Appendix B: Original Comments from Reviewers

Dr. Morton Barlaz,

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General Comment
Overall, I think that the report and documentation are very well done. A lot of thought has gone into the model to make it comprehensive. A strength of this activity is that a consulting firm with real world project experience (Cornerstone) was involved in developing the cost data.

A. Model Methods

1. Does LFGCost-Web include a reasonable range of energy recovery project types? Are there any other existing or emerging LFG utilization technologies that warrant consideration in future versions of the model?

Response: I think that the range provided is extensive. As noted in some of my general comments, I question whether there are enough CHP Projects in operation to warrant including in a model. An alternative would be to qualitatively point out that CHP projects will increase efficiency and therefore environmental benefits. As long as Cornerstone thinks that the data are no more uncertain than for the other energy recovery alternatives, including CHP is fine.

2. Are the estimated costs reasonable for typical project types and sizes (emphasis on review of Collection and Flaring System (C&F) and Standard Reciprocating Engine-Generator Set (ENG) modules)?

Response: I do not have a good background in the economics but rather rely on values presented by consultants such as Cornerstone and landfill owners such as Waste Management. If EPA is concerned with the numbers, then SCS Consultants does a lot of field work maintaining landfill gas collection systems and I would expect them to have excellent O&M and capital cost data. I can provide a contact if desired.

3. Are default input parameters appropriate?

Response:
a. With reference to this statement in the user's manual: "Landfill gas collection efficiency – The equipment used to collect LFG normally operates at efficiencies between 70 and 95 percent. The suggested default is 85 percent."

I think that 85% is too high unless the site is under final cover. Most gas is produced long before the landfill is under final cover so this value should be reevaluated. I have attached two documents that I prepared for ICF in support of EPA's WARM model. Both documents have been reviewed by both EPA-ORD and industry representatives. The documents review the available literature on collection efficiency and present what I consider to be the state-of-the-art (but not the state-of-the-practice) for modeling landfill gas collection efficiency.

b. The default GWP – I do not think the user should be forced to decide between 21 and 25. I assume that the value is the same as EPA uses in its annual Greenhouse Gas Inventory. I think IPCC is now recommending 28 as of 2013.

c. Figure 1 in the User's Manual: It is well documented that the gas collection efficiency changes (increases with time). I realize that this concept goes beyond LandGem but suggest that it is time

for EPA to start incorporating this issue into its landfill gas models. The background to handle a time varying collection efficiency is described in the aforementioned documents that I am attaching as well as in the manuscript listed below which I have also attached:

Levis, J. M. and M. A. Barlaz, 2011, "Is biodegradability a desirable attribute for discarded solid waste? Perspectives from a national landfill greenhouse gas inventory model," Environ. Sci. and Tech., 45, 13, p. 5470 – 76.

I can assist with this if desired.

d. Page 16 – when discussing lifetime CO_2 avoided – should the assumed energy grid mix be explicitly stated here? I see a default of 1.18 lb CO2/kwh. This number looks like the entire grid and not just the fossil fuel component. There is a lot of discussion in the LCA literature over appropriate values and I think some articulation of the logic for the approach would strengthen the document.

4. Are there any other aspects of the model that need to be changed or improved before using the results in project analysis or benefit cost analysis?

Response: I think that for the purpose of an analysis of costs and benefits, the work is marginally adequate without the changes described above. I do think that the changes described above would result in a much more robust and defensible analysis but the benefit to cost ratio is well above 1 so I suspect that it will be greater than one even with these changes.

There is an aspect of uncertainty that EPA has not considered and I think is important. Waste composition is changing rapidly and this is resulting in changes in the ultimate methane potential (L_0) and the decay rate (k). The amount of fiber discarded in the waste stream has and continues to decrease and this is resulting in more food waste in the waste discards stream. This is a result of increasing fiber recycling and less fiber use. As a result, the overall MSW decay rate is increasing since food waste degrades faster than fiber. This has an effect on collection efficiency since food waste degrades faster, the implication of which is that fewer wells are in place while the food waste is decomposing. At the same time, on a wet weight basis, L_0 is decreasing since food waste contains a lot of water and the degradable mass is relatively low. I understand that recognizing that these values are changing does not make it possible to recommend new values but I think EPA needs to point this out since the AP-42 defaults were derived in the 1990s.

A manuscript that illustrates the significance of changes in waste composition is also attached.

De la Cruz, F. B. and M. A. Barlaz, 2010, "Estimation of Waste Component Specific Landfill Decay Rates Using Laboratory-Scale Decomposition Data," Env. Sci. Technol., 44, 4722 - 28

B. Model Functionality

1. Does the model provide a useful and sensible structure for estimating project-level costs?

Response: Yes it does. I am using a Mac with Office 2011. I enabled macros and added the solver add-in. I nonetheless could not make the feature work where the model is to calculate the price required to break even on a project.

I do find the appearance of the INP-OUT sheet to be rather busy and think the appearance could be improved. Even bigger fonts and wider rows would help. I would also move the text on the top of the INST sheet to the INP-OUT sheet, or repeat it there, and list the "12 required inputs" or color code these cells.

2. Does the model itemize cost components and present them in the REPORT worksheet in an appropriate manner?

Response: I would like a disaggregated list of all the capital and O&M costs.

3. Are there any specific features that could be improved or added to the model to strengthen the usefulness of this tool?

Response: I find it overall to be a little clumsy. Everything is here but I would like a notice when I have input all the variables and am ready for a model run.

4. Does the model conduct a reasonable level of error checking?

Response: Yes, it seems to.

Row 20: Why does the model only allow me to start an energy recovery project ten years after the landfill opened but not six years after? This is probably someplace in the User's Manual but not intuitive and seemingly erroneous. When I get the error message, ideally it would either refer me to an embedded pdf file with the information I need for the specific variable, or give me a pop-up box with the information on the variable I am having trouble with.

C. Documentation (User's Manual)

1. Does the User's Manual clearly explain how to use the model?

Response:

<u>Waste Burial Rate</u>

I see on page 17 that the waste burial rate vary annually and the user can easily explore different rates. I think that this option should be mentioned earlier.

I found the description of the manner in which historical waste acceptance rate is calculated to be confusing. I think if it were rewritten without variable names in simple works it would be more comprehensible. (this is in reference to page 2 of the memo from Hilary Ward)

Page 11 – "Acreage should represent area of landfill for gas collection to feed project, not total landfill area. Gas collection and flaring cost estimates represent a complete new system (costs for expansion of an existing system will be <u>higher</u>); inaccurate cost estimates may result for smaller landfill areas (<10 acres) due to economic infeasibility of designing and installing an entire new collection and flaring system."

I would expect costs for expansion of an existing system to be lower since some

infrastructure is already in place.

Page 14: tax credits are mentioned here but not in the 6/14/14 memo from Kirsten Cappel. Revenue is not mentioned in that memo either and I think it needs to be.

2. Does the documentation clearly explain the assumptions and methodology incorporated in the model?

Response: Yes

3. Does the documentation clearly and appropriately explain the uncertainty, caveats, and limitations to consider when using the model? Please fully explain. What additional recommendations would you make to better address these factors?

Response: The document does a reasonable job of documenting uncertainty. As noted elsewhere, I think uncertainty in k and L_0 should be discussed.

D. Application of LFGcost-Web to regulatory benefit-cost analysis

1. Does the reviewer have any comments on EPA's approach of using cost equations derived from the model to estimate overall costs for the proposed regulations? Would you make any suggestions to improve this approach?

Response: As described elsewhere, I would modify the manner in which collection efficiency it treated. Specifically, allow it to vary with time and use values below 85% prior to final cover installation.

2. Are there any model implementation issues not addressed in the June 2015 memo that should be considered in when using LFGCost in regulatory benefit-cost analysis?

Response: Tax credits are not mentioned – perhaps this is intentional given the type of analysis but the reason they are excluded should be stated.

Section 2.1: I think that this section could be clearer if written in words without the variable names. Basically, the user can enter annual tons disposed and allow it to vary, or assume a constant rate coupled with site lifetime. The text is hard to follow.

Section 2.2 EPA refers to the model calculation as "emissions" when it is actually either "production" of "collectable gas" (a point of confusion in AP-42). I urge EPA to only use "emissions" for gas that is not collected and also to unambiguously clarify whether they consider the AP-42 defaults to be "production" (this is what everyone assumes in practice) or "collectable gas" (which is how the AP-42 defaults were derived).

Equation 4b: Justify use of a 100 yr GWP of 25 with a citation.

Section 2.3: The idea to use NSPS values for the initial gas production and AP-42 values to determine when controls could be removed is very good.

Section 2.4: In the second line, the reference to Section 2.1 should be 2.2.

Why is it assumed that the "GCCS would collect all of the emitted gas"? 100% collection efficiency is very rare.

Section 3. Cost Equations
It is stated that the % of design area filled would track the ratio of waste in place/design capacity. This is a rough approximation since new waste goes on top of old waste and at some point in the life of a landfill, a lot of waste is added to the pile with no additional acreage. An alternate approach would be to use a value of mass/acre which could be derived from the literature (See Camobreco et al, 1999, "Life-Cycle Inventory of a Modern Municipal Solid Waste Landfill," Waste Management and Research, 17, 6, p. 394 – 408.), or derive mass/acre from average density and average height.

Equation 6: I am surprised by the assumption of drilling to within 10' of the liner. I will defer to Cornerstone on this but every time that I have been associated with drilling activity, there has been a huge degree of caution about getting close to the liner and 20' seemed to be closer to the rule – at least double check with Cornerstone.

3. Are there other models that could be used in lieu of LFGCost-Web or could complement components of LFGCost-Web when calculating the regulatory costs of controlling LFG emissions from municipal solid waste landfills?

Response: No, certainly not to my knowledge.

Additional Comments

Kirsten Cappel memo of 6/16/14 Memo

Comments on Table 1
Knockout, Blower and Flare system – I am surprised that EPA did not specify 2-3 systems and ask a vendor for a quote to make this more accurate.

Vertical gas extraction wells – specify this is the cost to drill for clarity

Comments on Table 3
Is the $2600/well the annual cost to operate, tune and maintain each well? Text to define "Collection" would be useful.

LFG Overview White Paper

Page 3 – I am surprised by the statement that if a landfill is deep, collection costs tend to be higher. The actual cost might be higher but I would expect you collect more gas per well as a deeper landfill. It seems to me that the proper way to analyze this is $/cubic foot of gas recovered and I am not sure that this analysis was done before making the statement.

Critical Analysis of Literature on Landfill Gas Collection Efficiency

Prepared by Morton Barlaz, October 28, 2012

Introduction

The objective of this chapter is to review literature on landfill gas emissions and collection efficiency. The first section of this chapter presents alternative methods for the calculation of the gas collection efficiency. This is followed by a section on the use of temporally-weighted collection efficiencies as opposed to an individual point estimate. The third section of this chapter reviews the literature on emissions measurements and collection efficiency and this chapter concludes with a summary and recommendations.

Calculation of Collection Efficiency

There are at least two alternatives for the calculation of collection efficiency. The conceptual model that is typically used to calculate emissions is given in equation 1. This conceptual model has been used in several life-cycle approaches (e.g., WARM, the EPA-ORD Decision Support Tool).

$$CH_4 \text{ Emissions} = CH_4 \text{ production} * (1 - \text{collection efficiency}) * (1 - CH_4 \text{ oxidation}) \quad (1)$$

While theoretically correct, equation 1 is only useful if there are data to support separate measurement of the collection efficiency and methane oxidation.

To be consistent with the factors defined in equation 1, the collection efficiency should be calculated based on equation 2.

$$\text{Collection efficiency } (\%) = \frac{CH_4 \text{ collected}}{CH_4 \text{ collected} + CH_4 \text{ emitted} + CH_4 \text{ oxidized}} \quad (2)$$

The use of equation 2 requires the availability of data on all terms and requires that methane emissions be quantified separately from methane oxidation. Where such data are available, the collection efficiency calculated by equation 2 is consistent with the use of collection efficiency in equation 1. However, in many cases measurements of methane emissions occur after the uncollected gas has been subjected to methane oxidation in the cover soil.

An alternative way to calculation collection efficiency is given in equation 3.

$$\text{Collection efficiency } (\%) = \frac{\text{methane collected}}{\text{methane collected} + \text{emissions}} \quad (3)$$

In equation 3, a separate value is not available for methane oxidation. As such, the denominator of equation 3 does not reflect 100% of methane generation and the efficiency calculated by

equation 3 will be higher than a true efficiency. In the literature review, efficiencies are calculated using equations 2 and 3 where data supporting data are available.

Incorporation of Landfill Gas Collection Efficiency into Life-Cycle Models

A method is required to represent the gas collection efficiency of either the average ton of waste disposed in a landfill or a specific ton placed at a specific time. As most models treat a generic ton of waste in an average landfill, a method has been developed to calculate the efficiency of an average or representative ton. The method described in this section is adopted from a paper by Levis and Barlaz (2011).

Landfill gas collection systems are installed in part based on the age of the landfill cell. As a result, waste buried earlier in the life of a landfill cell will be under gas collection for less time than waste buried later in the life of a landfill cell. It is therefore necessary to temporally average the collection efficiency for each year of cell operation. To illustrate this, a gas collection scenario was based on the following assumptions:

- a cell life of 5 years
- no gas collection in place for the first two years of cell operation (6 mo for bioreactors)
- the collection efficiency prior to cell closure and intermediate cover installation is 50% (i.e., years 3 to 5, or 0.5 to 3 yr for a bioreactor)
- after cell closure at the end of year 5, the collection efficiency is 75%
- 10 years after final waste placement (i.e., 15 years after initial waste placement), a final cover is installed and the gas collection efficiency increases from 75% to 95%

This gas collection system installation schedule was used to calculate a temporally averaged gas collection efficiency which is the volume of gas collected divided by the volume of gas produced over 100 years as it applies to the 5 years of waste buried in a single landfill cell.

The calculated temporally averaged landfill gas collection efficiencies for waste disposed in traditional and bioreactor landfills that collect gas are shown in Table . The results in Table 1 reflect an average mass of waste as opposed to the first mass buried. Thus, even though it was assumed that no gas collection is installed at a traditional landfill for two years, waste disposed in year two comes under some collection within a year of burial; hence the gas collection efficiency for waste buried in year two is non-zero.

Table 1. Temporally averaged landfill gas collection efficiencies[a]

Waste Age (yr)	Collection Efficiency (%) Traditional Landfill	Bioreactor Landfill
1	0	25
2	45	55
3	60	60
4	65	65
5	70	70
6	75	75
7	75	75
8	75	75
9	75	75
10	75	75
11	75	75
12	79	79
13	83	83
14	87	87
15	91	91
≥16	95	95

[a] Value represents the behavior of an average mass of MSW in a landfill with gas collection. The calculation procedure is described in the text. These values are based on an assumed schedule for the installation of a gas collection system, a landfill cell life of 5 years and the installation of final cover 15 years after a cell opens as described in the text.

Review of Studies on Landfill Gas Collection Efficiency

The objective of this section is to summarize published studies on landfill gas collection efficiency. Critical aspects of each study are presented and analyzed to assess what information can be used to inform the selection of model parameters for models in which emissions are estimated. Throughout this review, an effort was made to define the type of landfill cover on which emissions measurements were made so to differentiate the performance of gas collection systems on daily, intermediate and final covers. Studies are reviewed individually in chronological order to support an analysis of appropriate models and parameters to be used to estimate methane emissions.

Mosher et al., 1999

Mosher et al. (1999) reported on methane emissions at nine U.S. landfills using both static chambers (six of the landfills) and a tracer (five of the landfills). Two of the nine landfills did not have any gas collection, two (Rochester and PLF-C) were closed and had a final cover that included a geomembrane plus soil and five had a soil or geomembrane cover on between 18 and 63% of the landfill. Thus with the exception of the closed sites, the measurements encompass more than one type of cover which makes them difficult to use for assignment of collection efficiencies as a function of cover type. In all cases, emissions were reduced by methane oxidation.

Emissions at Rochester were reported to be 1750 liters CH_4/min and collection was reported as 16650 CH_4/min. This would result in a collection efficiency of 90.5% [100*(16650/(1750+16650)] using eqn. 3. However, there is a statement in the manuscript that gas collection was not accurately measured and was therefore estimated based on waste in place and an assumed oxidation value. If this is the case, then there is significant uncertainty in the calculated efficiency, although this site had the lowest emission rate in gm CH_4/m^2/day.

Emissions at PLF-C were reported to be 3900 liters CH_4/min and collection was reported as 15100 liters CH_4/min. This would result in a collection efficiency of 79.4% [100*(15100/(3900 +15100)] using eqn 3. Later in the manuscript, it is noted that here was “measurable off-site migration of gas” at this landfill.

In summary, collection efficiencies of 79.4% and 90.5% were reported for two closed landfills in which the final cover was a geomembrane plus soil. As discussed above, gas collection at Rochester is uncertain which casts some doubt on the precision of the 90.5% value. However, Rochester has the lowest emissions of any of the landfills which is consistent with a high collection efficiency. Given the presence of a geomembrane, it is likely that the measured emissions were not reduced methane oxidation.

