Landfill Gas Monte Carlo Model Documentation and Results

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Overview

EPA's Waste Reduction Model (WARM) includes the disposal of waste in a landfill as one of the materials management pathways. The manner in which landfill gas is managed has a significant impact on the overall global warming potential (GWP) of a landfill. As such, it is important for a landfill life-cycle model to properly reflect the manner in which gas is managed. Landfill gas is produced over relatively long periods of time after waste burial, with the actual period of time dependent upon the decay rate. Therefore, even at landfills that include energy recovery, there will be a period of time when the energy recovery system is not operational on the front end and a period of time after closure when the landfill is not producing sufficient gas to operate an energy recovery project. Numerous factors will affect these times including the mass of waste disposed annually, the length of time that the landfill is open, and the landfill gas decay rate, which is a function of climate amongst other factors.

The objective of this analysis is to estimate the fraction of total produced landfill gas that is used beneficially, flared, and vented to the atmosphere at landfills that use the gas beneficially. Participants at EPA's Landfill Gas Experts Meeting held in October 2012 agreed that this type of analysis would be needed to improve upon the landfill gas collection efficiency modeling in WARM and other models. While this analysis provides updated estimates of emissions for a range of U.S. landfills, site-specific factors should be used where they are available. The model developed for this exercise considers three gas collection scenarios: 1) Best Case, 2) Typical, and 3) Worst Case. These cases are defined by the time between waste burial and initial gas collection, and the time before a long-term interim cover is in place. In addition to the three gas collection scenarios, this analysis also considers four bulk MSW decay rates: 0.02 yr^{-1}, 0.04 yr^{-1}, 0.06 yr^{-1}, and 0.12 yr^{-1}. The three gas collection scenarios and four decay rates create a total of twelve cases to be analyzed by pairing each gas collection scenario with each decay rate. While there are many alternatives for beneficial reuse, for this exercise, it was assumed that the gas was converted to electricity using an internal combustion engine. Monte Carlo analysis was used to develop an estimate of the fraction of produced gas that is vented directly, flared and utilized for energy recovery in consideration of range for annual waste deposition and landfill operating life. An additional twelve scenarios were analyzed in which the landfill gas only flared with no beneficial reuse. Here too, the time period over which a flare is required varies with the landfill size and waste deposition rate.

Methane oxidation was also considered in this analysis. A fraction of the gas that is not collected will be oxidized in a soil cover. Thus, uncollected methane refers to that methane released to the landfill cover while methane emissions refer to methane that was not oxidized in the cover.

A U.S. national average landfill scenario was also developed and analyzed with and without energy recovery, and these results were compared to a landfill gas collection consistent with Californian regulations to show how U.S. emissions could change with stricter collection requirements.

Section 1 below provides detailed descriptions of the different worksheets within the landfill model developed for this analysis. Section 2 presents results that will be used to update the landfill gas collection and oxidation factors in WARM.

1. Model Worksheet Descriptions

The Landfill Gas Model developed for this exercise is contained in an Excel workbook with 8 worksheets described in **Table 1**.

Table 1. List and descriptions of the worksheets in the landfill model.

Worksheet	Description
Read Me	Contains information on worksheets and model notes.
Material Properties	Decay rate and methane yield for each material.
LFG Collection Parameters	Enter landfill-wide inputs and calculates the time at which is flare may be turned off (flare cutoffs), and the time interval over which there is enough gas for energy recovery (energy cutons and energy cutoffs).
Potential Collection Efficiency	Annual collection efficiency for each year of waste burial if system stays on indefinitely. Used to calculate flare cutoff and energy cuton and cutoff.
Actual Collection Efficiency	Uses the cutons and cutoffs to calculate actual total collection efficiency in each year.
Energy Collection Efficiency	Uses the cutons and cutoffs to calculate actual total collection efficiency to energy recovery in each year.
Flare Collection Efficiency	Uses the cutons and cutoffs to calculate actual total collection efficiency to flare in each year.
Results	Shows the volume and percent of methane to energy recovery, flare, and released to atmosphere for each material.

Component specific decay rates and methane yields for all the waste materials are entered in the Material Properties worksheet. Inputs related to landfill gas generation and control are entered in the LFG Collection Parameters worksheet. Calculations in this worksheet then estimate when flares and energy recovery can or must be in operation based on inputs for minimum required gas flows. The timing of the flare and energy recovery is then used to calculate actual collection efficiencies for the flare and energy recovery. The temporally averaged collection efficiencies are estimates of the average proportion of gas collected after waste has been buried for a specified period of time. The efficiencies must be averaged because waste buried at different times has to wait different lengths of time before initial collection, interim cover, long-term cover, and final cover. These collection efficiencies are then used to determine the volume of methane generated, collected, oxidized, flared, recovered for energy, and emitted for each material over 100 years.

Read Me Worksheet

The Read Me worksheet contains information on the contents of the other worksheets and notes on the model.

Material Properties Worksheet

Component specific decay rates and methane yields for all the waste materials are entered in the Material Properties worksheet. The default values are shown in

Table **2**. The component-specific field decay rate is calculated based on the provided field decay rate specified for mixed MSW in the Landfill Gas and Waste Inputs table in the LFG Collection Parameters worksheet.

Table 2. The Material Properties table contains the methane yield and decay rate for each of the materials considered in the analysis (Material Properties worksheet; Cells C2:F16). [a]

Material Properties		
Material	**Methane Yield (m3/dry Mg)**	**Field Decay Rate ($k = 0.04\ yr^{-1}$)**
Branches	62.6	0.015
Grass	194.8	0.298
Leaves	65.3	0.171
Food Scraps	399.5	0.144
Corrugated Containers	195.1	0.02
Magazines/Third-class Mail	174.0	0.122
Newspaper	74.3	0.033
Office Paper	263.6	0.029
Phonebooks	74.3	0.033
Textbooks	263.6	0.029
Dimensional Lumber	13.7	0.082
Medium-density Fiberboard	4.6	0.064
Wood Flooring	19.8	0.033
Mixed MSW	125[a]	0.04

a. The methane yields remain under review and do not affect the results of the analysis presented in this report.
b. This is equivalent to the AP-42 methane yield of 100 m^3/wet Mg.

LFG Collection Parameters Worksheet

The LFG Collection Parameters worksheet is where inputs related to landfill gas generation, collection, flare operations, and energy generation from landfill gas are entered. The potential landfill gas generation and collection are then calculated to determine when gas collection must operate (due to regulation) and when it is possible to recover energy, e.g., the default assumption is that a landfill must have 350 cfm of recoverable gas for energy recovery to be viable.

Inputs

The Landfill Waste Acceptance and Operating Life Distributions table (Table 3) lists the log-normal distribution parameters for waste acceptance and the number of operating years. These distributions were developed from the LMOP Database data for landfills that are potential candidates for energy recovery projects.

Table 3. The Landfill Waste Acceptance and Operating Life Distributions table (LFG Collection Parameters worksheet; Y13:AC16) lists the log-normal distribution parameters developed from the LMOP database.

Landfill Waste Acceptance and Operating Life Distributions				
Distributions	**Mean**	**StDev**	**LN Mean**	**LN StDev**
Waste acceptance	200,000	261,000	4.76	1.03
Operating years	56.6	39.6	3.85	0.62

The first input table is the Landfill Waste Acceptance and Operating Life Inputs table (Table 4) where values for the annual mass of accepted waste and the number of operating years are entered. These values can also be randomly chosen based on the distributions shown in the Landfill Waste Acceptance and Operating Life Distributions table (Table 3), and this is how the Monte Carlo analysis is eventually performed. The Current Value column shows the value currently being used. A value may be entered in the Override Value column to use that constant value instead of a random value, and the Using Override column indicates if an override is being used while the Current Random Value

Table 4. Landfill Waste Acceptance and Operating Life Inputs table displays and accepts values for waste acceptance and operating life (LFG Collection Parameters worksheet; Cells Y7:AC10). For all example calculations we will assume the mean values of 200,000 tpy and 56 years of operation.

Landfill Waste Acceptance and Operating Life Inputs				
Iteration Values	**Current Value**	**Override Value**	**Current Random Value**	**Using Override**
Waste acceptance	200,000	200,000	*[VARIES]*	TRUE
Operating years	56	56	*[VARIES]*	TRUE

After the waste acceptance and years of operation are determined, the next input table is the Landfill Gas and Waste Inputs table (Table 5) where the bulk methane yield, decay rate, and basic gas collection and use values are entered. The Gas collection scenario entry is chosen between Best Case, Typical and Worst Case. The actual values (collection times and collection efficiencies) for each of these scenarios are entered in the Traditional Landfill Gas Collection Inputs table (Table 6). The scenarios differ in the time to initial collection (0.5 - 5 yr) and time to interim cover (3 - 5 yr).

Table 5. Landfill Gas and Waste Inputs table where general inputs related to gas generation and collection are entered (LFG Collection Parameters Worksheet; Cells S5:U12).

Landfill Gas and Waste Inputs		
Parameter	**Value**	**Default**
Base Lo (m3 Ch4/metric ton)	100	100
k (yr^-1)	0.04	0.04
Gas collection scenario	Typical	
Collects Energy	TRUE	
Collects gas	TRUE	
Downtime (%)	3	3

Table 6. Traditional Landfill Gas Collection Inputs table (LFG Collection Parameters Worksheet; Cells S14:W23).

Traditional Landfill Gas Collection Inputs				
Parameter	**Current Values**	**Best Case**	**Typical**	**Worst Case**
Time until initial gas collection (yr)	2	0.5	2	5
Initial gas collection efficiency (%)	50	50	50	50
Time to increased gas collection efficiency (yr)	5	3	5	5
Increased gas collection efficiency (%)	75	75	75	75
Time from initial waste placement to long term cover (yr)	15	15	15	15
Gas collection efficiency under long term cover (%)	82.5	82.5	82.5	82.5
Time from final waste placement to final cover (yr)	1	1	1	1
Gas collection efficiency under final cover (%)	90	90	90	90

The Flare Inputs table (Table 7) contains the inputs used to determine when a LFG collection system is required to be put in place and how long it is required to operate. The Actual NMOC concentration for cutoff is the best estimate value for NMOC concentration based on AP-42, since landfills can measure the actual concentrations after collection begins. The 16 year minimum operation time is mandated by the U.S. EPA, as is the requirement that the flare operates until closure (Flare must operate until operations cease = TRUE) or sometime after closure (Number of years flare must operate after operations cease).

Table 7. The Flare Inputs table (LFG Collection Parameters Worksheet; Cells S25:U36).

Flare Inputs		
Parameter	**Value**	**Default**
Actual NMOC concentration for cutoff (ppmv)	595	595
NMOC molecular weight (g/mol)	86.18	86.18
NMOC cutoff (Mg/yr)	50	50
Temperature (degrees C)	20	20
Flare min time on (yr)	16	16
Number of years flare must operate after operations cease	0	

The Energy Inputs table is used to enter the cuton and cutoff criteria for the energy system (Table 8). The rest of the calculations in the LFG Collection Parameters worksheet estimate the length of time that the flare and energy recovery systems operate based on the inputs described in Tables 4 to 8.

Table 8. The Energy Inputs table (LFG Collection Parameters Worksheet; Cells S38:U42).

Energy Inputs		
Parameter	**Value**	**Default**
Min LFG collection (cfm)	350	350
Min energy operation time (years)	5	5
Time to install (years)	1	1

Some of the uncollected methane is oxidized to CO_2 as it passes through the landfill cover. The values presented in Table 9 were modified from the U.S. EPA recommendations for methane oxidation (Federal Register, V. 78, No. 230, p. 71971). In the EPA recommendations, the fraction of uncollected methane that is oxidized varies with the methane flux (mass per area per time) and ranges from 10% to 35%. Measurement or estimation of the methane flux is possible on a site-specific basis but requires assumptions on landfill geometry and waste density to estimate flux for a generic landfill as is represented by WARM. As such, the methane oxidation values published by EPA were used as guidance for the values presented in Table 9. Landfills with a final cover and a gas collection system in place will have a relatively low flux through the cover and this justifies the upper end of the range (35%) given by EPA. Similarly, landfills without a gas collection system in place will have a relatively high flux, suggesting that 10% is most appropriate. Landfills with a gas collection system in place but prior to final cover placement were assigned an oxidation rate of 20%. Based on preliminary calculations for a variety of landfill geometries and waste densities, it was determined that the methane flux would justify an oxidation rate of 25% most but not all of the time. As such, a value of 20% was adopted.

