_o \cdot (M_i/10) \cdot e^{-k \cdot t_{ij}} \tag{4-4}$$

QCH_4	annual CH_4 generation in the year of the calculation (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	CH_4 generation rate (yr^{-1})
L_o	potential CH_4 generation capacity (m^3/Mg)
M_i	mass of waste accepted in the ith year (Mg)
t_{ij}	age of the jth section of waste mass M_i accepted in the ith year (decimal years, e.g., 3.2 years)

LandGEM is a relatively simple first-order method to calculate annual methane generation. It produces a time dependent generation profile and shows the pattern of degradation process over time, but its flexibility to deal with the effects of varying waste composition on CH_4 generation is limited. [26]

4.1.4 2006 IPCC Guidelines First-Order Decay (FOD) Method

The 2006 IPCC Guidelines methodology [20] for estimating CH_4 emissions from SWDS is based on the First-Order Decay (FOD) method described in an earlier IPCC report [28]. It is assumed that the degradable organic component (degradable organic carbon, DOC) in waste decays slowly throughout a few decades, during which CH_4 and CO_2 are generated. If conditions are constant, the amount of carbon remaining in the waste becomes the only factor affecting the rate of CH_4 generation. This leads to the trend that the CH_4 emissions from landfilled waste are highest in the first few years after disposal, then gradually decline as the degradable carbon in the waste is consumed during the degradation processes.

As shown in Table 4-1, there are three tiers of method to estimate CH_4 emissions from SWDS.

Equation (4-5) is used to estimate methane emissions from solid waste disposal for a single year.

$$CH_4\ emissions = \left[\sum_x CH_4\ generated_{x,T} - R_T\right] \cdot (1 - OX_T) \tag{4-5}$$

CH_4 emissions	CH_4 emitted in year *T*, Gg
CH_4 generated	amount of CH_4 generated from decomposable material
T	inventory year
x	waste category or type/material
R_T	recovered CH_4 in year *T*, Gg
OX_T	oxidation factor in year *T*, (fraction)

Table 4-1 Three Tiers of Method to Estimate CH_4 Emissions from SWDS [20]

Tier	*Method*	*Activity Data*	*Parameters*
Tier 1	IPCC FOD method	default	default
Tier 2	IPCC FOD method	good quality country-specific activity data on current and historical waste disposal at SWDS[a]	default (some)
Tier 3	1) IPCC FOD method, or 2) country specific methods	good quality country-specific activity data on current and historical waste disposal at SWDS[a]	1) nationally developed key parameters[b], or 2) measurement derived country-specific parameters[b]

a. Historical waste disposal data for 10 years or more should be based on country-specific statistics, surveys or other similar sources. Data are needed on amounts disposed at the SWDS.

b. Key parameters should include the half-life, and either methane generation potential (L_o) or DOC content in waste and the fraction of DOC which decomposes (DOC_f).

There are a series of equations for the calculation of CH_4 generated, the complete equations are provided in Annex B . The original document provides default values for some parameters.

The 2006 IPCC guidelines FOD method, like LandGEM, produces time dependent generation profile and shows the pattern of degradation process over time. It requires a large amount of data on current as well as historic waste deposition, composition and management practices; it is suggested to collect data for at least 50 years [12]. Due to the consideration of many factors that may affect landfill gas emission, the results produced by this method are relatively accurate. [26, 29]

4.1.5 Back-Calculation Method

Because of the development of greenhouse gas monitoring and reporting programs in recent years, such as the Greenhouse Gas Reporting Program (GHGRP) [30] of the U.S. EPA, as measured data at landfill facilities level become available, these data can be used to increase the accuracy of the model estimations. The GHGRP requires that, facilities emitting 25,000 metric tons or more of GHGs (CO_2 e) per year are required to report their annual emissions starting from 2010 [31]. A summary about GHGRP emission measurement and calculation methodologies is provided in Annex C.

The back-calculation method is based on directly measured amounts of CH_4 recovered from landfill gas and is expressed by Equation (4-6) (Equation HH-8 in 40 CFR § 98.343 [32]). The first part of the equation considers the portion of CH_4 in the landfill gas that is not collected by the landfill gas collection system, and the second part considers the portion that is captured. [2]

$$\mathrm{CH_4},\ \text{Solid Waste} = \left[\left(\frac{R}{CE \times f_{REC}} - R\right) \times (1 - OX) + R \times \left(1 - (DE \times f_{Dest})\right)\right] \tag{4-6}$$

◆ CH_4, Solid Waste	CH_4 emissions from the landfill in the reporting year (metric tons)
◆ R	Quantity of recovered CH_4 from Equation HH-4 of EPA's GHGRP (metric tons)
◆ CE	Collection efficiency estimated at the landfill, considering system coverage, operation, and cover system materials from Table HH-3 of EPA's GHGRP. If area by soil cover type information is not available, the default value of 0.75 should be used. (percent)
◆ f_{REC}	fraction of hours the recovery system was operating (percent)
◆ OX	oxidation factor (percent)
◆ DE	destruction efficiency (percent)
◆ f_{Dest}	fraction of hours the destruction device was operating (fraction)

Due to the use of directly measured facility-level data from many landfills, this method provides a much more accurate estimation than other methods.

4.1.6 Summary

A summary of the classification, kinetics order and characteristics of the developed models described above is provided in Table 4-2. It should be noted that both the rationality of model and the quality of data play vital roles in the accuracy of the estimation. Sometimes a simpler model with higher quality (higher tier) data can produce more accurate results than a complex model.

Table 4-2 Developed Models for Estimation of Methane Emission from Landfills

Model	*Classification*	*Kinetics Order*	*Characteristics*
1. Themelis & Ulloa Method	stoichiometrical model	NA	• simple method based on the empirical formula of MSW • gives rough estimation about the maximum generation of methane per ton of MSW
2. 1996 IPCC Guidelines Default Method	simplified deterministic model / static model	Zero-Order	• simple method based on mass balance equation, tending to make overestimation • unable to deal with the amount and composition change of waste over time
3. U.S. EPA LandGEM	simplified deterministic model / dynamic model	First-Order	• relatively simple method, generating time dependent emission trend • lacks the flexibility to deal with the amount and composition change of waste over time
4. 2006 IPCC Guidelines FOD Method	complex deterministic model / dynamic model	First-Order	• relatively complex method, generating time dependent emission trend • requires data on waste generation, waste composition and waste management practices over several decades • provides relatively accurate estimation
5. Back-Calculation Method	stochastic model (empirical model)	NA	• uses directly measured facility-level data • generates the most accurate estimation among all methods

NA – Not Applicable

4.2 Country- or Region-Specific Models

The U.S. EPA Landfill Methane Outreach Program (LMOP) [33] is a program that promotes the recovery and beneficial use of biogas generated from municipal solid waste (MSW). Several country- or region-specific landfill gas generation models have been developed for the program, and they are organized by the Global Methane Initiative (GMI) [34].

These models can be used to estimate landfill gas generation rates, and potential landfill gas recovery rates for landfills that have, or plan to have, gas collection and control systems in specific countries or regions. The modeling results can help evaluate the feasibility and potential benefits of collecting and using LFG for energy recovery.

A list of these models is shown in Table 4-3. They are similar methods with different country- or region-specific parameter values, and some of them are mutually referenced. The equations of all models are based on U.S. EPA LandGEM model (Version 3.02), except for the Ecuador Landfill Gas Model, whose equations are based on the Mexico Landfill Gas Model (Version 1.0). The 2006 IPCC Guidelines FOD Method has been referenced by all these models.

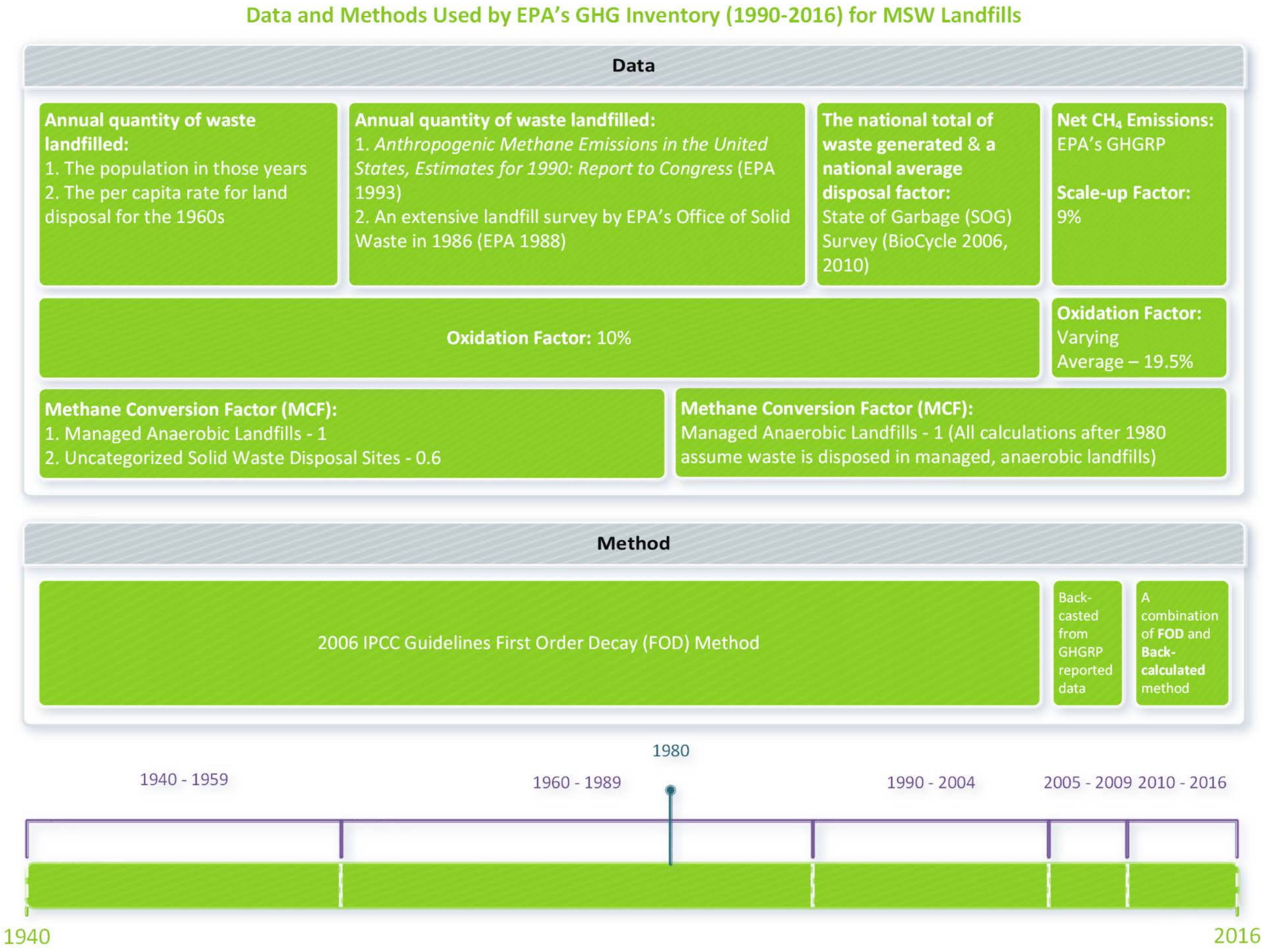
Table 4-3 Country- or Region-Specific Landfill Gas Models

Region	*Model*
Asia	China Landfill Gas Model (Version 1.1) [35] Philippines Landfill Gas Model (Version 1.0) [36] Thailand Landfill Gas Model (Version 1.0) [37]
Central America	Central American Landfill Gas Model (Version 1.0) [38]. Applicable Countries: Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, and Panama
Europe	Ukraine Landfill Gas Model (Version 1.0) [39]
North America	Mexico Landfill Gas Model (Version 2.0) [40]
South America	Colombia Landfill Gas Model (Version 1.0) [41] Ecuador Landfill Gas Model (Version 1.0) [42]

4.3 Current LFG Emission Estimates at the U.S. Level

Methane emissions from landfill are related to historical situation, as suggested by the 2006 IPCC Guidelines [12], at least 50 years of data about waste generation, waste composition and waste management practices should be used. Generally, such data from several decades ago are not available or are insufficient and relatively inaccurate, although the data quality has been improving over time.

In the U.S. EPA's GHG Inventory [2], different data and methods were used to different time periods to estimate methane emission from landfills, as per the requirement of the 2006 IPCC Guidelines. A summary of the data and methods used is shown in Figure 4-1, which is a good example to demonstrate how the IPCC guidelines method could be used for different periods of time; the detailed documentation can be found in Section 7.1 of EPA's GHG Inventory and its Annex 3.14 [43].



Data and Methods Used by EPA's GHG Inventory (1990-2016) for MSW Landfills

Data

Annual quantity of waste landfilled:
1. The population in those years
2. The per capita rate for land disposal for the 1960s

Annual quantity of waste landfilled:
1. *Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress* (EPA 1993)
2. An extensive landfill survey by EPA's Office of Solid Waste in 1986 (EPA 1988)

The national total of waste generated & a national average disposal factor: State of Garbage (SOG) Survey (BioCycle 2006, 2010)

Net CH_4 Emissions: EPA's GHGRP

Scale-up Factor: 9%

Oxidation Factor: 10%

Oxidation Factor: Varying Average – 19.5%

Methane Conversion Factor (MCF):
1. Managed Anaerobic Landfills - 1
2. Uncategorized Solid Waste Disposal Sites - 0.6

Methane Conversion Factor (MCF): Managed Anaerobic Landfills - 1 (All calculations after 1980 assume waste is disposed in managed, anaerobic landfills)

Method

2006 IPCC Guidelines First Order Decay (FOD) Method

Back-casted from GHGRP reported data

A combination of **FOD** and **Back-calculated** method

Figure 4-1 Data and Methods Used by U.S. EPA's GHG Inventory (1990-2016) for MSW Landfills

As reported in the inventory, in 2016, landfill methane (CH_4) emissions in the U.S. were approximately 107.7 *million metric tons of CO_2 e*, or 4306 *kilotons (kt) of CH_4*, accounting for about 16.4 percent of total U.S. anthropogenic CH_4 emissions in 2016. Landfills were the third largest source of methane emissions in the U.S., behind enteric fermentation (the largest) and natural gas systems. Additionally, in 2016, GHG emissions from all waste sectors in the U.S. were 131.5 *Mt CO_2 e*, or 2.0 percent of total U.S. GHG emissions. These data are shown in Table 4-4.

Table 4-4 U.S. Landfill CH_4 Emissions: 1990 – 2016 [2]

Year	*1990*	*2005*	*2012*	*2013*	*2014*	*2015*	*2016*
Emissions (kt)	7182	5310	4680	4531	4509	4467	4306
Emissions (Mt CO_2 e)	179.6	132.7	117.0	113.3	112.7	111.7	107.7

The U.S. landfill CH_4 emissions projections to 2030, as estimated by EPA [44], are shown in Table 4-5.

Table 4-5 U.S. Landfill CH_4 Emissions Projections: 2010 – 2030 [44]

Year	*2010*	*2015*	*2020*	*2025*	*2030*
Emissions (Mt CO_2 e)	129.7	128.4	127.7	128.0	128.0

From these results, it is shown landfill methane emissions in the U.S. have decreased significantly since 1990 and are estimated to stay stable to 2030.

4.4 Current LFG Emission Estimates at the Global Level

In 2012, U.S. EPA [3] estimated global landfill methane emissions, past and projected from 1990 to 2030, (Table 4-6). These numbers were calculated by a combination of 1) National Communications projections reported by countries when available, 2) 2006 IPCC Guidelines tier 1 method, and 3) other methods (e.g. the tier 2 method), and various data sources. The detailed documentation on methods applied for each country and data sources can be found in Table G-5 and Appendix H to the EPA's Report [45].

Table 4-6 Global Methane Emissions from Landfill: 1990 – 2030 [3]

Year	*1990*	*1995*	*2000*	*2005*	*2010*	*2015*	*2020*	*2025*	*2030*
Emissions (Mt CO_2 e)	706.1	755.4	769.8	794.0	846.7	875.6	905.0	933.3	959.4

Between 1990 and 2005, global landfill CH_4 emissions were estimated to have increased by about 12 percent, from 706 to 794 *Mt CO_2 e*. Growing populations, increases in personal income, and expanding industrialization result in increases in waste generation amount and are driving factors for this trend. In 2005, landfilling of solid waste was the third largest individual source of global CH_4 emissions, after enteric fermentation (the largest) and natural gas & oil systems. From 2005 to 2030, emissions are projected to increase by about 21 percent from 794 to 959 *Mt CO_2 e*. Also, the waste sector accounted for 13 percent of total non-CO_2 GHG emissions in 2005, of which 58 percent were contributed by landfilling of solid waste (CH_4). Therefore, the fraction of landfill CH_4 emissions to total non-CO_2 GHG emissions was about 7.5 percent. [3]

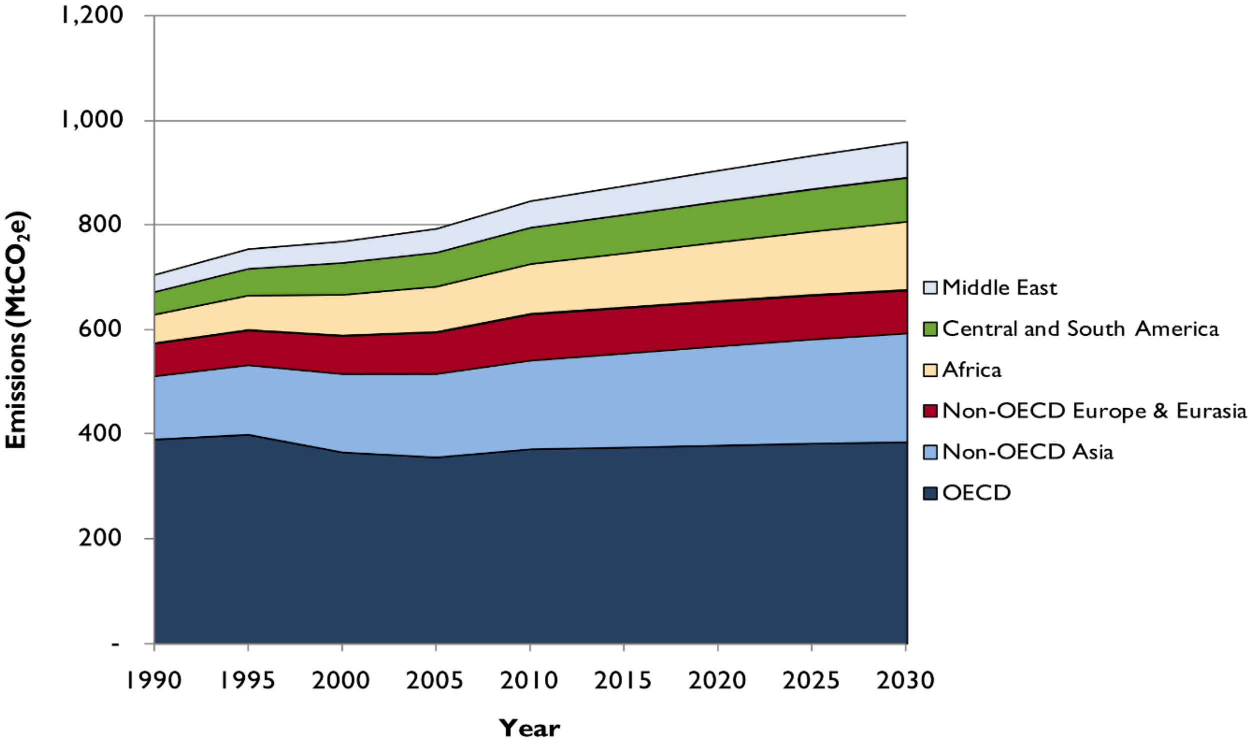


Figure 4-2 CH_4 Emissions from Landfilling of Solid Waste: 1990 – 2030 (*Mt CO_2 e*) [3]

Landfill wastes are projected to be stable or decline in developed countries due to regulations that encourage such practices. On the other hand, the trend of landfill methane in developing countries is expected to increase due to increased urbanization and a parallel increase in controlled landfilling. However, both developed and developing countries are experiencing increased public scrutiny of GHGs from landfilling (and other waste management activities). [3]

Table 4-7 shows the landfill methane emissions projections for different regions; the top five emitting countries are United States, Mexico, Russia, China and Malaysia.