Galle et al., 2001

Galle et al. (2001) measured methane emissions on a landfill in Sweden using a time correlation tracer method with tracer and methane concentrations measured by FTIR Absorption Spectroscopy. The landfill had been open since 1960 and in the years leading up to the study,

the landfill received about 18,000 tons a year which is low by U.S. standards. Though not explicitly stated, it appears that the landfill was active at the time of testing. Therefore, the landfill was most likely covered with an intermediate cover. Methane emissions were measured to be 38 kg/hr and gas collection was reported as 9 kg/hr. The authors also introduced modeled gas production as well as estimated methane oxidation but these terms were not utilized for this analysis. The author estimates that their emissions estimate was ± 15%. Based on the methane collection and emissions data, a collection efficiency of 19.1% [100*(9/(38+9)] was calculated and actual emissions would have been reduced by methane oxidation.

Given the age of the landfill and the relatively small volume of waste, this landfill does not appear to be representative of a U.S. landfill.

Huitric et al. 2006 and 2007

Huitric et al. (2006 and 2007) presented a series of two papers in the proceedings of the SWANA LFG Symposium that describe work at the LA Sanitation District's Palos Verdes Landfill. In the 2007 paper, the cover is described as 7' of clay (the earlier paper says 5' of clay but this does not affect the conclusions). The landfill was closed in 1980.

This efficiency would include methane oxidation based on the manner in which emissions were measured. LFG emissions were calculated on the premise that the methane concentration is proportional to the emission rate. The concentration was measured by FID surface scan under very strict conditions as specified by local regulations. The concentration at the landfill surface was also calculated based on the assumption that no gas was collected by using the U.S. EPA's Industrial Source Complex (ISC) air dispersion model. The ratio of the measured concentration to the concentration calculated by assuming no gas collection was taken to represent the fraction emitted, so one minus this fraction is the fraction collected and oxidized. Flux chamber measurements were also made and were never significantly greater than zero. However, they were not used for the collection efficiency calculation. (It is recognized that flux chamber measurements will not capture above ground leakage from well boots, header pipes, etc.)

Measurements in 2006 showed ~95% collection efficiency while an efficiency of 99% was reported in the 2007 paper. The increase was attributed to improvements in the gas collection and control system (GCCS) design. While the method used to calculate collection efficiency is a little hard to follow and is subject to some uncertainty, the results show high collection efficiencies. All results reflect the combined effects of gas collection and methane oxidation.

The results are of limited applicability given the cover design and the waste age. The results show that for 25 to 30 year old waste in an arid region, a high collection and control efficiency can be achieved with a well operated GCCS.

Spokas et al., 2006

Spokas et al. (2006) presented a study in which they did a carbon balance on three French landfills. They started with the following equation to address all aspects of a landfill methane balance.

Methane generated = emitted + oxidized + recovered + migrated + Δ storage (4)

Methane generation was estimated from a gas production model. Emitted methane was measured by using either static chambers or an atmospheric tracer technique. Methane oxidation was measured by using a stable isotope technique. Recovered methane was based on direct measurements at each landfill and methane migration was based on calculation of methane diffusion through liners. Maximum potential methane storage was calculated from an estimate of waste porosity and changes in the methane concentration of collected gas, and was used as an upper limit of the value required to close a mass balance.

A total of nine cells at the three landfills that were tested, including Montreuil-sur-Barse (MSB), Lapouyade (L), and Grand Landes (GL). The cover characteristics and depth of each landfill are presented in Table 2. MSB and GL are relatively shallow. The higher surface area to volume of these landfills would likely decrease gas collection efficiency relative to a deeper landfill.

To eliminate the need for a gas production model and the storage term, the collection efficiency was calculated as in eqn. 2 and the results are summarized in Table 2. As calculated by eqn. 2, collection efficiencies for final clay covers were uniformly above 90% while the collection efficiency for the temporary cover was slightly above 50% in the summer and over 90% in the winter. One potential explanation for this is that the covers were moist and frozen in the winter, thus decreasing their effective gas conductivity. The GCL at MSB exhibited a collection efficiency of 52% while the efficiency for the geomembrane final cover was 98.7%. Collection efficiencies were also calculated using eqn. 3 for comparison to other literature, which exclude the oxidation and migration terms. The difference between eq. 2 and eq. 2 is minor in consideration of the uncertainty of these types of studies (Table 2).

Interestingly, with reference to Spokas' work, Borjesson et al. (2007) suggests that "… their efficiency rates at over 90% may be overestimates, since the flux measurements with SF6 tracer measurements were done on the edge of the landfill rather than at some distance (Morcet, M., personal communication, 2003)."

The authors suggested the following values for collection efficiency based on their work:
35% for an active cell with a GCCS
65% for a temporary cover with a GCCS
85% for a cell with final clay cover and GCCS
90% for a GM covered cell with a GCCS
These values would appear to be conservative based on the values in Table 2.

Table 2 Landfill Emissions Measurements and Calculated Collection efficiency Based on Data in Spokas et al. (2006).

Site Description	Thickness (m)	Recovery (kg CH_4/day)	Emissions (kg CH_4/day)	Oxdn (kg CH_4/day)	Migration (kg CH_4/day)	Collection (collection + emissions) (eqn. 3)	Collection (collection + emissions + oxidation) (eqn. 2)	Oxidized (oxidized + emitted)
MSB: final clay with LFG recovery	4.3 -4.7	102	8.1	0.3	1.1	92.6	92.4	3.6
MSB: final GCL with LFG recovery	4.3 - 4.7	55.8	49.4	2.1	1.1	53.0	52.0	4.1
L: final clay with LFG recovery, summer	9.9 - 15	3935	298.6	83.5	20	92.9	91.1	21.9
L: final clay with LFG recovery, winter	9.9 - 15	3893	56	9.8	20	98.6	98.3	14.9
L: thin temporary clay cover, summer	9.9 - 15	346	287	6.5	3	54.7	54.1	2.2
L: thin temporary clay cover, winter	9.9 - 15	293.2	15	2.3	4	95.1	94.4	13.3
L: thin temporary clay cover, w/out LFG summer	9.9 - 15	0	5369	7.1	3			
GL: final clay with vertical wells	5.9 -6.9	1101	0.01	4[a]	5.1	100.0	99.6	99.8
GL: final geomembrane with horizontal LFG recovery	5.9 -6.9	799	6.2	4[a]	4.9	99.2	98.7	39.2

MSB = Montreuil-sur-Barse; L = Lapouyade; GL = Grand Landes

a. Methane oxidation was estimated since it could not be calculated in the absence of methane emissions for the clay cover.

Lohila et al. 2007

Lohila et al. (2007) measured emission for a landfill in Finland by using eddy covariance. The landfill received about 1000 tpd at the time of the study and the waste depth was 20 m. The gas collection system was drawing gas from an 8 ha area and the authors estimated the area covered by the emissions measurement to be 7 ha. The measurement area included an open area with active waste disposal, and an area covered with 0.2 – 0.5 m (6-15") of compost soil plus 0.5 – 2 m (15-60") diamicton and clay. Diamicton can be defined "as a wide range of non-sorted to poorly sorted terrigenous sediment, i.e. sand or larger size particles that are suspended in a mud matrix" from Wikipedia. The mixture of diamicton and clay appears equivalent to an intermediate cover with an oxidizing layer for a U.S. landfill.

In this study, the effectiveness of the gas collection system was assessed by turning the system off for either 4 or 7 days. In the first test, the system was turned off for 7 days and the mean emission rate increased from 0.37 to 1.79 mg/(m^2/sec). This resulted in a calculated collection efficiency of 79.3% [100*(1.79-0.37)/1.79] using eqn. 3. During the first test, the authors reported that the wind direction was favorable for EC measurements. A second test was conducted over a 4 day period when conditions were not suitable for EC measurements. Thus, during the second test, emissions were measured by using static chambers and high variability was noted with some chambers exhibiting net oxidation. The calculated collection efficiency was 40% but this result does not appear to be reliable. In both cases, emissions were reduced by methane oxidation prior to emissions measurement.

Finally, the authors report an average emission rate over the landfill of 27 m^3/(ha-hr) and gas collection of 60 m^3/(ha-hr) at pump station 2. The authors suggest an overall average collection efficiency of 69% [1-27/(60+27)]*100. If it is assumed that the emissions are attributable to 7 ha and gas collection is attributable to 8 ha, then the emissions could be scaled from 27 to 30.85 27 m^3/(ha-hr) by multiplying by 8/7. This results in a collection efficiency of 66% which is likely not significantly different from 69%. These values all represent emissions from an intermediate cover with some exposed waste that is not under collection. This would suggest a higher efficiency for an intermediate cover with complete GCCS coverage. Of course, these efficiencies also include the influence of methane oxidation.

Borjesson et al., 2007 and Borjesson et al., 2009

Borjesson et al. published two papers (2007 and 2009) describing the results of emissions measurement work that was conducted on three landfills in Sweden between 2001 and 2003. The results are summarized in Table 3. With reference to Table 3, these values were taken directly from the two publications. Where the values differed between the papers, the value in the more recent (2009) paper was used as it is assumed that the value published later represents a refinement of the data.

Emissions measurements were conducted by using a tracer gas release method with a Fourier transform infrared (FTIR) detector. Three types of covers were evaluated including (1) one meter of clay, (2) a mixture of sludge and soil, and (3) a mixture of sludge and wood chips. The 1 m of clay is likely between a long-term intermediate cover and a final cover on a U.S. landfill and will be considered as a final cover although there is no mention of a gas collection layer, a

drainage layer or a vegetative layer as would be expected on a final cover at a U.S landfill. Furthermore, many final covers at U.S. landfills include a geomembrane. The sludge-soil mixture is most equivalent to an intermediate cover given that there are no conductivity specifications for intermediate cover for U.S. landfills. As a result, soils types used as intermediate cover vary widely. The sludge and wood chip cover is difficult to relate to any material used even as daily cover in the U.S. and appears unusual as wood chips would increase the porosity and conductivity, thus allowing for increased infiltration and decreased gas collection relative to a soil cover. These materials are not typically used at U.S. landfills.

The Filbrona landfill had some horizontal gas collection piping. Depending on the exact configuration of the GCCS at the time of the testing, the presence of horizontal collectors may have increased collection relative to a vertical system. The 2007 paper points out that Hogbytorp emits as much methane as a much larger landfill even though the larger landfill produces a lot more gas. This means the collection efficiency is considerably lower for Hogbytorp. The gas system was later upgraded and there was an improvement in collection. Nonetheless, the commentary and data suggest that Hogbytorp was not well run.

The authors calculated the collection efficiency using the equivalent of eqn. 2 where methane production was calculated as:

$$CH_4 \text{ Production} = \{CH_4 \text{ emissions}/(1-0.01*\%\ CH_4 \text{ oxdn.})\} + CH_4 \text{ Recovery} \quad (5)$$

In this formulation, the authors recognize that methane oxidation must be considered in the methane production term. The calculated collection efficiency is suitable for use in equation 1. The manuscript indicates that the emissions data have an uncertainty of 18% though it is not clear how to incorporate this in a quantitative manner. The authors also acknowledge considerable uncertainty in the estimate of methane oxidation and recognize that methane oxidation varies over time, an observation that has been made by others as well (e.g., Chanton et al., 2011a, 2011b).

All site data and collection efficiencies are summarized in Table 3. The authors reported a mean collection efficiency of 51% for all of the measurements. However, this mean was calculated by combining data from sites with different cover types and after giving equal weight to two very low measurements, 14 and 21% which were for Hagby when the GCCS had operational problems. A second collection efficiency was calculated using equation 3. As expected, these values are slightly higher because all gas production is not included in the denominator as described above. The difference between the two values ranges between 2 and 21% with two exceptions. Differences of 2 – 21% are likely within the overall uncertainty in the collection efficiency calculation. In the case of Hagby, there are differences of about 50% for the two estimates of collection efficiency. However, these two measurements were made during the time when there were problems with GCCS operations and as such, they are outliers. It is recognized that there may be times when gas collection is either partially or wholly dysfunctional for some period of time. However, this is likely on the order of 1-2% of the time (estimates from owners are required) and could be considered as a separate term as opposed to incorporation of these values into an average collection efficiency in which they are given equal weight with a functioning system. The same issue arises in the EPA report described below.

In summary, for intermediate cover (Hogbytrop, Blaberget), collection efficiencies ranged from 29 – 59% using equations 4 and 5, and using 35 – 63% using equation 3. Recall that Hogbytrop can be characterized as a landfill that is not well run. For long-term intermediate/final cover (Visby, Hagby, Kristianstad), collection efficiencies ranged from 52 – 67% using equations 4 and 5, and using 63-76% using equation 3. These ranges exclude the two low values from Hagby given problems with GCCS at the time of operation.

Table 2 Landfill Emissions Measurements and Calculated Collection efficiency Based on Data in Borjesson et al. (2009).

Landfill Site	Cover Description & Comments	Date	Emissions kg/hr	Gas recovery kg/hr	CH4 Oxdn (%)	Prodn kg/hr	Efficiency (recovery/prodn) (eqn. 2)	Efficiency Collect/(Collect + Emit) (eqn. 3)
Filborna[a] (Helsingborg)	wood chips + sludge (not relevant to US)	4-Apr-01	308	852	18	1229	69	73.4
		16-Nov-01	386	832	18	1304	64	68.3
		23-Nov-01	441	820	15	1340	61	65.0
		6-Dec-01	256	987	6.2	1260	78	79.4
		7-Dec-01	361	1006	6.2	1391	72	73.6
		2-Jul-02	346	806	22	1250	64	70.0
		10-Mar-03	403	939	6.2	1369	69	70.0
Hogbytorp[c] (Upplands-Bro)	sewage sludge + soil (int. cover); small landfill (200,000 tons)	6-Jun-01	258	140	25	486	29	35.2
		11-Apr-02	393	202	6	620	33	33.9
		10-Nov-03	382	291	7.7	705	41	43.2
Blaberget (Sundsvall)	sewage sludge + soil (int. cover)	9-Mar-02	33.8	58.3	15	98	59	63.3
Visby	1 m clay	13-Jun-01	28	48	37	92	52	63.2
		4-Jun-02	19.2	39	37	69	57	67.0
		5-Jun-02	18.6	39	37	68	57	67.7
		26-Nov-03	12.8	32.4	38	53	61[b]	71.7

Table 2 Landfill Emissions Measurements and Calculated Collection efficiency Based on Data in Borjesson et al. (2009) (contd.)

Landfill Site	Cover Description & Comments	Date	Emissions kg/hr	Gas recovery kg/hr	CH4 Oxdn (%)	Prodn kg/hr	Efficiency (recovery/prodn)	Efficiency Collect/(Collect + Emit)
Hagby (Taby)	1 m clay	18-Apr-01	49	155	37	233	67	76.0
		22-Apr-02	124	32	37	229	14	20.5
		13-Nov-03	141	65.7	43	312	21	31.8
Heljestorp (Vanersborg)	wood chips + sludge (not relevant to US)	29-Mar-01	136	134	6.2	279	48	49.6
		22-May-02	191	262	25	517	51	57.8
Kristianstad	1 m clay	12-Apr-01	43	117	38	187	63	73.1

Notes

a. Filborna had the GCCS turned off on Nov 28, 2001 so no efficiency was calculated.
b. Value reported was 65 in 2007 paper.

Green et al., 2011

Methane emissions were measured at four MSW landfills in California and Colorado using a four corners approach of vertical radial plume mapping with tunable diode lasers to quantify methane concentrations. Field measurements were conducted on two separate occasions at each landfill, with each field campaign lasting several days. Each landfill had intermediate or long-term soil cover. The average result for each field campaign is summarized in Table 4 and collection efficiencies ranged from 72% - 92% based on equation 2.

Table 4 Summary of Collection Efficiencies Reported by Green et al. (2011)

Landfill	Climate	Collection Efficiency (eqn. 2)
DADS	semi-arid	82
		76
Lancaster	arid	92
		81
TriCities	moderate	86
		88
Kirby Canyon	moderate	84
		72

Goldsmith et al. (2012)

Goldsmith et al. (2012) reported methane emissions for 20 landfills across the U.S. based on a vertical plume mapping method in which 2 tunable diode lasers (TDLs) were used to measure methane concentrations upwind and downwind of a source. This method represents an extension of EPA's OTM-10 methodology. The manuscript includes considerable discussion on how to calculate the flux and it is important to recognize that there is some uncertainty in the area contributing to flux. As such, when the flux is normalized to a specific area, there is uncertainty in the emissions estimate. The emissions measurements include the combined effects of gas that is not captured and methane oxidation.

The emissions results were categorized as follows:

- Working face, no cover
- Temporary soil cover which means 15-30 cm of soil
- Intermediate cover which means 60-120 cm of soil
- Final cover which means 1-2 m of soil

In general, working face emissions in wet warm areas like Mississippi exhibited higher emissions that emissions in cool dry climates such as Colorado. A similar trend was observed for temporary, intermediate and final covers. Results for 10 landfills with final covers were reported. Of the 10, only one had a geosynthetic cap and emissions at this landfill were barely above background on the basis of two field campaigns.