Table 9. Oxidation rates at various stages of landfill gas collection (LFG Collection Parameters Worksheet; Cells S60:U64).

Oxidation		
Oxidation percent	**Value**	**Default**
Without gas collection or final cover	10	10
With gas collection before final cover	20	20
After final cover installation	35	35

Calculations

Most of the calculations performed in the LFG Collection Parameters are in columns B through P. A description of the values in each column is provided in Table 10.

Table 10. Description of calculation columns in the LFG Collection Parameters worksheet.

Column Title	Column Address	Description
Landfill Age (yr)	B	Time since initial waste burial in years.
Mass of MSW, tons/yr	C	Mass of waste buried in each year. Assumed to be a constant value from the Landfill Waste Acceptance and Operating Life Inputs table (Table 3).
Temporally Averaged Collection Efficiency, %	D	The potential collection efficiency (if collection is not turned off) calculated in the Potential Collection Efficiency worksheet based on the parameters in the chosen gas collection scenario and values in the Traditional Landfill Gas Collection Inputs table (Table 5).
Methane Generation (m3/yr)	E	Generated methane in each year based on first order decay model and L0 and k from the Landfill Gas and Waste Inputs table (Table 4).
Methane Collected (m3/yr)	F	Applies collection efficiency from Temporally Averaged Collection Efficiency column to generated methane to calculate the collected methane including downtime.
Gas Collected (m3/yr)	G	Multiplies the Methane Collected values by 2 to estimate collected landfill gas (assumes 50/50 CO_2/CH_4 split).
Gas Collected (cfm)	H	Converts the Gas Collected column values from m3/yr to cfm.
LFG Generation (ft3/min)	I	Converts the Methane Generation in m3 CH_4/yr column values to ft3 LFG/minute assuming that the gas is 50% CH_4.
Flare Cutoff NMOC (Mg/yr)	L	Calculates the generated NMOCs based on the actual L0 (100 m3/Mg) and NMOC concentration (595 ppmv) from the Flare Inputs table (Table 7).

The Flare On and Flare Off columns are used to calculate whether a flare is required and how long it must operate in the Flare On/Off Years table (Table 11). The flare begins the year collection begins based on the chosen collection scenario (Best Case: 0.5 yr; Typical: 2 yr; Worst Case: 5 yr). The flare turns off after the landfill is closed, less than 50 Mg/yr of NMOC are produced and 16 years have passed since the flare was installed.

Table 11. Flare On/Off Years table which calculates when the flare must operate (LFG Collection Parameters Worksheet; Cells S45:U49)

Flare On/Off Years	
Parameter	**Value**
Flare required	TRUE
Flare cuton Year	2
Flare cutoff year	71

The Energy On and Energy Off columns are similarly used to calculate when it is possible to operate an energy recovery system in the Energy On/Off Years table (Table 12). The Energy On/Off criteria are shown in the Energy Inputs table (Table 8). The default assumptions are that there must be more than 350 cfm of landfill gas collected for at least 5 years for a system to operate at all. The system then becomes operational 1 year after 350 cfm is collected, and operates as long as 350 cfm is collected.

Table 12. The Energy On/Off Years table calculates whether and when energy recovery can occur (LFG Collection Parameters Worksheet; Cells S51:U55)

Energy On/Off Years	
Parameter	**Value**
Can operate energy system?	TRUE
Energy on (year)	7
Energy off year	100

Potential Collection Efficiency Worksheet

Landfill gas collection systems are installed in part based on the age of the landfill cell. Initial gas collection typically begins during cell filling (0.5 - 5 yr after initial waste burial). The collection efficiency then increases as more wells are installed and the waste is deeper (3 - 5 yr after initial waste burial). Collection efficiency further increases when long-term cover is applied some time later (e.g., 15 yr after initial waste burial). After operations cease, final cover is applied to the entire site. This means that waste buried earlier in the cell's life will be under gas collection for less time than waste buried later in the cell's life. It is therefore necessary to temporally average the collection efficiency for each year of cell operation. The gas installation schedule and collection efficiencies for each collection scenario are used to calculate a temporally averaged gas collection efficiency for each year after waste burial.

The Potential Collection Efficiency Worksheet is used to calculate the temporally averaged collection efficiency used in column D of the LFG Collection Parameters worksheet. The worksheet's purpose is to calculate the amount of gas that could be collected if the system remained active indefinitely. The values in the Traditional Landfill Gas Collection Inputs table (Table 5) are copied into cells A3:B17 for use in the calculations. These values are used to calculate the time to initial collection, time to increased gas collection efficiency, and time to long-term cover (Rows 20, 21, and 22, respectively) for each year of waste burial. The values vary as each new cell and area of long-term cover are completed (e.g., waste buried late in the cell life is under collection sooner than waste buried earlier). The time to each increase in collection efficiency is calculated for each year of waste burial (0-100). These values are then used to perform the calculations in cells A32:CY235. This large calculation table begins with the time since waste burial in column A. The Collection Efficiency for Waste Buried in Year *N* columns (C:CY) convert the collection times and efficiencies for the collection scenario into the actual collection efficiencies experienced by waste buried in year *N* based on the conditions provided in the Collection Efficiency Table Description (Table 12).

Table 13. The Collection Efficiency Table Description describes how the annual collection efficiencies are calculated for each year of waste burial (Potential Collection Efficiency Worksheet; Cells A24:C30).

Collection Efficiency Table Description
Cells are blank if waste burial year > the number of operating years.
Collection efficiency equals final cover gas collection efficiency (B12) if waste burial year (Row 33) + time since waste burial (Column A) >= Time to final cover (B13).
Collection efficiency equals long term cover gas collection efficiency (B10) if time since waste burial (Column A) >= Time to long-term cover (Row 22).
Collection efficiency equals interim cover gas collection efficiency (B8) if time since waste burial (Column A) >= Time to long-term cover (Row 21).
Collection efficiency equals initial gas collection efficiency (B6) if time since waste burial (Column A) >= Time to long-term cover (Row 20).
Collection efficiency equals 0 otherwise (i.e., Waste burial year (Row 33) + Time since waste burial (Column A) < Time to initial collection).

The collection efficiency calculations follow basic rules. There is no value if the year of waste burial is greater than the number of operating years because that is an invalid year. If the total time passed (i.e., waste burial year + time since waste burial) is greater that the time to final cover, then the final cover gas collection efficiency is used, since time to final cover is based on total landfill age. Otherwise if the time since waste burial is greater than the time to long-term cover, then the long-term cover collection efficiency is used. Otherwise if the time since waste burial is greater than the time to increased gas collection efficiency, then the increased collection efficiency is used. Otherwise if the time since waste burial is greater than the time to initial collection, then the initial gas collection is used. Otherwise gas collection has not yet begun, and the collection efficiency is zero.

Actual Collection Efficiency Worksheet

The Actual Collection Efficiency Worksheet is similar to the Potential Collection Efficiency Worksheet, except it considers the shutting off of the gas collection system to calculate the actual temporally averaged gas collection efficiency. This is done by adding the collection off years to the conditions in the Collection Efficiency Table Description table (Table 12). The additional first condition is that the collection efficiency equals zero if the total time passed (i.e., waste burial year + time since waste burial) is greater than the collection off year (i.e., the maximum of the flare off year and energy off year). The collection off year is either the last year that the flare operates or the last year that energy recovery operates, whichever is later. The flare off year is determined by the values in the Flare Inputs table (Table 7). The flare turns off when less than 50 Mg/yr of NMOC are produced, 16 years have passed since it turned on, and operations have ceased. The energy system turns off when less than 350 cfm of landfill gas can be collected.

Energy Collection Efficiency Worksheet

The Energy Collection Efficiency Worksheet is similar to the Actual Collection Efficiency Worksheet except it only calculates the percentage of the gas that is collected for energy recovery, and so it uses the Energy On and Energy Off times to calculate the proportion of the generated gas being recovered for energy. Energy recovery can occur if more than 350 cfm is collected for at least 5 years. Energy collection begins the year after 350 cfm is collected and ends after 350 cfm is no longer collected.

Flare Collection Efficiency Worksheet

The Flare Collection Efficiency Worksheet is similar to the Energy Collection Efficiency Worksheet, but it calculates the proportion of the gas being flared before and after energy recovery is possible. The collection efficiency for each year of waste burial is therefore equal to the difference between the actual collection efficiency and the energy collection efficiency. The flare begins the year that gas collection begins based on the chosen collection scenario (Best Case: 0.5 yr; Typical: 2 yr; Worst Case: 5 yr).). The flare turns off when less than 50 Mg/yr of NMOC are produced, 16 years have passed since it turned on, and operations have ceased.

Results Worksheet

The LFG collection Parameters worksheet calculates the periods over which the collection system will operate with a flare or energy recovery. Once these times are established, the volume of gas that is vented, flared and collected for energy recovery over a 100 year time horizon is calculated for each individual waste component using its specific methane potential and decay rate. The calculations are similar to the methane generation and collection columns in the LFG Collection Parameter worksheet, except the decay rate and methane potential for each material found in the Material Properties worksheet are used.

Monte Carlo Analysis

The Monte Carlo analysis uses randomly chosen values from the waste acceptance and operating years distributions from the Landfill Waste Acceptance and Operating Life Inputs table (Table 4), and then copies the associated results for each waste material into a separate spreadsheet. This is repeated for a large number of random values (e.g., 1000) to provide a representative sample of U.S. landfills. Then the total volume of methane generated, flared, recovered for energy, and emitted is calculated for all of the samples to determine the national average collection efficiencies for flaring and beneficial recovery for each material.

2. Results

The Monte Carlo analysis was performed for each of the gas collection scenarios for every decay rate and with and without energy recovery. Tables 14-25 show the results for landfills that recover energy, and Tables 26-37 show the results for landfills that do not recover energy, and only use a flare. The results show that the impact of the gas collection scenario is dependent on the decay rate of the material. For example, only 33% of methane from grass is emitted in the best case scenario (decay rate = 0.04 yr^{-1}), but 57% is emitted in the worst case scenario because grass is the fastest degrading material, so more of its methane is generated earlier. Branches are the slowest degrading material, so the best case scenario only captures 2% more methane than the worst case (k = 0.04 yr^{-1}). The results show a similar impact of bulk decay rate (e.g., the collection scenario has a greater impact at k = 0.12 yr^{-1} than at k = 0.02 yr^{-1}). The results also show that materials that degrade quickly also have a larger percent of their gas flared because the flares are used before energy recovery is possible, and the gas system is typically shutoff when energy recovery ceases. Relative to the flare only scenarios, the energy recovery scenarios collect more gas for slow degrading materials because gas collection is shut-off earlier in the flare only scenarios.

The results are further summarized in Figures 1 to 12 which show the percent of methane flared and beneficially used from each material for each gas collection scenario and decay rate. The total bar heights are equivalent to the overall collection efficiency and the relative fractions that are flared and used beneficially are illustrated. The figures show that the impact of the gas collection scenario depends on both the bulk decay rate and the material decay rate. A decay rate of 0.02 yr^{-1} leads to the most gas collection in every case, but a decay rate of 0.12 yr^{-1} can be the second best (for slowly degrading materials) to worst (for rapidly degrading materials) depending on the collection scenario and material decay rate. Fast degrading materials achieve the best and worst collection efficiencies. Grass, food scraps, and magazines have the highest decay rates, and achieve greater than 70% treatment with best case collection and a bulk decay rate of 0.02 yr^{-1}, but less than 40% collection with worst case collection and a bulk decay rate of 0.12 yr^{-1}. The overall collection efficiencies are influenced by the rate of material decay and the amount of gas produced before a gas collection system is installed and after a gas control device is terminated.