Table 4-7 Projected Baseline Emissions for MSW Landfills by Region: 2010–2030 (*Mt* CO_2 *e*) [44]

Country / Region	*2010*	*2015*	*2020*	*2025*	*2030*	*CAGR*[a] *(2010-2030)*
Top 5 Emitting Countries						
United States	129.7	128.4	127.7	128.0	128.0	-0.1%
Mexico	56.4	59.5	62.5	65.2	67.7	0.9%
Russia	47.2	46.1	44.8	43.4	42.1	-0.6%
China	47.1	48.2	49.0	49.4	49.3	0.2%
Malaysia	29.9	32.5	35.1	37.8	40.3	1.5%
Rest of Regions						
Asia	133.2	135.1	138.4	141.5	144.4	0.4%
Africa	101.2	106.5	111.9	117.3	122.4	1.0%
Europe	87.2	92.4	96.8	100.9	104.6	0.9%
Central & South America	71.4	74.2	76.8	79.1	81.1	0.6%
Middle East	67.3	72.3	77.1	81.7	86.1	1.2%
Eurasia	55.8	58.6	61.5	64.3	66.8	0.9%
North America	20.3	21.9	23.3	24.8	26.5	1.3%
World Total	**846.7**	**875.6**	**905.0**	**933.3**	**959.4**	**0.6%**

a. CAGR: Compound Annual Growth Rate

5. Calculation and Analysis

5.1 Methane Generation and Emission per ton of MSW in the U.S.

5.1.1 Maximum Methane Generation per ton of MSW in the U.S.

As noted earlier, in 2006, Themelis and Ulloa [6] used the empirical formula of MSW to estimate the maximum generation of methane per ton of MSW by Equation (4-1). While the formula ($C_6H_{10}O_4$) was developed for combustion process [46], since some components of MSW are combustible but are not degradable, such as plastics, and also the moisture content in MSW was assumed to be 60%, a more accurate estimation can be made based on detailed data.

Table 5-1 presents data on chemical composition and empirical formula of MSW components, carbon (C) is always assigned 6 in empirical formulas because there are ten organic molecule starting with C_6.

Table 5-1 Chemical Composition and Empirical Formula of Dry MSW Components

Component	*Percent by weight (dry basis) [47]*						*Empirical Formula*
	Carbon	*Hydrogen*	*Oxygen*	*Nitrogen*	*Sulfur*	*Ash*	
Organic							
Food wastes	48.0	6.4	37.6	2.6	0.4	5.0	$C_6H_{9.6}O_{3.5}N_{0.28}S_{0.02}$
Mixed paper							$C_6H_{9.6}O_{4.6}N_{0.036}S_{0.01}$ [6]
Paper	43.5	6.0	44.0	0.3	0.2	6.0	$C_6H_{9.9}O_{4.6}N_{0.035}S_{0.01}$
Cardboard	44.0	5.9	44.6	0.3	0.2	5.0	$C_6H_{9.7}O_{4.6}N_{0.035}S_{0.01}$
Plastics	60.0	7.2	22.8	-	-	10.0	$C_6H_{8.6}O_{1.7}$
Textiles	55.0	6.6	31.2	4.6	0.15	2.5	$C_6H_{8.6}O_{2.6}N_{0.43}S_{0.006}$
Rubber	78.0	10.0	-	2.0	-	10.0	$C_6H_{9.2}N_{0.13}$
Leather	60.0	8.0	11.6	10.0	0.4	10.0	$C_6H_{9.6}O_{0.9}N_{0.86}S_{0.015}$
Yard wastes	47.8	6.0	38.0	3.4	0.3	4.5	$C_6H_{9.0}O_{3.6}N_{0.37}S_{0.014}$
Wood	49.5	6.0	42.7	0.2	0.1	1.5	$C_6H_{8.7}O_{3.9}N_{0.02}S_{0.005}$
Inorganic							
Glass	0.5	0.1	0.4	<0.1	-	98.9	
Metals	4.5	0.6	4.3	<0.1	-	90.5	
Dirt, ash, etc.	26.3	3.0	2.0	0.5	0.2	68.0	

Table 5-2 shows the amount of landfilled MSW in the U.S. in 2015 and the typical moisture content in different components of MSW.

Table 5-2 Amount of Landfilled MSW in the U.S. (2015) and Typical Moisture Content

Materials	*Amount [48]*		*Moisture Content (Typical) [49]*	*Dry Weight in Total MSW (Percentage)*	*Empirical Formula*
	Weight (kt)	*Percentage*			
Paper and Paperboard	18280	13.3%	6%	12.50%	$C_6H_{9.6}O_{4.6}N_{0.036}S_{0.01}$
Glass	6970	5.1%	2%		
Metals					
Ferrous	9970	7.2%			
Aluminum	2440	1.8%	2%		
Other Nonferrous	660	0.5%	3%		
Total Metals	13070	9.5%			
Plastics	26010	18.9%	2%		
Rubber and Leather[a]	4480	3.3%			
Rubber	3570	2.63%	2%	2.58%	$C_6H_{9.2}N_{0.13}$
Leather	910	0.67%	10%	0.60%	$C_6H_{9.6}O_{0.9}N_{0.86}S_{0.015}$
Textiles	10530	7.6%	10%	6.84%	$C_6H_{8.6}O_{2.6}N_{0.43}S_{0.006}$
Wood	11060	8.0%	20%	6.40%	$C_6H_{8.7}O_{3.9}N_{0.02}S_{0.005}$
Other	3040	2.2%			
Total Materials in Products	93440	67.9%			
Other Wastes					
Food	30250	22.0%	70%	6.60%	$C_6H_{9.6}O_{3.5}N_{0.28}S_{0.02}$
Yard Trimmings	10800	7.8%	50%	3.90%	$C_6H_{9.0}O_{3.6}N_{0.37}S_{0.014}$
Miscellaneous Inorganic Wastes	3210	2.3%			
Total Other Wastes	44260	32.1%			
Total MSW Landfilled	137700	100.0%			

a. Rubber and leather are divided following the fraction of durable and nondurable goods in total rubber and leather landfilled, by roughly assuming rubber is durable and leather is nondurable.

Taking into account that paper and paperboard, leather, textiles, wood, food and yard trimmings are biodegradable organic wastes, their fraction in total landfilled waste is calculated to be 59.4% on wet basis, and is 36.8% on dry basis.

The empirical formula of dry degradable organic waste is calculated as $C_6H_{9.21}O_{3.73}N_{0.20}S_{0.01}$; ignoring nitrogen (N) and sulfur (S), then Equation (4-1) (or Equation (2-4)) is rebalanced as follows:

$$C_6H_{9.21}O_{3.73} + 1.83H_2O = 3.22CH_4 + 2.78CO_2 \tag{5-1}$$

Based on the data and the equation above, 1 ton of MSW, which contains 368.4 *kg* of $C_6H_{9.21}O_{3.73}$, will generate 0.135 *ton* (or 189 Nm^3) of CH_4 at maximum. Comparing to 0.149 *ton* (or 208 Nm^3) of CH_4 per ton of MSW, which was estimated by Themelis and Ulloa [6], these numbers are 9% lower.

5.1.2 Actual Methane Emissions per ton of MSW in the U.S.

Table 5-3 shows the actual methane emissions per ton of MSW in the U.S. from 1990 to 2015, based on reported estimates [48, 50]. Comparing to the maximum generation of 0.135 ton CH_4 / ton MSW, the actual emissions per unit are much lower, for example, in 2015, methane emissions per ton of MSW was 0.0324 ton, which is only 24% of the estimated maximum generation per unit. The reason of the gap could be: 1) landfill gas collection systems, landfill gas destruction (flaring) and utilization projects reduce the methane emissions, 2) the intrusion of air at some parts of the landfill diverts the anaerobic degradation to aerobic degradation, 3) the biodegradable components in MSW cannot fully biodegrade due to their intrinsic properties and other limiting factors such as water content, temperature and pH.

Table 5-3 Actual Methane Emissions per ton of MSW in the U.S.: 1990 – 2015

Year	*1990*	*2000*	*2005*	*2010*	*2014*	*2015*
Landfilled MSW (kt) [48]	145270	140260	142290	136310	136170	137700
CH_4 Emissions from Landfill (Gg CO_2 e) [50]	179551	141408	132742	124802	112716	111665
CH_4 Emissions from Landfill (kt)	7182	5656	5310	4992	4509	4467
CH_4 Emissions (t / t of MSW)	0.0494	0.0403	0.0373	0.0366	0.0331	0.0324

In Table 5-3, a decreasing trend in methane emissions per ton of MSW is shown; this may be attributed to the diversion of organic waste from landfilling to other waste treatment practices, such as windrow, composting and anaerobic digestion.

It should be noticed that, since there exists lag time between the deposition of MSW in landfill and the start of landfill gas generation, and the waste disposed in previous years also influences current emissions a lot, such statistics calculated from the landfill methane emissions and landfilled MSW quantities in the same year are not ideally comparable, however, as a normalized statistic, methane emissions per ton of MSW deposited in a certain year is still a useful indicator on this issue.

5.1.3 Reconciliation of LFG Generation with Emission and Other Destinations of LFG

In the previous section, the maximum generation of methane in U.S. landfills was estimated at 0.135 ton CH_4 / ton MSW, while the methane emissions calculated from the EPA estimates [48, 50] were only 0.0324 ton CH_4 / ton MSW. In this section, we shall explore the difference between these numbers.

In Table 5-4, the biodegradable organic fraction $(f_b)_i$ indicates that the organic components in MSW can only biodegrade to certain degrees. The fraction of the biodegraded dry MSW components are calculated by using the dry weight of that component in total MSW to multiply the corresponding $(f_b)_i$. The overall degree of the biodegradation of the dry biodegradable components in U.S. MSW is estimated to be 53.6% (= 20.5 / 38.2). Therefore, if the theoretical maximum CH_4 generation from U.S. MSW is 0.135 ton CH_4 / ton MSW, then the expected CH_4 generation at 53.6% biodegradation would be 0.072 ton CH_4 / ton MSW. In addition, the organic content OC_i can be compared to the empirical formulas of different MSW components calculated in Section 5.1.1.

Table 5-4 Biodegradability of Various Components in MSW

Waste component	u_i *(kg H_2O/kg wet component) [15]*	OC_i *(kg C/kg dry component) [15]*	$(f_b)_i$ *(kg biodeg. C/kg C) [15]*	*Wet Weight in Total MSW (%) [48]*	*Dry Weight in Total MSW (%)*	*Biodeg. Dry Weight in Total MSW (%)*
Food Waste	0.6	0.48	0.8	22.0	8.8	7.0
Yard Waste	0.5	0.48	0.7	7.8	3.9	2.7
Paper and Cardboard	0.08	0.44	0.5	13.3	12.2	6.1
Textiles	0.1	0.55	0.2	7.6	9.0	1.4
Wood	0.2	0.5	0.5	8.0	16.0	3.2
Total	\	\	\	**58.7**	**38.2**	**20.5**

u_i – Moisture Content, OC_i – Organic Content, $(f_b)_i$ – Biodegradable Organic Fraction

In an attempt to use this expected CH_4 generation value to estimate the U.S. landfill CH_4 emissions, the following numbers were obtained by Nickolas Themelis from the master tabulation of all U.S. landfills by the LMOP of EPA [51].

The following assumptions were made in this computation:

a) The capacities of the electrical generators using LFG were added (2,989 MW) and the sum was multiplied by 8,000 hours per year to arrive to the maximum possible MWh generated in the U.S. landfills (23,912,000 MWh/year). Then, the tonnage of methane used in this generation was calculated by considering the high heating value of methane (55.5 MJ/kg) [52] and assuming 40% thermal efficiency in the conversion of methane energy to electrical energy (3.88 Mt CH_4).

b) Using the same LMOP tabulation, the flowrates of LFG recorded by U.S. landfills were added up (1413.2 million standard cubic feet (mmscfd) per day), and the average methane percentage in LFG was 46.9%, then the corresponding tonnage of methane was calculated as 4.89 Mt CH_4.

c) The total tonnages of landfilled MSW in operational landfills were added up (330.83 Mt) and multiplied to the expected 0.072 ton CH_4 / ton MSW, resulted in 23.82 Mt CH_4. Then the emissions were estimated by deducting the amount for generating electricity (3.88 Mt CH_4) and the flared amount (4.89 Mt CH_4) from the expected generation (23.82 Mt CH_4), which resulted in 15.05 Mt CH_4.

This estimated emissions are much larger than EPA's estimation for 2016, which was 4.31 Mt [2]. The gap can be partially attributed to the reasons as stated in Section 5.1.2, while more efforts are needed to further mind this gap.

Another issue to be noted is the underestimation of the U.S. landfilled MSW in the EPA's annual summary figures and tables about waste management [48]. In the calculations above, the total tonnages of landfilled MSW in operational landfills were estimated to be 330.83 Mt (2016), whereas the number in EPA's summary figures and tables was only 137.7 Mt (2015). According to Shin [53], in 2011, the tonnage of landfilled MSW in the U.S. was 247 million tons, which was 113 million tons larger than EPA's estimation. The underestimation of landfilled MSW in EPA's figures and tables is further confirmed in Section 5.2.3, where the total tonnage of landfilled MSW in all the GHGRP landfills is calculated as 280.9 Mt in 2015.

5.2 Landfill Methane Generation, Recovery and Emission in Different Climate Zones

As discussed in previous chapters, climate plays a critical role in landfill gas generation and emission. U.S. EPA Envirofacts database [54] provides GHGRP facility-level data, including GHG data and many other data elements used to determine GHG values. The location of landfills can be found in GHGRP Data Summary Spreadsheets [55]. By combining these data with the climate zone GIS data [56], then the characteristics of landfill gas at different climate zones can be obtained. The classification methods used and the associated results are presented in the following sections.

5.2.1 Köppen-Geiger Climate Classification and IPCC SRES Emissions Scenarios

The Köppen-Geiger climate classification is one of the most widely used climate classification systems. In this system, the climates are divided into five main groups: 1) equatorial, 2) arid, 3) warm temperate, 4) snow and 5) polar [57]. In 2010, Rubel and Kottek [56] made an updated world map of Köppen-Geiger climate classification, in which the sub climate groups were classified based on temperature and precipitation observations for the period 1951-2000. They also provided a series of digital world maps for the extended period 1901-2100 to depict global trends in observed climate and projected climate change scenarios. The projected global climate maps were developed by considering different IPCC emissions scenarios.

In 2000, IPCC [58] developed a set of emissions scenarios to reflect the significant changes (since 1992) in the understanding of driving forces of emissions and methodologies from the previous scenarios. The driving forces of future GHG emission trajectories were identified as demographic change, social and economic development, and the rate and direction of technological change. In order to describe the relationships between these driving forces and their evolution and add context for the scenario quantification, four different narrative storylines were developed.

In total, there are 40 scenarios. All the scenarios based on the same storyline constitute a scenario “family”, in which each scenario represents a specific quantitative interpretation of the corresponding storyline. There are two types of scenarios in each scenario family: 1) harmonized scenarios and 2) scenarios that explore additional uncertainties beyond differences in methodologic approaches.

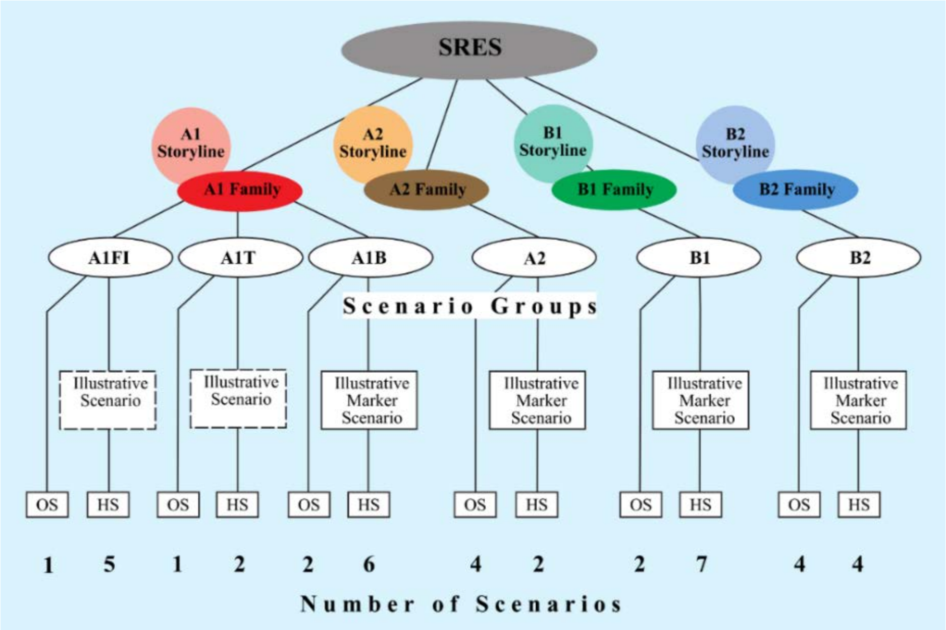


Figure 5-1 Schematic Illustration of IPCC SRES Scenarios [58]

As shown in Figure 5-1, six scenario groups are divided in four families (A1, A2, B1, B2). There are three scenario groups (A1FI, A1T, A1B) in A1 family which explore different energy technology developments while holding the other driving forces constant. Each scenario group is assigned an illustrative scenario, and for each of the four groups, a marker scenario is assigned. Although the marker scenarios are considered as illustrative of a particular storyline, all scenarios should be considered to have the same possibilities. The characteristics of the four scenario families are summarized in Table 5-5.

Table 5-5 Main Characteristics of the Four IPCC SRES Storylines and Scenario Families [58]

Scenario Family	*Scenario Group*	*Underlying Theme*	*Characteristics*
A1	A1FI A1T A1B	convergence among regions, capacity building, and increased cultural and social interactions	• ***Demography***: global population peaks in mid-century and declines thereafter • ***Economy***: very rapid economic growth, a substantial reduction in regional differences in per capita income • ***Technology***: rapid introduction of new and more efficient technologies, three A1 groups differ in directions of technological change in the energy system (A1FI: fossil intensive, A1T: non-fossil, A1B: a balance across all sources)
A2	A2	a very heterogeneous world, self-reliance and preservation of local identities	• ***Demography***: continuously increasing global population • ***Economy & Technology***: primarily regionally oriented economic development, per capita economic growth and technological change are more fragmented and slower than in other storylines.
B1	B1	a convergent world, emphasis on global solutions to economic, social, and environmental sustainability	• ***Demography***: global population peaks in mid-century and declines thereafter • ***Economy***: rapid changes in economic structures toward a service and information economy • ***Technology***: reductions in material intensity, and the introduction of clean and resource-efficient technologies
B2	B2	a world in which the emphasis is on local solutions to economic, social, and environmental sustainability	• ***Demography***: continuously increasing global population at a rate lower than A2 • ***Economy***: intermediate levels of economic development • ***Technology***: less rapid and more diverse technological change than in the B1 and A1 storylines

Because of the equal possibility of each scenario, it is recommended by IPCC to use a range of SRES scenarios with a variety of assumptions regarding driving forces in any analysis. Thus, Rubel and Kottek [56] provided the digital world maps of Köppen-Geiger climate classification for different time periods according to four IPCC SRES scenarios: A1FI, A2, B1, B2. The data have been extracted and processed to Figure 5-2, which shows the U.S. map of Köppen-Geiger climate classification for 2001-2025.