The data were not used to calculate collection efficiencies because the area of gas collection did not match with the area of the emissions measurements. As a result, the data is of limited value for informing an estimate of collection efficiency. It is however noteworthy that emissions at the landfills with final covers that included a geosynthetic cap were barely above background, thus supporting a relatively high collection efficiency. In addition, given the presence of a geomembrane, it is likely that the measured emissions were not impacted methane oxidation. Finally, the manuscript notes that even within climate categories, different regions tend to utilize different types of soil which will impact the extent of collection and emissions. This issue was not addressed quantitatively.

U.S. EPA, 2012

The U.S. EPA reported on emissions measurements at three landfills. Emissions measurements were made using EPA Method OTM-10. The method is similar to that used by Goldsmith et al (2012) except that only one instrument was used and data could not be corrected for upwind methane. Thus, the area contributing to flux may be less certain than the work reported by Goldsmith et al. (2012). Three landfills were tested. Site A includes 32 acres of intermediate cover. Site B has an 86 acre cell with intermediate cover but some parts of the intermediate cover did not have gas extraction and some wells were added in 2008 and 2010. The site stopped accepting waste in 2010 just prior to the measurement campaign. A second 6 acre site had been accepting waste for three months at the time of measurement and no gas wells were installed. Separate measurements were conducted on this area. Site C was closed in 2005 and is 76 acres that was capped with a geosynthetic.

The reported collection efficiencies were as in eqn. 3. As discussed above, the denominator therefore does not represent total production and therefore the calculated efficiencies are elevated. Collection efficiencies were also calculated based on assumptions of methane oxidation between 5 and 20%. However, these calculations add uncertainty to an already uncertain value and were not considered here.

The report presented two estimates of collection efficiency for site A:

- 70% (upper and lower error bounds of 64% and 75%)
- 77% (upper and lower error bounds of 67% and 84%)

The report presented a point estimate collection efficiency of 38% for Site B, with upper and lower error bounds of 31% and 46%. As noted above, Site B included intermediate cover but the gas extraction system was not functional over the entire 86 acres at the time of the tests. As such, while Site B is within the regulations in terms of GCCS installation, it is not representative of the performance on an intermediate cover with a fully functional GCCS.

The report presented two estimates of collection efficiency for site C:

- 73% (error bounds of 51 – 88%)
- 88% (error bounds of 72 – 95%)

The 73% is surprisingly low but there is no analysis of this value in the report.

The report concludes that "the data collected does not support the use of collection efficiency values of 90% of greater as has been published in other studies." Unfortunately, there is not a citation for this statement so the "other studies" cannot be identified. While the values measured for Site C help to inform the appropriate range of collection efficiencies, they are probably best applied to landfills with geosynthetic covers.

Summary and Recommendations

A summary of all reported measurements is presented in Table 5 and the associated statistics are summarized in Table 6. Entries are sorted by cover type to facilitate comparison across studies. The use of equation 2 or 3 to calculate the collection efficiency is noted in Table 5. Given the relatively small differences between equations 2 and 3 as reviewed for each study, all values are considered together. The values calculated using equation 3 are slightly higher than values calculated by using equation 2 but the difference is likely less than the associated uncertainty.

Before reviewing the summary, some discussion of cover classifications is appropriate. Many soils are used for intermediate cover and given the absence of a requirement for the conductivity of an intermediate cover, considerably variability can be expected, even without consideration of variation in the quality of the GCCS. Initially, cover types were divided into intermediate and final covers. However, this may be overly simplistic as many landfills use what is referred to as a long-term interim cover. This long-term interim cover may be in use for years to decades before additional waste is placed. In this context, a formal Subtitle D final cover may not be placed for years to decades but the long-term interim cover that is used would be expected to restrict gas emissions in a manner that is close to a Subtitle D final cover. Given the ambiguity, summary statistics are calculated with the 1m clay covers described in Borjesson classified as both intermediate and final covers (Table 5). As presented in Table 6, the final cover summary statistics in which the Borjesson data are classified as intermediate cover then include only data where the cover was specifically specified to be final.

With respect to the intermediate covers, several outliers were identified (14, 21, 19, 29, 33) and summary statistics were calculated with and without these values. Outliers were associated with landfills that were either not well run or with measurements made when the gas collection system was not fully functional over the areas of the emissions measurements. The calculated average ranges from 60.2 – 72.6% (medians 62 - 77%) and a value of 75% still appears reasonable though standard deviations are on the order of 20% (Table 6).

In the case of final covers, it is important to recognize that there are many configurations including clay only, geosynthetic clays and geomembrane plus clay. The average for final covers is 77.5% when the Borjesson data are included and 87.3% when these data are excluded. The overall range for final covers was 14 – 99.6% across all cover types (median = 73, mean = 71.2, std. dev. =25.4). This range includes the high values reported by Huitric for an unusually thick clay cover on an older landfill as well as the lowest values of Borjesson which appear to be outliers.

Based on this analysis, the limited data set and the uncertainty in all of the values, the following is suggested:

- Interim cover: 75% collection efficiency with lower values (~50%) used for waste under a daily rather than an interim cover

- Long-term interim cover which is used prior to Subtitle D final cover installation: 82.5% which is the average of 75% and 90%

- Final cover: 90%

It is recognized that uncertainty remains in all of the values.

As explained in this chapter, some collection efficiencies do not consider the oxidation of methane as part of the gas production term. As a result, efficiencies calculated in this manner are biased high. For the most part, the difference between the efficiency calculated using equations 2 and 3 is small and likely within the uncertainty of the values. While, measurements of emissions include emissions plus methane oxidation, measurements of collection accurately reflect collected gas. As such, it remains appropriate to apply a methane oxidation factor to the uncollected methane.

Finally, it is apparent that even the best operated GCCS can have days of weak performance. For life-cycle modeling, it may be appropriate to add an additional factor which is the fraction of the time that the system is operational and the fraction of the time when the GCCS is either not-operational (i.e., collection efficiency of zero) or operating at a reduced level (i.e., collection efficiency of perhaps 50% of the default value). Such an approach would take into account the fact that the GCCS may not be fully operational 100% of the time. In cases where the energy recovery system is not operational but the gas is diverted to a flare, this too could be considered as methane would be used beneficially for the time of diversion from a beneficial use to a flare.

Table 5 Summary of Published Studies on Landfill Gas Collection Efficiency

Study	Cover Type	Estimated efficiency using equation 2 unless noted	Comments
Intermediate Covers			
Galle et al., 2001	Not clear, presumably intermediate cover	19.1[a]	Given the age of the landfill and the relatively small volume of waste, this landfill does not appear to be representative of a U.S. landfill. Because eqn. 3 was used, these values are biased high.
Spokas et al., 2006	Intermediate clay	54.1, 94.4	
Lohila et al., 2007	compost soil plus diamicton and clay	79.3[a,b], 40[a,b]	Assume comparable to an intermediate cover. The lower value is likely inaccurate because static chambers were used for the emissions measurement and high variability was reported. The authors also reported an efficiency of 66 – 69% for an intermediate cover with some exposed waste.
Borjesson et al., 2007; Borjesson et al., 2009	sewage sludge + soil	29, 33, 41	Assume comparable to an intermediate cover; small landfill (200,000 tons), landfill not well operated
Borjesson et al., 2007; Borjesson et al., 2009	sewage sludge + soil	59	Assume comparable to an intermediate cover
Borjesson et al., 2007; Borjesson et al., 2009	1 m clay	52, 57, 57, 61	Assume comparable to an intermediate cover (see discussion and Table 6)
Borjesson et al., 2007; Borjesson et al., 2009	1 m clay	67, 14, 21	Assume comparable to an intermediate cover; the low values (14, 21) were attributed to GCCS operational problems (see discussion and Table 6)
Borjesson et al., 2007; Borjesson et al., 2009	1 m clay	63	Assume comparable to an intermediate cover (see discussion and Table 6)

Study	Cover Type	Estimated efficiency using equation 2 unless noted	Comments
Green et al. 2011	intermediate	82, 76	
	intermediate	92, 81	
	intermediate	86, 88	
	intermediate	84, 72	
U.S. EPA (2012)	Intermediate	70[a],77[a]	Because eqn. 3 was used, these values are biased high.
U.S. EPA (2012)	Intermediate	38[a]	Gas extraction system was not functional over the entire test area at the time of the tests. Because eqn. 3 was used, these values are biased high.
Final Covers			
Mosher et al., 1999	Final cover with geomembrane (Rochester)	90.5	Value is uncertain as gas collection was not accurately measured and was therefore estimated based on waste in place and an assumed oxidation value. Given presence of geomembrane, emissions were likely not impacted by oxidation so attribute value to eqn. 2
Mosher et al., 1999	Final cover with geomembrane (Rochester)	79.4	Given presence of geomembrane, emissions were likely not impacted by oxidation so attribute value to eqn. 2.
Borjesson et al., 2007; Borjesson et al., 2009	1 m clay	52, 57, 57, 61	Assume comparable to a final cover (see discussion and Table 6)
Borjesson et al., 2007; Borjesson et al., 2009	1 m clay	67, 14, 21	Assume comparable to a final cover (see discussion and Table 6); the low values (14, 21) were attributed to GCCS operational problems
Borjesson et al., 2007; Borjesson et al., 2009	1 m clay	63	Assume comparable to a final cover (see discussion and Table 6)

Study	Cover Type	Estimated efficiency using equation 2 unless noted	Comments
Huitric et al., (2006, 2007)	7 ft (2.3 m) clay	95-99[a]	Landfill closed in 1980 so low production likely low. Unusually thick clay cover. Value entered as 97.
Spokas et al., 2006	Final clay cover	99.6	
Spokas et al., 2006	Final clay	92.4, 98.3	
Spokas et al., 2006	Final clay cover	91.1	
Spokas et al., 2006	Final geomembrane	98.7	
Spokas et al., 2006	Final geosynthetic clay	52	
Goldsmith et al. (2012)	geomembranes		Not quantified but emissions barely above background
U.S. EPA (2012)	Geosynthetic cap	73[a], 88 [a]	Because eqn. 3 was used, these values are biased high.
Not Applicable			
Borjesson et al., 2007; Borjesson et al., 2009	wood chips + sludge	69, 64, 61, 78, 72, 64, 69	Cover not relevant to U.S. landfills
Borjesson et al., 2007; Borjesson et al., 2009	wood chips + sludge	48, 51	Cover not relevant to U.S. landfills

a. Based on equation 3.
b. The methane collection efficiency was calculated from measurements of emissions with and without operation of the GCCS.
c. The methane collection efficiency was estimated by comparing measured methane concentrations at the landfill surface to modeled concentrations assuming no methane collection.

Table 6 Summary Statistics for Cover Data

	Intermediate Cover with Borjesson data	Intermediate Cover without Borjesson data	Final cover with Borjesson data	Final cover without Borjesson data
All Data Included				
Median	62.0	74.0	73	91.1
Mean	60.2	64.7	71.2	87.3
Standard deviation	23.4	23.5	25.4	14.4
Outliers Excluded				
Median	74.0	77.0	79.4	No outliers excludes
Mean	72.6	71.4	77.5	
Standard deviation	13.3	18.4	18.0	

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Landfill Gas Monte Carlo Model Documentation and Results

June 18, 2014

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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

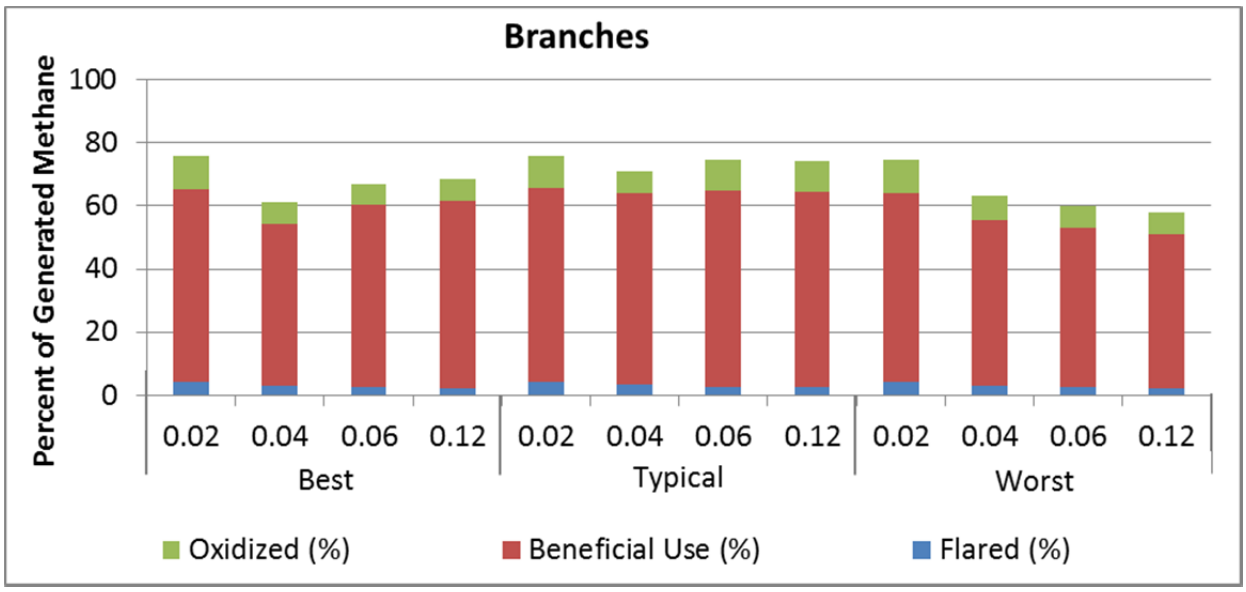

Figure 1. The percent methane flared and recovered for energy from branches for each gas collection scenario and decay rate.

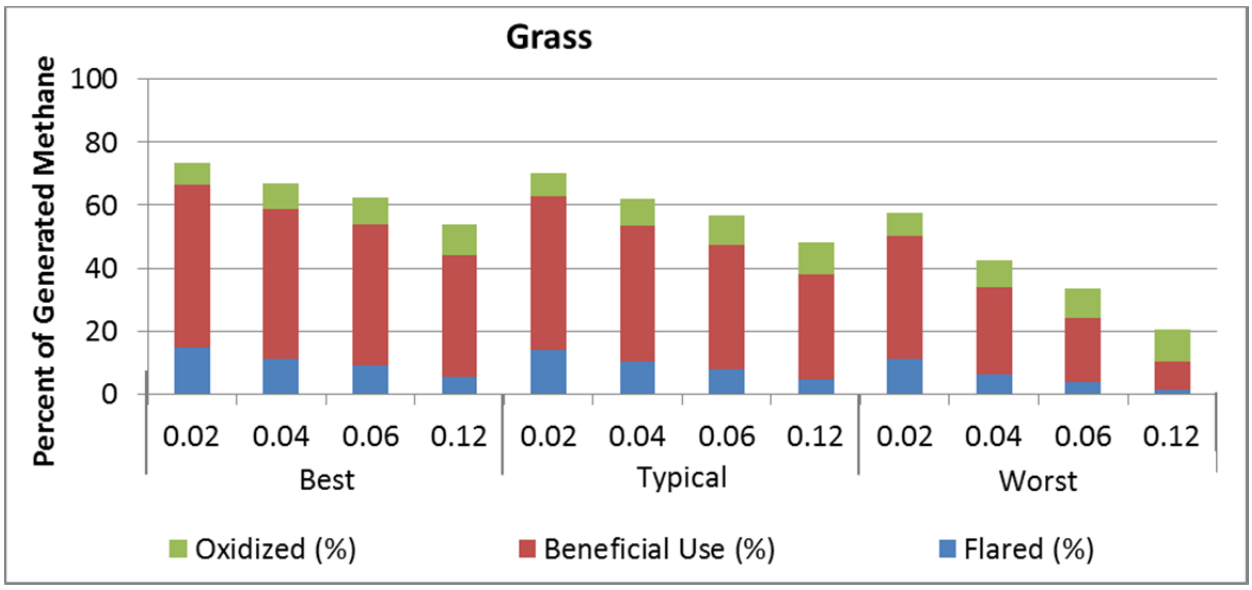

Figure 2. The percent methane flared and recovered for energy from grass for each gas collection scenario and decay rate.