The fraction of the total volume of methane produced that is oxidized is also calculated for a 100 year time period and reported in the Results tables. Here too, the decay rate will play a role. The methane oxidation rate is lowest prior to any gas collection functionality and highest after final closure. Thus, for a material that decays rapidly, more methane will be produced prior to final closure and the cumulative methane oxidation will be lower. For example, looking at grass (high decay rate) and newspaper (low decay rate), more methane attributable to newsprint is oxidized in every case.

Table 14. Methane flared, recovered for energy, oxidized, and emitted for a decay rate of 0.02 yr^{-1} and best case gas collection with energy recovery.

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (% of Production)	Methane Emitted (%)
Branches	4.2	60.9	10.7	24.2
Grass	15.1	51.2	6.9	26.8
Leaves	12.6	57.8	6.5	23.1
Food Scraps	11.6	59.5	6.6	22.3
Corrugated Containers	4.6	61.3	10.3	23.8
Magazines/Third-class Mail	10.7	60.8	6.7	21.8
Newspaper	5.4	62.3	9.5	22.8
Office Paper	5.2	62.0	9.7	23.1
Phonebooks	5.4	62.3	9.5	22.8
Mixed MSW	5.9	62.6	9.0	22.4
Dimensional Lumber	8.7	62.7	7.4	21.3
Medium-density Fiberboard	7.6	63.0	7.9	21.5
Wood Flooring	5.4	62.3	9.5	22.8

Table 15. Methane flared, recovered for energy, oxidized, and emitted for a decay rate of 0.02 yr^{-1} and typical gas collection with energy recovery.

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (%of Production)	Methane Emitted (%)
Branches	4.1	61.1	10.5	24.2
Grass	14.1	48.5	7.4	30.0
Leaves	11.9	56.0	6.9	25.2
Food Scraps	11.1	57.9	6.9	24.1
Corrugated Containers	4.4	61.5	10.2	23.9
Magazines/Third-class Mail	10.3	59.5	6.9	23.3
Newspaper	5.3	62.2	9.4	23.1
Office Paper	5.0	62.0	9.6	23.3
Phonebooks	5.3	62.2	9.4	23.1
Mixed MSW	5.8	62.5	9.0	22.8
Dimensional Lumber	8.4	61.9	7.5	22.3
Medium-density Fiberboard	7.3	62.5	8.0	22.2
Wood Flooring	5.3	62.2	9.4	23.1

Table 16. Methane flared, recovered for energy, oxidized, and emitted for a decay rate of 0.02 yr^{-1} and worst case gas collection with energy recovery.

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (% of Production)	Methane Emitted (%)
Branches	4.1	59.9	10.5	25.4
Grass	10.9	39.2	7.7	42.2
Leaves	10.3	49.8	7.0	32.8
Food Scraps	9.8	52.6	7.0	30.7
Corrugated Containers	4.4	60.2	10.2	25.2
Magazines/Third-class Mail	9.2	54.8	7.0	28.9
Newspaper	5.2	60.6	9.3	24.9
Office Paper	4.9	60.5	9.6	24.9
Phonebooks	5.2	60.6	9.3	24.9
Mixed MSW	5.6	60.6	9.0	24.8
Dimensional Lumber	7.8	58.6	7.5	26.2
Medium-density Fiberboard	6.9	59.8	7.9	25.3
Wood Flooring	5.2	60.6	9.4	24.9

Table 17. Methane flared, recovered for energy, oxidized, and emitted for a decay rate of 0.04 yr^{-1} and best case gas collection with energy recovery.

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (%of Production)	Methane Emitted (%)
Branches	3.2	53.8	13.2	29.8
Grass	11.7	47.2	7.9	33.2
Leaves	10.5	54.3	7.1	28.1
Food Scraps	9.9	56.2	7.0	26.8
Corrugated Containers	3.6	55.8	12.2	28.5
Magazines/Third-class Mail	9.4	57.9	6.9	25.8
Newspaper	4.7	59.5	10.1	25.8
Office Paper	4.4	58.5	10.6	26.5
Phonebooks	4.7	59.5	10.1	25.8
Mixed MSW	5.2	60.6	9.2	24.9
Dimensional Lumber	7.8	60.9	7.2	24.1
Medium-density Fiberboard	6.9	61.7	7.6	23.8
Wood Flooring	4.6	59.4	10.1	25.9

Table 18. Methane flared, recovered for energy, oxidized, and emitted for a decay rate of 0.04 yr^{-1} and typical gas collection with energy recovery.

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (% of Production)	Methane Emitted (%)
Branches	3.4	53.5	13.0	30.1
Grass	10.7	42.6	8.6	38.1
Leaves	10.0	50.6	7.7	31.7
Food Scraps	9.6	52.9	7.5	30.0
Corrugated Containers	3.8	55.3	12.0	28.8
Magazines/Third-class Mail	9.1	54.9	7.4	28.6
Newspaper	4.9	58.6	10.0	26.5
Office Paper	4.5	57.8	10.6	27.1
Phonebooks	4.9	58.6	10.0	26.5
Mixed MSW	5.4	59.6	9.2	25.8
Dimensional Lumber	7.8	58.7	7.4	26.1
Medium-density Fiberboard	7.0	59.9	7.8	25.3
Wood Flooring	4.8	58.6	10.1	26.5

Table 19. Methane flared, recovered for energy, oxidized, and emitted for a decay rate of 0.04 yr^{-1} and worst case gas collection with energy recovery.

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (%of Production)	Methane Emitted (%)
Branches	3.2	52.1	13.0	31.6
Grass	6.4	27.4	8.9	57.3
Leaves	7.4	39.6	8.0	45.1
Food Scraps	7.4	43.1	7.7	41.8
Corrugated Containers	3.6	53.7	12.0	30.7
Magazines/Third-class Mail	7.3	46.3	7.6	38.9
Newspaper	4.5	56.0	10.0	29.5
Office Paper	4.2	55.5	10.6	29.7
Phonebooks	4.5	56.0	10.0	29.5
Mixed MSW	4.9	56.4	9.3	29.4
Dimensional Lumber	6.6	52.5	7.5	33.3
Medium-density Fiberboard	6.1	54.9	7.9	31.1
Wood Flooring	4.4	56.0	10.1	29.5

Table 20. Methane flared, recovered for energy, oxidized, and emitted for a decay rate of 0.06 yr^{-1} and best case gas collection with energy recovery.

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (% of Production)	Methane Emitted (%)
Branches	2.6	53.0	13.3	31.1
Grass	8.5	45.1	8.6	37.7
Leaves	8.0	52.5	7.7	31.8
Food Scraps	7.7	54.6	7.5	30.2
Corrugated Containers	3.0	56.1	11.8	29.1
Magazines/Third-class Mail	7.3	56.5	7.3	28.9
Newspaper	3.9	60.8	9.3	26.0
Office Paper	3.6	59.8	9.9	26.7
Phonebooks	3.9	60.8	9.3	26.0
Mixed MSW	4.3	61.9	8.5	25.3
Dimensional Lumber	6.3	60.3	7.1	26.3
Medium-density Fiberboard	5.6	61.8	7.3	25.3
Wood Flooring	3.9	60.8	9.3	26.0

Table 21. Methane flared, recovered for energy, oxidized, and emitted for a decay rate of 0.06 yr^{-1} and typical gas collection with energy recovery.

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (%of Production)	Methane Emitted (%)
Branches	2.7	51.5	13.6	32.2
Grass	8.1	39.2	9.4	43.3
Leaves	7.9	47.3	8.4	36.3
Food Scraps	7.7	49.8	8.2	34.4
Corrugated Containers	3.1	54.4	12.2	30.3
Magazines/Third-class Mail	7.4	52.1	7.9	32.6
Newspaper	4.1	58.7	9.6	27.6
Office Paper	3.8	57.8	10.3	28.1
Phonebooks	4.1	58.7	9.6	27.6
Mixed MSW	4.6	59.5	8.9	27.1
Dimensional Lumber	6.5	56.7	7.6	29.1
Medium-density Fiberboard	5.8	58.7	7.8	27.7
Wood Flooring	4.1	58.7	9.7	27.6

Table 22. Methane flared, recovered for energy, oxidized, and emitted for a decay rate of 0.06 yr^{-1} and worst case gas collection with energy recovery.

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (% of Production)	Methane Emitted (%)
Branches	2.6	50.5	13.2	33.7
Grass	3.7	20.3	9.5	66.5
Leaves	4.8	32.6	8.6	54.0
Food Scraps	5.0	36.4	8.4	50.2
Corrugated Containers	2.9	52.8	11.8	32.5
Magazines/Third-class Mail	5.1	40.1	8.1	46.7
Newspaper	3.6	55.3	9.4	31.7
Office Paper	3.4	55.0	9.9	31.7
Phonebooks	3.6	55.3	9.4	31.7
Mixed MSW	3.9	55.2	8.7	32.2
Dimensional Lumber	5.0	47.8	7.7	39.5
Medium-density Fiberboard	4.7	51.5	7.8	36.1
Wood Flooring	3.6	55.3	9.4	31.7

Table 23. Methane flared, recovered for energy, oxidized, and emitted for a decay rate of 0.12 yr^{-1} and best case gas collection with energy recovery.

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (%of Production)	Methane Emitted (%)
Branches	2.3	54.2	11.9	31.6
Grass	5.4	38.7	9.9	46.0
Leaves	5.4	46.2	8.9	39.5
Food Scraps	5.4	48.5	8.6	37.5
Corrugated Containers	2.5	57.6	10.3	29.6
Magazines/Third-class Mail	5.2	50.7	8.3	35.7
Newspaper	3.2	60.5	8.3	28.0
Office Paper	3.0	60.2	8.7	28.1
Phonebooks	3.2	60.5	8.3	28.0
Mixed MSW	3.5	60.4	7.9	28.2
Dimensional Lumber	4.7	55.4	7.8	32.0
Medium-density Fiberboard	4.3	57.8	7.7	30.2
Wood Flooring	3.2	60.5	8.3	28.0

Table 24. Methane flared, recovered for energy, oxidized, and emitted for a decay rate of 0.12 yr^{-1} and typical gas collection with energy recovery.

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (% of Production)	Methane Emitted (%)
Branches	2.4	52.2	12.3	33.0
Grass	5.0	32.8	10.5	51.7
Leaves	5.1	40.0	9.7	45.2
Food Scraps	5.1	42.4	9.4	43.1
Corrugated Containers	2.7	55.3	10.7	31.3
Magazines/Third-class Mail	5.1	44.8	9.1	41.0
Newspaper	3.4	57.4	8.8	30.5
Office Paper	3.2	57.3	9.1	30.4
Phonebooks	3.4	57.4	8.8	30.5
Mixed MSW	3.7	56.9	8.4	31.0
Dimensional Lumber	4.7	50.2	8.6	36.5
Medium-density Fiberboard	4.4	53.1	8.3	34.1
Wood Flooring	3.4	57.4	8.8	30.4

Table 25. Methane flared, recovered for energy, oxidized, and emitted for a decay rate of 0.12 yr^{-1} and worst case gas collection with energy recovery.

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (%of Production)	Methane Emitted (%)
Branches	2.3	48.7	12.1	36.9
Grass	1.2	9.2	10.0	79.5
Leaves	2.2	18.6	9.7	69.5
Food Scraps	2.5	22.2	9.5	65.8
Corrugated Containers	2.5	50.5	10.5	36.5
Magazines/Third-class Mail	2.7	25.8	9.3	62.2
Newspaper	2.9	49.4	8.8	38.9
Office Paper	2.8	50.3	9.1	37.8
Phonebooks	2.9	49.4	8.8	38.9
Mixed MSW	3.1	47.5	8.5	40.9
Dimensional Lumber	3.1	34.7	8.8	53.5
Medium-density Fiberboard	3.2	39.7	8.5	48.6
Wood Flooring	2.9	49.5	8.8	38.8

Table 26. Methane flared, oxidized, and emitted for a decay rate of 0.02 yr^{-1} and best case gas collection without energy recovery.