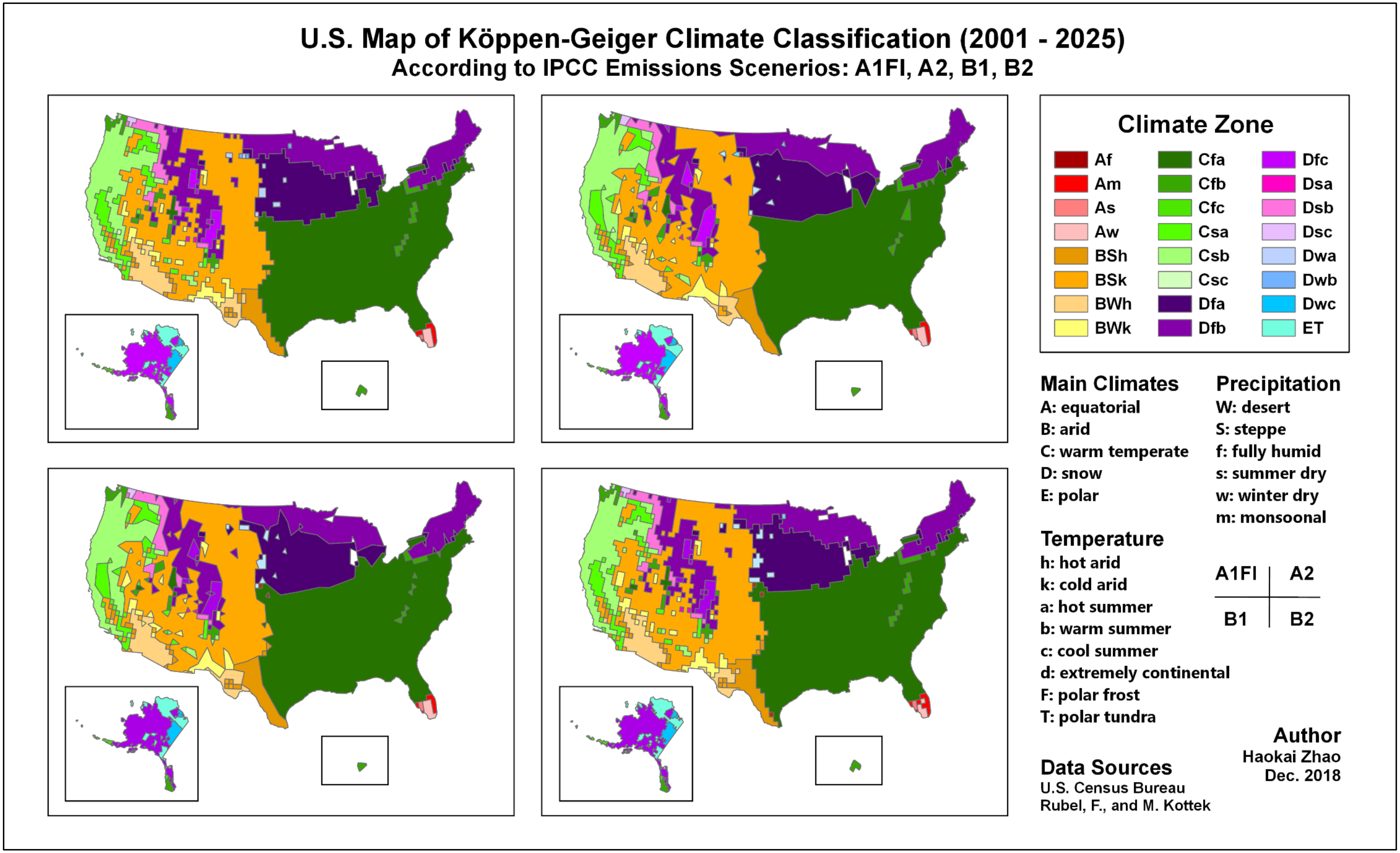


Figure 5-2 U.S. Map of Köppen-Geiger Classification (2001 – 2025)

According to International Energy Agency (IEA) [59], in 2016, coal, primary and secondary oil and natural gas constituted about 81% of the total primary energy supply (TPES) in the world, and fossil fuels had dominated the global energy supply for many years. Besides, since the differences between the four climate classification maps in Figure 5-2 are not very significant, the analysis in this section will be based on the map according to A1FI (fossil intensive) emissions scenario, which contains 24 climate zones (out of 31 in total in the world), and the procedure is transferable to other emissions scenarios.

In addition, it is interesting to observe the overlapping map of climate and nightlights. As shown in Figure 5-3, the nightlights map obtained from NASA [60] is overlapped with U.S. climate zone map (2001-2025, A1FI), it shows nightlights can be an illustrative indicator to reflect the degree of human activity and the habitability of certain climate zone.

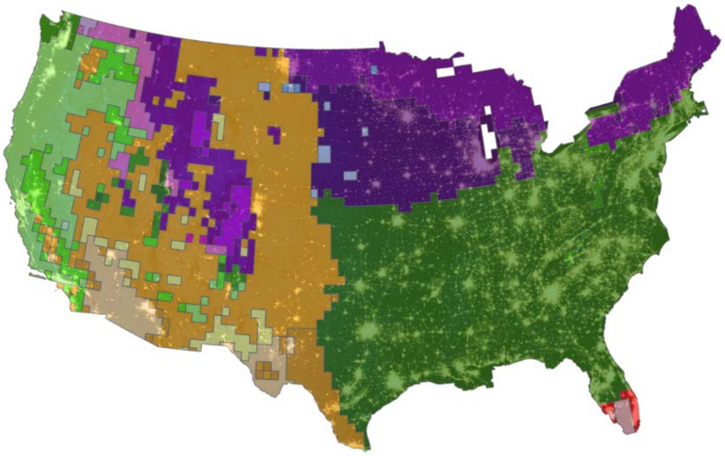


Figure 5-3 Comparison of Climate Zones and Nightlights Distribution in Contiguous U.S.

5.2.2 Methane Generation Rate (*k*)

As discussed in section 3.4, methane generation rate (*k*) of MSW is an important factor in landfill gas generation or emission models, and it varies in different climate zones. In GHGRP, landfills report *k* values that are used in the estimation of landfill gas generation, there are three ways to conduct the calculation [61]:

1) Bulk Waste Option
2) Modified Bulk Waste Option:
    - Bulk MSW Waste (excluding inerts and C&D waste)

- Bulk C&D (Construction and Demolition) Waste
- Inerts (e.g. glass, plastics, metal, cement)

3) Waste Composition Option:
   - Food Waste
   - Garden
   - Sewage Sludge
   - Paper
   - Wood and Straw
   - Textiles
   - Diapers
   - Inerts (e.g. glass, plastics, metal, cement)

The default values of *k* are provided in Table HH-1 of GHGRP Subpart HH: Municipal Solid Waste Landfills [32], which are presented in Table 5-6. Unlike the default values of *k* recommended by IPCC in Table 3-5, which are given under the consideration of mean annual temperature (MAT), mean annual precipitation (MAP) and potential evaporation (PET), the values provided by GHGRP are according to the precipitation plus recirculated leachate (P+RL). For Waste Composition Option, the potential evapotranspiration (PET) rate is an additional criterion. For Bulk Waste Option, the default *k* values are given as fixed numbers, while for the other two options, the default values are given as ranges.

The *k* values used by individual landfills in GHGRP are obtained from U.S. EPA Envirofacts database [54]; the detailed information can be found in Annex G. The reporting year is selected as 2017, while the data table contains the information from the first year of reporting to GHGRP to the current (selected) reporting year, which can be traced back to 2010 as the earliest.

After confirming that there is no outlier in the data, the typical values of *k* under five main climate types are summarized in Table 5-7, as the means of data samples. The ranges (min, max) and the sample sizes of *k* are shown in Table 5-8 and Table 5-9, respectively. It should be noted that there is an additional bulk waste type in Waste Composition Option from the data, which is not listed in the GHGRP documentation. The results of this type under Waste Composition Option are similar to that of Bulk Waste Option, although there still exist differences. The more detailed results of 24 climate zones are provided in Annex D.

Table 5-6 Default Values of Methane Generation Rate (*k*) in GHGRP [32]

Bulk Waste Option[a]			*Modified Bulk Waste Option*[a,b]			*Waste Composition Option*[a,c]							
Bulk Waste			*Bulk MSW Waste*[d]	*Bulk C&D Waste*	*Inerts*	*Food Waste*	*Garden*	*Sewage Sludge*	*Paper*	*Wood and Straw*	*Textiles*	*Diapers*	*Inerts*
P+RL<20 inches/year	P+RL:20-40 inches/year	P+RL>40 inches/year											
0.02	0.038	0.057	0.02 – 0.057	0.02 – 0.04	0	0.06 – 0.185	0.05 – 0.1	0.06 – 0.185	0.04 – 0.06	0.02 – 0.03	0.04 – 0.06	0.05 – 0.1	0

P+RL – Precipitation plus Recirculated Leachate; PET – Potential Evapotranspiration.

a. Landfills that use leachate recirculation can elect to use the greater value rather than calculating the recirculated leachate rate.

b. Use the lesser value when P+RL is less than 20 inches/year. Use the greater value when P+RL is greater than 40 inches/year. Use the average of the range of values when P+RL is 20 to 40 inches/year (inclusive).

c. Use the lesser value when the PET rate exceeds the mean annual P+RL. Use the greater value when the PET rate does not exceed the mean annual P+RL.

d. Excluding inerts and C&D waste.

Table 5-7 Typical Values (Mean) of Methane Generation Rate (*k*) under Five Main Climate Types

Main Climate	*Bulk Waste Option*	*Modified Bulk Waste Option*			*Waste Composition Option*								
	Bulk Waste	*Bulk MSW Waste*[a]	*Bulk C&D Waste*	*Inerts*	*Bulk Waste*	*Food Waste*	*Garden*	*Sewage Sludge*	*Paper*	*Wood and Straw*	*Textiles*	*Diapers*	*Inerts*
A	0.045	0.055	0.04	0	0.053								0
B	0.022	0.02	0.02	0	0.021			0.185	0.06		0.06	0.1	0
C	0.049	0.050	0.036	0	0.047	0.091	0.058	0.112	0.06	0.03	0.06	0.1	0
D	0.039	0.040	0.032	0	0.039	0.185	0.1	0.144	0.06	0.028	0.06	0.1	0
E													
Overall	0.045	0.046	0.034	0	0.043	0.148	0.075	0.126	0.06	0.029	0.06	0.1	0

a. Excluding inerts and C&D waste.

Table 5-8 Ranges of Methane Generation Rate (*k*) under Five Main Climate Types

Main Climate	*Bulk Waste Option*	*Modified Bulk Waste Option*			*Waste Composition Option*								
	Bulk Waste	*Bulk MSW Waste*[a]	*Bulk C&D Waste*	*Inerts*	*Bulk Waste*	*Food Waste*	*Garden*	*Sewage Sludge*	*Paper*	*Wood and Straw*	*Textiles*	*Diapers*	*Inerts*
A	0.02 – 0.057	0.0295 – 0.057	0.04	0	0.038 – 0.057								0
B	0.02 – 0.038	0.02	0.02	0	0.02 – 0.038			0.185	0.06		0.06	0.1	0
C	0.02 – 0.057	0.02 – 0.057	0.02 – 0.04	0	0.02 – 0.057	0.06 – 0.185	0.05 – 0.1	0.06 – 0.185	0.06	0.02 – 0.04	0.06	0.1	0
D	0.02 – 0.057	0.02 – 0.057	0.02 – 0.04	0	0.02 – 0.057	0.185	0.1	0.1225 – 0.185	0.06	0.025 – 0.03	0.06	0.1	0
E													
Overall	0.02 – 0.057	0.02 – 0.057	0.02 – 0.04	0	0.02 – 0.057	0.06 – 0.185	0.05 – 0.1	0.06 – 0.185	0.06	0.02 – 0.04	0.06	0.1	0

a. Excluding inerts and C&D waste.

Table 5-9 Sample Sizes of Methane Generation Rate (*k*) under Five Main Climate Types

Main Climate	*Bulk Waste Option*	*Modified Bulk Waste Option*			*Waste Composition Option*									*Total*
	Bulk Waste	*Bulk MSW Waste*[a]	*Bulk C&D Waste*	*Inerts*	*Bulk Waste*	*Food Waste*	*Garden*	*Sewage Sludge*	*Paper*	*Wood and Straw*	*Textiles*	*Diapers*	*Inerts*	
A	28	12	16	6	19								17	98
B	118	21	21	12	92			1	1		1	1	76	344
C	984	227	150	136	662	4	6	12	2	5	4	1	598	2791
D	208	87	67	61	192	6	4	6	10	9	7	6	188	851
E														
Total	1338	347	254	215	965	10	10	19	13	14	12	8	879	4084

a. Excluding inerts and C&D waste.

When analyzing the results, we should pay attention to the sample sizes. Overall, according to Table 5-9, the warm temperate (C) climate type contains 2791 samples, accounting for 68% of the total 4084 samples, followed by the snow (D) climate type with 851 samples and arid (B) climate type with 344 samples. The equatorial (A) climate type contains only a few samples (98) and there is no sample in polar (E) climate type. The distribution of the samples in the three calculation options are similar to the overall distribution.

As for specific climate zone, according to Table A-6, the warm temperate / fully humid / hot summer (Cfa) climate zone is the one which has the most samples (2436) among all 24 climate zones, followed by the snow / fully humid/ hot summer (Dfa) climate zone's 535 samples. 8 climate zones have no sample in them, and there are also several climate zones containing only a small number of samples, it should be kept in mind that this may lead to the unrepresentativeness of the results.

For Bulk Waste Option, the results show that the k value of bulk waste in warm temperate (C) climate is the highest, followed by equatorial (A) climate, snow (D) climate, then arid (B) climate. For the additional bulk waste type under Waste Composition Option, the sequence would be equatorial (A), warm temperate (C), snow (D) and arid (B). These may imply that precipitation/water plays a more important role than temperature in the generation of landfill gas; the heat generated during the anaerobic degradation reaction in landfills can be a possible reason. Besides, according to the relationship between methane generation rate (k) and half-life ($t_{1/2}$) as indicated by Equation (3-6), the higher the k value, the lower the corresponding $t_{1/2}$ value would be, which means the waste would degrade faster.

For Modified Bulk Waste Option, the order of main climate types, from in which the k value is high to in which that is low, would also be equatorial (A), warm temperate (C), snow (D), and arid (B). This trend has been observed in both bulk MSW waste (excluding inerts and C&D waste) and bulk C&D waste.

For Waste Composition Option, except for that additional bulk waste type and inerts, the sample sizes of individual waste components are only 86 in total, accounting for 2% of all 4084 samples, thus the results are incomplete and may be unrepresentative. An interesting point is that, there are two samples in Cfa climate zone whose reported k value for wood and straw are 0.04, exceeding the upper limit of the default value, which is 0.03. The two samples were reported by the operators of Laurel Ridge Landfill (GHGRP ID: 1002341) in Lily, Kentucky for 2015 and 2016. These data are not treated as outliers;

however, their validity needs to be confirmed. Overall, to obtain more accurate results, it is suggested that more landfills should use Waste Composition Option and report *k* values of individual waste components.

5.2.3 Methane Generation, Recovery and Emission

Many of the landfills in GHGRP operate with landfill gas collection systems, and they report data related to information such as annual quantity of recovered methane, annual average methane concentration (in LFG), estimated gas collection efficiency, as well as annual methane generation and emission, which are estimated using several methods.

The total reported values on landfill gas generation, recovery and emission quantities are not directly comparable since the gases are generated from different quantities of waste. This associates with the normalization of the data. These values can be transformed to corresponding ratios (t CH_4 / t MSW) by dividing the reported annual waste disposal quantities, and then become comparable. The data are also obtained from the Envirofacts database [54], except for the location of the landfills, which is gathered from the GHGRP Data Summary Spreadsheets [55]. All data are for the reporting year 2017, and the detailed information can be found in Annex G.

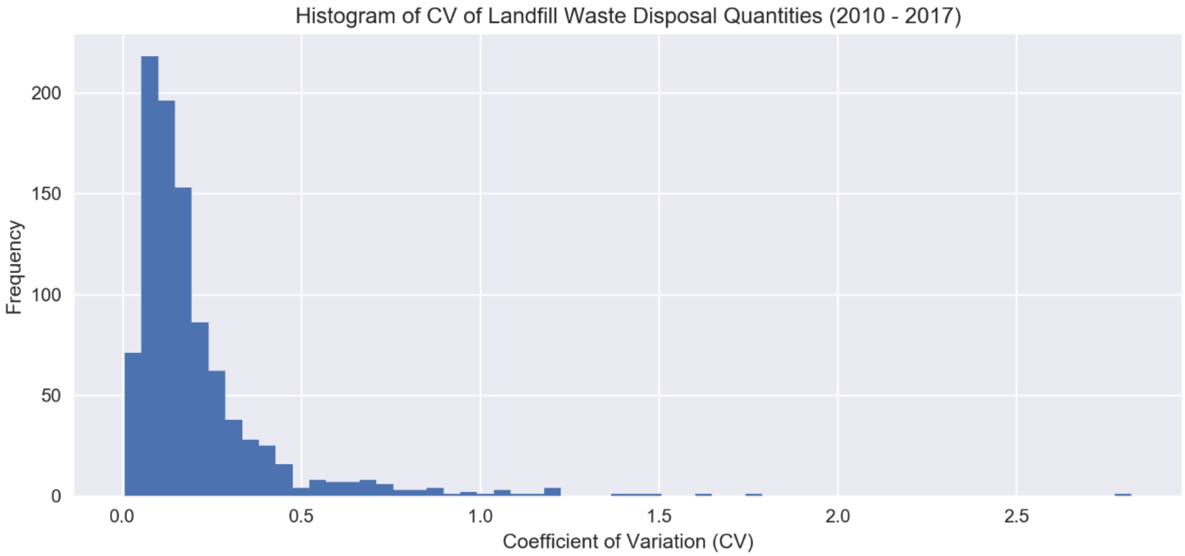


Figure 5-4 Histogram of CV of Landfill Waste Disposal Quantities (2010 - 2017)

Before calculating the ratios, the waste disposal quantities data are investigated. In a single reporting year, landfills not only report the waste disposal quantities in that year, but also report previous annual disposals from the first year of reporting to the GHGRP. Therefore, in order to measure the variability of the data, the standard deviation and the mean of waste disposal quantities in multiple years are calculated, then the coefficients of variation (CV) are derived (CV = standard deviation / mean). Figure 5-4 presents the histogram of CV values of landfill waste disposal quantities. It is found that 80% of the 962 landfills in the data set have a CV less than 0.273, and 90% of the landfills have a CV less than 0.407. This shows the waste disposal in most landfills is relatively stable through years, which is good for the rationality of the ratios since they will be calculated on the basis of waste disposal quantities in a single year 2017.