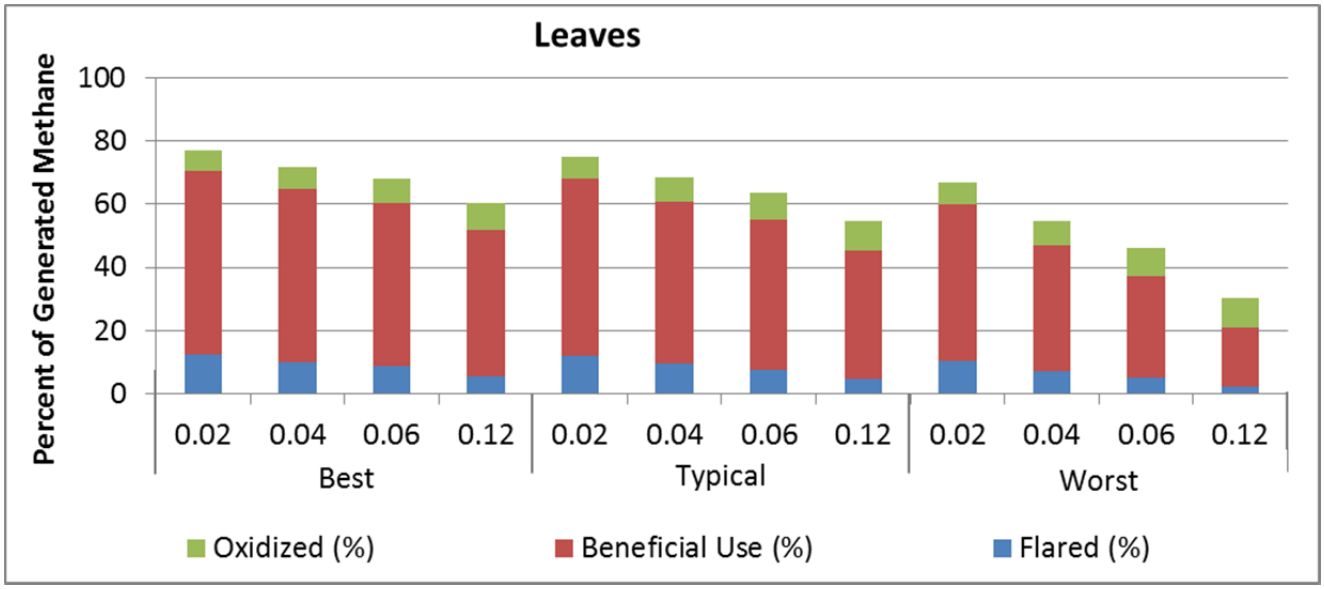

Figure 3. The percent methane flared and recovered for energy from leaves for each gas collection scenario and decay rate.

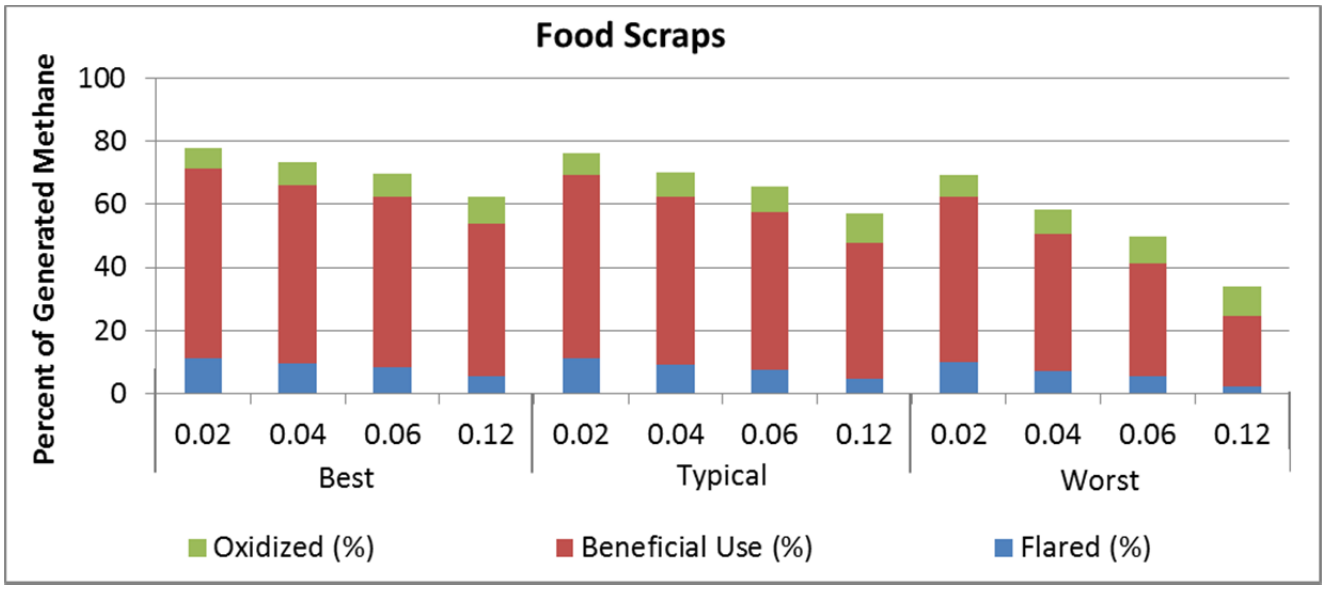

Figure 4. The percent methane flared and recovered for energy from food scraps for each gas collection scenario and decay rate.

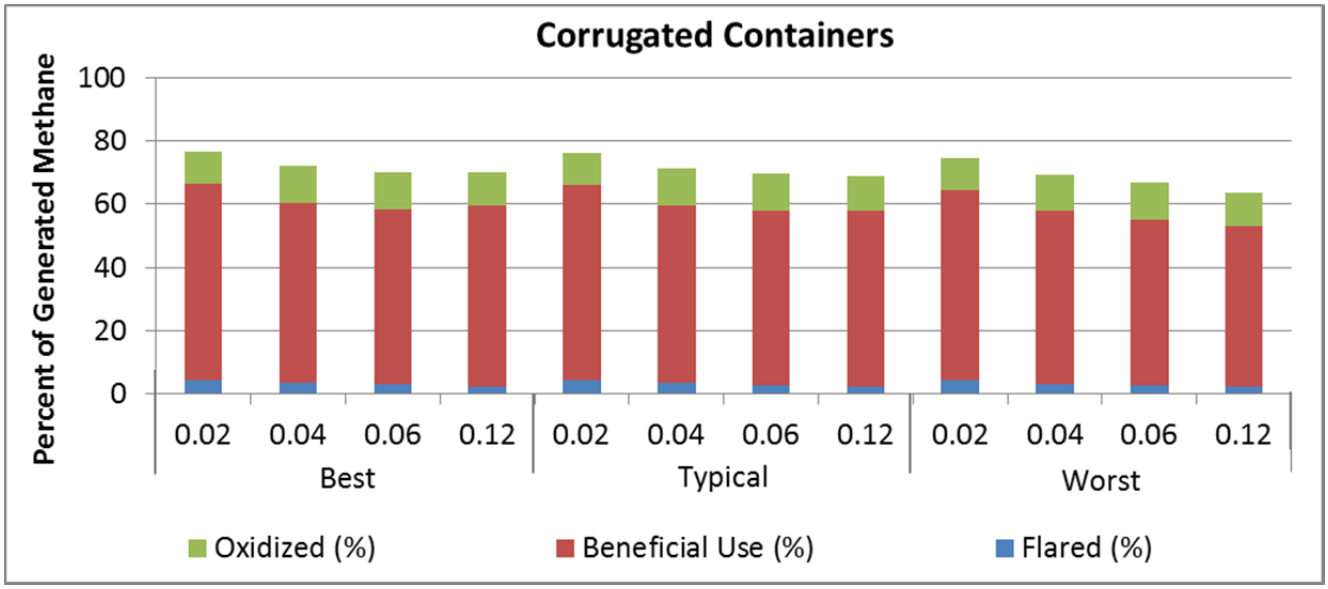

Figure 5. The percent methane flared and recovered for energy from corrugated containers for each gas collection scenario and decay rate.

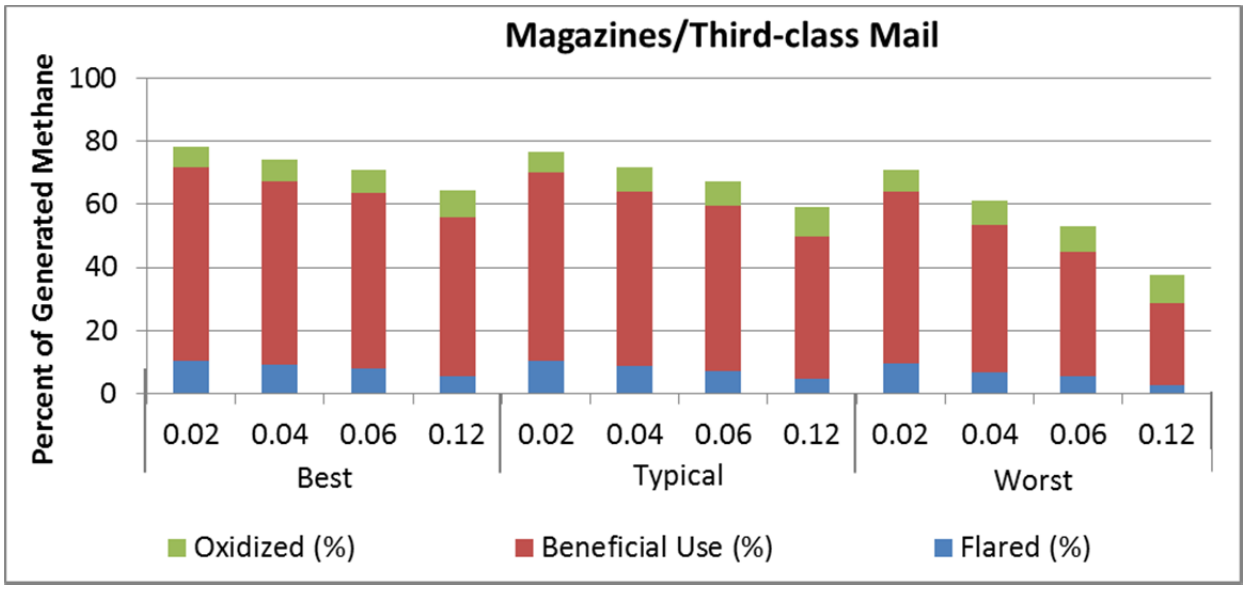

Figure 6. The percent methane flared and recovered for energy from magazines and third class mail for each gas collection scenario and decay rate.

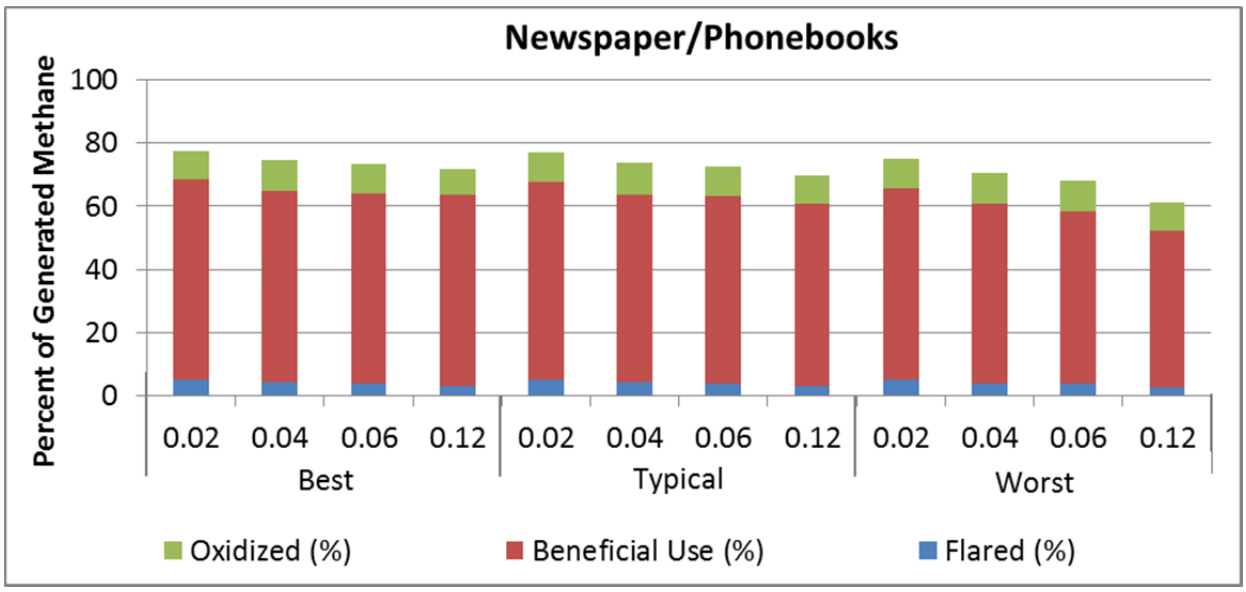

Figure 7. The percent methane flared and recovered for energy from newspaper and phonebooks for each gas collection scenario and decay rate.

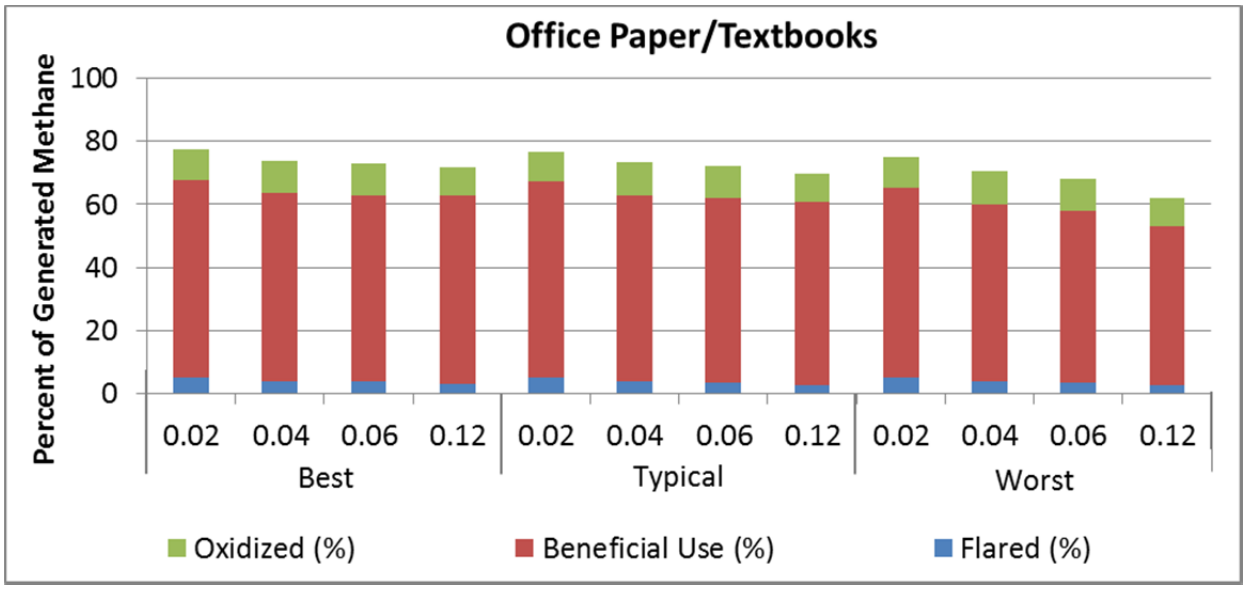

Figure 8. The percent methane flared and recovered for energy from office paper and textbooks for each gas collection scenario and decay rate.

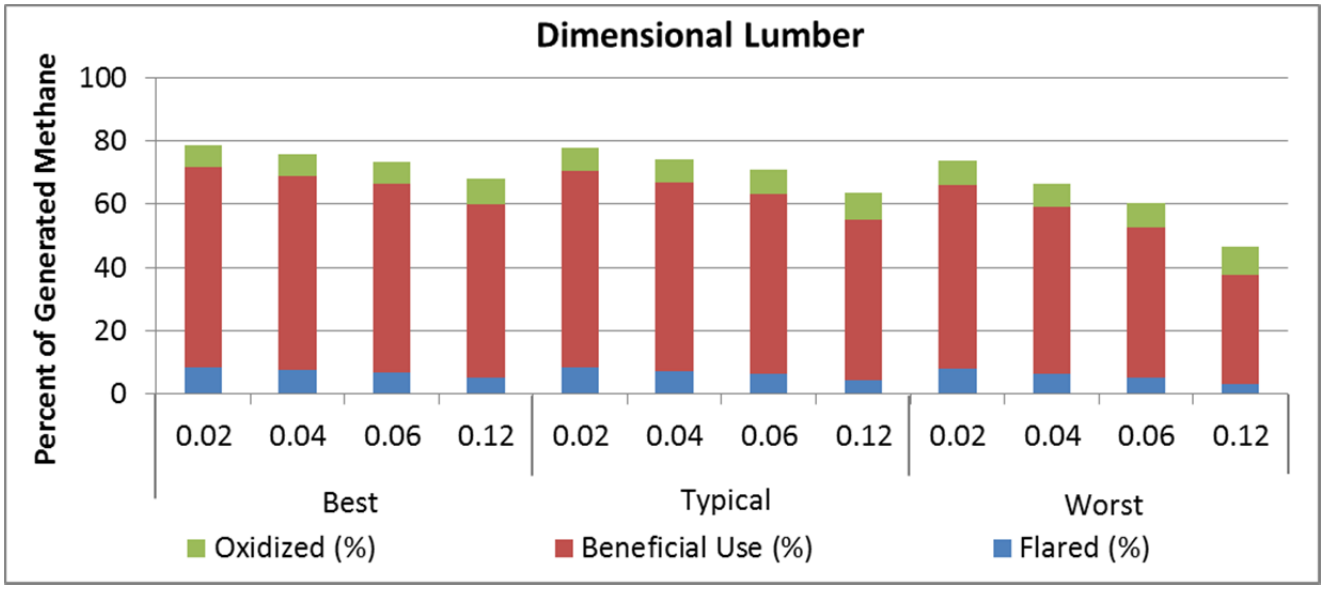

Figure 9. The percent methane flared and recovered for energy from dimensional lumber for each gas collection scenario and decay rate.