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (% of Production)	Methane Emitted (%)
Branches	30.9	0.0	21.7	47.3
Grass	55.7	0.0	9.6	34.7
Leaves	53.4	0.0	11.3	35.3
Food Scraps	52.0	0.0	12.1	36.0
Corrugated Containers	32.2	0.0	21.2	46.6
Magazines/Third-class Mail	50.3	0.0	12.9	36.8
Newspaper	35.5	0.0	19.7	44.8
Office Paper	34.5	0.0	20.1	45.3
Phonebooks	35.5	0.0	19.7	44.8
Mixed MSW	37.2	0.0	18.9	43.8
Dimensional Lumber	45.5	0.0	15.2	39.3
Medium-density Fiberboard	42.4	0.0	16.6	41.0
Wood Flooring	35.5	0.0	19.7	44.8

Table 27. Methane flared, oxidized, and emitted for a decay rate of 0.02 yr^{-1} and typical case gas collection without energy recovery.

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (%of Production)	Methane Emitted (%)
Branches	30.4	0.0	21.8	47.8
Grass	52.2	0.0	10.0	37.8
Leaves	51.2	0.0	11.5	37.2
Food Scraps	50.1	0.0	12.3	37.6
Corrugated Containers	31.7	0.0	21.2	47.1
Magazines/Third-class Mail	48.6	0.0	13.1	38.3
Newspaper	34.9	0.0	19.8	45.4
Office Paper	33.9	0.0	20.2	45.9
Phonebooks	34.9	0.0	19.8	45.4
Mixed MSW	36.5	0.0	19.0	44.5
Dimensional Lumber	44.3	0.0	15.3	40.4
Medium-density Fiberboard	41.5	0.0	16.7	41.8
Wood Flooring	34.8	0.0	19.8	45.4

Table 28. Methane flared, oxidized, and emitted for a decay rate of 0.02 yr^{-1} and worst case gas collection without energy recovery.

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (% of Production)	Methane Emitted (%)
Branches	29.0	0.0	21.8	49.2
Grass	40.2	0.0	10.1	49.6
Leaves	43.6	0.0	11.6	44.8
Food Scraps	43.6	0.0	12.3	44.1
Corrugated Containers	30.1	0.0	21.3	48.7
Magazines/Third-class Mail	43.0	0.0	13.1	43.8
Newspaper	32.8	0.0	19.8	47.4
Office Paper	32.0	0.0	20.2	47.7
Phonebooks	32.8	0.0	19.8	47.4
Mixed MSW	34.2	0.0	19.0	46.7
Dimensional Lumber	40.4	0.0	15.3	44.3
Medium-density Fiberboard	38.3	0.0	16.7	45.0
Wood Flooring	32.8	0.0	19.8	47.4

Table 29. Methane flared, oxidized, and emitted for a decay rate of 0.04 yr^{-1} and best case gas collection without energy recovery.

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (%of Production)	Methane Emitted (%)
Branches	35.0	0.0	20.0	45.0
Grass	54.3	0.0	8.9	36.8
Leaves	56.8	0.0	9.0	34.1
Food Scraps	56.9	0.0	9.3	33.8
Corrugated Containers	37.6	0.0	18.8	43.5
Magazines/Third-class Mail	56.7	0.0	9.7	33.7
Newspaper	43.6	0.0	16.2	40.2
Office Paper	41.9	0.0	16.9	41.1
Phonebooks	43.6	0.0	16.2	40.2
Mixed MSW	46.2	0.0	15.0	38.8
Dimensional Lumber	54.5	0.0	11.0	34.5
Medium-density Fiberboard	52.2	0.0	12.2	35.6
Wood Flooring	43.5	0.0	16.2	40.3

Table 30. Methane flared, oxidized, and emitted for a decay rate of 0.04 yr^{-1} and typical gas collection without energy recovery.

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (% of Production)	Methane Emitted (%)
Branches	34.2	0.0	20.1	45.8
Grass	48.5	0.0	9.7	41.8
Leaves	52.4	0.0	9.7	37.9
Food Scraps	52.9	0.0	9.9	37.2
Corrugated Containers	36.7	0.0	19.0	44.4
Magazines/Third-class Mail	53.1	0.0	10.2	36.7
Newspaper	42.2	0.0	16.4	41.4
Office Paper	40.7	0.0	17.1	42.2
Phonebooks	42.2	0.0	16.4	41.4
Mixed MSW	44.6	0.0	15.3	40.1
Dimensional Lumber	51.8	0.0	11.5	36.7
Medium-density Fiberboard	49.9	0.0	12.6	37.5
Wood Flooring	42.1	0.0	16.5	41.4

Table 31. Methane flared, oxidized, and emitted for a decay rate of 0.04 yr^{-1} and worst case gas collection without energy recovery.

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (%of Production)	Methane Emitted (%)
Branches	32.6	0.0	19.9	47.5
Grass	29.7	0.0	9.7	60.6
Leaves	39.3	0.0	9.8	50.9
Food Scraps	41.4	0.0	10.0	48.6
Corrugated Containers	34.8	0.0	18.8	46.4
Magazines/Third-class Mail	43.0	0.0	10.2	46.7
Newspaper	39.3	0.0	16.3	44.4
Office Paper	38.1	0.0	17.0	44.9
Phonebooks	39.3	0.0	16.3	44.4
Mixed MSW	41.1	0.0	15.2	43.8
Dimensional Lumber	44.7	0.0	11.4	43.9
Medium-density Fiberboard	44.3	0.0	12.5	43.2
Wood Flooring	39.2	0.0	16.3	44.5

Table 32. Methane flared, oxidized, and emitted for a decay rate of 0.06 yr^{-1} and best case gas collection without energy recovery.

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (% of Production)	Methane Emitted (%)
Branches	37.6	0.0	18.7	43.7
Grass	50.6	0.0	9.2	40.2
Leaves	55.2	0.0	8.9	36.0
Food Scraps	56.0	0.0	8.9	35.1
Corrugated Containers	41.2	0.0	17.1	41.7
Magazines/Third-class Mail	56.5	0.0	9.0	34.5
Newspaper	48.1	0.0	14.0	37.9
Office Paper	46.3	0.0	14.8	38.9
Phonebooks	48.1	0.0	14.0	37.9
Mixed MSW	50.6	0.0	12.8	36.6
Dimensional Lumber	56.3	0.0	9.7	33.9
Medium-density Fiberboard	55.2	0.0	10.5	34.3
Wood Flooring	48.0	0.0	14.1	38.0

Table 33. Methane flared, oxidized, and emitted for a decay rate of 0.06 yr^{-1} and typical gas collection without energy recovery.

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (%of Production)	Methane Emitted (%)
Branches	36.9	0.0	18.8	44.3
Grass	44.5	0.0	10.0	45.6
Leaves	50.2	0.0	9.5	40.3
Food Scraps	51.5	0.0	9.5	39.0
Corrugated Containers	40.3	0.0	17.3	42.4
Magazines/Third-class Mail	52.4	0.0	9.6	37.9
Newspaper	46.7	0.0	14.2	39.0
Office Paper	45.1	0.0	15.0	39.9
Phonebooks	46.7	0.0	14.2	39.0
Mixed MSW	49.0	0.0	13.1	37.9
Dimensional Lumber	53.3	0.0	10.2	36.5
Medium-density Fiberboard	52.7	0.0	10.9	36.4
Wood Flooring	46.6	0.0	14.3	39.1

Table 34. Methane flared, oxidized, and emitted for a decay rate of 0.06 yr^{-1} and worst case gas collection without energy recovery.

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (% of Production)	Methane Emitted (%)
Branches	34.1	0.0	18.9	47.0
Grass	21.6	0.0	9.9	68.5
Leaves	32.6	0.0	9.7	57.7
Food Scraps	35.6	0.0	9.7	54.7
Corrugated Containers	36.9	0.0	17.4	45.8
Magazines/Third-class Mail	38.2	0.0	9.8	52.0
Newspaper	41.7	0.0	14.3	44.0
Office Paper	40.6	0.0	15.1	44.3
Phonebooks	41.7	0.0	14.3	44.0
Mixed MSW	43.1	0.0	13.2	43.7
Dimensional Lumber	42.6	0.0	10.4	47.0
Medium-density Fiberboard	43.9	0.0	11.0	45.1
Wood Flooring	41.6	0.0	14.4	44.0

Table 35. Methane flared, oxidized, and emitted for a decay rate of 0.12 yr^{-1} and best case gas collection without energy recovery.

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (%of Production)	Methane Emitted (%)
Branches	44.5	0.0	15.3	40.2
Grass	42.7	0.0	10.1	47.2
Leaves	49.1	0.0	9.4	41.5
Food Scraps	50.8	0.0	9.2	40.0
Corrugated Containers	48.5	0.0	13.5	38.0
Magazines/Third-class Mail	52.3	0.0	9.1	38.6
Newspaper	53.8	0.0	10.9	35.3
Office Paper	52.7	0.0	11.4	35.8
Phonebooks	53.8	0.0	10.9	35.3
Mixed MSW	55.0	0.0	10.2	34.8
Dimensional Lumber	55.0	0.0	9.0	36.0
Medium-density Fiberboard	55.7	0.0	9.2	35.1
Wood Flooring	53.8	0.0	10.9	35.3

Table 36. Methane flared, oxidized, and emitted for a decay rate of 0.12 yr^{-1} and typical gas collection without energy recovery.

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (% of Production)	Methane Emitted (%)
Branches	43.7	0.0	15.3	41.0
Grass	36.4	0.0	10.7	52.8
Leaves	42.7	0.0	10.1	47.2
Food Scraps	44.6	0.0	10.0	45.4
Corrugated Containers	47.3	0.0	13.5	39.2
Magazines/Third-class Mail	46.4	0.0	9.8	43.8
Newspaper	51.5	0.0	11.1	37.4
Office Paper	50.8	0.0	11.6	37.6
Phonebooks	51.5	0.0	11.1	37.4
Mixed MSW	52.2	0.0	10.5	37.3
Dimensional Lumber	50.0	0.0	9.6	40.4
Medium-density Fiberboard	51.5	0.0	9.7	38.8
Wood Flooring	51.5	0.0	11.1	37.4

Table 37. Methane flared, oxidized, and emitted for a decay rate of 0.12 yr^{-1} and worst case gas collection without energy recovery.

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (%of Production)	Methane Emitted (%)
Branches	39.3	0.0	15.4	45.4
Grass	9.5	0.0	10.2	80.3
Leaves	18.7	0.0	10.0	71.3
Food Scraps	22.0	0.0	10.0	68.0
Corrugated Containers	41.6	0.0	13.6	44.8
Magazines/Third-class Mail	25.3	0.0	9.9	64.8
Newspaper	42.7	0.0	11.3	46.1
Office Paper	42.8	0.0	11.8	45.4
Phonebooks	42.7	0.0	11.3	46.1
Mixed MSW	41.8	0.0	10.7	47.5
Dimensional Lumber	32.9	0.0	9.8	57.3
Medium-density Fiberboard	36.8	0.0	9.9	53.3
Wood Flooring	42.7	0.0	11.3	46.0

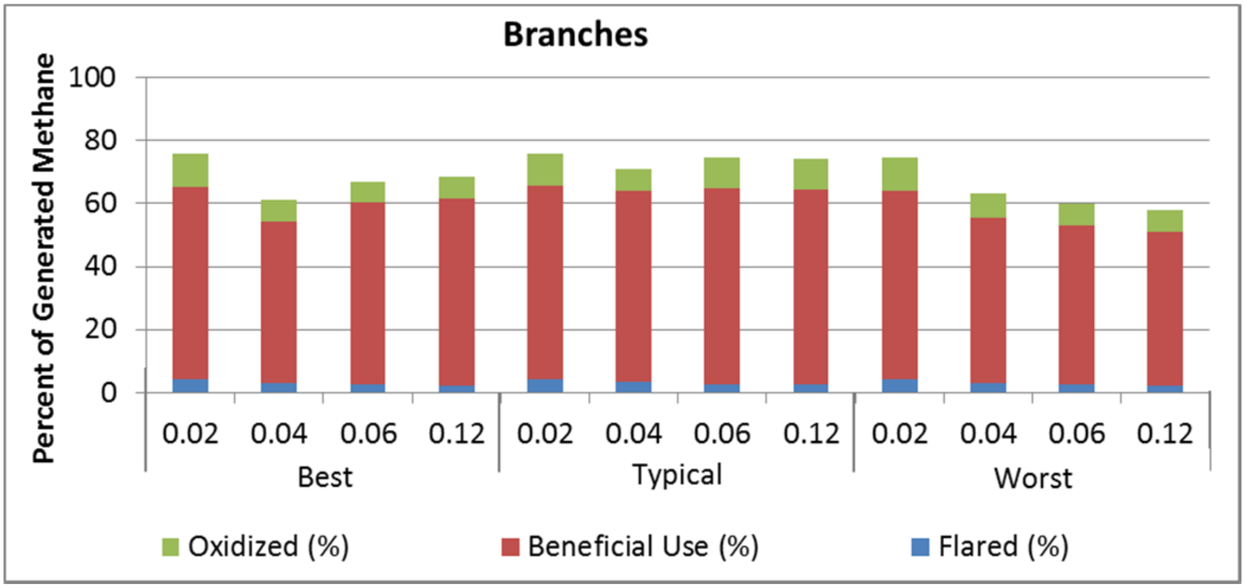

Figure 1. The percent methane flared and recovered for energy from branches for each gas collection scenario and decay rate.