Besides, the total tonnage of landfilled MSW in all GHGRP landfills was 310.5 million tons in 2017, and was 280.9 million tons in 2015; while in EPA annual summary figures and tables about waste management [48], the tonnage of landfilled MSW in the U.S. was 137.7 million tons in 2015, which was only a half of the estimation from the GHGRP dataset. Since the GHGRP dataset was reported by individual landfills, the tonnage of waste was estimated by either using scales to weigh loads or using working capacity of each vehicle/container, it can be more reliable. The underestimation in EPA's annual summary figures and tables was also pointed out by Shin [53].

Landfills report three methane generation values using three estimation equations, as explained in 40 CFR § 98.343 [32]. Equation HH-1 is from 2006 IPCC Guidelines FOD Method, which is the same as Equation (A-6). It is based on model parameters like quantity of waste disposed, degradable organic carbon (DOC), and methane generation rate (k), etc. Equation HH-5 is based on the result of Equation HH-1 after excluding the oxidized quantity by multiplying (1 - OX), where OX is the oxidation fraction. Equation HH-7 is based on the measured methane recovery and estimated gas collection efficiency, which also takes into account the oxidation. In short, Equation HH-1 and Equation HH-5 are based on model estimation, whereas Equation HH-7 is based on measurement. For the calculation of methane generation ratio, the results of all three equations are used, since the differences between the original modeled generation, the modeled generation after oxidation and the measured generation can be reflected.

The methane recovery is estimated using Equation HH-4, which is based on measurement. The resulted values of Equation HH-4 are selected for the calculation of the methane recovery ratio.

Landfills with landfill gas collection systems report two methane emission values using two estimation equations, as explained in 40 CFR § 98.343 [32]. Equation HH-6 is based on modeled methane generation and measured methane recovery. Equation HH-8, which has been discussed in Section 4.1.5, is based on measured methane recovery and estimated gas collection efficiency. Besides, for those landfills that do not have landfill gas collection systems, the methane emissions are equal to the methane generation, as calculated from Equation HH-5.

Usually, only one emission value for each landfill will be reported. After checking, it is found that, for those landfills with landfill gas collection systems, the single reported emission value is either from Equation HH-6 or Equation HH-8, and there is no explicit explanation on how landfill operators determine which value to use. For landfills without landfill gas collection systems, the reported emissions should be obtained by using Equation HH-5.

The single emission value of each landfill that is reported in the subpart level summary table is selected for the calculation of methane emission ratio, instead of the two emission values from Equation HH-6 and Equation HH-8. The reasons are: 1) it is assumed that landfills (with landfill gas collection systems) have good judgement on the selection of the two emission values to report, 2) the summary table contains emission values for all landfills, including those with gas collection systems and those without, 3) the emission values calculated from Equation HH-6 and Equation HH-8 can be treated as deducting the recovered amount from the generated amount, since the generation and recovery varies between landfills, and those two parts are also subject to analyze in this section, a single emission value determined by landfill should be enough for analysis and can reduce some unnecessary confusions.

The typical values of methane generation ratio, recovery ratio, emissions ratio and estimated collection efficiency under the five main climate types are presented in Table 5-10. The ranges and the sample sizes of these statistics are summarized in Table 5-11 and Table 5-12. Except for the estimated collection efficiency, whose typical values are calculated as the means and whose ranges are presented from the min to the max of the samples. The typical values for the ratio statistics are calculated as the medians, and the corresponding ranges are provided with 90% confidence intervals.

Table 5-10 Typical Values of Methane Generation Ratio, Emission Ratio, Recovery Ratio and Estimated Collection Efficiency under Five Main Climate Types

Main Climate	*Generation Ratio (HH-1)*	*Generation Ratio (HH-5)*	*Generation Ratio (HH-7)*	*Recovery Ratio*	*Emission Ratio*	*Estimated Collection Efficiency*
A	0.0463	0.0380	0.0191	0.0151	0.0135	0.682
B	0.0243	0.0203	0.0102	0.0083	0.0141	0.680
C	0.0409	0.0333	0.0266	0.0214	0.0137	0.712
D	0.0384	0.0315	0.0268	0.0237	0.0125	0.766
E						
Overall	0.0395	0.0315	0.0252	0.0210	0.0136	0.720

The unit for all ratio statistics is *t* CH_4 / *t* MSW.

Table 5-11 Ranges of Methane Generation Ratio, Emission Ratio, Recovery Ratio and Estimated Collection Efficiency under Five Main Climate Types

Main Climate	*Generation Ratio (HH-1)*	*Generation Ratio (HH-5)*	*Generation Ratio (HH-7)*	*Recovery Ratio*	*Emission Ratio*	*Estimated Collection Efficiency*
A	0.0260 – 0.0653	0.0226 – 0.0588	0.0113 – 0.0347	0.0055 – 0.0216	0.0037 – 0.0633	0.3 – 0.95
B	0.0135 – 0.0471	0.0104 – 0.0353	0.0032 – 0.0441	0.0007 – 0.0315	0.0013 – 0.0532	0.07 – 0.98
C	0.0152 – 0.1041	0.0123 – 0.0881	0.0083 – 0.0734	0.0037 – 0.0562	0.0026 – 0.0738	0.111 – 0.95
D	0.0188 – 0.0905	0.0148 – 0.0788	0.0093 – 0.0692	0.0060 – 0.0573	0.0027 – 0.0501	0.098 – 0.95
E						
Overall	0.0152 – 0.1002	0.0122 – 0.0844	0.0066 – 0.0715	0.0031 – 0.0559	0.0023 – 0.0665	0.07 – 0.98

The unit for all ratio statistics is *t* CH_4 / *t* MSW.

The sample sizes of climate type A (equatorial) are all small (less than 30), thus the ranges may be unrepresentative.

Table 5-12 Sample Sizes of Methane Generation Ratio, Emission Ratio, Recovery Ratio and Estimated Collection Efficiency under Five Main Climate Types

Main Climate	*Generation Ratio (HH-1)*	*Generation Ratio (HH-5)*	*Generation Ratio (HH-7)*	*Recovery Ratio*	*Emission Ratio*	*Estimated Collection Efficiency*
A	16	16	16	16	20	19
B	48	48	47	48	88	62
C	492	492	492	492	644	600
D	127	127	127	127	177	157
E						
Total	683	683	682	683	929	838

The reason is, except for estimated collection efficiency, extreme values have been found in other statistics. As shown in Figure 5-4, the CV of the waste disposal in some landfills is large, the everchanging pattern indicated by large CV values can lead to extreme ratios as they are calculated on a single year basis. By choosing 90% confidence interval, no value in Table 5-11 exceeds the theoretical maximum methane generation per ton of MSW calculated in Section 5.1.1, while when choosing 95% confidence interval, there will be many values exceeding that theoretical number much, which make the ranges unreasonable. The more detailed results for the 24 climate zones are provided in Annex E.

For typical values of methane generation ratio, HH-1 ratio and HH-5 ratio have similar pattern that, in equatorial (A) climate, the typical generation ratio is the highest, followed by that in warm temperate (C) climate, snow climate (D) and arid (B) climate. This consistency has been expected since the difference between Equation HH-1 and Equation HH-5 is only oxidation, and according to GHGRP documentation [32], the oxidation fraction takes the factors like cover type, coverage fraction into account, but not climate.

While the HH-7 ratio, which is based on measurement, shows a different pattern: the typical generation ratio in warm temperate (C) and snow (D) climate are very close and are higher than that in equatorial (A) climate, the lowest typical generation ratio is still in arid (B) climate. The lack of sufficient samples in equatorial (A) climate can be a possible reason, while this needs to be further analyzed. Besides, the HH-7 ratios are all significantly less than the corresponding HH-1 and HH-5 ratios, this implies there may exist systematical overestimation in the landfill gas generation model used, which is the 2006 IPCC Guidelines FOD Method.

The typical values of the estimated collection efficiency are all relatively high (around 70%) and indicate small variations in different main climates. This should be one reason that the patterns of the recovery ratio and the generation ratio (HH-7) are similar.

The overall typical methane emission ratio is estimated to be 0.0136 ton CH_4 / ton MSW. An interesting finding is that, the typical values of methane emission ratio show little difference in different main climates. To better understand this, more knowledge about how the landfill operators determine which emission value to report is needed. In specific climate zones, there are some more obvious differences, while the results in many climate zones need more samples to support.

5.3 Global Methane Emissions from Landfill: 1970-2017

5.3.1 National Greenhouse Gas Emission Profiles: UNFCCC and EDGAR

1. ***United Nations Framework Convention on Climate Change (UNFCCC)***

The United Nations Framework Convention on Climate Change (UNFCCC) is an international environmental treaty whose objective is “to achieve stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system”. Under the requirements of the convention, the parties to the convention should report their greenhouse gas (GHG) emissions on a regular basis. [62]

Currently, there are 197 parties (196 states and 1 regional economic integration organization) to the UNFCCC [63], the parties are divided into three main groups, which differ in commitments [64]: Annex I Parities, Annex II Parties and Non-Annex I Parties. Annex I Parties include the industrialized (developed) countries and countries with economies in transition (the EIT Parties), the industrialized countries classified were members of the Organization for Economic Co-operation and Development (OECD) in 1992, they form a separate Annex II group, and Non-Annex I countries are mostly developing countries.

The convention requires each Annex I Party to report its annual GHG inventory covering emissions and removals of direct GHGs from five sectors, and the time span should start from the base year to two years before the inventory is due. The direct GHGs are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), sulphur hexafluoride (SF_6) and nitrogen trifluoride (NF_3), and the five sectors are 1) energy, 2) industrial processes and product use, 3) agriculture, 4) land use, land-use change and forestry (LULUCF), and 5) waste. The inventory includes two parts: Common Reporting Format (CRF) tables and National Inventory Report (NIR). It is required that Annex I Parties should use 2006 IPCC Guidelines for National Greenhouse Gas Inventories. [65]

Annex I Parties are also required to submit National Communications (NCs) every four years and Biennial Reports (BRs) to the convention secretariat [66, 67]. These reports cover a broad range of topics related to the convention’s mission [68, 69], including national circumstances, GHG inventory information, policies and measures as well as their projections, vulnerability assessment and adaptation measures, financial resources and technology transfer, research and systematic observation, education, training and public awareness, etc. The latest reports are NC7 and BR3, respectively.

Non-Annex I Parties are required to submit their first National Communication (NC) within three years of entering the convention, and every four years thereafter [70]. Some Non-Annex I Parties are also required to submit their first Biennial Update Report (BUR) by 2014 and every two years thereafter according to their capabilities and the level of support provided for reporting [71]. These reports should be prepared in accordance with the guidelines contained in decision 2/CP.17 [72], which further refers to the guidelines contained in decision 17/CP.8 [73]. It is implied that countries should use the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, the Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories, and the Good Practice Guidance for Land Use, Land-Use Change and Forestry.

UNFCCC GHG data portal [74] maintains reported data from all parties. Under waste sector, there is a category “Solid Waste Disposal on Land”, landfill gas emissions data of each country are extracted by filtering that category from the GHG profile summary table. Since the data portal doesn’t support downloading data of a specific category for all parties, the GHG profile summary tables are downloaded country by country. According to the report submission procedures introduced above, the data of Annex I countries cover a complete time series from 1990 to 2016, and the data of most Non-Annex I countries are scattered in some years within this time period. 1994 and 2000 are the two years when significantly more countries reported their GHG emissions than in other years.

2. *Emissions Database for Global Atmospheric Research (EDGAR)*

The Emissions Database for Global Atmospheric Research (EDGAR) provides global anthropogenic emissions of greenhouse gases and air pollutants by country and on spatial grid for historical and current time. In EDGAR v4.3.2 emissions for carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) were calculated per sector and country over a time period from 1970 to 2012. [75]

The emissions and trends were estimated based on latest scientific knowledge (at the time when data were published), available global statistics, best-available emission factors, and methods recommended by 2006 IPCC Guidelines. The application of the same methodology and mainly default emission factors to all world countries helped achieve the comparability and transparency. Some official data submitted by the Annex I countries to the UNFCCC were used, especially those about the emission control measures which were not described by international statistics, but in order to maintain cross-country consistency and impartiality, the emissions reported by countries were not used. [76]

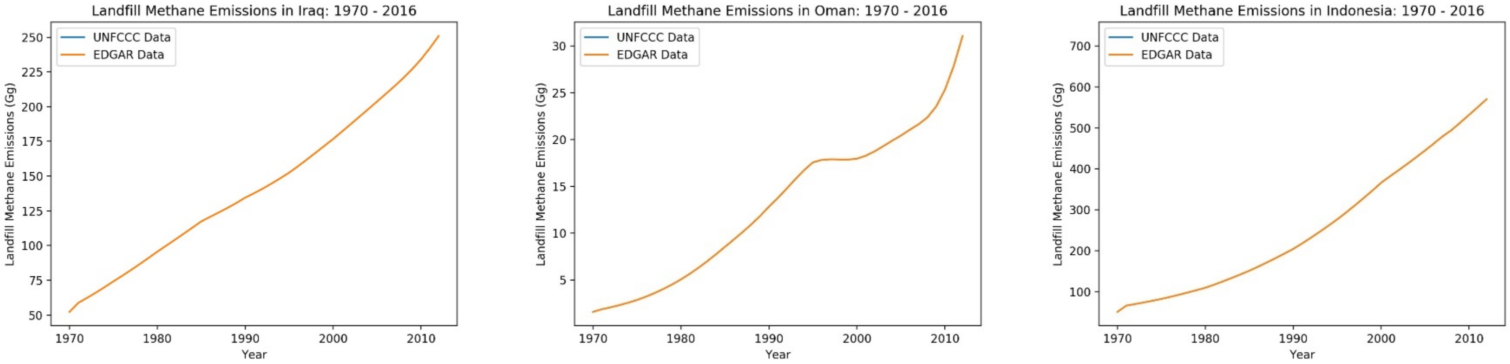
The source sectors divided are the same as those used in the UNFCCC reporting, as they all follow the 2006 IPCC Guidelines. The landfill methane emissions per country data are extracted from the methane emissions summary table [75] by filtering the category "Solid Waste Disposal on Land", the time period covered is from 1970 to 2012.

5.3.2 Comparison between UNFCCC Data and EDGAR Data

The two data sets of landfill methane emissions cover different time periods, also, the emissions data of Non-Annex I countries in the UNFCCC data set are incomplete. It would be desirable if a complete emissions time series for each country could be constructed based on the two data sets.

In 2006 IPCC Guidelines [77], the time series consistency issue is discussed and several techniques are provided to resolve data gaps, such as the overlap technique, the surrogate method, interpolation and trend extrapolation, etc. While it is required to evaluate the specific circumstances when selecting a technique, for example, generally the overlap technique is only preferred when there is a consistent relationship between two data sets. Therefore, before applying these techniques, the characteristics of the two data sets should be examined.

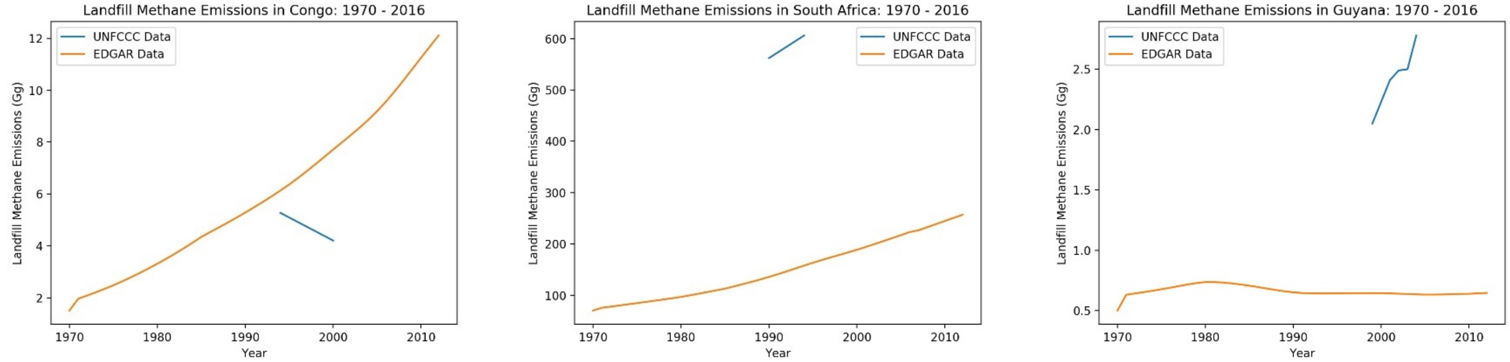
The emission unit in the UNFCCC data is *kiloton (kt)* CO_2 *equivalent*, whereas the emission unit in the EDGAR data is *Gigagram (Gg)* CH_4. Thus, in order to make the two data sets comparable, the emissions in the former are divided by 25, which is the default global warming potential (GWP) value used in this report. Then, the landfill methane emissions profile of each country is plotted; the gaps in the UNFCCC data are filled by linear interpolation.