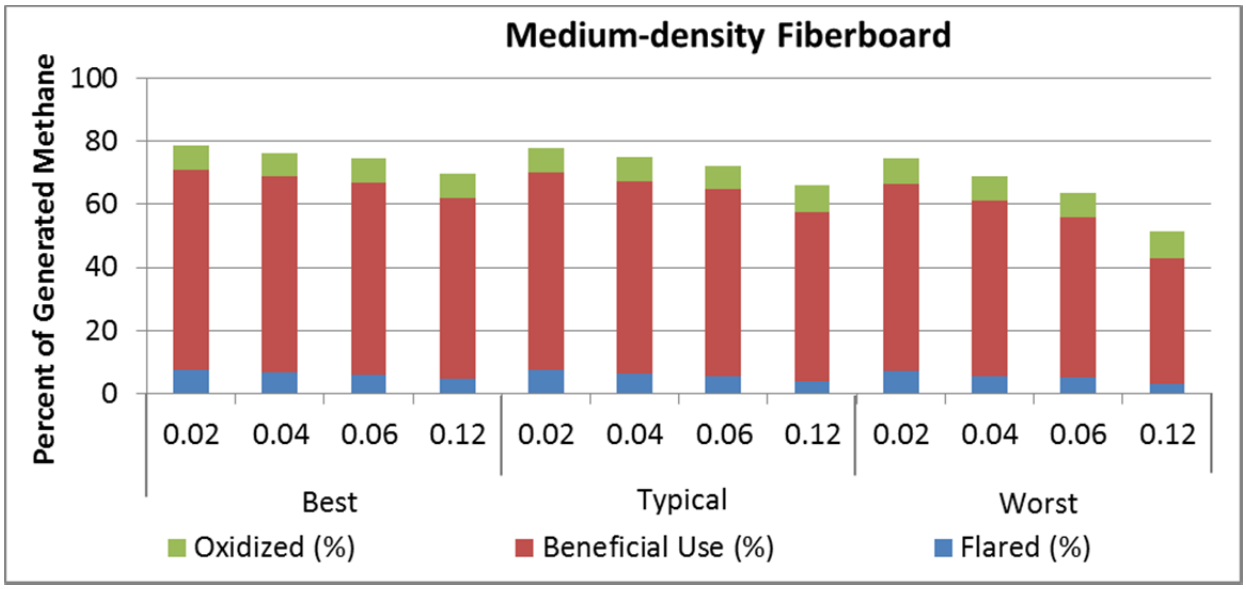

Figure 10. The percent methane flared and recovered for energy from medium-density fiberboard for each gas collection scenario and decay rate.

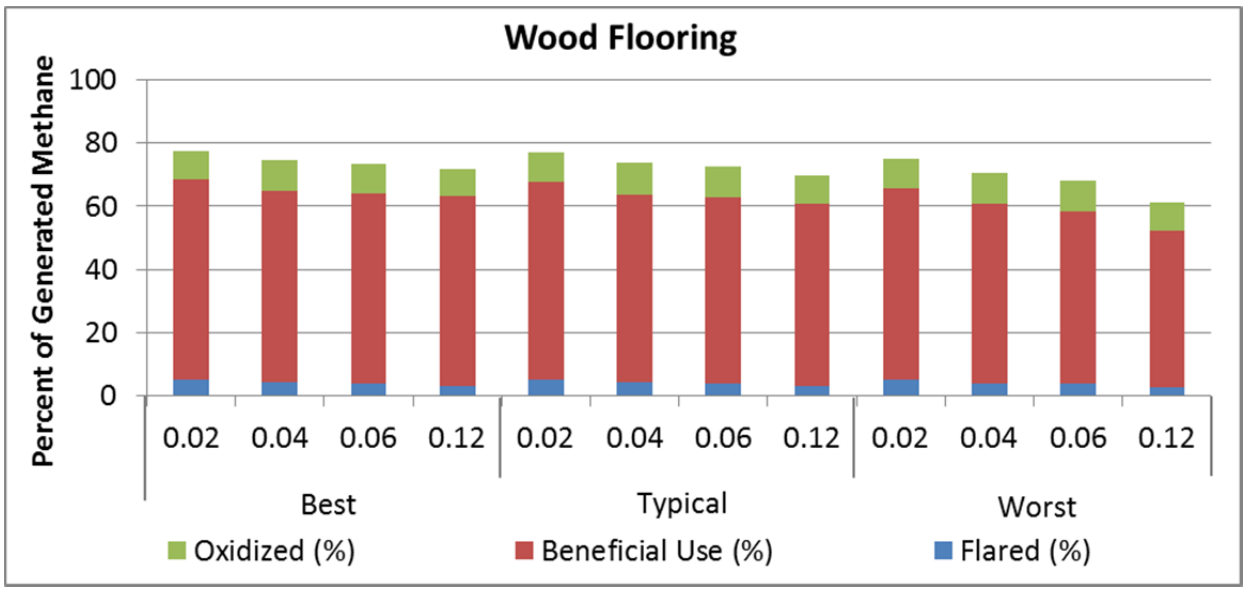

Figure 11. The percent methane flared and recovered for energy from wood flooring for each gas collection scenario and decay rate.

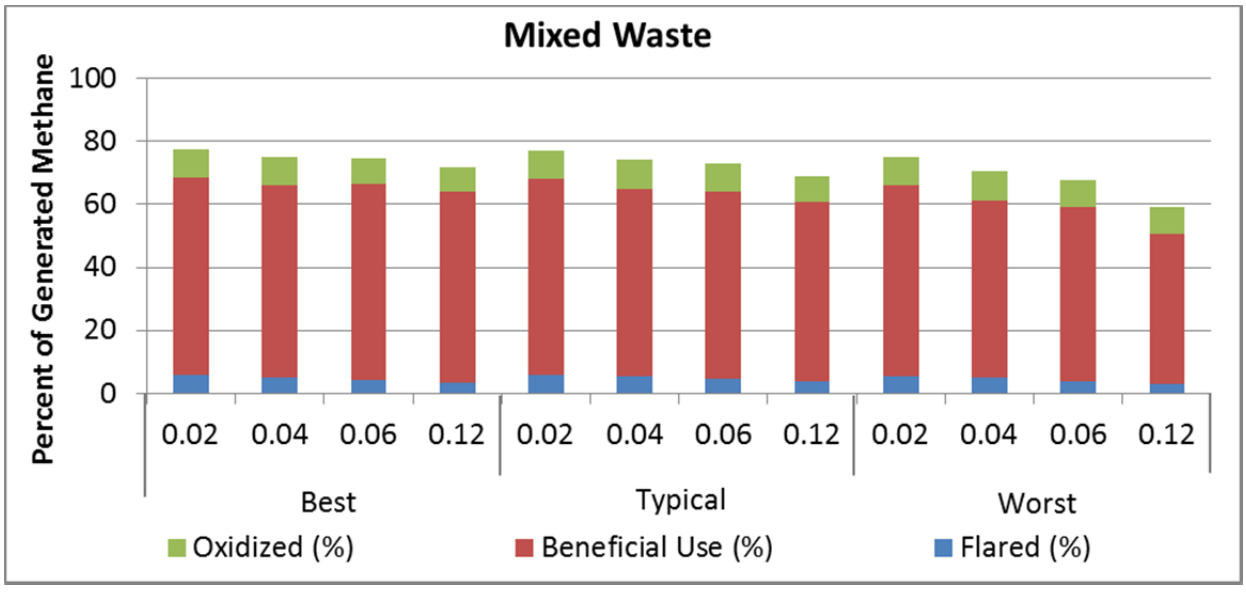

Figure 12. The percent methane flared and recovered for energy from mixed waste for each gas collection scenario and decay rate.

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

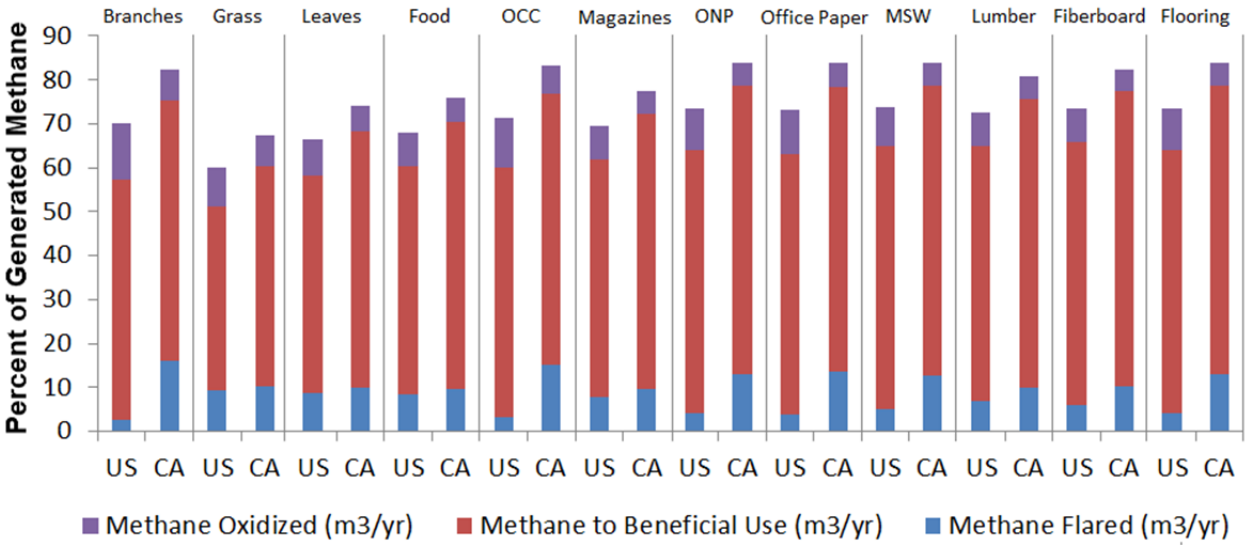

Figure 13. Comparison of current U.S. average methane treatment with potential treatment under a California regulatory scheme for landfills with energy recovery.

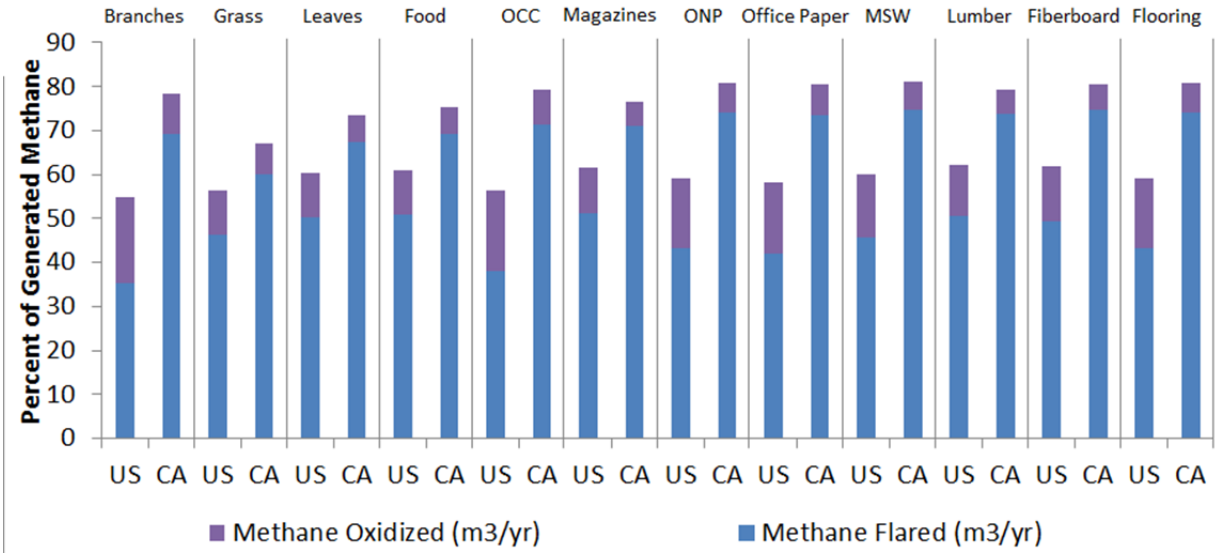

Figure 14. Comparison of current U.S. average methane treatment with potential treatment under a California regulatory scheme for landfills without energy recovery.

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Is Biodegradability a Desirable Attribute for Discarded Solid Waste? Perspectives from a National Landfill Greenhouse Gas Inventory Model

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Supporting Information

ABSTRACT: There is increasing interest in the use of biodegradable materials because they are believed to be "greener". In a landfill, these materials degrade anaerobically to form methane and carbon dioxide. The fraction of the methane that is collected can be utilized as an energy source and the fraction of the biogenic carbon that does not decompose is stored in the landfill. A landfill life-cycle model was developed to represent the behavior of MSW components and new materials disposed in a landfill representative of the U.S. average with respect to gas collection and utilization over a range of environmental conditions (i.e., arid, moderate wet, and bioreactor). The behavior of materials that biodegrade at relatively fast (food waste), medium (biodegradable polymer) and slow (newsprint and office paper) rates was studied. Poly(3-hydroxybutyrate-co-3-hydroxyoctanoate) (PHBO) was selected as illustrative for an emerging biodegradable polymer. Global warming potentials (GWP) of 26, 720, −1000, 990, and 1300 kg CO_2e wet Mg^{-1} were estimated for MSW, food waste, newsprint, office paper, and PHBO, respectively in a national average landfill. In a state-of-the-art landfill with gas collection and electricity generation, GWP's of −250, 330, −1400, −96, and −420 kg CO_2e wet Mg^{-1} were estimated for MSW, food waste, newsprint, office paper and PHBO, respectively. Additional simulations showed that for a hypothetical material, a slower biodegradation rate and a lower extent of biodegradation improve the environmental performance of a material in a landfill representative of national average conditions.

INTRODUCTION

The U.S. Environmental Protection Agency (EPA) estimates that 135 million metric tons (1 *t* = 1 Mg) of municipal solid waste (MSW) were discarded in U.S. landfills in 2008.[1] While efforts to reduce waste generation and to manage waste by recycling and composting will continue, landfills remain a significant component of waste management infrastructure. It is therefore important to understand the impacts of landfill disposal on a material's environmental performance. There are currently 503 landfills in the U.S. at which the gas is converted to energy[2] and an estimated additional 545 landfills at which energy recovery is viable.[3] Nonetheless, as a result of gas generated prior to installation of gas collection systems, and fugitive emissions, landfills are estimated to be the second largest source of anthropogenic methane emissions in the U.S.[4] Recently, efforts have been made to develop biodegradable materials because they are assumed to be "greener" alternatives. Poly(lactic) acid (PLA), which is manufactured from agricultural products as opposed to petroleum, is one such material that has found use in disposable cups, cutlery, and other food service applications.[5] While material biodegradability will reduce the volume occupied in a landfill, an evaluation of the environmental performance of a new material must include the production, use, and disposal phases of the product life-cycle. In recent work, the effect of the rate of methane generation from individual MSW components was combined with a hypothetical schedule for landfill gas collection to illustrate the importance of incorporating waste component-specific decay rates in analyses of the fraction of generated methane that is collected.[6]

To the extent that environmental performance at the end-of-life is a factor in the development and selection of materials to be used in various products, manufacturers must have an understanding of the national disposal infrastructure as opposed to performance in a specific landfill. The objective of this study was to develop and parametrize a landfill life-cycle model to represent national average conditions. The model was parametrized to represent landfills with and without gas collection, and landfills that flare or use the collected gas beneficially. Landfills operated under a range of environmental conditions (i.e., arid, moderate, wet, and bioreactor) were considered and the model was used to study the behavior of materials that biodegrade at relatively fast (food waste), medium (biodegradable polymer) and slow (newsprint and office paper) rates. The goal of this study is to provide guidance to manufacturers on environmental performance during landfill disposal that reflects U.S. landfill infrastructure.