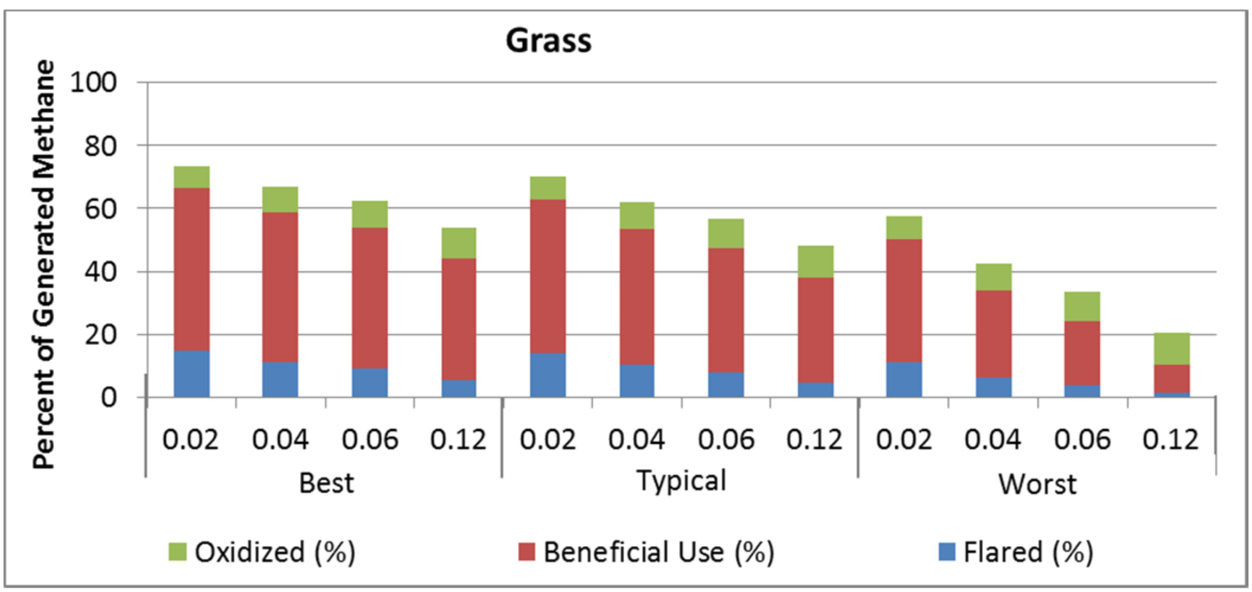

Figure 2. The percent methane flared and recovered for energy from grass for each gas collection scenario and decay rate.

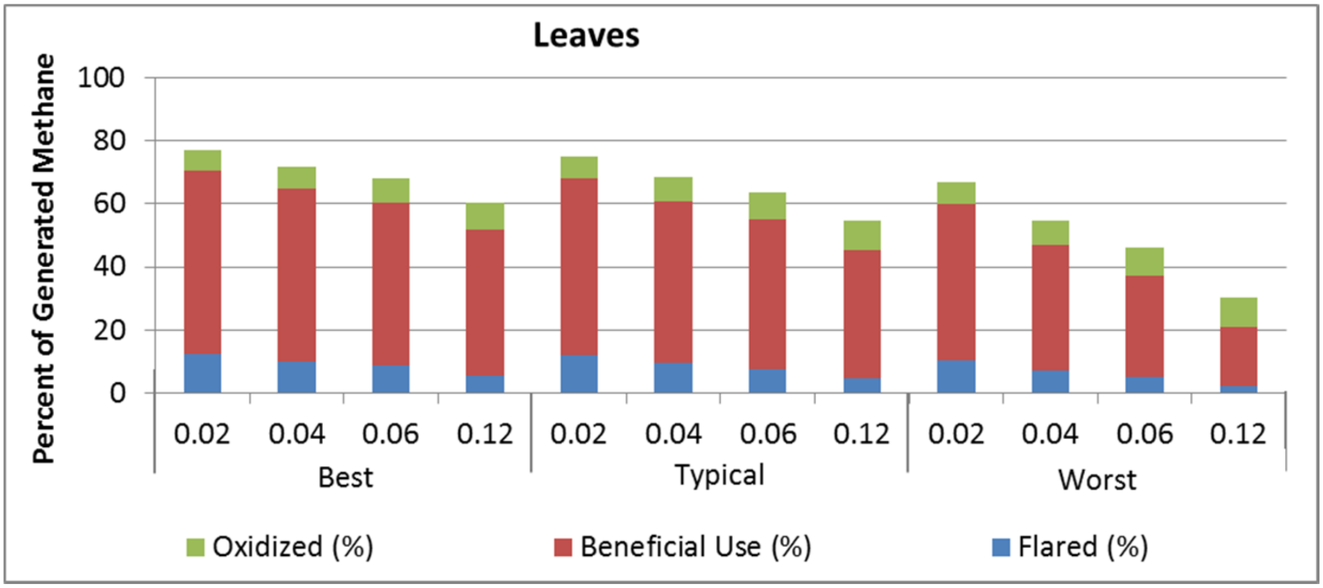

Figure 3. The percent methane flared and recovered for energy from leaves for each gas collection scenario and decay rate.

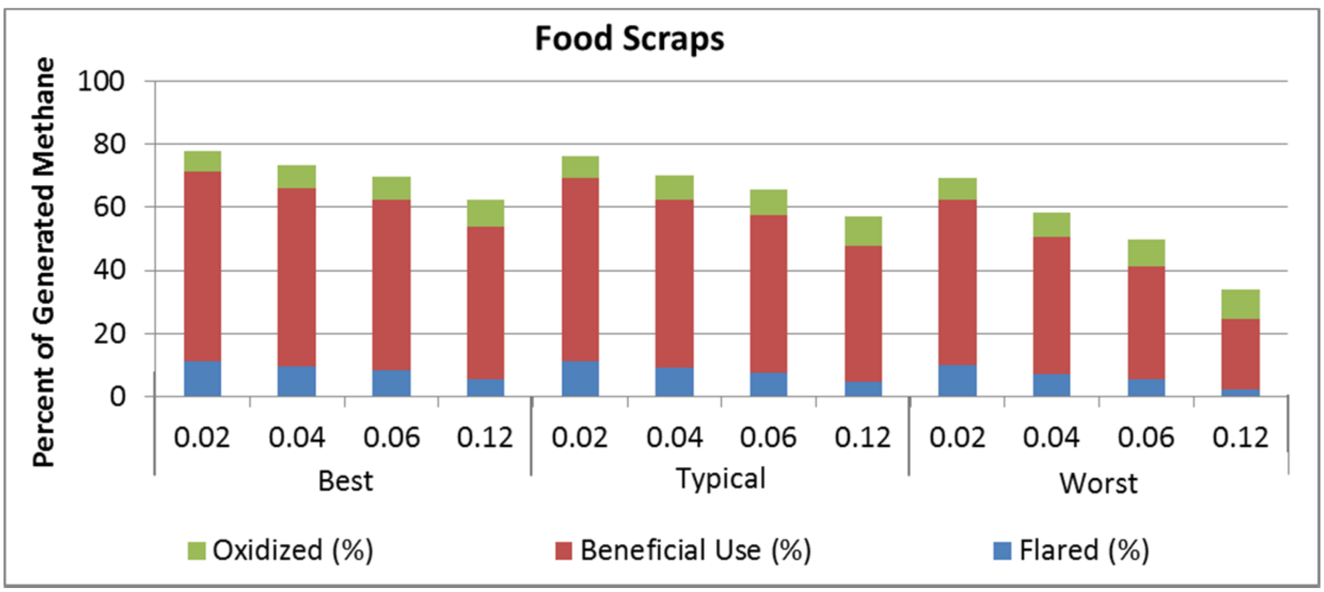

Figure 4. The percent methane flared and recovered for energy from food scraps for each gas collection scenario and decay rate.

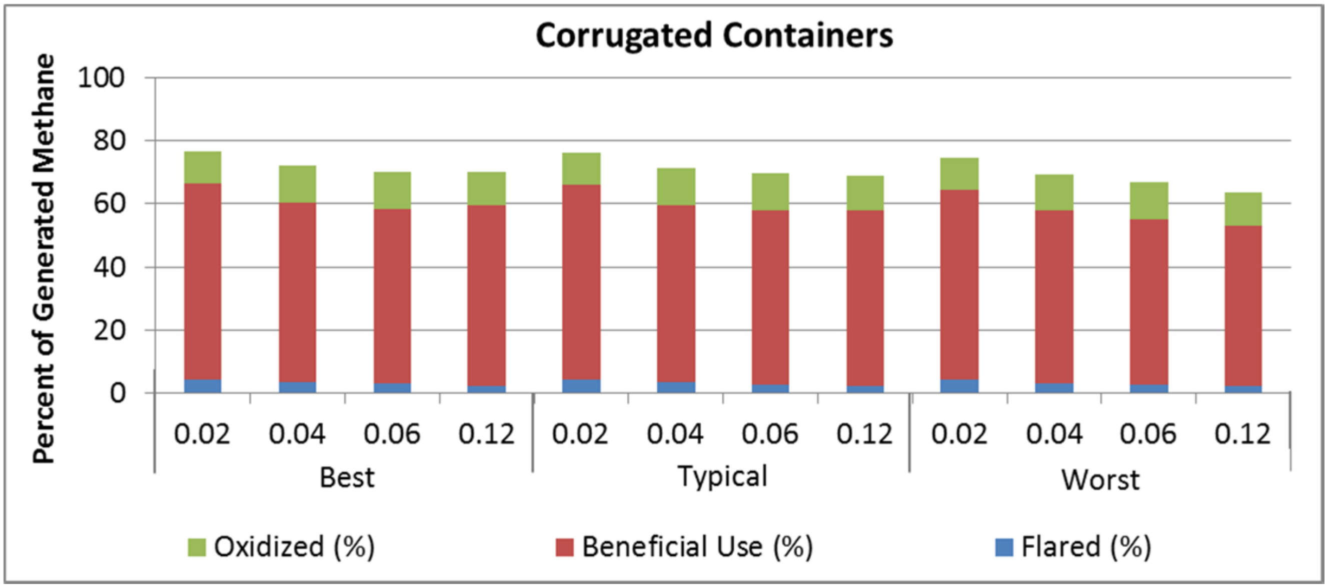

Figure 5. The percent methane flared and recovered for energy from corrugated containers for each gas collection scenario and decay rate.