Landfill Methane Emissions in Iraq: 1970 - 2016

Landfill Methane Emissions in Oman: 1970 - 2016

Landfill Methane Emissions in Indonesia: 1970 - 2016

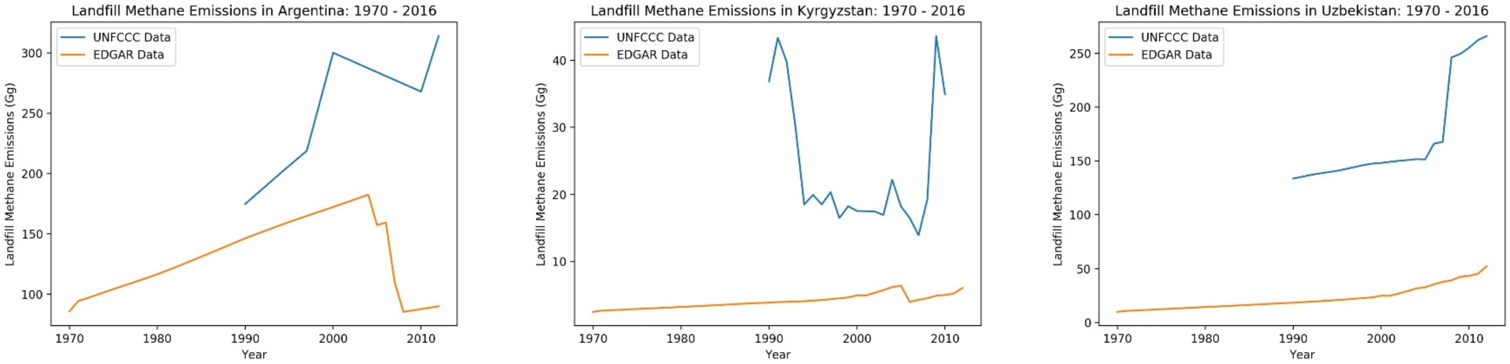
Figure 5-5 Examples of country where there is no or only a single UNFCCC data value


Landfill Methane Emissions in Congo: 1970 - 2016

Landfill Methane Emissions in South Africa: 1970 - 2016

Landfill Methane Emissions in Guyana: 1970 - 2016

Figure 5-6 Examples of country where there are only a few UNFCCC data


Landfill Methane Emissions in Argentina: 1970 - 2016

Landfill Methane Emissions in Kyrgyzstan: 1970 - 2016

Landfill Methane Emissions in Uzbekistan: 1970 - 2016

Figure 5-7 Examples of country where the two data sets are significantly different

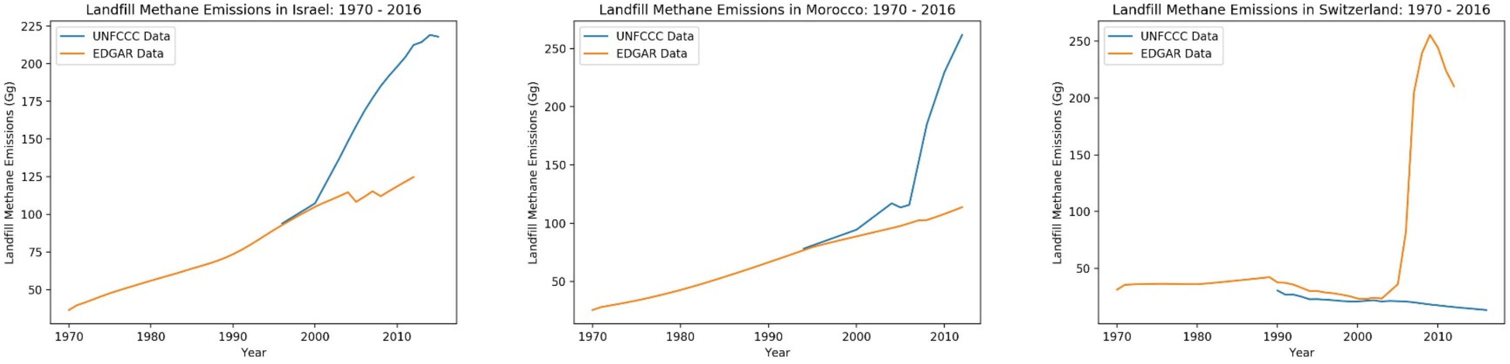


Figure 5-8 Examples of country where the two data sets are close at some time periods but are significantly different at the rest of the time

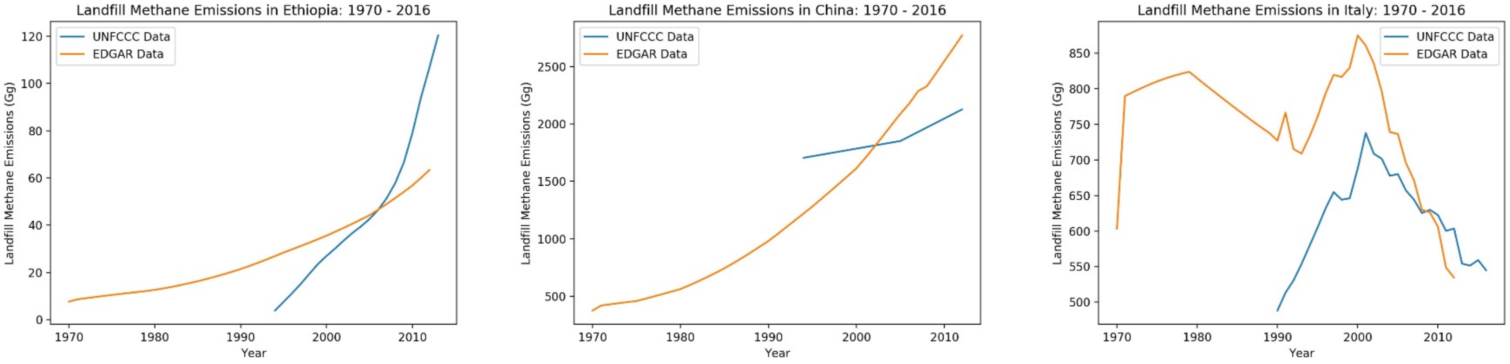


Figure 5-9 Examples of country where the two data sets have similar trends but different slopes

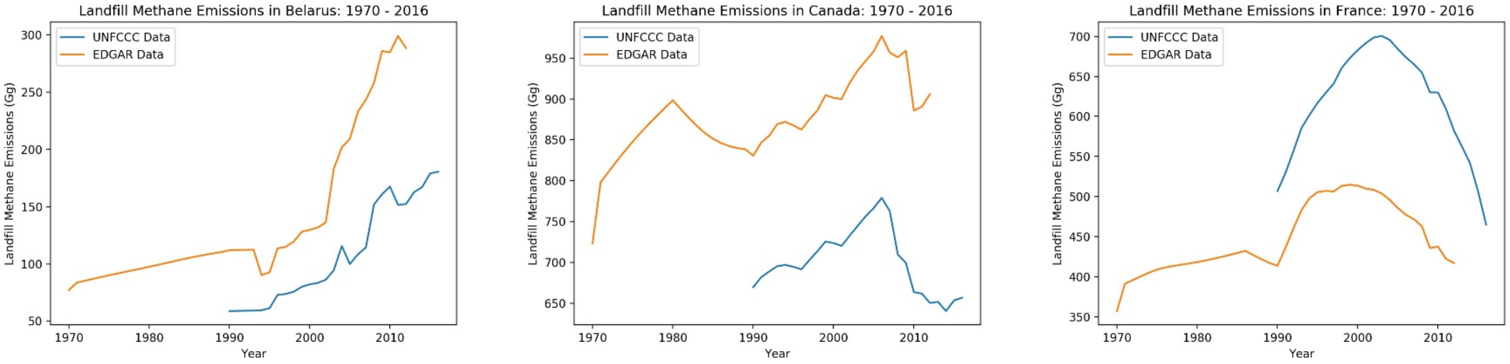


Figure 5-10 Examples of country where the two data sets have similar trends but significantly different scales

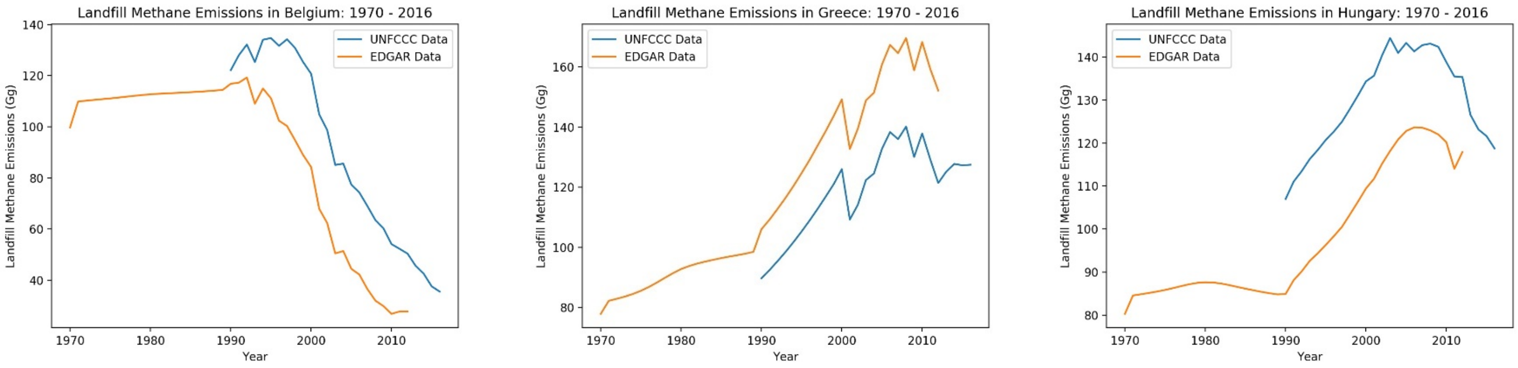


Figure 5-11 Examples of country where the two data sets have very similar trends but slightly different scales

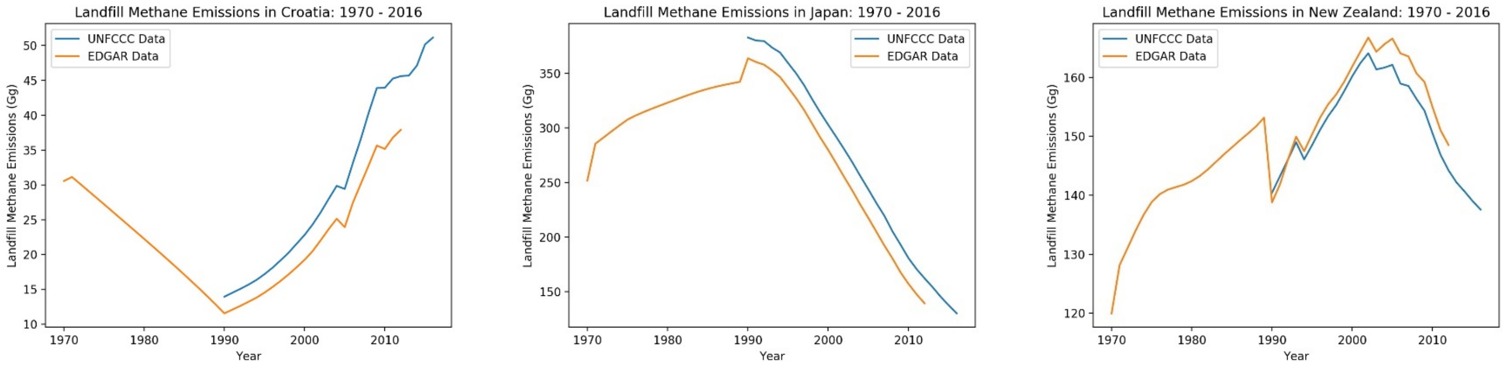


Figure 5-12 Examples of country where the two data sets are close

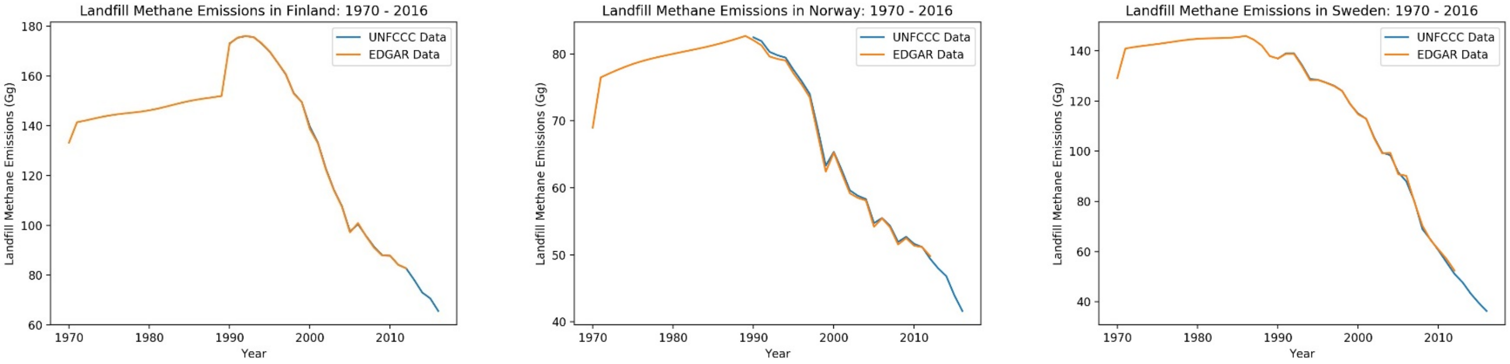


Figure 5-13 Examples of country where the two data sets are almost identical

The main observations from the figures can be summarized as follows, which cover most types of data issue that can be found between the two data sets:

1) The differences between the two data sets can be significant. As shown in Figure 5-5 and Figure 5-6, in some countries, there is no or there are only a very small number of the UNFCCC data. Besides, as shown in Figure 5-7, the two data sets in some countries differ largely in both trends and scales, which makes it challenging to combine them.
2) In some countries, there exist moderate discrepancies between the two data sets. Figure 5-8 shows that, the two data sets are close at some time periods but vary a lot at the rest of the time. In Figure 5-9, the general trends of the two data sets are similar, while the rates of change in emissions are different. Moreover, as shown in Figure 5-10, in some countries, the two data sets have similar trends, but the scales differ significantly, which can hardly be attributed to the use of different GWP values. The overlap technique may help in such case.
3) The differences between the two data sets can be small or close to being identical in a few countries. As shown in Figure 5-11, the two data sets have very similar trends but slightly different scales, which can be caused by the use of different factors, like GWP values. And Figure 5-12 shows that the two data sets are very similar to each other in some countries. Additionally, as shown in Figure 5-13, the two data sets can be almost the same. Possibly they are developed by the same methods and source data in those countries.

In general, the two data sets have varying degrees of difference in most countries. The EDGAR data are estimated using the same method, which is based on international statistics and emission factors. While the UNFCCC data are reported by individual countries, although there are general guidelines to refer, the methods and data used by countries can be different. For example, there are three tiers of FOD method in 2006 IPCC Guidelines. Hardly can a single technique be applied to combine these two data sets appropriately for all countries, the specific circumstances of each country should be considered.

5.3.3 Landfill Methane Emissions by World Region and by Income Group

In order to construct a complete time series of landfill methane emissions at the global level, the EDGAR data set is selected because of its thorough coverage of time and space, as well as its application of the same method to all countries. Also, as discussed in Section 5.3.1, the Revised 1996 IPCC Guidelines are still referred by some countries under the UNFCCC, which could make their estimations outdated.

The time period covered by the EDGAR data set is from 1970 to 2012. In an attempt to estimate more recent emissions, the urban and total population data of all countries are obtained from the World Bank [78, 79], covering the time period from 1960 to 2017. In the 2006 IPCC Guidelines [20], it is indicated that population, especially urban population, is a main driver for solid waste disposal; the missing waste disposal data can be assumed to be proportional to population. Furthermore, assuming that, the ratio of landfill methane emissions to urban population remain constant since 2012, then the emissions after 2012 can be estimated by multiplying that ratio and the urban population in the corresponding year.

1. *Landfill Methane Emissions by World Region*

Figure 5-14 presents the landfill methane emissions by region of the world, from 1970 to 2017; the world region information is also obtained from the population data set of the World Bank. The emissions after 2012 show a rapid rising trend, which is basically the trend of urban population growth. Since the rapid growth of urban population can lead to the same rapid growth of solid waste generation and disposal, if there is no significant implementation of landfill methane mitigation measures in the world, the rapid growth of landfill methane emissions should also be expected.

Table 5-13 Estimations of Global Methane Emissions from Landfill

Source	*Unit*	*1990*	*1995*	*2000*	*2005*	*2010*	*2015*
EDGAR	*Mt*	25.586	27.452	27.379	28.062	28.836	31.077
	Mt CO_2 *e*	639.7	686.3	684.5	701.6	720.9	776.9
U.S. EPA [3]	*Mt* CO_2 *e*	706.1	755.4	769.8	794.0	846.7	875.6

According to the EDGAR data, global methane emissions from landfill was 29.092 *Mt*, or 727.3 *Mt* CO_2 *e* in 2012. As shown in Table 5-13, the estimations using the EDGAR data are all lower than the estimations of U.S. EPA [3]. In Section 4.4, it was introduced that the data and methodologies used by EPA were mostly country reported values and 2006 IPCC Guidelines methods, and some Non-Annex I countries may have used older IPCC Guidelines to calculate the emissions for reporting. Overall, the results imply that the estimations using IPCC Guidelines are all greater than those using EDGAR approach, which is mainly based on emission factors and international statistics.

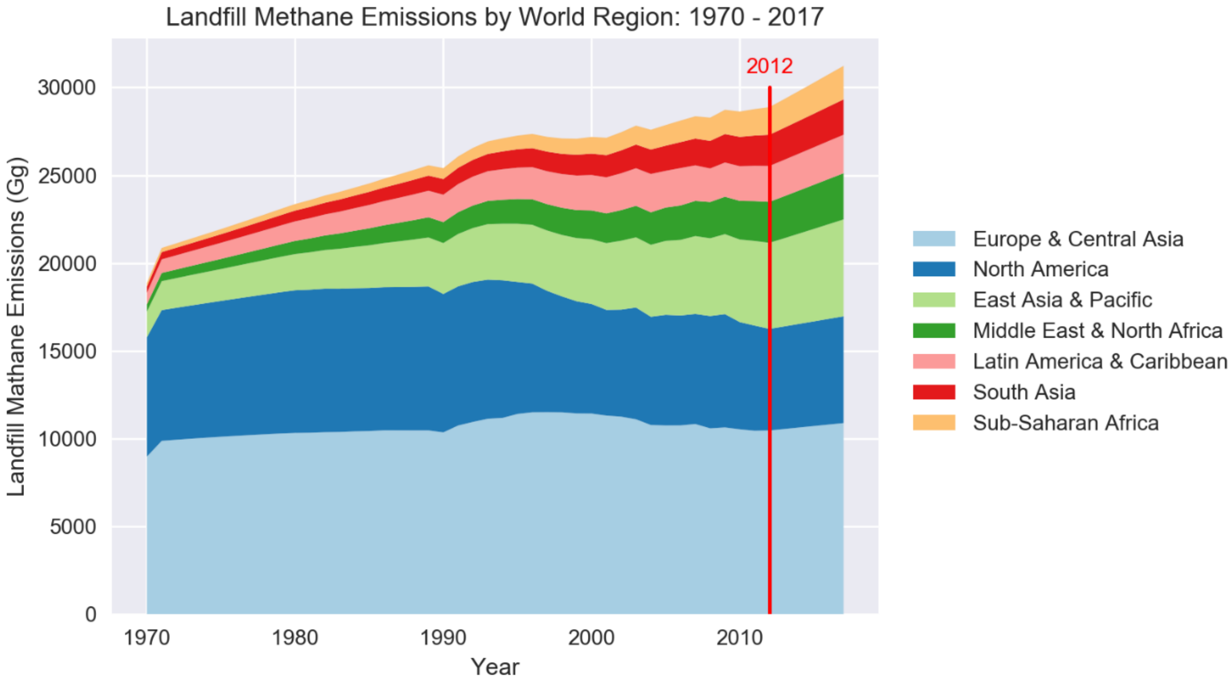


Figure 5-14 Landfill Methane Emissions by World Region: 1970 – 2017

Table 5-14 shows the top 10 countries with regard to landfill methane emissions and the emissions of the rest of world regions. The rankings are based on the emissions in 2012, which is the latest year in the EDGAR data. The emissions from the top 10 emitting countries account for 58.4% of the world total in 2012. There are distinct disparities between the rankings here and those in Table 4-7, this once again indicates the difference between the estimations using IPCC Guidelines and those using EDGAR method. In addition, there are differences between the countries and the regions covered by the EDGAR data and the world region attributes data, some countries and regions in the resulted final data set don't have corresponding world region information, thus their emissions cannot be attributed to certain world regions. The emissions from those countries and regions account for a very small portion of the world total, making the world total results in Table 5-14 slightly less than those in Table 5-13.

Table 5-14 Landfill Methane Emissions by World Region: 1970 – 2017 (*Mt CO_2 e*)

Country / World Region	*1970*	*1980*	*1990*	*2000*	*2010*	*2012*	*2017*
Top 10 Emitting Countries							
United States	151.6	180.5	176.2	133.4	130.4	121.9	127.9
China	9.4	14.1	24.5	40.4	63.7	69.2	79.6
Russia Federation	28.3	31.5	33.7	41.5	58.1	63.6	64.7
Turkey	2.6	4.1	7.8	34.4	39.2	41.4	46.5
India	7.3	12.4	17.6	23.7	31.8	33.6	37.9
United Kingdom	52.6	58.9	56.7	54.4	28.6	24.4	25.7
Canada	18.1	22.5	20.8	22.5	22.1	22.6	24.0
Iran, Islamic Republic of	2.4	4.5	7.9	11.2	14.6	15.3	16.9
Brazil	4.4	8.5	12.5	17.0	14.5	14.9	15.8
Indonesia	1.3	2.7	5.1	9.2	13.3	14.3	16.1
Rest of the World Regions							
Europe & Central Asia	141.1	163.7	161.0	155.5	137.6	132.3	135.5
Middle East & North Africa	8.0	14.1	21.9	29.8	40.4	42.9	48.9
Sub-Saharan Africa	5.1	9.3	15.4	23.7	36.0	39.4	47.7
East Asia & Pacific	25.9	34.8	42.8	42.6	40.6	39.0	42.2
Latin America & Caribbean	11.9	19.4	26.5	33.4	34.9	36.3	39.0
South Asia	1.5	2.9	4.6	6.8	9.9	10.7	12.4
North America	0.006	0.007	0.008	0.008	0.008	0.008	0.008
World Total	**471.6**	**583.9**	**635.0**	**679.4**	**715.6**	**721.9**	**780.6**

2. ***Landfill Methane Emissions by Income Group***

As discussed in Section 2.4, economic development or income level is a key factor that affects the waste generation and therefore can affect the trend of landfill gas generation and emission. The World Bank [80] classifies economies by income using Gross National Income (GNI) per capita as thresholds. As of July 1 2018, the thresholds for 1) low income economies, 2) lower middle income economies, 3) upper middle income economies and 4) high income economies are 1) $995 or less in 2017, 2) between $996 and $3895, 3) between $3896 and $12055, 4) $12056 or more, respectively. With income level data of the economies [81], global landfill methane emissions time series are constructed by income group.