MODELING APPROACH

A landfill life-cycle model was developed to estimate greenhouse gas (GHG) emissions attributable to the disposal of

Received: March 2, 2011
Accepted: May 13, 2011
Revised: May 10, 2011
Published: May 27, 2011

Table 1. Properties for Mix of U.S. Landfill Facilities

landfill type	annual precipitation (cm)[a]	decay rate (yr^{-1})	percent of waste received[b]	no. of years gas is collected for energy generation[c]	percent of gas generated in 100 years
arid	<51	0.02[a]	20.0	100	82
moderate	$51 < x < 102$	0.038[a]	28.9	76	94
wet	>102	0.057[a]	41.1	59	98
bioreactor	N/A	0.12[d]	10.0	39	99.9

[a] From U.S. EPA, 2010.[4] [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.[4] [c] Criteria to estimate this value are described in the text. [d] Judgment based on values reported in Barlaz et al., 2010[20] and Tolaymat et al., 2010.[21]

biodegradable materials in landfills. The model was used to analyze the behavior of MSW and a range of illustrative materials that exhibit varying biodegradation rates to study the effect of biodegradability on environmental performance. Both point estimates and Monte Carlo analyses were conducted. For MSW, the waste composition was based on U.S. EPA, 2009.[1]

Landfill Model. An estimate of the global warming potential (GWP) attributable to the disposal of materials in a landfill requires consideration of landfill construction, operations, final cover placement, gas and leachate management, and long-term maintenance and monitoring (eq 1).

$$\begin{aligned}\text{totalGWP} = {} & \text{construction}CO_2 + \text{operations}CO_2 + \text{finalcover } CO_2 \\ & + \text{leachatemgmt}CO_2 + \text{longtermmonitoring } CO_2 \\ & + 25\times\text{fugitivemethane} - \text{electricityoffsets} \\ & - \left(\frac{44}{12}\right)\text{Cstored} \end{aligned} \quad (1)$$

Each of the terms in eq 1 are in mass units (kg). GHG emissions associated with all aspects of the landfill except gas management and carbon storage have been shown to be small relative to these parameters. As such, emissions for landfill construction (1.4 kg CO_2e Mg^{-1}), operations (3.9 kg CO_2e Mg^{-1}), final cover placement (1.2 kg CO_2e Mg^{-1}), leachate management (0.31 kg CO_2e Mg^{-1}) and long-term maintenance (0.06 kg CO_2e Mg^{-1}) were adopted from Camobreco, 1999.[7] The GHG emissions and sinks associated with gas management and the storage of biogenic carbon were developed in this study with carbon storage factors adopted from Staley and Barlaz, 2009.[8] Landfill gas generation was modeled using a first order decay model as in the EPA's LandGEM model.[9] The decay rate (k) is dependent on climate and landfill operation strategy (traditional vs bioreactor). Thus, the fraction of waste disposed in U.S. landfills was divided into three climate categories for traditional landfills (arid, moderate, wet) to reflect differences in k associated with moisture. Bioreactor landfills, in which leachate and sometimes other liquids are recirculated to increase k, were considered as a fourth category. The mass of total waste disposed into each landfill category was adopted from U.S. EPA, 2010.[4] Table 1 presents the parameters associated with each landfill category. The mass of waste disposed in bioreactor landfills was assumed to be 10% of the mass disposed in U.S. landfills and this mass was subtracted from the mass disposed in moderate and wet landfills as described in Table 1. In each of the three traditional landfill categories, there are landfills that (1) do not collect gas, (2) flare the gas, and (3) use the gas for energy. The percentage of waste in landfills with gas collection and the percentage of these landfills with energy recovery were calculated using EPA estimates for methane generation (12.4 million Mg), flared (3.3 million Mg), and combusted for energy (3.3 million Mg).[4] Based on the assumption that landfills collect 75% of the generated gas, the EPA GHG Inventory[4] estimates that 69% of landfilled waste was disposed in landfills with gas collection (flared or converted to energy) and 50% of that waste was disposed in landfills with energy recovery. It was assumed that all bioreactor landfills were included in the 69% of landfills that collect gas, which results in an estimate that 66% of waste in traditional landfills is disposed in landfills with gas collection. It is recognized that there is uncertainty in these estimates and the sensitivity of these assumptions is explored with the results.

In contrast to LandGEM,[9] in which MSW is treated as one substrate, the k and methane yield (L_0) of each MSW component was modeled separately to study the influence of biodegradability on methane generation and subsequent collection and emissions. Component-specific decay rates were calculated as described in De la Cruz and Barlaz, 2010.[6] Calculation of component-specific decay rates requires specification of a bulk MSW decay rate as given in Table 1.

For waste in landfills that utilize the methane beneficially, it was necessary to estimate the period over which there was sufficient gas to operate energy recovery equipment. First, it was assumed that all recovered methane is converted to electrical energy although in practice some gas is used directly in industrial boilers along with other beneficial uses. Second, it was assumed that landfills could only generate electricity while the gas flow rate was above 0.236 m^3 s^{-1} (500 ft^3 min^{-1}) at 50% methane. For each landfill category, the length of time that the landfill gas flow was above this threshold was determined by modeling methane generation for a 2100 Mg day^{-1} landfill that accepted waste for 40 years at the decay rates given in Table 1. As the decay rate decreases, the length of time over which gas generation is above the 0.236 m^3 s^{-1} threshold increases and of course, this time would increase if the waste acceptance rate was higher. All calculations were based on a 100 year time horizon at which point a landfill would have produced most of its methane (Table 1). For landfills that utilize the gas for energy, the gas produced at a rate lower than the aforementioned threshold was assumed to be flared between the threshold year and year 100.

Landfill gas collection systems are installed in part based on the age of the landfill cell. 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.

Table 2. Material Properties for Food Waste, Newsprint, Office Paper, PHBO, and MSW

material	moisture content (%)	field decay rate (yr^{-1})[a]	methane yield (m^3 dry Mg^{-1})[b]	carbon storage factor (kg C dry Mg^{-1})[b]
food waste	70	0.144	300	80
newsprint	6	0.033	74.3	420
office paper	6	0.029	217	50
PHBO	0	0.072	341	356
MSW[c]	21	N/A[d]	67.2	125

[a] The field-scale decay rates for food waste, newsprint, and office paper were adopted from De la Cruz and Barlaz, 2010[6] and are based on a decay rate of 0.04 yr^{-1} for MSW. The decay rate for PHBO was estimated as described in the text, and also based on a decay rate of 0.04 yr^{-1} for MSW. [b] The methane yields and carbon storage factors for MSW, food waste, newsprint and office paper, were adopted from Staley and Barlaz, 2009.[8] The corresponding values for PHBO were estimated as described in the text. [c] Values were calculated as the weighted average of the component specific values for moisture content, methane yield and carbon storage factor. Component specific data and waste composition are given in SI Table S1. [d] A bulk MSW decay rate is not meaningful because methane generation curves for individual waste components were summed.

Gas collection schemes were based on the assumption that a typical cell life is 5 years and that no gas collection is in place for the first two years of cell operation (6 mo for bioreactors). Further, the collection efficiency prior to cell closure and intermediate cover installation is 50% (i.e., years 3−5, or 0.5−3 years for a bioreactor). After cell closure at the end of year 5, the collection efficiency is assumed to be 75%. It is further assumed that 10 years after final waste placement (i.e., 15 years after initial waste placement), a final cover is installed and the gas collection efficiency increases from 75% to 95%. This gas collection system installation schedule was used to calculate a temporally averaged gas collection efficiency which is the volume of gas collected divided by the volume of gas produced over 100 years as it applies to the 5 years of waste buried in a single landfill cell. All of the gas collection system default values can be varied in the model as described with the Results and Discussion.

Some fraction of the uncollected methane is oxidized to CO_2 as it passes through the landfill cover. Ten percent oxidation was assumed as recommended in the U.S. EPA's AP-42 database[10] and as used in the U.S. GHG inventory.[4] It is likely conservative as other studies estimate methane oxidation of 22−55%.[11] When electrical energy is recovered, it is assumed to offset coal and natural gas generation at 72.5% coal and 27.5% natural gas, which represents the adjusted proportion of each fuel on the national grid.[12] This leads to a CO_2 offset of 1.02 kg CO_2e kWh^{-1}. Methane was assumed to be converted to electricity using a heat rate of 11.6 MJ/kWh, which was developed from vendor literature. Finally, the mass of methane was multiplied by 25 to express as CO_2e using the 100 year warming potential.[13]

Modeling of Individual Waste Components. In addition to MSW, the analysis was conducted for four individual materials to illustrate the effects of decay rate and methane yield on GHG emissions from waste materials. The four materials were food waste, newsprint, office paper, and poly(3-hydroxybutyrate-co-3-hydroxyoctanoate) (PHBO) ($C_{13}H_{21}O_4$). The properties for each material are shown in Table 2. Several material properties for PHBO had to be developed including the methane yield, decay rate, and carbon storage factor (CSF). The theoretical methane yield for PHBO was calculated to be 755 mL g $PHBO^{-1}$ using the Buswell equation as cited in Parkin and Owen, 1986.[14] This value was adjusted using the average mineralization of 45.2% measured in a reactor study,[15] resulting in an effective ultimate yield of 341 mL g $PHBO^{-1}$. Equation 2 was used to estimate a decay rate for PHBO that is applicable at field-scale using laboratory-scale decay rates for MSW and PHBO.

Table 3. Decay Rate For MSW, PHBO, and the Ratio between them

	laboratory-scale MSW decay rate (yr^{-1})[b]	laboratory-scale PHBO decay rate (yr^{-1})[b]	k_{phbo}/k_{msw}
reactor 4[a]	10.9	20.9	1.92
reactor 5[a]	10.6	18.0	1.70
reactor 6[a]	10.1	18.6	1.85
average	10.5	19.2	1.83

[a] Reactor numbers as assigned in Federle et al., 2002.[15] [b] Calculated from data in Federle et al., 2002[15] as given in the SI (Figures S1−S8).

$$k_{f,\,phbo} = k_{f,\,MSW}\frac{k_{1,\,phbo}}{k_{1,\,MSW}} \quad (2)$$

where, $k_{f,phbo}$ is the field-scale decay rate of PHBO, $k_{f,MSW}$ is the field-scale decay rate of MSW, $k_{l,phbo}$ is the laboratory-scale decay rate of PHBO, and $k_{l,MSW}$ is the laboratory-scale decay rate of MSW. The laboratory-scale decay rates for PHBO and MSW were estimated by regression analysis of the data in Federle et al., 2002.[15] For MSW, the regression was performed on the log of the difference between total methane production and each generation value (Figures S1−S4 of the Supporting Information (SI)). The decay rate for PHBO was determined by analyzing the mineralization rate. Since PHBO mineralization stabilized much sooner than total CH_4, the regression was only performed on the data up to day 77.9 at which time decay had essentially ceased (SI Figures S5−S8). It should be noted that this is an upper estimate for the decay rate of PHBO, since the PHBO was ground before testing and the other materials were shredded to about 2 × 5 cm.

Table 3 shows the laboratory decay rates for MSW, PHBO and the ratio between them. The ratio was used to estimate the decay rate of PHBO in actual landfill environments for each landfill category (Table 2). A CSF for PHBO was determined using its carbon content (647 kg C Mg^{-1}) and reported mineralization (45.2%), resulting in an average CSF of 356 kg C Mg $PHBO^{-1}$ with a range of 307 to 381 based on the reactor data.[15]

Sensitivity Analysis. Many of the input values in this model are uncertain. For example, it is difficult to estimate the fraction of waste disposed in landfills with gas collection (point estimate 69%), as well as the fraction of this waste that is in landfills with energy recovery (point estimate 50%). In contrast to these point estimates, data voluntarily submitted to the Landfill Methane Outreach Program (LMOP) database[2] suggest that 84% of waste

is disposed in landfills with gas collection, and 66% of this waste is in landfills with energy recovery. These numbers are likely higher because the LMOP database consists of landfills that voluntarily submit information. Larger landfills and landfills that have state-of-the-art gas collection systems are most likely to submit data and thus be overrepresented.

A 10 000 iteration Monte Carlo analysis was performed on several model inputs. The inputs included in the analysis and the values used for their respective triangular distributions are given in the Results and Discussion section.

Table 4. Temporally Averaged Landfill Gas Collection Efficiencies.[a]

	collection efficiency (%)	
waste age (yr)	traditional landfill	bioreactor landfill
1	0	25
2	45	55
3	60	60
4	65	65
5	70	70
6	75	75
7	75	75
8	75	75
9	75	75
10	75	75
11	75	75
12	79	79
13	83	83
14	87	87
15	91	91
≥16	95	95

[a] Value represents the behavior of an average mass of MSW in a landfill with gas collection. The calculation procedure is described in the Modeling Approach section. These values are based on an assumed schedule for the installation of a gas collection system, a landfill cell life of 5 years and the installation of final cover 15 years after a cell opens as described in the text.

RESULTS AND DISCUSSION

The calculated temporally averaged landfill gas collection efficiencies for waste disposed in traditional and bioreactor landfills that collect gas are shown in Table 4. The results in Table 4 reflect an average Mg of waste as opposed to the first Mg buried. Thus, even though it was assumed that no gas collection is installed at a traditional landfill for two years, waste disposed in year two comes under some collection within a year of burial; hence the gas collection efficiency for waste buried in year two is nonzero.

The GHG emissions associated with food waste, newsprint, office paper, PHBO, and MSW are shown in Figure 1a by landfill subprocess. Temporally averaged collection efficiencies, defined as total methane collection/total methane production were 51, 41, 56, 57, and 49% for MSW, food waste, newsprint, office paper and PHBO, respectively. These values are relatively low due to the estimate that 31% of waste is buried in landfills that do not collect gas. The collection efficiency varies as a function of decay rate as materials with a higher decay rate will produce more gas prior to the installation of gas collection while waste that degrades more slowly will have greater collection efficiencies since more of the gas will be produced after collection systems are in place. Methane oxidation was assumed to reduce fugitive emissions by 10% in the base case. Biogenic carbon storage is also a significant component of the carbon footprint (Figure 1a) while the energy offsets reduce the GWP from the fugitive methane emissions by 6−11%.

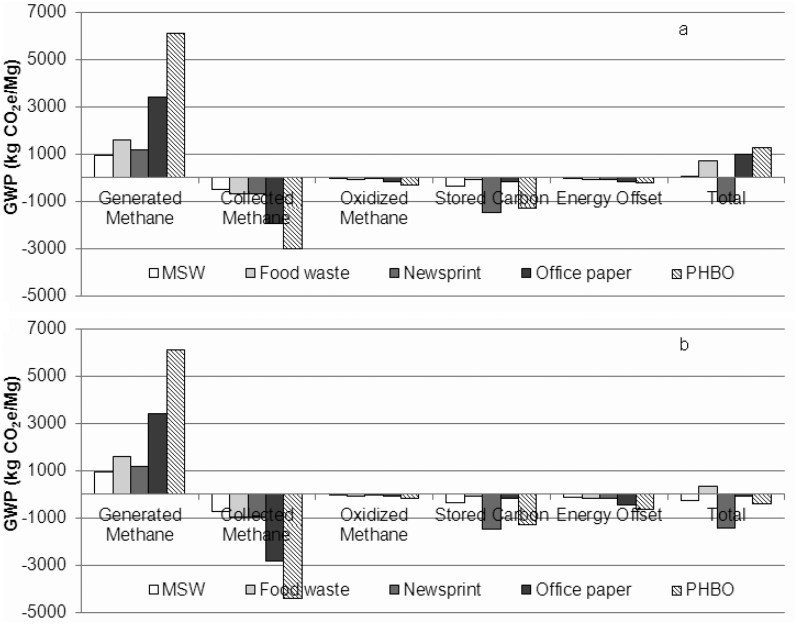

Figure 1. Greenhouse gas emissions for each waste component and average MSW by process and expressed per wet Mg. These data represent (a) a national average landfill and thus reflect landfills with and without gas collection and energy recovery and (b) a state-of-the-art landfill. Fossil CO_2e emissions from landfill construction, operations, closure, postclosure and leachate management lead to an additional 6.9 kg CO_2e Mg^{-1} that is included in the total for each of the waste streams.

Table 5. Inputs and Triangular Distribution Parameters Used in the Monte Carlo Analysis

input	current	minimum[a]	maximum[a]
waste discarded in landfills with gas collection (%)	69	60	84[b]
waste in landfills with gas collection that recover energy (%)	50	40	66[b]
time until final cover is in place after initial waste placement (yr)	15	12	20
gas collection efficiency under final cover (%)	95	85	98
oxidation rate (%)	10	10	40[c]
landfill decay rate (yr^{-1})			
arid	0.02	0.015[d]	0.025[d]
moderate	0.038	0.029[d]	0.048[d]
wet	0.057	0.043[d]	0.071[d]
bioreactor	0.12	0.09[d]	0.15[d]

[a] Values based on judgment unless otherwise stated. [b] Maximum value based on voluntary reports in LMOP database.[2] [c] A published review suggests a mean of 36% oxidation.[11] [d] The decay rates were varied by ±25%.

The results in Figure 1a contrast considerably with the results for a landfill that represents the state-of-the-art as opposed to a national average. Results for a scenario closer to a state-of-the-art landfill are presented in Figure 1b where it is assumed that all landfills have gas collection systems and convert the methane to electrical energy. The methane collection schedule, cell life and oxidation rates remain as for Figure 1a. As expected, collected methane and the energy offsets increase; with energy offsets reducing the CO_2e from the fugitive methane emissions by 25−78%.

The CO_2e signature of PHBO is inferior to that of other materials in national average landfills, but not in state-of-the-art landfills. This inferiority in the base case may be counterintuitive as the methane yields of food waste and PHBO are comparable on a dry basis, and the PHBO decay rate is lower than that of food waste (Table 2). However, the results (Figure 1) are expressed on a wet basis and the methane yields are 90, 70, 200, and 340 m^3 wet Mg^{-1} for food waste, newsprint, office paper and PHBO, respectively. Thus, the higher methane yield for PHBO on a wet basis increases CO_2e for a national average landfill. For a state-of-the-art landfill, the CO_2e signature for PHBO is second only to newsprint because its decay rate is about half that of food waste, so more of the gas generated from PHBO can be collected. It also has the second highest CSF of any material analyzed, which leads it to have net negative CO_2e.