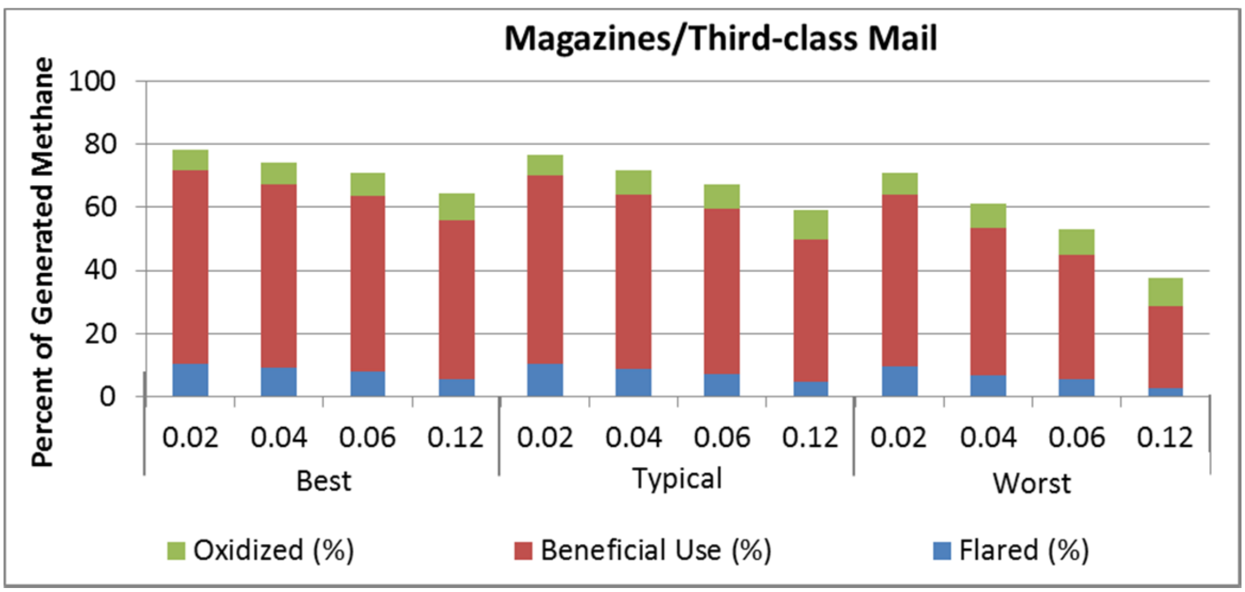

Figure 6. The percent methane flared and recovered for energy from magazines and third class mail for each gas collection scenario and decay rate.

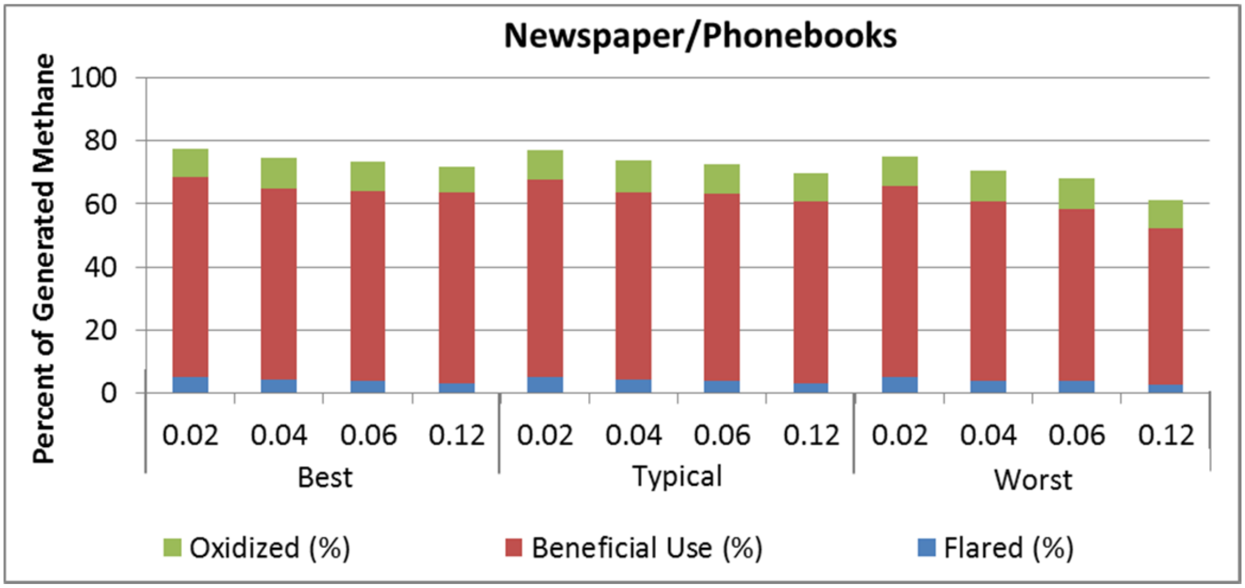

Figure 7. The percent methane flared and recovered for energy from newspaper and phonebooks for each gas collection scenario and decay rate.

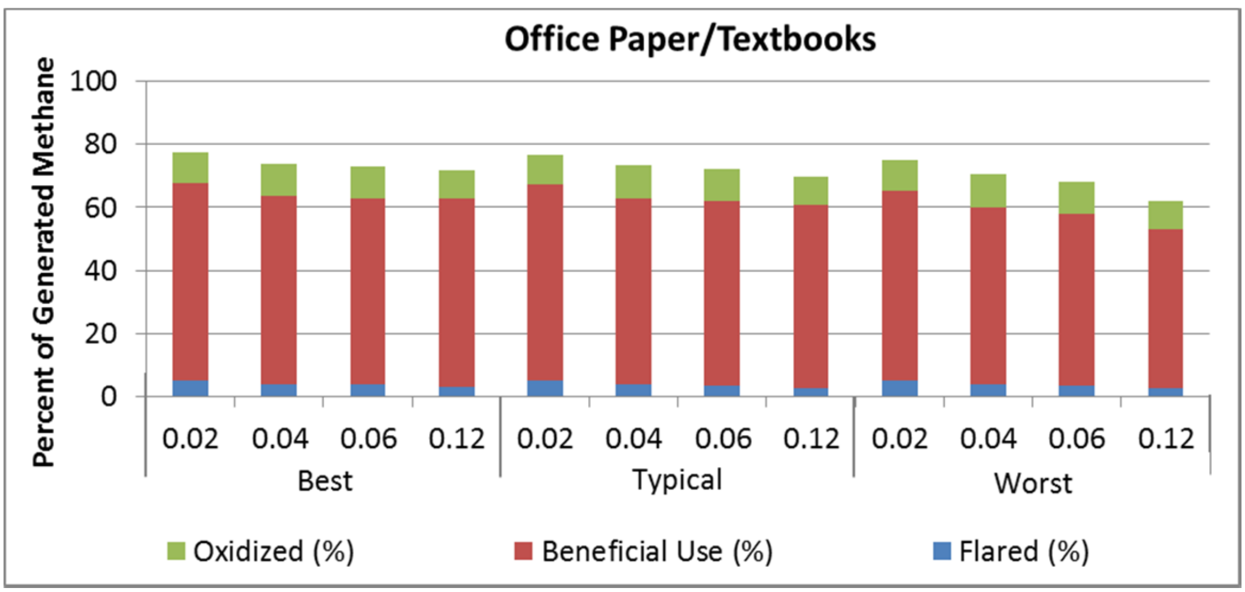

Figure 8. The percent methane flared and recovered for energy from office paper and textbooks for each gas collection scenario and decay rate.

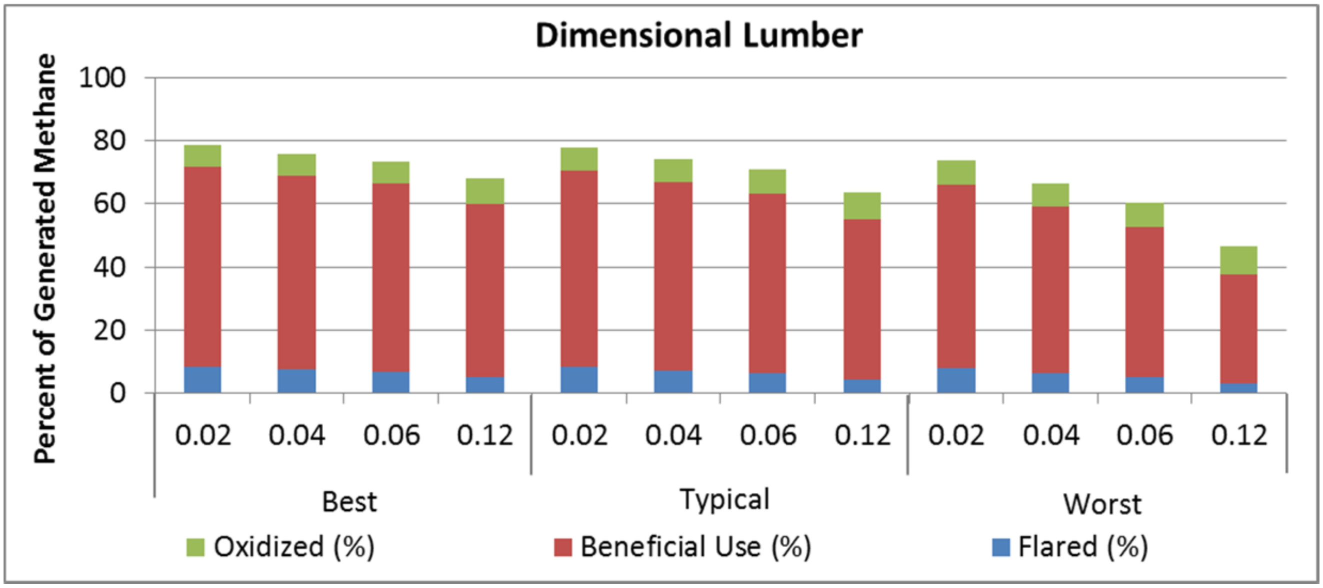

Figure 9. The percent methane flared and recovered for energy from dimensional lumber for each gas collection scenario and decay rate.

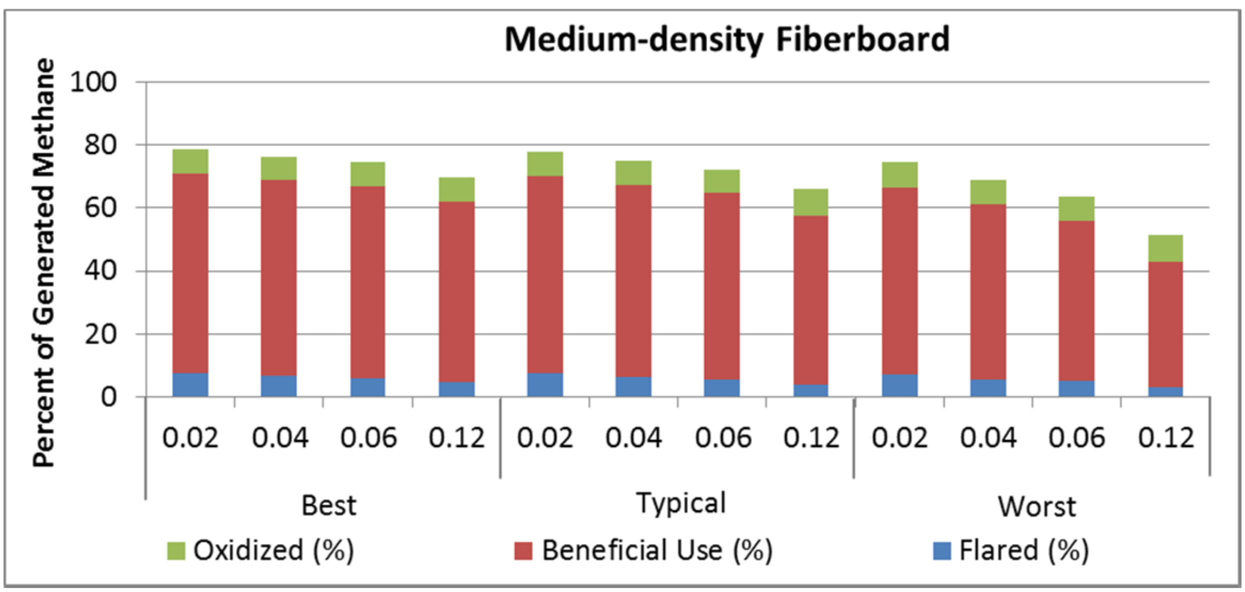

Figure 10. The percent methane flared and recovered for energy from medium-density fiberboard for each gas collection scenario and decay rate.