In Figure 5-15, it is shown clearly that higher income level group emits more landfill methane, besides, there is an increasing trend in upper middle income group and a decreasing trend in high income group. Table 5-15 shows the breakdown of landfill methane emissions by income group through years.

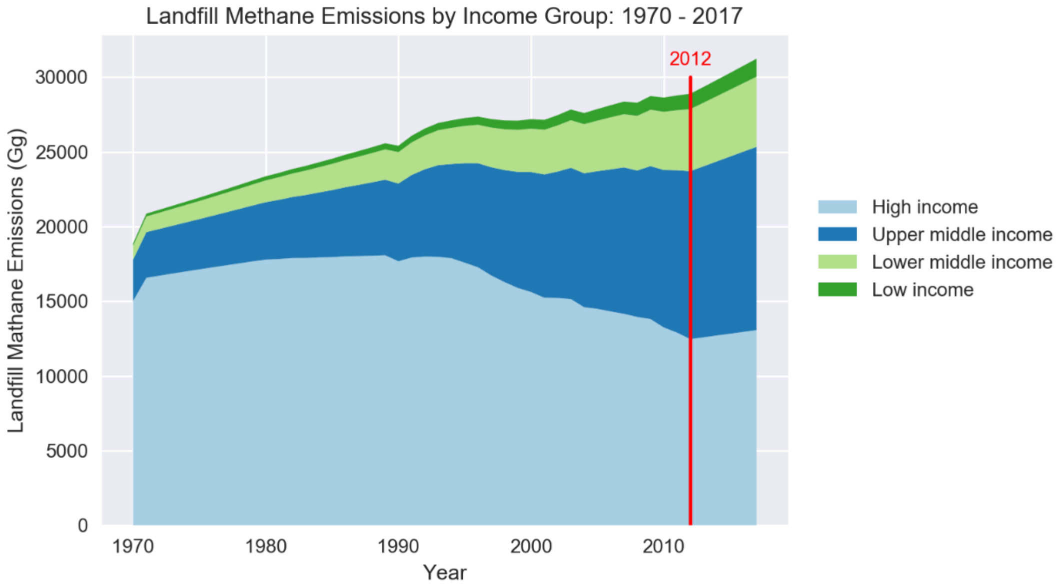


Figure 5-15 Landfill Methane Emissions by Income Group: 1970 – 2017

It should be noted that, the income level of the economies changes over time, thus the current classification may be different from the past. The increasing trend in upper middle income group is reflected in some countries included in this group, such as China, Russia, Turkey, Iran and Brazil, as shown in Table 5-14. On one hand, such rise can be attributed to the increase of waste generation in the relevant countries. On the other hand, the large amount of waste exports to some of these countries also play a vital role in this increasing trend.

Table 5-15 Landfill Methane Emissions by Income Group: 1970 – 2017 (*Mt* CO_2 *e*)

Income Group	*1970*	*1980*	*1990*	*2000*	*2010*	*2012*	*2017*
High Income	375.3	444.6	441.9	390.5	331.3	311.7	326.7
Upper Middle Income	69.2	95.9	129.9	200.6	263.2	280.7	306.5
Lower Middle Income	23.0	36.5	52.6	72.6	97.3	103.8	117.4
Low Income	4.0	6.9	10.6	15.8	23.7	25.6	30.0
World Total	**471.6**	**583.9**	**635.0**	**679.4**	**715.6**	**721.9**	**780.6**

For example, China has been the largest waste importer in the last decades. It is reported that, from 2010 to 2017, China imported an average of 26 Mt wastepaper per year, accounting for 55 percent of world imports in 2017 [82], and from 1992 to 2016, China had imported 106 Mt of plastic waste for a cumulative 45.1% of the world total imports [83]. Although many of these imported wastes are destined for recycling, due to the impurity and contamination in the waste, a significant portion could eventually end in landfills. Since 2017, China has tightened the standards and has also banned the imports of certain types of wastes, which has raised significant challenges for former major exporters to deal with huge quantities of the affected wastes [82, 83]. In the near future, the exports of these wastes may continue and could be diverted to some other countries, but this should not be the ultimate solution, many efforts are still needed to address this challenge.

5.3.4 Landfill Methane Emissions per capita by World Region and by Income Group

To derive the per capita estimations, the landfill methane emissions data estimated in the previous section are divided by the total population [79] of the corresponding countries or regions. Due to different data availability of countries or regions in the data sets which are used to develop the results, the estimations of a few economies are missing. The estimation results for the countries of the UNFCCC Parties can be found in Annex F.

1. ***Landfill Methane Emissions per capita by World Region***

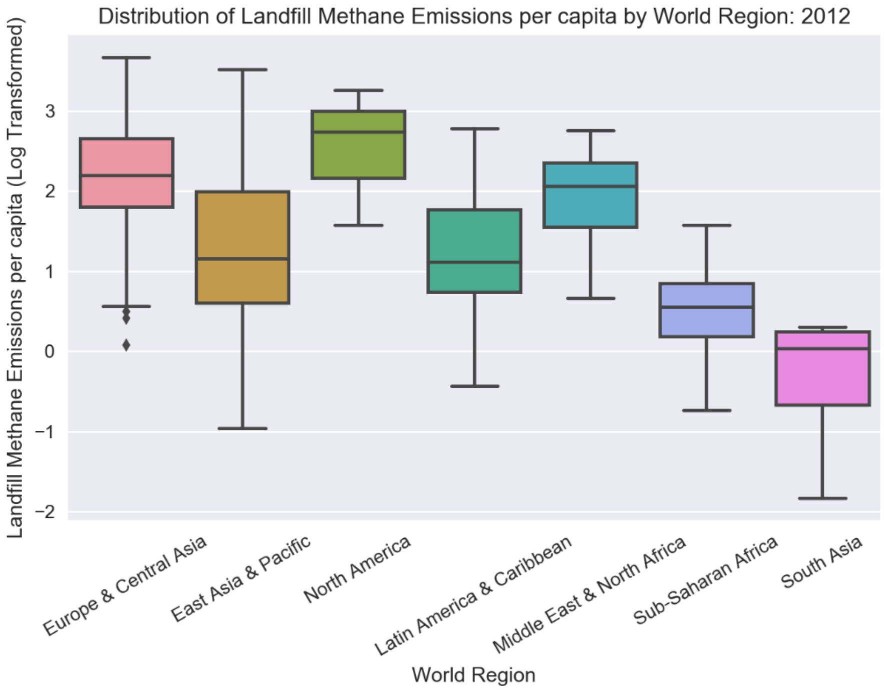


Figure 5-16 Distribution of Landfill Methane Emissions per capita by World Region: 2012

Figure 5-16 shows the distribution of landfill methane emissions per capita in different world regions. The year selected is 2012, as it is the most recent year in the original EDGAR data set. To show the differences better, the data have been log-transformed in the figure.

In Table 5-16, the per capita landfill methane emissions in different regions of the world are calculated by dividing the total emissions in a region by the total population in that region. The results are sorted from high to low by the estimations for year 2012. It is shown that in 2012, on average every person on the planet emitted 4.10 *kg* of landfill methane (102.50 $kg\ CO_2\ e$).

The per capita emission in North America is the highest, although it has decreased a lot since 1980, the per capita emission in North America and in Europe & Central Asia are still significantly higher than those in other regions, among which South Asia region has the lowest per capita emissions.

Table 5-16 Landfill Methane Emissions per capita by World Region: 1970 – 2017 (*kg*)

World Region	*1970*	*1980*	*1990*	*2000*	*2010*	*2012*	*2017*
North America	29.98	32.24	28.39	19.92	17.77	16.57	16.76
Europe & Central Asia	12.32	13.17	12.45	13.42	11.99	11.84	12.03
Middle East & North Africa	3.00	4.01	4.69	5.22	5.72	5.81	5.98
Latin America & Caribbean	2.27	3.07	3.51	3.84	3.31	3.35	3.40
East Asia & Pacific	1.15	1.34	1.61	1.82	2.15	2.21	2.41
Sub-Saharan Africa	0.71	0.97	1.22	1.43	1.66	1.73	1.83
South Asia	0.50	0.68	0.79	0.88	1.02	1.06	1.12
World Average	**5.16**	**5.30**	**4.84**	**4.47**	**4.16**	**4.10**	**4.18**

2. *Landfill Methane Emissions per capita by Income Group*

Figure 5-17 shows the distribution of landfill methane emissions per capita by income group in year 2012. Again, the data have been log-transformed in the figure to show the differences clearer. It is shown that, generally, the economies with higher income emit more landfill methane per capita.

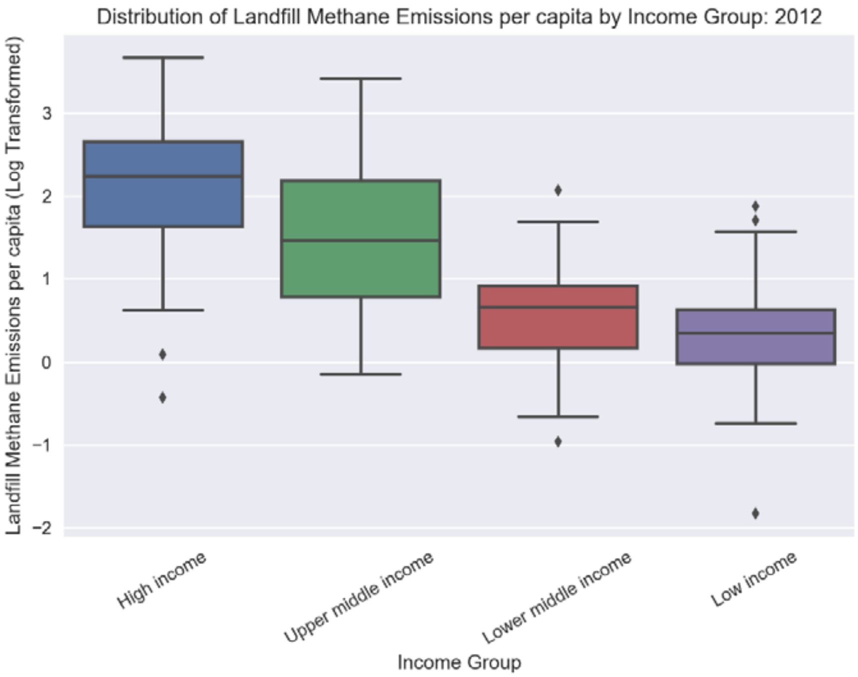


Figure 5-17 Distribution of Landfill Methane Emissions per capita by Income Group: 2012

Table 5-17 presents the per capita landfill methane emissions in different income groups, which are calculated by dividing the total emissions in an income group by the total population in that group.

Table 5-17 Landfill Methane Emissions by Income Group: 1970 – 2017 (*kg*)

Income Group	*1970*	*1980*	*1990*	*2000*	*2010*	*2012*	*2017*
High Income	17.42	18.84	17.39	14.30	11.28	10.49	10.67
Upper Middle Income	1.96	2.25	2.59	3.56	4.33	4.55	4.77
Lower Middle Income	0.77	1.03	1.23	1.38	1.58	1.63	1.68
Low Income	0.78	0.98	1.12	1.28	1.45	1.51	1.58
World Average	**5.16**	**5.30**	**4.84**	**4.47**	**4.16**	**4.10**	**4.18**

6. Conclusions

A broad range of topics have been discussed in this report, including the gas-generating processes in landfill, the theories about modelling landfill gas generation and emission, the developed models and the current estimations, as well as the calculation and analysis on several aspects. The findings provide both theoretical knowledge and practical data on landfill methane emissions.

Although as discussed in Section 3.6, the order of the estimation model is not very important, the kinetics order of many existing estimations models is first order. Currently, the most widely used model could be the 2006 IPCC Guidelines First-Order Decay (FOD) Method, which has been used by many countries to develop their national greenhouse gas inventories. And in recent years, new methods based on direct measurements have been developed, such as the Back-Calculation Method used in the GHGRP.

The empirical formula of dry degradable organic waste in the U.S. is estimated as $C_6H_{9.21}O_{3.73}$ when ignoring nitrogen (N) and sulfur (S). Methane generation per ton of MSW in the U.S. has been calculated to be 0.135 *ton* (or 189 Nm^3) at maximum, which is 9% less than the previous estimation.

The actual landfill methane emissions per ton of MSW in the U.S. are much lower than this theoretical maximum generation value. The reason of the gap could be: 1) landfill gas collection systems, landfill gas destruction (flaring) and utilization projects reduce the methane emissions, 2) the intrusion of air at some parts of the landfill diverts the anaerobic degradation to aerobic degradation, 3) the biodegradable components in MSW cannot fully biodegrade due to their intrinsic properties and other limiting factors such as water content, temperature and pH. Under dry basis, the degree of the biodegradation of the biodegradable components in U.S. MSW has been estimated to be 53.6%. At this degree, the expected methane generation would be 0.072 ton CH_4 / ton MSW. Besides, the excessive underestimation of the quantity of landfilled MSW in the U.S. in EPA's annual summary figures and tables of waste management has also been detected.

For methane generation rate k, the order of main climate types, from in which the k value of bulk waste is high to in which that is low, would be warm temperate (C), equatorial (A), snow (D), and arid (B), or ACDB under another calculation option. This indicates that precipitation/water may play a more important role than temperature in the generation of landfill gas. The details are provided in Section 5.2.2 and Annex D.

For methane generation ratio, those based on model estimation show the pattern that, in equatorial (A) climate, the typical generation ratio is the highest, followed by that in warm temperate (C) climate, snow climate (D) and arid (B) climate. While for those based on measurement, the typical generation ratio in warm temperate (C) and snow (D) climate are very close and are higher than that in equatorial (A) climate, the lowest typical generation ratio is still in arid (B) climate. The lack of sufficient samples in equatorial (A) climate can be a possible reason, while this needs to be further analyzed.

Besides, the methane generation ratios based on measurement are all significantly less than the corresponding ratios based on model estimation, this implies there may exist systematical overestimation in the landfill gas generation model used, which is the 2006 IPCC Guidelines FOD Method.

The typical values of estimated collection efficiency are all relatively high (around 70%) and show small variations in different main climates. An interesting finding is that, the typical values of methane emission ratio show little difference in different main climates. To better understand this, more knowledge about how the landfill operators determine which emission value to report is needed. The details about landfill methane generation ratio, recovery ratio, emission ratio and estimated collection efficiency are provided in Section 5.2.3 and Annex E.

The UNFCCC data and the EDGAR data are two separate sources of landfill methane emissions in different countries. Generally, there are varying degrees of difference between the two data sets in most countries because of the different methodologies used to develop them. After comparison, the EDGAR data are selected as the basis to construct a complete time series of landfill methane emissions at the global level. It is estimated that the global methane emissions from landfills are 727.3 $Mt\ CO_2\ e$ in 2012. If there is no significant implementation of landfill methane mitigation measures in the world, the rapid growth of landfill methane in the near future should be expected. Besides, it is estimated that, in 2012, every person on the planet emits 4.10 *kg* of landfill methane (102.50 $kg\ CO_2\ e$) on average annually.

By world region, the per capita landfill methane emissions in North America and in Europe & Central Asia are significantly higher than those in other regions, among which South Asia region has the lowest per capita emissions. By income group, it has been shown that, for both total emissions and per capita emissions, higher income group emits more than lower income group. The detailed calculation results are provided in Section 5.3.3, Section 5.3.4 and Annex F.

Annexes

A. Concentrations of Trace Components in Landfill Gas

Table A-1 Concentrations of Trace Components in Landfill Gas [84]

Component	*Concentration (mg/m^3)*
Ethane	0.8 – 48
Ethylene	0.7 – 31
Propane	1.4 – 13
Propene	0.04 – 10
Butane	0.3 – 23
Butene	1 – 21
Pentane	0 – 12
2-Methylpentane	0.02 – 1.5
3-Methylpentane	0.02 – 1.5
Hexane	3 – 18
Cyclohexane	0.03 – 11
2-Methylhexane	0.04 – 16
3-Methylhexane	0.04 – 13
Cyclohexene	2 – 6
Heptane	3 – 8
2-Methylheptane	0.05 – 2.5
3-Methylheptane	0.05 – 2.5
Octane	0.05 – 75
Nonane	0.05 – 400
Cumene	0 – 32
Bicyclo[3.2.1]octane-2,3-methyl, 4-methylene	15 – 350
Decane	0.2 - 137
Bicyclo[3.2.0]hexane-2,2-methyl, 5-methylethyl	12 – 153
Undecane	7 – 48
Dodecane	2 – 4
Tridecane	0.2 – 1
Benzene	0.03 – 7
Ethylbenzene	0.5 – 236

Component	*Concentration (mg/m^3)*
1,3,5-Methylbenzene	10 – 25
Toluene	0.2 – 615
m/p-Xylene	0 – 376
o-Xylene	0.2 – 7
Trichlorofluormethane	1 – 84
Dichlorofluormethane	4 – 119
Chlorotrifluormethane	0 – 10
Dichloromethane	0 – 6
Trichloromethane	0 – 2
Tetrachloromethane	0 – 0.6
Chloroethylene	0 – 264
Dichloroethylene	0 – 294
Trichloroethylene	0 – 182
Tetrachloroethylene	0.1 – 142
Chlorobenzene	0 – 0.2

B. Mathematical Equations of 2006 IPCC Guidelines FOD Method

All equations below are from 2006 IPCC Guidelines for National Greenhouse Gas Inventories [20].