Results are presented by landfill category (arid, moderate, wet, bioreactor) in SI Figures S9−S12. In general, the volume of collected methane increases as the decay rates decrease so the environmental performance of waste generated in arid regions, which was estimated as 20% of the national total, is highest. The GHG performance of bioreactor landfills is superior to that of moderate and wet landfills due to the assumption that all bioreactors collect gas. One limitation to the modeling approach is that a constant methane oxidation factor is assumed which suggests that the mass of oxidized methane increases as fugitive emissions increase. In reality, the fraction of the uncollected methane that is oxidized will decrease as fugitive emissions increase because oxygen availability is a limiting factor in methane oxidation and a lower methane flux translates to the potential to meet a higher fraction of the stoichiometric oxygen demand.[16]

A Monte Carlo analysis was performed by varying the parameters presented in Table 5. The cumulative distribution functions (CDFs) for the GHG emissions associated with each waste component and MSW developed from the Monte Carlo analysis

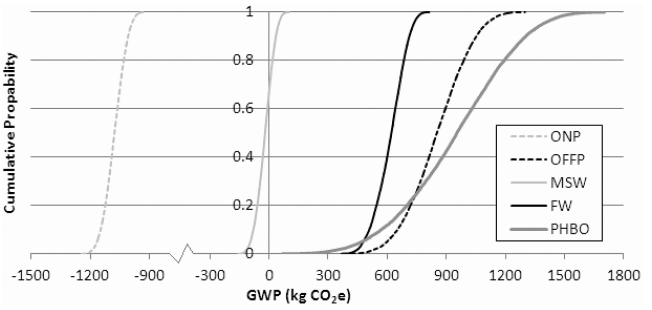

Figure 2. Cumulative distribution functions for each material. Ranges used for each uncertain input are given in Table 5. ONP = old newsprint, MSW = municipal solid waste, FW = food waste, OFFP = office paper.

are presented in Figure 2. Summary statistics for each CDF are shown in Table S2. PHBO has the greatest range among the waste streams (1600 kg CO_2e) because it has the highest methane yield which translates to more opportunity for changes in collection, beneficial use, and oxidation to affect the final results. Similarly, office paper has the second highest methane yield and the second greatest range (930 kg CO_2e). Spearman rank correlations were determined between major inputs and the net CO_2e associated with MSW disposal (Table 6). The oxidation rate shows the greatest correlation, which is partially due to its large range. Further research into the bounds of this range, and a modeling approach that incorporates changes in methane oxidation as a function of the controlling variables (soil moisture content, temperature, porosity and methane flux) could reduce the uncertainty. While work on these issues is ongoing, it appears premature to incorporate in this snapshot of the U.S. landfill infrastructure. The fraction of waste disposed in landfills that collect gas is the second most sensitive variable while the sensitivity of landfill decay rates varies based on the amount of waste in each landfill category. Here too, uncertainty exists and when the decay rates were varied by ±50%, as opposed to ±25%, the Spearman rank correlation coefficients increase from 0.066 to 0.078, 0.075 to 0.14, 0.081 to 0.18 and 0.041 to 0.066 for arid, moderate, wet, and bioreactor decay rates, respectively.

Decay Rate Analysis. The significance of the decay rate and methane yield is further illustrated by a parametric analysis. A hypothetical biogenic polymer consisting of 50% carbon in an oxidation state of a carbohydrate was analyzed at four degrees of mineralization, with decay rates varying from 0.001 to 1.0 yr^{-1}.

Table 6. Spearman Rank Correlation Coefficients between Uncertain Inputs and the Net CO_2e Associated With MSW Disposal

input	Spearman Correlation
oxidation rate	−0.749
percentage of waste discarded in landfills that collect gas	−0.577
gas collection efficiency under final cover	−0.166
time until final cover is in place after final waste placement	0.117
wet landfill decay rate	0.081
moderate landfill decay rate	0.075
percentage of waste discarded in landfills with collection that recover energy	−0.066
arid landfill decay rate	0.066
bioreactor decay rate	0.041

Table 7. Material Properties for Hypothetical Biogenic Polymer

percent mineralization	L_0 (m^3 CH_4 Mg^{-1})[a]	CSF (kg C Mg^{-1})[a]
100	465	0
66	307	170
33	153	335
0	0	500

[a] Values were calculated for a hypothetical polymer that contains 50% organic carbon and is in the oxidation state of a carbohydrate, meaning that 50% of the reactive carbon will be converted to methane and 50% to carbon dioxide.

The 0% mineralization case simulates a recalcitrant biogenic material. The methane yields and CSFs for this hypothetical polymer are given in Table 7. The results indicate that decreased material decay rates and decreased mineralization lead to decreased CO_2e (Figure 3). These results suggest that for a national average landfill, in which not all gas is collected and converted to energy, optimal performance would be achieved for biogenic materials that are recalcitrant under anaerobic conditions.

Environmental Implications. The described approach provides a framework for a producer to consider the GHG performance of a material during the disposal phase. The input parameters could be adjusted to reflect regions or countries with alternate practices on landfill gas. In addition, the analysis could be extended to reflect for example, that an estimated 18.9% of U.S. nonrecovered MSW is disposed by waste-to-energy (WTE) combustion.[1] Analyses of WTE have been presented previously.[17−19] Similarly, for a product such as a biodegradable bag that is used strictly for yard waste, a scenario in which a significant percentage of the product is managed by composting or anaerobic digestion could be developed. So too, the behavior of a material where some fraction is discarded as litter could be considered. The scenario presented here is applicable to a biodegradable material that is managed with MSW, the majority of which is disposed in landfills in the U.S. The results show that a rapidly degradable material increases CO_2e relative to a more slowly degradable or recalcitrant material.

Ultimately, material development and selection should consider emissions associated with material production, potential differences in the use phase that could be attributed to the material, and end-of-life management. If emissions for the production of a biodegradable material are comparable or higher than emissions associated with manufacturing a material from petroleum-based feedstocks, and disposal emissions are higher for the biodegradable material as illustrated here, then it is hard to rationalize a suggestion that the biodegradable material is the preferable alternative, assuming of course, the availability of petroleum-based feedstocks.

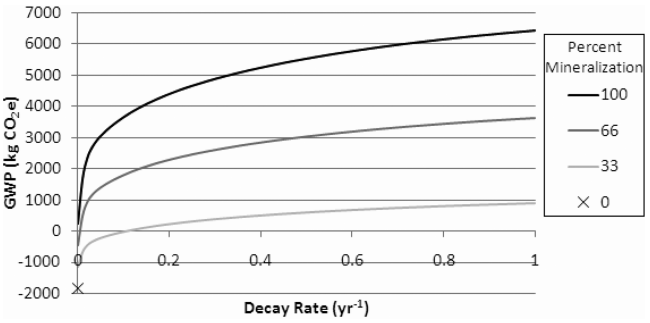

Figure 3. The effect of decay rate on the GWP associated with a hypothetical carbohydrate-based biogenic polymer with varying levels of mineralization.

■ ASSOCIATED CONTENT

Supporting Information. Waste composition, summary statistics for Monte Carlo analysis, methane production data from PHBO biodegradation study, derivation of mineralization factor (PHBO) and decay rates (MSW and PHBO) based on reactor data, and CO_2e for landfills in each category (arid, moderate, wet, bioreactor). This material is available free of charge via the Internet at http://pubs.acs.org.

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■ ACKNOWLEDGMENT

This research was supported by Procter & Gamble. J.W.L. was supported in part by a Fiessinger Fellowship from the Environmental Research and Education Foundation.

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Accepted for publication, Environmental Science and Technology, May 13, 2011

Is biodegradability a desirable attribute for discarded solid waste?

Supporting Information

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Table S1. MSW composition and material properties.

Material	Composition (wet weight %)	Moisture Content (wet basis %)	Field Decay Rate (yr^{-1})[a]	Methane Yield (m^3 dry Mg^{-1})[b]	Carbon Storage Factor (kg dry Mg^{-1})[b]
Textiles	6.3	10	0.029	51.5	10
Wood (non-C&D)	8.9	20	0.015	62.6	380
Food waste	18.6	70	0.144	300	80
Leaves	2.8	30	0.171	30.6	470
Grass	2.1	60	0.298	144	240
Branches	2.1	30	0.015	62.6	380
Misc. organics	2.3	50	0.131	145	270
Newspaper	0.6	6	0.033	74.3	420
Office paper	1.1	6	0.029	217	50
Glossy paper	0.7	6	0.122	84.4	270
OCC/Kraft bags	4.6	5	0.02	152	260
Mixed Paper	13.6	6	0.031	146	240
Inorganics	36.2	0	N/A	N/A	N/A

[a] Calculated for an MSW decay rate of 0.04 yr^{-1} and adopted from De la Cruz and Barlaz, 2010.[1]

[b] Adopted from Staley and Barlaz, 2010.[2]

Table S2. Summary statistics from Monte Carlo analysis.

	Food waste (kg CO_2e)	Newsprint (kg CO_2e)	Office paper (kg CO_2e)	PHBO (kg CO_2e)	MSW (kg CO_2e)
Mean	615	-1078	852	945	-21
Std Dev	77	53	153	278	44
2.5th Percentile	458	-1181	556	392	-107
25th Percentile	561	-1115	746	751	-52
Median	621	-1077	852	954	-20
75th Percentile	673	-1040	961	1147	10
97.5th Percentile	750	-977	1143	1455	59

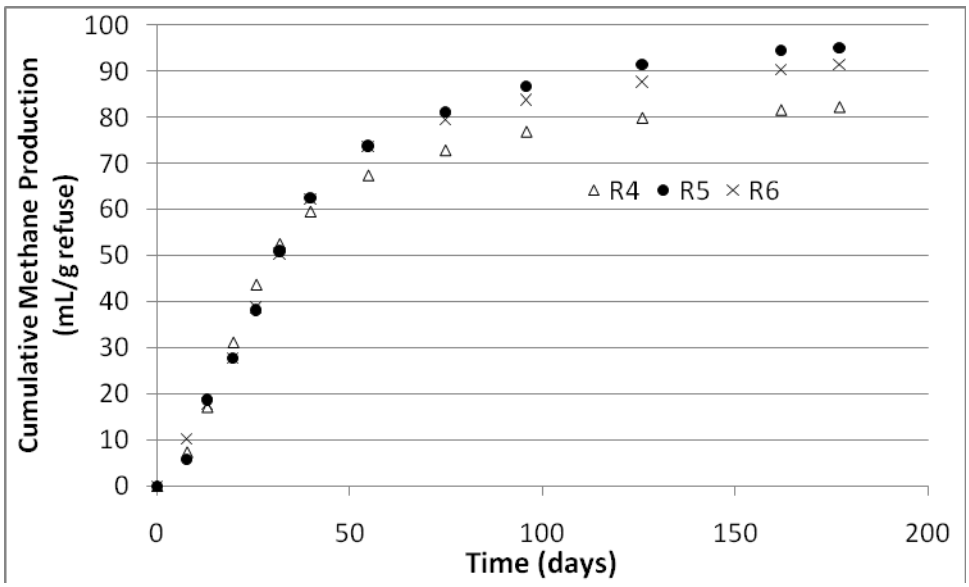

Figure S1. Cumulative methane production in each PHBO reactor.

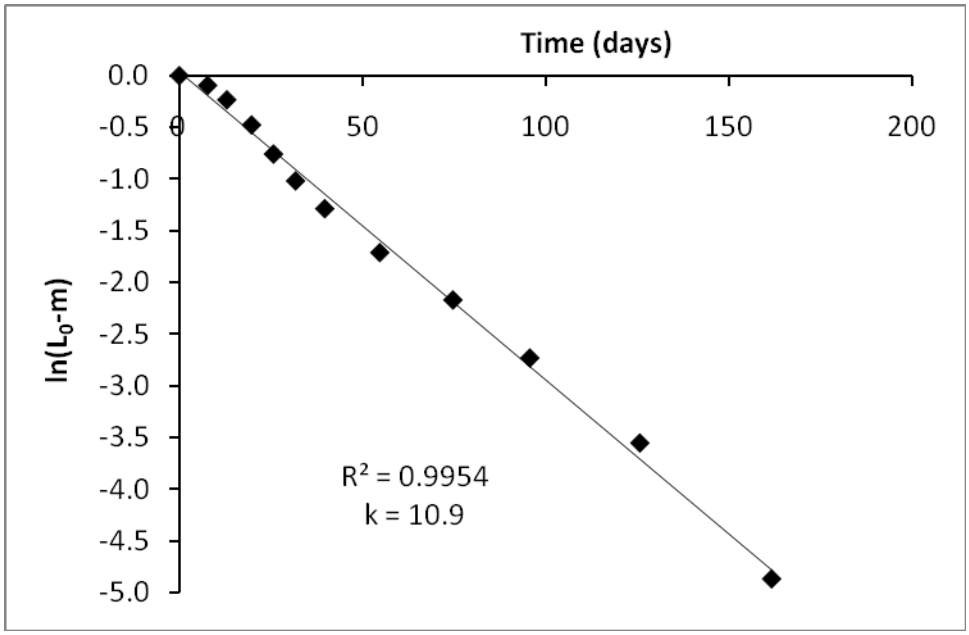

Figure S2. Log of the difference between total methane production and current production for reactor 4.

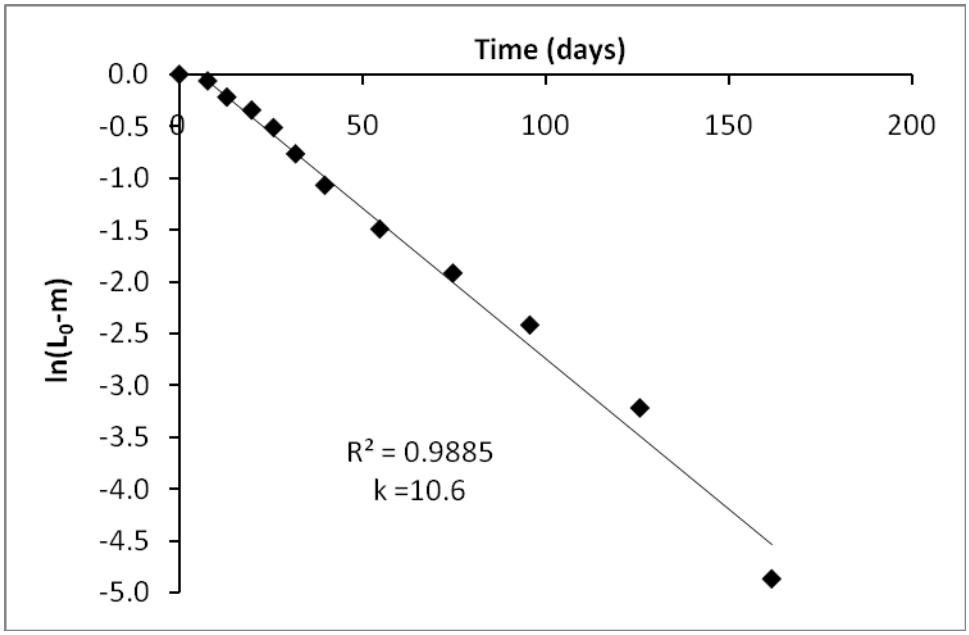

Figure S3. Log of the difference between total methane production and current production for reactor 5.

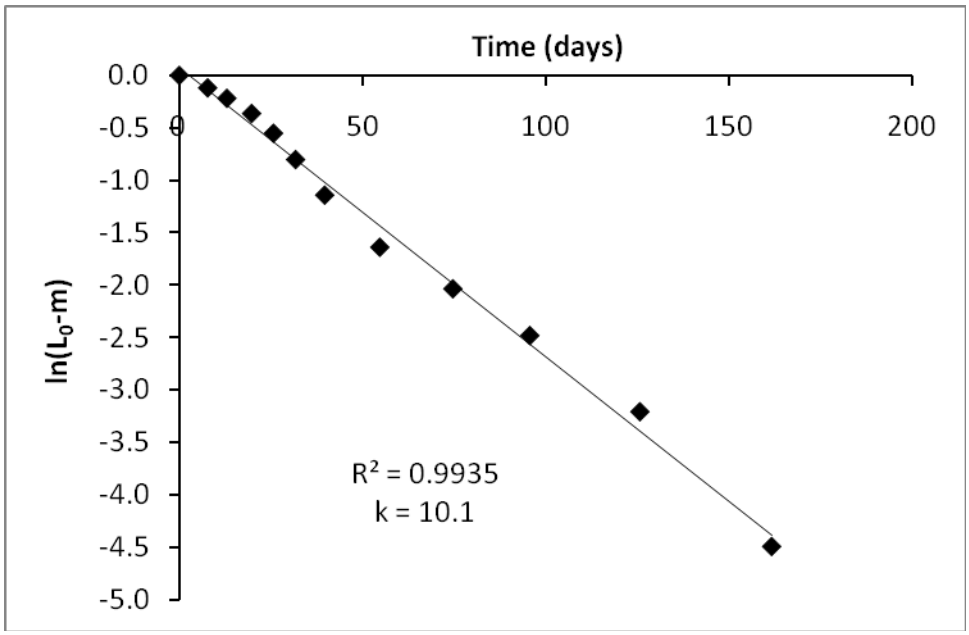

Figure S4. Log of the difference between total methane production and current production for reactor 6.