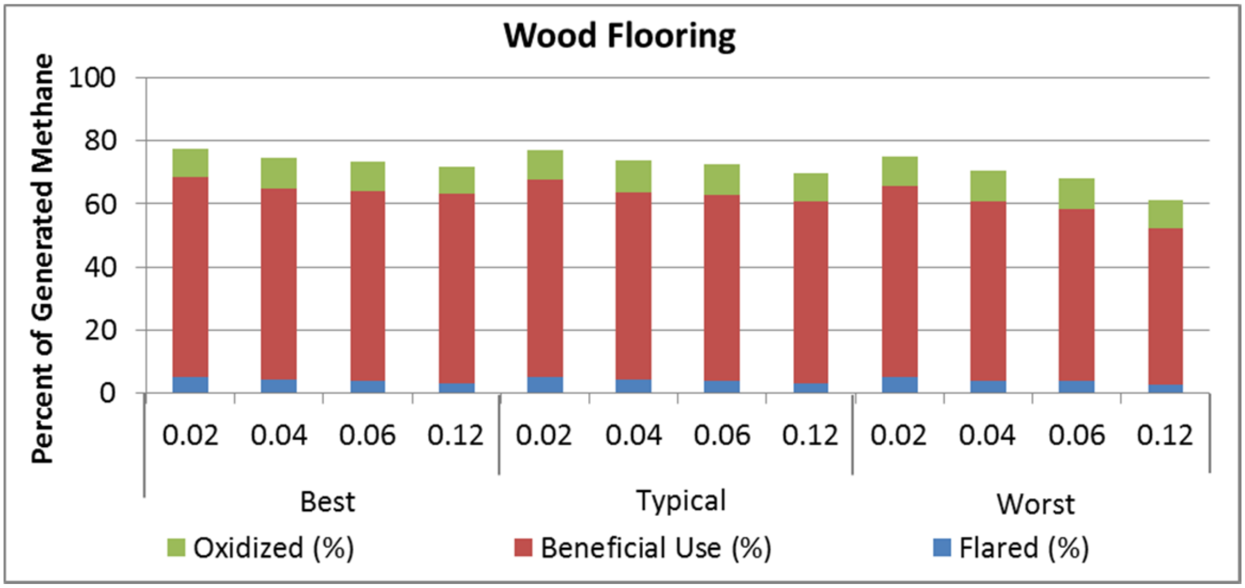

Figure 11. The percent methane flared and recovered for energy from wood flooring for each gas collection scenario and decay rate.

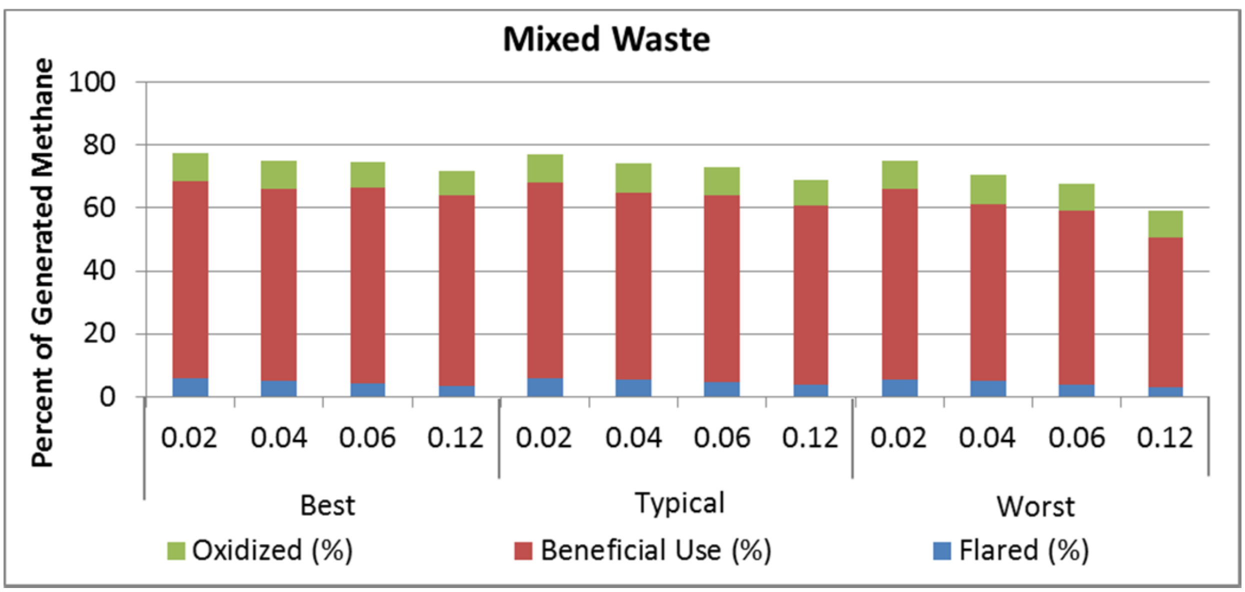

Figure 12. The percent methane flared and recovered for energy from mixed waste for each gas collection scenario and decay rate.

U.S. Average Scenarios

A U.S. average scenario was also developed for the flare only and energy recovery scenarios. Table 38 shows the proportion of waste received in each landfill type. These values were used with the typical landfill gas collection results to develop U.S. average scenarios with energy recovery (Table 39) and without energy recovery (Table 40).

Table 38. Proportion of landfill types and decay in the U.S. average scenario.

Landfill type	Annual Precipitation (cm)[a]	Decay Rate (yr-1)[a]	Percent of Waste Received[b]
Arid	<51	0.02	20.0
Moderate	51 < x <102	0.04	28.9
Wet	>102	0.06	41.1
Bioreactor	N/A	0.12[c]	10.0

[a.] From U.S. EPA, 2010.

[b.] The mass of waste disposed in bioreactor landfills was assumed to be 10%. This mass was subtracted from the mass disposed in moderate and wet landfills in equal proportions, after which the fraction disposed in each category was corrected. The original mass disposal by category was adopted from U.S. EPA, 2010.

[c.] Judgment based on values reported in Barlaz et al., 2010 and Tolaymat et al., 2010.

Table 39. Methane flared, recovered for energy, oxidized, and emitted for the U.S. average scenario with typical gas collection with energy recovery.

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (% of production)	Methane Emitted (%)
Branches	3.2	54.1	12.7	30.1
Grass	9.7	41.4	8.9	40.0
Leaves	9.0	49.3	8.0	33.7
Food Scraps	8.7	51.6	7.8	31.9
Corrugated Containers	3.5	56.2	11.6	28.7
Magazines/Third-class Mail	8.2	53.7	7.7	30.4
Newspaper	4.5	59.3	9.6	26.7
Office Paper	4.2	58.6	10.1	27.1
Phonebooks	4.5	59.3	9.6	26.7
Mixed MSW	5.0	59.9	9.0	26.2
Dimensional Lumber	7.1	57.7	7.6	27.6
Medium-density Fiberboard	6.3	59.2	7.9	26.6
Wood Flooring	4.5	59.2	9.6	26.7

Table 40. Methane flared, recovered for energy, oxidized, and emitted for the U.S. average scenario with typical gas collection without energy recovery.

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (% of production)	Methane Emitted (%)
Branches	35.5	0.0	19.4	45.1
Grass	46.4	0.0	10.0	43.6
Leaves	50.3	0.0	10.0	39.7
Food Scraps	50.9	0.0	10.2	38.8
Corrugated Containers	38.2	0.0	18.2	43.6
Magazines/Third-class Mail	51.3	0.0	10.5	38.2
Newspaper	43.5	0.0	15.7	40.8
Office Paper	42.1	0.0	16.3	41.5
Phonebooks	43.5	0.0	15.7	40.8
Mixed MSW	45.5	0.0	14.7	39.8
Dimensional Lumber	50.7	0.0	11.5	37.7
Medium-density Fiberboard	49.5	0.0	12.4	38.0
Wood Flooring	43.4	0.0	15.7	40.9

California Regulatory Scenarios

A separate set of landfill gas collection scenarios was analyzed for each of the decay rates with and without energy recovery based on California regulatory requirements. The purpose of these scenarios is to show how landfill gas emissions can been mitigated through increased regulatory requirements. Table 41 shows the parameters used for landfill gas collection in each of the scenarios, and Tables 42-49 show the results for each decay rate with (Tables 42-45) and without energy recovery (Tables 46-49).

Table 41. Landfill gas collection parameters for California regulator scenarios. Any unspecified parameters were the same as the Typical landfill gas collection scenario.

Traditional Landfill Gas Collection Inputs	
Parameter	**Values**
Time until initial gas collection (yr)	1
Initial gas collection efficiency (%)	50
Time to increased gas collection efficiency (yr)	2
Gas collection efficiency under increased scenario cover (%)	80
Time from initial waste placement to long term cover (yr)	8
Gas collection efficiency under long term cover (%)	85
Time from final waste placement to final cover (yr)	1
Gas collection efficiency under final cover (%)	90
Flare cutoff	Below 100 cfm collected gas
Downtime (%)	1.1

Table 42. Methane flared, recovered for energy, oxidized, and emitted for the California regulatory gas collection scenario with energy recovery (k = 0.02).

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (% of production)	Methane Emitted (%)
Branches	19.2	65.1	4.4	11.4
Grass	15.1	57.1	5.3	22.4
Leaves	13.5	63.8	4.7	18.0
Food Scraps	13.2	65.4	4.5	16.8
Corrugated Containers	18.5	65.6	4.3	11.5
Magazines/Third-class Mail	13.1	66.6	4.4	15.9
Newspaper	16.9	66.9	4.3	11.9
Office Paper	17.4	66.5	4.3	11.8
Phonebooks	16.9	66.9	4.3	11.9
Mixed MSW	16.2	67.4	4.2	12.2
Dimensional Lumber	13.6	68.1	4.3	14.1
Medium-density Fiberboard	14.3	68.2	4.2	13.2
Wood Flooring	17.0	66.8	4.3	11.9

Table 43. Methane flared, recovered for energy, oxidized, and emitted for the California regulatory gas collection scenario with energy recovery (k = 0.04).

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (% of production)	Methane Emitted (%)
Branches	19.2	57.2	6.9	16.7
Grass	12.3	51.0	6.5	30.2
Leaves	11.8	59.0	5.5	23.7
Food Scraps	11.6	61.0	5.3	22.1
Corrugated Containers	18.1	59.4	6.4	16.1
Magazines/Third-class Mail	11.5	62.8	5.1	20.6
Newspaper	15.7	63.5	5.4	15.4
Office Paper	16.3	62.5	5.6	15.5
Phonebooks	15.7	63.5	5.4	15.4
Mixed MSW	14.6	64.9	5.1	15.4
Dimensional Lumber	11.7	65.7	4.7	17.8
Medium-density Fiberboard	12.4	66.4	4.7	16.5
Wood Flooring	15.7	63.5	5.4	15.4

Table 44. Methane flared, recovered for energy, oxidized, and emitted for the California regulatory gas collection scenario with energy recovery (k = 0.06).

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (% of production)	Methane Emitted (%)
Branches	14.8	56.7	8.4	20.1
Grass	8.9	47.7	7.4	36.0
Leaves	8.8	56.7	6.2	28.2
Food Scraps	8.7	59.2	5.9	26.2
Corrugated Containers	13.9	60.1	7.3	18.7
Magazines/Third-class Mail	8.6	61.4	5.7	24.4
Newspaper	11.7	65.4	5.7	17.3
Office Paper	12.3	64.2	6.0	17.5
Phonebooks	11.7	65.4	5.7	17.3
Mixed MSW	10.8	66.7	5.3	17.3
Dimensional Lumber	8.6	65.5	5.1	20.8
Medium-density Fiberboard	9.0	66.9	5.0	19.1
Wood Flooring	11.7	65.3	5.7	17.3

Table 45. Methane flared, recovered for energy, oxidized, and emitted for the California regulatory gas collection scenario with energy recovery (k = 0.12).