The equation for the estimation of DOC using default carbon content values:

$$DOC = \sum_i (DOC_i \cdot W_i) \qquad \text{(A-1)}$$

◆ DOC	fraction of degradable organic carbon in bulk waste, Gg C/Gg waste
◆ DOC_i	fraction of degradable organic carbon in waste type *i* e.g., the default value for paper is 0.4 (wet weight basis)
◆ W_i	fraction of waste type *i* by waste category e.g., the default value for paper in MSW in Eastern Asia is 0.188 (wet weight basis)

The equation for the calculation of decomposable DOC from waste disposal data:

$$DDOCm = W \times DOC \times DOC_f \times MCF \qquad \text{(A-2)}$$

◆ DDOCm	mass of decomposable DOC deposited, Gg
◆ W	mass of waste deposited, Gg
◆ DOC	degradable organic carbon in the year of deposition, fraction, Gg C/Gg waste
◆ DOC_f	fraction of DOC that can decompose (fraction)
◆ MCF	CH_4 correction factor for aerobic decomposition in the year of deposition (fraction)

The equation for the transformation from DDOCm to L_o:

$$L_o = DDOCm \cdot F \cdot 16/12 \qquad \text{(A-3)}$$

◆ L_o	CH_4 generation potential, Gg CH_4
◆ DDOCm	mass of decomposable DOC deposited, Gg
◆ F	fraction of CH_4 in generated landfill gas (volume fraction)
◆ 16/12	molecular weight ratio CH_4/C (ratio)

The equation for the calculation of DDOCm accumulated in the SWDS at the end of year T:

$$DDOCma_T = DDOCmd_T + (DDOCma_{T-1} \cdot e^{-k}) \qquad \text{(A-4)}$$

$DDOCma_T$	DDOCm accumulated in the SWDS at the end of year *T*, Gg
$DDOCma_{T-1}$	DDOCm accumulated in the SWDS at the end of year (*T-1*), Gg
$DDOCmd_T$	DDOCm deposited into the SWDS in year *T*, Gg
k	reaction constant, $k = \ln(2)/t_{1/2}$ (y^{-1})
$t_{1/2}$	half-life time (y)

The equation for the calculation of DDOCm decomposed at the end of year T:

$$DDOCm\ decomp_T = DDOCma_{T-1} \cdot (1 - e^{-k}) \qquad \text{(A-5)}$$

$DDOCm\ decomp_T$	DDOCm decomposed in year *T*, Gg

The equation for the calculation of CH_4 generated from decayed DDOCm:

$$CH_4\ genrated_T = DDOCm\ decomp_T \cdot F \cdot 16/12 \qquad \text{(A-6)}$$

CH_4 generated	amount of CH_4 generated from decomposable material
$DDOCm\ decomp_T$	DDOCm decomposed in year *T*, Gg
F	fraction of CH_4, by volume, in generated landfill gas (fraction)

The equation for the calculation of CH_4 emissions from solid waste disposal for a single year:

$$CH_4\ emissions = \left[\textstyle\sum_x CH_4\ generated_{x,T} - R_T\right] \cdot (1 - OX_T) \qquad \text{(4-5) (A-7)}$$

CH_4 emissions	CH_4 emitted in year *T*, Gg
CH_4 generated	amount of CH_4 generated from decomposable material
T	inventory year
x	waste category or type/material
R_T	recovered CH_4 in year *T*, Gg
OX_T	oxidation factor in year *T*, (fraction)

C. U.S. EPA GHGRP Emission Measurement and Calculation Methodologies

Table A-2 is summarized from [85], and Table A-3 is summarized from [86].

Table A-2 EPA GHGRP Emission Calculation Methodologies According to GHG Category

Calculation for	*Methodology*	
	Tier	*Parameter*
1. CO_2 Emissions from Combustion[a]	Tier 4 Methodology: Continuous Emission Monitoring System (CEMS)	1) the stack gas CO_2 concentration 2) the stack gas flow rate 3) the appropriate conversion factors
	Tier 3 Methodology: Use Fuel-Specific Data	1) the measured fuel characteristics (such as carbon content and molecular weight) 2) the measured fuel quantity (measured with flow meters, tank drop measurements, weigh scales, etc.)
	Tier 2 Methodology: Use a Mix of Default and Fuel-Specific Data	1) an emission factor 2) a measured high heating value 3) the estimated fuel quantity
	Tier 1 Methodology: Use Default Values	1) an emission factor 2) the default high heating value 3) the estimated fuel quantity
2. CH_4 and N_2O Emissions from Combustion[b]	Most units use 1) an emission factor that is multiplied by 2) annual fuel use and 3) the high heating value of the fuel (either a default or measured high heating value is used, depending on the circumstances).	
3. CO_2 Emissions from Sorbent Use	For units that use acid gas emission controls and do not measure emissions with a CEMS, CO_2 emissions created by the reaction of the sorbent with the acid gas must also be determined, using 1) the quantity and 2) chemical properties of the sorbent.	

a. 1) Use of the four methodologies is subject to certain restrictions based on unit size and fuel combusted.
2) For heterogeneous fuels such as municipal solid waste, CEMS (Tier 4 Methodology) are generally considered the most accurate emissions estimation method.
3) For Tier 2 and Tier 1 Methodologies, the fuel quantity estimate is based on company records (e.g., fuel purchases).
4) The emission factors used in Tiers 1 and 2 and the default high heating values used in Tier 1 are representative averages based on multiple fuel samples taken across the country. For homogeneous fuels, such as pipeline-quality natural gas, these methodologies often provide a very accurate emissions estimate.

b. Units that monitor and report annual heat input according to part 75 requirements use an emission factor and the measured annual heat input.

Table A-3 EPA GHGRP Emission Calculation Methodologies According to Source Category

GHG Emission Source Category	*Subcategory*		*Specific Source Description/Example*	*GHG Released*	*Emission Calculation Methodologies*
1. Direct-Emitting Facilities	Emissions from Fuel Combustion	Combustion of a Fossil Fuel	Coal, Natural Gas, Petroleum Products	Carbon Dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O)	1) Continuous Emission Monitoring System (CEMS), 2) Measured Fuel Composition Data, 3) Default Emission Factors
		Combustion of Biomass Feedstock	Wood, Landfill Gas		
	Process Emissions	Chemical Transformation of Raw Materials	Iron and Steel Production, Cement Production, Petrochemical Production, Nitric Acid Production		1) Continuous Emission Monitoring System (CEMS), 2) Mass Balance Approach, 3) Site-Specific Emission Factors, 4) Default Emission Factors
		Fugitive Emissions (Emissions of Gases due to Leaks or other Unintended or Irregular Releases)	from Petroleum and Natural Gas Systems and Underground Coal Mines	Methane (CH_4)	
			from Industrial Gas Production, Electrical Equipment Production and Use, Electronics Manufacturing, Aluminum Production, and Magnesium Production	Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), Sulfur Hexafluoride (SF_6)	
2. Suppliers[a]	\	\	Suppliers of certain fossil fuels and industrial gases report the emissions that would occur if the products that they place into the economy were fully released or oxidized.		Mass Balance Methods based on either: 1) Default Emission Factors 2) Reporter-Specific Emission Factors Derived from Testing 3) Direct Measurement of Carbon Quantities
3. CO_2 Injection Facilities[a,b]	\	\	Facilities that inject CO_2 underground for sequestration or other purposes are required to report the quantity of CO_2 that they receive for injection.		Mass Balance Approach

a. Reporters are generally allowed to determine quantities of product supplied / the mass of CO_2 received for injection by using standard industry practices for mass and volumetric flow calculations.

b. Facilities that conduct geologic sequestration are required to report information on the CO_2 received for injection and must develop and implement an EPA-approved monitoring, reporting, and verification (MRV) plan for reporting.

D. Climate Zone Statistics of Methane Generation Rate (*k*)

Table A-4 Typical Values (Mean) of Methane Generation Rate (*k*) in Different Climate Zones

Climate Zone			*Bulk Waste Option*	*Modified Bulk Waste Option*			*Waste Composition Option*								
			Bulk Waste	*Bulk MSW Waste*[a]	*Bulk C&D Waste*	*Inerts*	*Bulk Waste*	*Food Waste*	*Garden*	*Sewage Sludge*	*Paper*	*Wood and Straw*	*Textiles*	*Diapers*	*Inerts*
A	f		0.037	0.030	0.04	0	0.048								0
	m		0.057	0.057	0.04	0	0.057								0
	s														
	w														
B	S	h	0.024	0.02	0.02	0	0.025			0.185	0.06		0.06	0.1	0
		k	0.021	0.02	0.02	0	0.02								0
	W	h	0.02	0.02	0.02	0	0.02								0
		k	0.02												
C	f	a	0.052	0.051	0.037	0	0.050	0.185	0.1	0.149	0.06	0.03	0.06	0.1	0
		b	0.037	0.057	0.04	0	0.057								0
		c													
	s	a	0.024	0.02	0.02	0	0.021	0.06		0.06					0
		b	0.033	0.043	0.033	0	0.029		0.05	0.06					0
		c													
D	f	a	0.040	0.039	0.033	0	0.039	0.185	0.1	0.185	0.06	0.03	0.06	0.1	0
		b	0.040	0.041	0.032	0	0.041			0.123		0.025			0
		c	0.027				0.039								0
	s	a													
		b	0.037												
		c													
	w	a	0.038												
		b													
		c													
E		T													

a. Excluding inerts and C&D waste.

Table A-5 Ranges of Methane Generation Rate (k) in Different Climate Zones

Climate Zone			*Bulk Waste Option*	*Modified Bulk Waste Option*			*Waste Composition Option*								
			Bulk Waste	*Bulk MSW Waste*[a]	*Bulk C&D Waste*	*Inerts*	*Bulk Waste*	*Food Waste*	*Garden*	*Sewage Sludge*	*Paper*	*Wood and Straw*	*Textiles*	*Diapers*	*Inerts*
A	f		0.02 – 0.057	0.0295	0.04	0	0.038 – 0.057								0
	m		0.057	0.057	0.04	0	0.057								0
	s														
	w														
B	S	h	0.02 – 0.038	0.02	0.02	0	0.02 – 0.038			0.185	0.06		0.06	0.1	0
		k	0.02 – 0.038	0.02	0.02	0	0.02								0
	W	h	0.02	0.02	0.02	0	0.02								0
		k	0.02												
C	f	a	0.02 – 0.057	0.02 – 0.057	0.02 – 0.04	0	0.038 – 0.057	0.185	0.1	0.06 – 0.185	0.06	0.02 – 0.04	0.06	0.1	0
		b	0.02 – 0.057	0.057	0.04	0	0.057								0
		c													
	s	a	0.02 – 0.038	0.02	0.02	0	0.02 – 0.038	0.06		0.06					0
		b	0.02 – 0.057	0.02 – 0.05	0.02 – 0.04	0	0.02 – 0.057		0.05	0.06					0
		c													
D	f	a	0.02 – 0.057	0.02 – 0.057	0.03 – 0.04	0	0.038 – 0.057	0.185	0.1	0.185	0.06	0.03	0.06	0.1	0
		b	0.02 – 0.057	0.02 – 0.057	0.02 – 0.04	0	0.02 – 0.057			0.1225 – 0.123		0.025			0
		c	0.02 – 0.057				0.02 – 0.057								0
	s	a													
		b	0.02 – 0.057												
		c													
	w	a	0.038												
		b													
		c													
E		T													

a. Excluding inerts and C&D waste.

Table A-6 Sample Sizes of Methane Generation Rate (k) in Different Climate Zones

Climate Zone			*Bulk Waste Option*	*Modified Bulk Waste Option*			*Waste Composition Option*									*Total*
			Bulk Waste	*Bulk MSW Waste*[a]	*Bulk C&D Waste*	*Inerts*	*Bulk Waste*	*Food Waste*	*Garden*	*Sewage Sludge*	*Paper*	*Wood and Straw*	*Textiles*	*Diapers*	*Inerts*	
A	f		17	1	1	1	8								6	34
	m		11	11	15	5	9								7	58
	s						2								4	6
	w															0
B	S	h	31	2	3	1	12			1	1		1	1	8	61
		k	63	10	10	4	58								47	192
	W	h	16	9	8	7	22								21	83
		k	8													8
C	f	a	850	208	138	124	572	1	1	7	2	5	4	1	523	2436
		b	17	7	3	2	2								4	35
		c														0
	s	a	50	8	6	6	35	3		3					19	130
		b	67	4	3	4	53		5	2					52	190
		c														0
D	f	a	121	53	39	33	124	6	4	2	10	5	7	6	125	535
		b	62	34	28	28	62			4		4			58	280
		c	13				6								5	24
	s	a														0
		b	11													11
		c														0
	w	a	1													1
		b														0
		c														0
E		T														0
Total			1338	347	254	215	965	10	10	19	13	14	12	8	879	4084

a. Excluding inerts and C&D waste.

E. Climate Zone Statistics of Methane Generation, Recovery and Emission

Table A-7 Typical Values of Methane Generation Ratio, Recovery Ratio, Emission Ratio and Estimated Collection Efficiency in Different Climate Zones

Climate Zone			*Generation Ratio (HH-1)*	*Generation Ratio (HH-5)*	*Generation Ratio (HH-7)*	*Recovery Ratio*	*Emission Ratio*	*Estimated Collection Efficiency*
A	f		0.0421	0.0379	0.0208	0.0127	0.0195	0.721
	m		0.0436	0.0393	0.0190	0.0171	0.0106	0.646
	s		0.0490	0.0367	0.0216	0.0233	0.0038	0.813
	w							
B	S	h	0.0267	0.0200	0.0182	0.0099	0.0068	0.703
		k	0.0235	0.0208	0.0113	0.0092	0.0156 (0.0011 – 0.0889)	0.693 (0.28 – 0.95)
	W	h	0.0255	0.0201	0.0068	0.0049	0.0103	0.625
		k					0.0153	
C	f	a	0.0436 (0.0183 – 0.1183)	0.0358 (0.0157 – 0.0955)	0.0277 (0.0087 – 0.0798)	0.0218 (0.0041 – 0.0581)	0.0156 (0.0027 – 0.0881)	0.703 (0.111 – 0.95)
		b	0.0378	0.0283	0.0152	0.0148	0.0154	0.751
		c						
	s	a	0.0235 (0.0120 – 0.0435)	0.0196 (0.0096 – 0.0392)	0.0199 (0.0030 – 0.0447)	0.0166 (0.0003 – 0.0313)	0.0051 (0.0012 – 0.0225)	0.740 (0.41 – 0.95)
		b	0.0284 (0.0099 – 0.0586)	0.0235 (0.0074 – 0.0527)	0.0227 (0.0110 – 0.0497)	0.0192 (0.0046 – 0.0477)	0.0101 (0.0023 – 0.0254)	0.771 (0.198 – 0.95)
		c						
D	f	a	0.0399 (0.0203 – 0.1075)	0.0317 (0.0146 – 0.0967)	0.0295 (0.0141 – 0.0735)	0.0241 (0.0078 – 0.0864)	0.0126 (0.0032 – 0.0597)	0.781 (0.23 – 0.95)
		b	0.0371 (0.0186 – 0.0652)	0.0315 (0.0156 – 0.0539)	0.0231 (0.0026 – 0.0513)	0.0223 (0.0021 – 0.0497)	0.0090 (0.0019 – 0.0354)	0.758 (0.29 – 0.91)
		c	0.0362	0.0294	0.0943	0.0500	0.0307	0.378
	s	a						
		b	0.0305	0.0275	0.0239	0.0224	0.0159	0.690
		c						
	w	a					0.0250	
		b						
		c						
E		T						
Overall			0.0395 (0.0152 – 0.1002)	0.0315 (0.0122 – 0.0844)	0.0252 (0.0066 – 0.0715)	0.021 (0.0031 – 0.0559)	0.0136 (0.0023 – 0.0665)	0.720 (0.07 – 0.98)

The unit for all ratio statistics is *t* CH_4 / *t* MSW. The climate zones with more than 30 samples are also given the ranges of corresponding typical values.

Table A-8 Sample Sizes of Methane Generation Ratio, Recovery Ratio, Emission Ratio and Estimated Collection Efficiency in Different Climate Zones

Climate Zone			*Generation Ratio (HH-1)*	*Generation Ratio (HH-5)*	*Generation Ratio (HH-7)*	*Recovery Ratio*	*Emission Ratio*	*Estimated Collection Efficiency*
A	f		6	6	6	6	8	7
	m		9	9	9	9	11	11
	s		1	1	1	1	1	1
	w							
B	S	h	10	10	10	10	13	15
		k	28	28	27	28	53	33
	W	h	10	10	10	10	18	14
		k					4	
C	f	a	416	416	416	416	559	497
		b	7	7	7	7	11	8
		c						
	s	a	31	31	31	31	33	37
		b	38	38	38	38	41	58
		c						
D	f	a	81	81	81	81	109	108
		b	43	43	43	43	59	44
		c	2	2	2	2	6	3
	s	a						
		b	1	1	1	1	2	2
		c						
	w	a					1	
		b						
		c						
E		T						
Total			683	683	682	683	929	838

F. Landfill Methane Emissions per capita by Country

Table A-9 Landfill Methane Emissions per capita by Country: 1970 – 2017 (*kg*)

World Region	*Country*	*Code*	*Income Group*	*1970*	*1980*	*1990*	*2000*	*2010*	*2012*	*2017*
East Asia & Pacific	Australia	AUS	High	35.33	36.50	36.87	27.49	22.63	18.67	18.78
	Brunei Darussalam	BRN	High	2.11	2.48	2.83	3.19	3.57	3.62	3.70
	Cambodia	KHM	Lower Middle	0.35	0.25	0.42	0.52	0.56	0.58	0.63
	China	CHN	Upper Middle	0.46	0.57	0.86	1.28	1.90	2.05	2.30
	Fiji	FJI	Upper Middle	3.06	4.41	5.04	6.15	6.88	7.03	7.37
	Indonesia	IDN	Lower Middle	0.44	0.74	1.13	1.73	2.19	2.29	2.44
	Japan	JPN	High	2.41	2.77	2.94	2.21	1.23	1.09	1.10
	Kiribati	KIR	Lower Middle	1.90	3.56	3.97	5.23	5.41	5.45	5.91
	Korea, Democratic People's Republic of	PRK	Low	3.80	4.40	4.57	4.70	4.79	4.83	4.90
	Korea, Republic of	KOR	High	1.20	2.14	3.25	3.59	1.87	1.87	1.86
	Lao People's Democratic Republic	LAO	Lower Middle	0.20	0.32	0.41	0.64	1.08	1.19	1.30
	Malaysia	MYS	Upper Middle	0.90	1.50	1.91	2.63	3.02	3.11	3.24
	Marshall Islands	MHL	Upper Middle	5.58	8.15	9.54	10.36	11.05	11.18	11.50
	Micronesia, Federated States of	FSM	Lower Middle	1.97	2.75	2.67	2.25	2.23	2.24	2.27
	Mongolia	MNG	Lower Middle	1.68	2.15	2.46	2.47	3.16	3.28	3.29
	Myanmar	MMR	Lower Middle	0.58	0.74	0.77	0.87	1.05	1.10	1.14
	Nauru	NRU	Upper Middle	14.47	18.69	18.66	18.76	18.75	18.37	18.37
	New Zealand	NZL	High	42.68	45.75	41.68	41.96	35.62	33.69	33.81
	Papua New Guinea	PNG	Lower Middle	0.22	0.38	0.45	0.39	0.38	0.38	0.39
	Philippines	PHL	Lower Middle	0.87	1.28	1.83	1.80	1.64	1.62	1.66
	Samoa	WSM	Upper Middle	1.54	2.09	2.09	2.19	1.96	1.91	1.80
	Singapore	SGP	High	4.43	5.48	5.41	5.32	5.47	5.46	5.46
	Solomon Islands	SLB	Lower Middle	0.59	0.91	1.22	1.45	1.93	2.03	2.26
	Thailand	THA	Upper Middle	0.49	0.82	0.93	1.01	1.59	1.72	1.86
	Timor-Leste	TLS	Lower Middle	0.32	0.51	0.68	0.82	1.03	1.09	1.15

World Region	***Country***	***Code***	***Income Group***	***1970***	***1980***	***1990***	***2000***	***2010***	***2012***	***2017***
	Tonga	TON	Upper Middle	1.52	2.08	2.28	2.31	2.36	2.38	2.35
	Tuvalu	TUV	Upper Middle	1.70	3.20	4.85	5.81	6.94	7.20	7.80
	Vanuatu	VUT	Lower Middle	0.85	1.34	1.78	2.14	2.50	2.58	2.63
	Viet Nam	VNM	Lower Middle	0.42	0.54	0.58	0.73	0.97	1.02	1.13
Europe & Central Asia	Albania	ALB	Upper Middle	8.69	9.27	9.48	10.09	10.90	11.06	12.09
	Armenia	ARM	Upper Middle	1.01	1.12	1.13	1.29	1.29	1.51	1.51
	Austria	AUT	High	19.09	20.93	20.55	13.10	7.88	6.76	6.87
	Azerbaijan	AZE	Upper Middle	0.94	1.01	1.02	1.16	1.84	2.16	2.21
	Belarus	BLR	Upper Middle	8.53	10.11	10.98	12.99	29.98	30.46	31.44
	Belgium	BEL	High	10.33	11.43	11.72	8.22	2.46	2.50	2.50
	Bosnia and Herzegovina	BIH	Upper Middle	0.35	0.27	0.14	0.50	6.86	6.79	7.03
	Bulgaria	BGR	Upper Middle	15.39	17.46	18.16	19.96	18.97	18.48	18.91
	Croatia	HRV	High	6.93	4.85	2.42	4.35	7.96	8.88	9.07
	Cyprus	CYP	High	25.68	31.54	33.65	38.30	38.58	39.30	39.05
	Czech Republic	CZE	High	6.73	8.29	7.67	10.48	12.26	12.51	12.59
	Denmark	DNK	High	11.83	12.78	12.67	9.28	6.29	6.07	6.11
	Estonia	EST	High	4.48	5.41	5.46	14.88	9.72	8.47	8.56
	Finland	FIN	High	28.92	30.59	34.69	26.80	16.38	15.29	15.37
	France	FRA	High	6.86	7.56	7.07	8.43	6.73	6.35	6.46
	Georgia	GEO	Lower Middle	1.02	1.13	1.16	1.25	1.63	1.90	1.97
	Germany	DEU	High	23.68	25.59	23.13	14.25	6.90	6.10	6.11
	Greece	GRC	High	8.86	9.62	10.40	13.81	15.13	13.77	14.08
	Hungary	HUN	High	7.76	8.18	8.18	10.72	12.02	11.89	12.12
	Iceland	ISL	High	22.56	24.47	23.85	30.41	28.42	23.89	23.93
	Ireland	IRL	High	14.13	15.62	15.86	15.77	8.12	8.28	8.41
	Italy	ITA	High	11.21	14.44	12.82	15.37	10.22	8.98	9.17
	Kazakhstan	KAZ	Upper Middle	5.78	6.06	6.27	8.89	9.75	9.89	9.96
	Kyrgyzstan	KGZ	Lower Middle	0.84	0.89	0.88	1.01	0.92	1.08	1.10
	Latvia	LVA	High	5.29	5.81	5.91	8.09	9.89	10.51	10.53

World Region	***Country***	***Code***	***Income Group***	***1970***	***1980***	***1990***	***2000***	***2010***	***2012***	***2017***
	Lithuania	LTU	High	8.88	10.07	11.14	13.10	14.16	14.25	14.39
	Luxembourg	LUX	High	7.53	8.38	8.36	6.09	2.95	2.32	2.36
	Macedonia, the former Yugoslav Republic of	MKD	Upper Middle	3.33	3.68	3.81	6.40	14.65	13.65	13.80
	Moldova, Republic of	MDA	Lower Middle	0.94	1.06	1.13	1.27	1.95	2.27	2.27
	Netherlands	NLD	High	36.70	39.93	38.23	24.15	9.74	8.46	8.69
	Norway	NOR	High	17.80	19.58	19.34	14.53	10.51	9.93	10.17
	Poland	POL	High	10.66	11.56	11.52	11.75	11.09	10.76	10.67
	Portugal	PRT	High	13.73	14.65	14.46	21.83	22.38	23.01	24.08
	Romania	ROU	Upper Middle	2.37	2.63	2.62	4.20	7.79	8.04	8.03
	Russian Federation	RUS	Upper Middle	8.69	9.06	9.08	11.33	16.26	17.78	17.90
	Slovakia	SVK	High	5.82	6.81	7.05	10.79	14.29	14.35	14.21
	Slovenia	SVN	High	7.50	7.84	8.23	10.51	8.27	8.21	8.39
	Spain	ESP	High	5.49	6.09	6.24	10.30	10.92	11.18	11.34
	Sweden	SWE	High	16.05	17.42	16.00	12.92	6.49	5.51	5.60
	Switzerland	CHE	High	5.06	5.72	5.61	3.27	31.22	26.29	26.33
	Tajikistan	TJK	Low	0.83	0.85	0.83	0.91	1.41	1.64	1.67
	Turkey	TUR	Upper Middle	2.96	3.74	5.76	21.76	21.66	22.19	23.02
	Turkmenistan	TKM	Upper Middle	0.92	0.95	0.94	1.10	1.73	2.02	2.10
	Ukraine	UKR	Lower Middle	5.16	5.40	5.35	6.42	7.66	7.94	8.00
	United Kingdom	GBR	High	37.81	41.83	39.59	36.95	18.20	15.34	15.58
	Uzbekistan	UZB	Lower Middle	0.82	0.90	0.90	1.01	1.52	1.75	1.74
Latin America & Caribbean	Antigua and Barbuda	ATG	High	2.58	3.27	3.26	2.87	2.19	2.08	2.02
	Argentina	ARG	High	3.58	4.15	4.47	4.65	2.13	2.14	2.15
	Bahamas	BHS	High	7.17	10.00	11.46	11.97	12.09	12.14	12.19
	Barbados	BRB	High	3.05	4.08	3.17	3.30	3.08	3.05	3.01
	Belize	BLZ	Upper Middle	1.35	1.60	1.52	1.52	1.40	1.39	1.40
	Bolivia	BOL	Lower Middle	1.27	1.69	2.25	2.64	2.44	2.48	2.55
	Brazil	BRA	Upper Middle	1.85	2.80	3.36	3.87	2.94	2.97	3.02

World Region	***Country***	***Code***	***Income Group***	***1970***	***1980***	***1990***	***2000***	***2010***	***2012***	***2017***
	Chile	CHL	High	3.38	4.02	4.16	4.38	2.08	2.10	2.11
	Colombia	COL	Upper Middle	1.90	2.62	3.02	3.28	3.49	3.53	3.61
	Costa Rica	CRI	Upper Middle	0.96	1.34	1.65	2.10	1.83	1.91	2.03
	Cuba	CUB	Upper Middle	6.44	9.15	10.24	10.65	10.95	10.97	11.00
	Dominica	DMA	Upper Middle	3.18	5.13	7.91	8.38	8.88	8.98	9.17
	Dominican Republic	DOM	Upper Middle	3.46	5.90	6.60	7.76	10.13	10.58	11.21
	Ecuador	ECU	Upper Middle	1.24	1.77	2.22	2.54	2.33	2.35	2.38
	El Salvador	SLV	Lower Middle	0.94	1.36	1.60	2.05	1.49	1.51	1.61
	Grenada	GRD	Upper Middle	2.48	3.18	3.26	3.57	3.55	3.55	3.57
	Guatemala	GTM	Upper Middle	0.86	1.10	1.26	1.46	1.66	1.70	1.76
	Guyana	GUY	Upper Middle	0.71	0.94	0.88	0.85	0.86	0.86	0.86
	Haiti	HTI	Low	1.41	1.80	2.69	3.61	6.10	6.56	7.21
	Honduras	HND	Lower Middle	0.62	0.97	1.20	1.36	1.57	1.61	1.71
	Jamaica	JAM	Upper Middle	3.47	5.08	5.48	5.83	6.11	6.18	6.32
	Mexico	MEX	Upper Middle	1.99	2.60	2.92	3.15	3.13	3.16	3.22
	Nicaragua	NIC	Lower Middle	1.24	1.64	1.76	1.88	2.01	2.04	2.07
	Panama	PAN	High	1.26	1.67	1.83	2.26	2.41	2.44	2.50
	Paraguay	PRY	Upper Middle	0.98	1.42	1.76	2.12	2.31	2.34	2.39
	Peru	PER	Upper Middle	2.22	2.83	3.12	3.41	2.62	2.66	2.69
	Saint Kitts and Nevis	KNA	High	2.68	3.58	3.41	3.18	3.09	3.11	3.08
	Saint Lucia	LCA	Upper Middle	1.69	2.39	2.73	2.55	1.59	1.58	1.59
	Saint Vincent and the Grenadines	VCT	Upper Middle	2.33	3.56	4.33	4.91	5.47	5.58	5.81
	Suriname	SUR	Upper Middle	1.32	2.68	2.75	2.84	2.75	2.74	2.73
	Trinidad and Tobago	TTO	High	0.73	0.82	0.63	0.81	0.67	0.65	0.64
	Uruguay	URY	High	3.61	4.30	4.59	4.84	5.04	5.07	5.10
	Venezuela	VEN	Upper Middle	3.01	3.84	4.23	4.52	4.59	4.59	4.60
Middle East & North Africa	Algeria	DZA	Upper Middle	1.90	2.29	2.95	3.62	4.32	4.44	4.64
	Bahrain	BHR	High	9.64	10.63	11.04	11.12	11.29	11.43	11.49
	Djibouti	DJI	Lower Middle	3.32	4.46	4.82	4.94	4.83	4.81	4.84

World Region	***Country***	***Code***	***Income Group***	***1970***	***1980***	***1990***	***2000***	***2010***	***2012***	***2017***
	Egypt	EGY	Lower Middle	1.99	2.27	2.24	2.19	1.94	1.94	1.93
	Iran, Islamic Republic of	IRN	Upper Middle	3.43	4.68	5.61	6.76	7.83	8.02	8.31
	Iraq	IRQ	Upper Middle	5.27	7.00	7.70	7.50	7.61	7.65	7.75
	Israel	ISR	High	12.26	14.43	15.77	16.69	15.54	15.76	15.82
	Jordan	JOR	Upper Middle	5.11	5.92	7.83	8.86	9.04	8.80	9.06
	Kuwait	KWT	High	10.00	12.47	12.82	12.30	13.36	13.20	13.20
	Lebanon	LBN	Upper Middle	5.81	8.39	10.10	10.65	10.87	10.92	11.02
	Libyan Arab Jamahiriya	LBY	Upper Middle	2.56	4.52	5.10	5.19	5.44	5.47	5.56
	Malta	MLT	High	1.81	1.90	1.88	4.38	11.72	5.58	5.60
	Morocco	MAR	Lower Middle	1.59	2.13	2.67	3.07	3.33	3.41	3.57
	Oman	OMN	High	2.18	4.38	7.08	7.92	8.33	8.97	9.66
	Qatar	QAT	High	10.43	11.25	11.97	12.72	13.04	12.64	12.69
	Saudi Arabia	SAU	High	4.29	7.16	8.89	9.76	10.12	10.10	10.24
	Syrian Arab Republic	SYR	Low	3.70	4.30	4.59	4.98	5.45	5.53	5.52
	Tunisia	TUN	Lower Middle	2.16	2.83	3.45	3.94	3.80	3.83	3.91
	United Arab Emirates	ARE	High	8.91	9.36	9.07	9.21	10.29	10.43	10.61
	Yemen	YEM	Low	0.81	1.10	1.47	1.97	2.53	2.65	2.89
North America	Canada	CAN	High	33.92	36.53	29.89	29.29	26.05	26.07	26.13
	United States	USA	High	29.58	31.78	28.23	18.91	16.86	15.53	15.71
South Asia	Afghanistan	AFG	Low	0.06	0.09	0.11	0.13	0.15	0.16	0.17
	Bangladesh	BGD	Lower Middle	0.15	0.39	0.56	0.69	0.95	1.01	1.13
	Bhutan	BTN	Lower Middle	0.13	0.27	0.46	0.78	1.19	1.25	1.39
	India	IND	Lower Middle	0.53	0.71	0.81	0.90	1.03	1.07	1.13
	Maldives	MDV	Upper Middle	0.25	0.64	0.78	0.85	1.26	1.33	1.41
	Nepal	NPL	Low	0.09	0.15	0.23	0.37	0.48	0.50	0.56
	Pakistan	PAK	Lower Middle	0.74	0.92	1.03	1.15	1.31	1.35	1.39
	Sri Lanka	LKA	Lower Middle	0.46	0.53	0.52	0.52	0.52	0.52	0.52
Sub-Saharan Africa	Angola	AGO	Lower Middle	0.61	0.93	1.27	1.74	2.29	2.41	2.55
	Benin	BEN	Low	0.47	0.92	1.25	1.46	1.68	1.72	1.83

World Region	Country	Code	Income Group	1970	1980	1990	2000	2010	2012	2017
	Botswana	BWA	Upper Middle	0.33	0.81	2.71	3.83	4.20	4.27	4.53
	Burkina Faso	BFA	Low	0.14	0.24	0.40	0.54	0.85	0.92	1.02
	Burundi	BDI	Low	0.09	0.16	0.24	0.33	0.45	0.48	0.54
	Cameroon	CMR	Lower Middle	0.53	1.12	1.49	1.83	2.16	2.22	2.34
	Cape Verde	CPV	Lower Middle	0.57	0.76	1.74	2.31	2.78	2.87	2.98
	Central African Republic	CAF	Low	1.07	1.66	1.86	1.91	2.00	2.10	2.18
	Chad	TCD	Low	0.43	0.81	0.92	0.97	0.99	1.00	1.03
	Comoros	COM	Low	0.54	0.86	1.09	1.11	1.11	1.12	1.14
	Congo	COG	Lower Middle	1.11	1.80	2.17	2.39	2.57	2.61	2.71
	Congo, the Democratic Republic of the	COD	Low	0.93	1.24	1.47	1.78	2.12	2.19	2.34
	Cote d'Ivoire	CIV	Lower Middle	0.71	1.26	1.38	1.59	1.15	1.20	1.25
	Equatorial Guinea	GNQ	Upper Middle	0.66	0.77	1.04	1.19	1.07	1.05	1.09
	Eritrea	ERI	Low	0.42	0.52	0.59	0.69	0.86		
	Ethiopia	ETH	Low	0.27	0.36	0.45	0.53	0.65	0.69	0.77
	Gabon	GAB	Upper Middle	0.86	2.22	3.15	3.96	4.14	4.09	4.20
	Gambia	GMB	Low	0.45	0.89	1.33	1.81	2.30	2.38	2.53
	Ghana	GHA	Lower Middle	0.86	1.07	1.32	1.70	2.08	2.16	2.30
	Guinea	GIN	Low	0.35	0.71	0.88	1.01	1.20	1.25	1.31
	Guinea-Bissau	GNB	Low	0.33	0.52	0.92	1.33	1.76	1.85	1.94
	Kenya	KEN	Lower Middle	0.33	0.57	0.63	0.76	0.93	0.97	1.05
	Lesotho	LSO	Lower Middle	0.37	0.53	0.67	1.00	1.33	1.40	1.51
	Liberia	LBR	Low	0.64	1.19	2.25	1.64	1.82	1.86	1.94
	Madagascar	MDG	Low	0.42	0.68	0.91	1.10	1.35	1.42	1.56
	Malawi	MWI	Low	0.22	0.40	0.52	0.68	0.73	0.74	0.79
	Mali	MLI	Low	0.39	0.56	0.75	0.97	1.33	1.41	1.56
	Mauritania	MRT	Lower Middle	0.40	0.92	1.59	2.04	2.49	2.55	2.78
	Mauritius	MUS	Upper Middle	1.49	1.92	2.01	1.94	1.81	1.79	1.77
	Mozambique	MOZ	Low	0.25	0.60	1.32	1.62	1.75	1.78	1.92

World Region	***Country***	***Code***	***Income Group***	***1970***	***1980***	***1990***	***2000***	***2010***	***2012***	***2017***
	Namibia	NAM	Upper Middle	1.13	1.37	1.56	1.91	2.72	2.91	3.26
	Niger	NER	Low	0.22	0.38	0.44	0.47	0.52	0.54	0.55
	Nigeria	NGA	Lower Middle	0.45	0.68	1.00	1.24	1.67	1.77	1.94
	Rwanda	RWA	Low	0.11	0.17	0.20	0.62	1.11	1.22	1.23
	Sao Tome and Principe	STP	Lower Middle	0.78	1.13	1.61	2.14	2.62	2.70	2.89
	Senegal	SEN	Low	0.94	1.30	1.45	1.53	1.64	1.68	1.76
	Seychelles	SYC	High	1.32	2.48	2.41	2.43	2.68	2.81	2.92
	Sierra Leone	SLE	Low	0.54	0.88	1.01	1.08	1.19	1.22	1.28
	Somalia	SOM	Low	0.85	1.07	1.09	1.22	1.38	1.41	1.50
	South Africa	ZAF	Upper Middle	3.09	3.26	3.62	4.13	4.75	4.85	5.05
	Sudan	SDN	Lower Middle	0.78	1.02	1.55	1.84	1.98	2.02	2.08
	Swaziland	SWZ	Lower Middle	0.41	0.90	1.22	1.21	1.12	1.11	1.15
	Tanzania, United Republic of	TZA	Low	0.32	0.70	0.96	1.17	1.49	1.59	1.78
	Togo	TGO	Low	0.61	0.80	0.97	1.14	1.37	1.42	1.51
	Uganda	UGA	Low	0.20	0.25	0.38	0.42	0.51	0.54	0.61
	Zambia	ZMB	Lower Middle	1.59	2.52	2.51	2.11	2.43	2.50	2.67
	Zimbabwe	ZWE	Low	0.81	1.20	1.70	2.06	1.96	1.93	1.89

G. Summary of Data Sources in the Calculation Part

Table A-10 Summary of Data Sources in the Calculation Part

Section	*Data*		*Time Covered by the Data*	*Source*	
5.1	Chemical composition of MSW components		\	Tchobanoglous, G., H. Theisen, and S. Vigil [47]	
	Amount of landfilled MSW in the U.S.		2015	U.S. EPA [48]	
	Typical moisture content of MSW components		\	Tchobanoglous, G., H. Theisen, and S. Vigil [49]	
	Methane emissions from landfill in the U.S.		1990 – 2016	UNFCCC [50]	
	LMOP Landfill Technical Data		2018	U.S. EPA [51]	
5.2	Köppen-Geiger climate classification		1901 – 2100	Rubel, F. and M. Kottek [56]	
	Landfills location data		2010 – 2017	U.S. EPA [55]	
	GHGRP facility-level data	Methane generation rate (k)	2010 – 2017	U.S. EPA [54] The names of the specific table in which the data are contained are listed on the right[a]	HH_WASTE_QTY_DETAILS
		Methane generation quantities (HH-1)			HH_LANDFILL_INFO
		Methane generation quantities (HH-5, HH-7)			HH_GAS_COLLECTION_SYSTEM_DETLS
		Methane recovery quantities			HH_GAS_COLLECTION_SYSTEM_DETLS
		Methane emission quantities			HH_SUBPART_LEVEL_INFORMATION
		Estimated collection efficiency			HH_GAS_COLLECTION_SYSTEM_DETLS
		Waste disposal quantities			HH_ANN_WASTE_DISPOSAL_QTY
5.3	Methane emissions from landfill (UNFCCC)		1990 – 2016[b]	UNFCCC [74]	
	Methane emissions from landfill (EDGAR)		1970 – 2012	Janssens-Maenhout, G., et al. [75]	
	Urban population		1960 – 2017	The World Bank [78]	
	Total population		1960 – 2017	The World Bank [79]	
	Income level		2018[c]	The World Bank [81]	

a. All the tables are in the subpart: *Municipal Solid Waste Landfills*.

b. The data of Non-Annex I parties are incomplete.

c. The time of the data which were used to determine the income level of economies is 2017.

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