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (% of production)	Methane Emitted (%)
Branches	10.0	58.2	8.7	23.1
Grass	5.6	37.8	9.1	47.5
Leaves	6.1	47.9	7.8	38.2
Food Scraps	6.2	51.0	7.4	35.5
Corrugated Containers	9.4	62.1	7.2	21.3
Magazines/Third-class Mail	6.3	53.7	7.0	33.0
Newspaper	8.0	65.5	5.7	20.8
Office Paper	8.4	65.1	5.9	20.6
Phonebooks	8.0	65.5	5.7	20.8
Mixed MSW	7.5	65.4	5.6	21.5
Dimensional Lumber	6.4	59.6	6.2	27.8
Medium-density Fiberboard	6.6	62.4	5.8	25.2
Wood Flooring	8.0	65.5	5.7	20.7

Table 46. Methane flared, recovered for energy, oxidized, and emitted for the California regulatory gas collection scenario without energy recovery (k = 0.02).

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (% of production)	Methane Emitted (%)
Branches	69.9	0.0	8.9	21.2
Grass	70.9	0.0	5.7	23.4
Leaves	74.7	0.0	5.4	19.9
Food Scraps	75.3	0.0	5.5	19.2
Corrugated Containers	70.6	0.0	8.6	20.8
Magazines/Third-class Mail	75.6	0.0	5.6	18.7
Newspaper	72.2	0.0	7.9	19.9
Office Paper	71.7	0.0	8.1	20.2
Phonebooks	72.2	0.0	7.9	19.9
Mixed MSW	72.9	0.0	7.5	19.5
Dimensional Lumber	75.4	0.0	6.2	18.4
Medium-density Fiberboard	74.8	0.0	6.6	18.6
Wood Flooring	72.2	0.0	7.9	19.9

Table 47. Methane flared, recovered for energy, oxidized, and emitted for the California regulatory gas collection scenario without energy recovery (k = 0.04).

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (% of production)	Methane Emitted (%)
Branches	71.5	0.0	8.6	20.0
Grass	63.1	0.0	6.6	30.3
Leaves	70.4	0.0	5.7	24.0
Food Scraps	72.1	0.0	5.5	22.4
Corrugated Containers	73.0	0.0	7.9	19.1
Magazines/Third-class Mail	73.6	0.0	5.3	21.1
Newspaper	75.7	0.0	6.6	17.8
Office Paper	75.0	0.0	6.9	18.1
Phonebooks	75.7	0.0	6.6	17.8
Mixed MSW	76.5	0.0	6.1	17.4
Dimensional Lumber	76.2	0.0	5.2	18.7
Medium-density Fiberboard	76.9	0.0	5.3	17.8
Wood Flooring	75.6	0.0	6.6	17.8

Table 48. Methane flared, recovered for energy, oxidized, and emitted for the California regulatory gas collection scenario without energy recovery (k = 0.06).

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (% of production)	Methane Emitted (%)
Branches	67.9	0.0	9.5	22.6
Grass	56.5	0.0	7.5	36.1
Leaves	65.2	0.0	6.3	28.5
Food Scraps	67.5	0.0	6.0	26.5
Corrugated Containers	70.7	0.0	8.3	21.0
Magazines/Third-class Mail	69.5	0.0	5.8	24.7
Newspaper	74.6	0.0	6.4	19.0
Office Paper	73.8	0.0	6.8	19.4
Phonebooks	74.6	0.0	6.4	19.0
Mixed MSW	75.3	0.0	5.9	18.8
Dimensional Lumber	73.2	0.0	5.4	21.4
Medium-density Fiberboard	74.7	0.0	5.3	19.9
Wood Flooring	74.5	0.0	6.4	19.0

Table 49. Methane flared, recovered for energy, oxidized, and emitted for the California regulatory gas collection scenario without energy recovery (k = 0.12).

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (% of production)	Methane Emitted (%)
Branches	66.0	0.0	9.4	24.6
Grass	43.4	0.0	9.1	47.5
Leaves	54.0	0.0	7.8	38.2
Food Scraps	57.1	0.0	7.4	35.6
Corrugated Containers	69.6	0.0	7.8	22.6
Magazines/Third-class Mail	59.8	0.0	7.0	33.1
Newspaper	72.2	0.0	6.1	21.7
Office Paper	72.0	0.0	6.4	21.6
Phonebooks	72.2	0.0	6.1	21.7
Mixed MSW	71.9	0.0	5.9	22.2
Dimensional Lumber	65.7	0.0	6.3	28.0
Medium-density Fiberboard	68.5	0.0	6.0	25.5
Wood Flooring	72.2	0.0	6.1	21.6

The results in Tables 50 and 51 show the average landfill gas results using the decay rate proportions in Table 38 and the California regulatory results (Tables 42-49). Figures 13 and 14 show a comparison of current U.S. average methane treatment with potential treatment under national and California regulatory schemes for landfills with (Figure 13) and without (Figure 14) energy recovery. In landfills with energy recovery, the California regulatory scenario reduces methane emissions by between 7 and 13% for each material, whereas without energy recovery emissions are reduced by 10 to 24% due to the more rigorous flare requirements.

Table 50. Methane flared, recovered for energy, oxidized, and emitted for the U.S. average scenario with typical gas collection with energy recovery.

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (% of Production)	Methane Emitted (%)
Branches	16.5	58.7	7.2	17.7
Grass	10.8	49.6	6.9	32.8
Leaves	10.3	57.9	5.9	25.9
Food Scraps	10.2	60.2	5.6	24.1
Corrugated Containers	15.6	61.2	6.4	16.8
Magazines/Third-class Mail	10.1	62.1	5.4	22.5
Newspaper	13.5	65.2	5.3	16.0
Office Paper	14.1	64.3	5.6	16.1
Phonebooks	13.5	65.2	5.3	16.0
Mixed MSW	12.6	66.2	5.0	16.1
Dimensional Lumber	10.3	65.5	5.0	19.3
Medium-density Fiberboard	10.8	66.6	4.8	17.8
Wood Flooring	13.6	65.1	5.3	16.0

Table 51. Methane flared, recovered for energy, oxidized, and emitted for the U.S. average scenario with typical gas collection without energy recovery.

Material	Methane Flared (%)	Methane to Energy Recovery (%)	Methane Oxidized (% of Production)	Methane Emitted (%)
Branches	69.2	0.0	9.1	21.8
Grass	60.0	0.0	7.0	33.0
Leaves	67.5	0.0	6.1	26.4
Food Scraps	69.4	0.0	5.9	24.8
Corrugated Containers	71.2	0.0	8.2	20.6
Magazines/Third-class Mail	70.9	0.0	5.7	23.3
Newspaper	74.2	0.0	6.7	19.1
Office Paper	73.6	0.0	7.1	19.4
Phonebooks	74.2	0.0	6.7	19.1
Mixed MSW	74.8	0.0	6.3	18.9
Dimensional Lumber	73.8	0.0	5.6	20.7
Medium-density Fiberboard	74.7	0.0	5.6	19.6
Wood Flooring	74.1	0.0	6.7	19.1

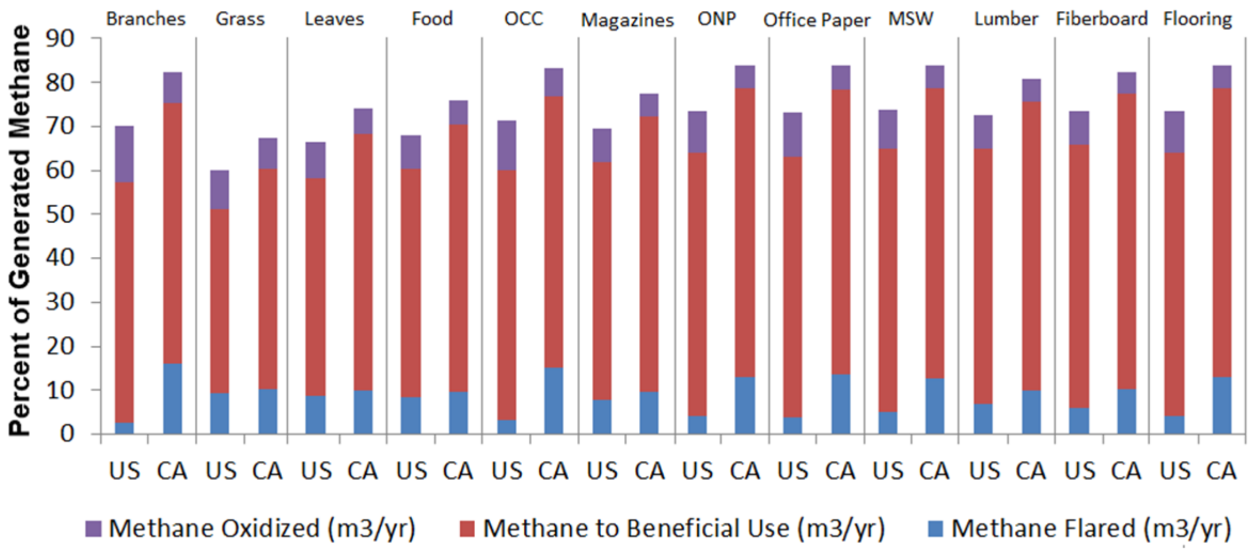

Figure 13. Comparison of current U.S. average methane treatment with potential treatment under a California regulatory scheme for landfills with energy recovery.

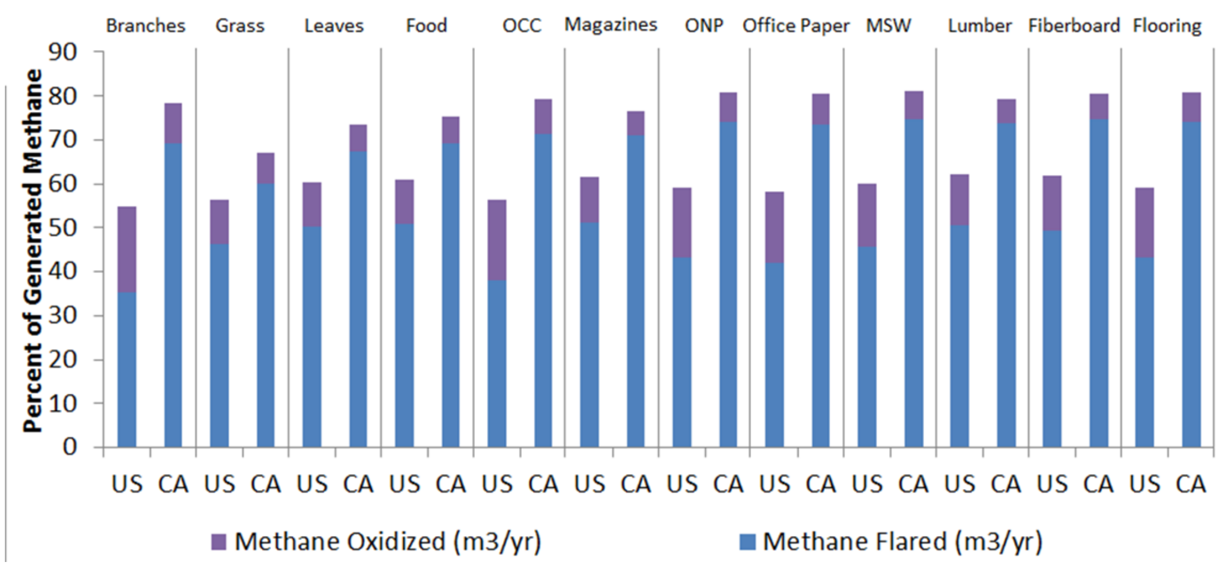

Figure 14. Comparison of current U.S. average methane treatment with potential treatment under a California regulatory scheme for landfills without energy recovery.