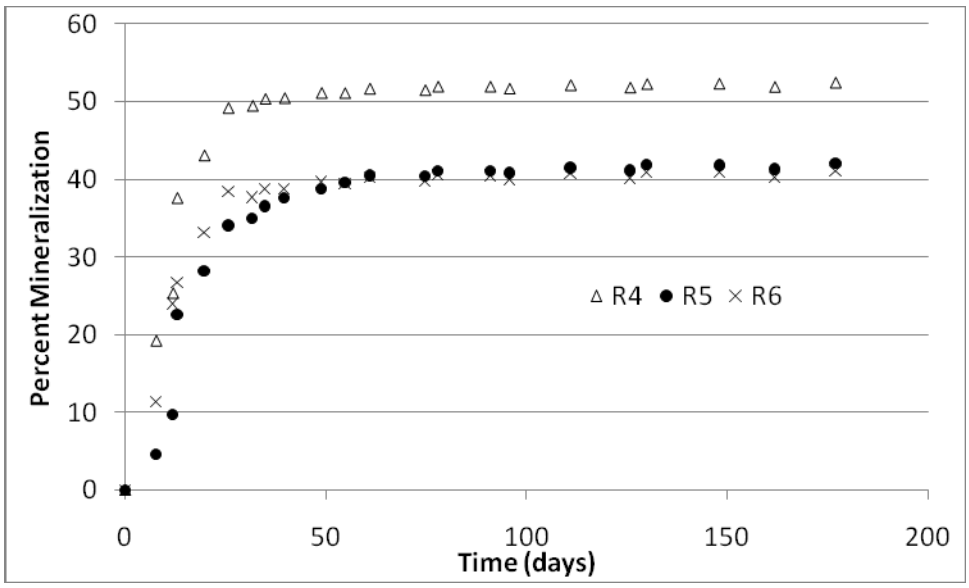

Figure S5. Percent PHBO mineralization in each reactor.

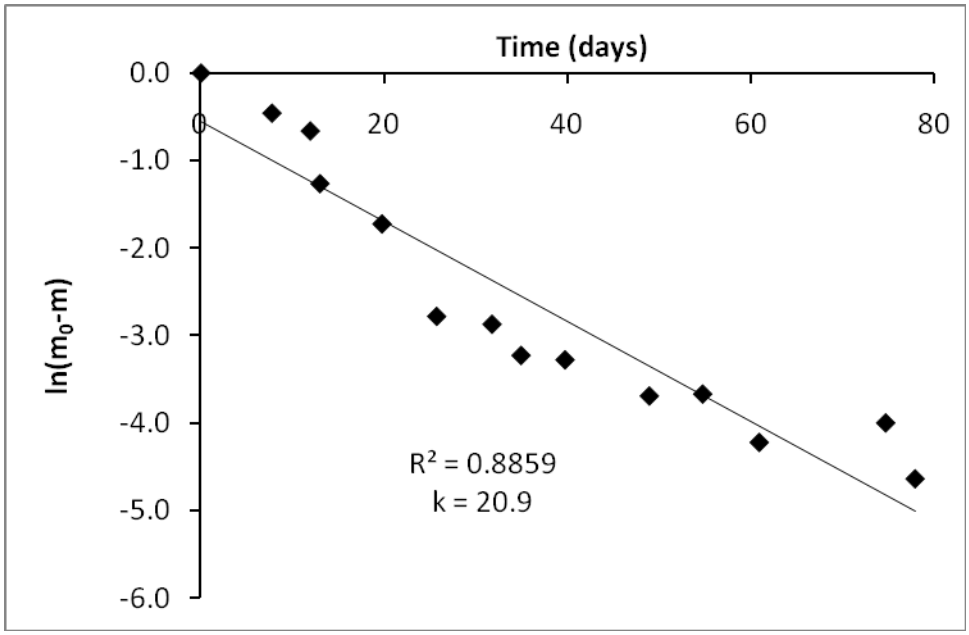

Figure S6. Log of the difference between final mineralization and current mineralization for reactor 4.

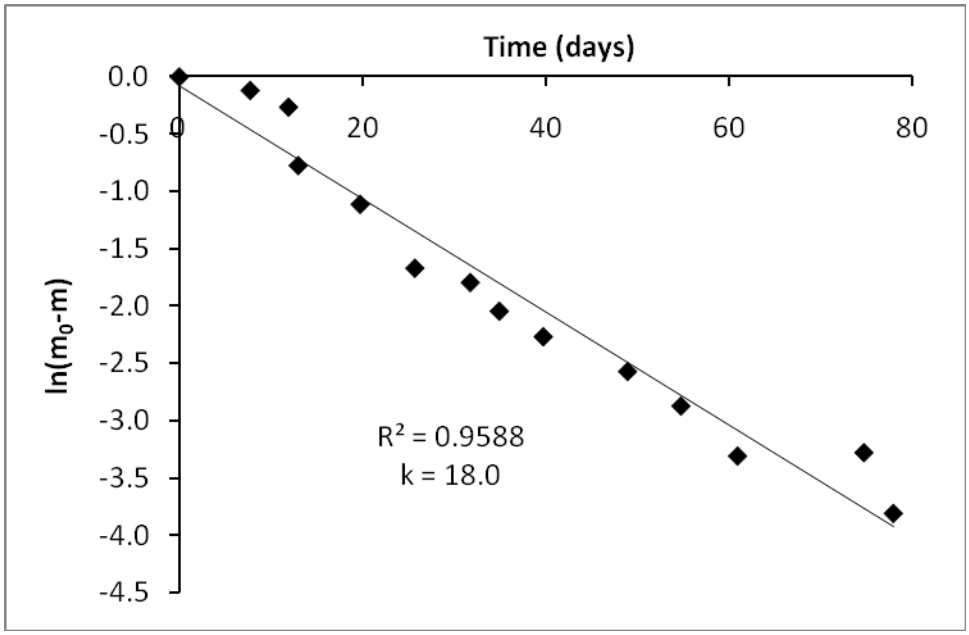

Figure S7. Log of the difference between final mineralization and current mineralization for reactor 5.

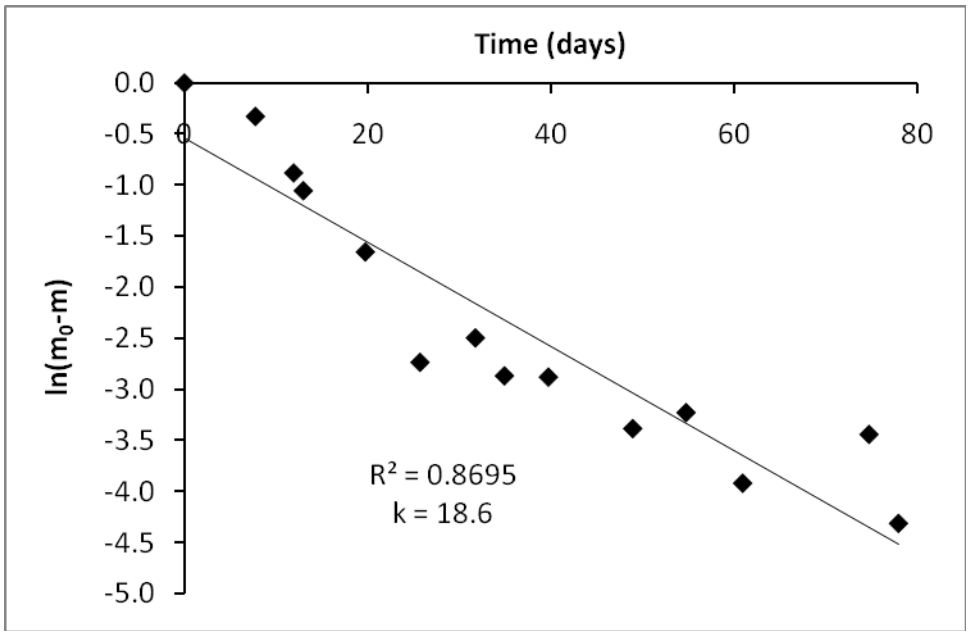

Figure S8. Log of the difference between final mineralization and current mineralization for reactor 6.

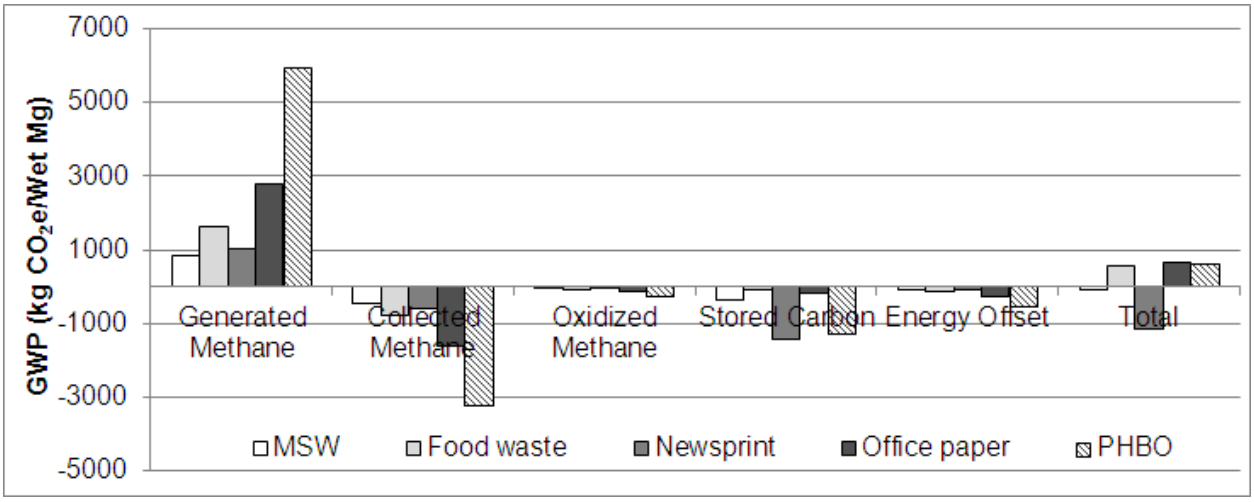

Figure S9. Greenhouse gas emissions for each waste component and average MSW by process from an arid landfill. These data represent the national average arid landfill and thus reflect landfills with and without gas collection and energy recovery. Fossil CO_2e emissions from landfill construction, operations, closure, post-closure and leachate management lead to an additional 6.9 kg CO_2e Mg^{-1} that is included in the total for each of the waste streams.

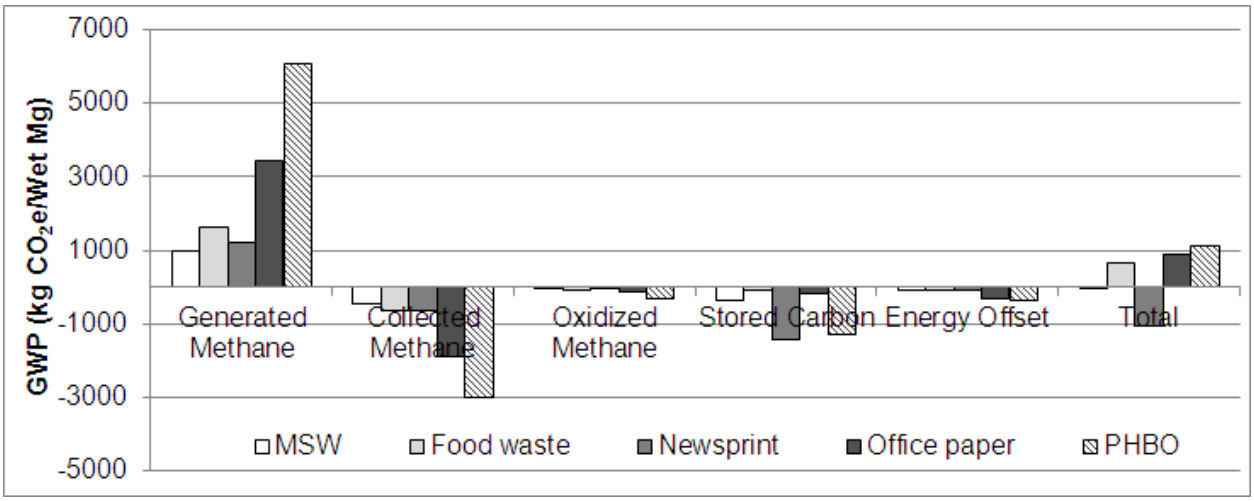

Figure S10. Greenhouse gas emissions for each waste component and average MSW by process from a landfill receiving moderate precipitation. These data represent the national average moderate landfill and thus reflect landfills with and without gas collection and energy recovery. Fossil CO_2e emissions from landfill construction, operations, closure, post-closure and leachate management lead to an additional 6.9 kg CO_2e Mg^{-1} that is included in the total for each of the waste streams.

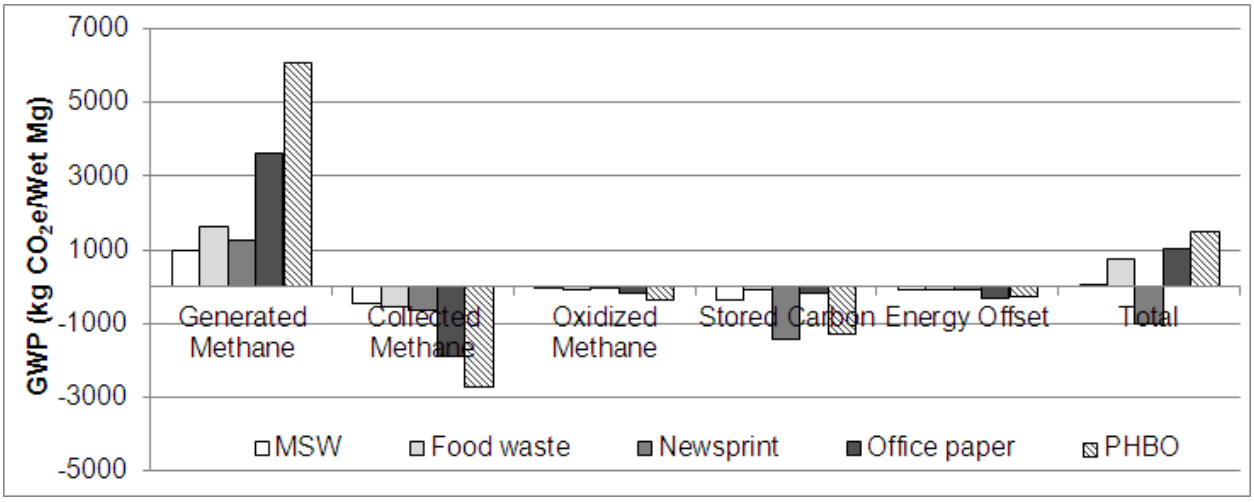

Figure S11. Greenhouse gas emissions for each waste component and average MSW by process from a landfill receiving high levels of precipitation. These data represent the national average wet landfill and thus reflect landfills with and without gas collection and energy recovery. Fossil CO_2e emissions from landfill construction, operations, closure, post-closure and leachate management lead to an additional 6.9 kg CO_2e Mg^{-1} that is included in the total for each of the waste streams.

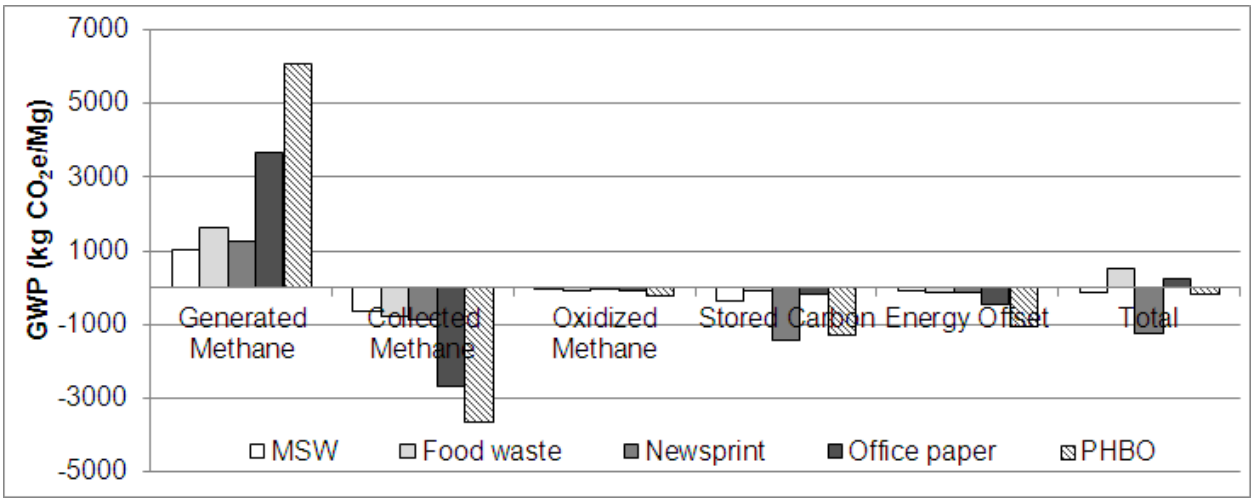

Figure S12. Greenhouse gas emissions for each waste component and average MSW by process from a bioreactor landfill. These data represent the national average bioreactor landfill and thus all of the landfills collect gas and 50% produce electricity. Fossil CO_2e emissions from landfill construction, operations, closure, post-closure and leachate management lead to an additional 6.9 kg CO_2e Mg^{-1} that is included in the total for each of the waste streams.

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Environ. Sci. Technol. **2010,** *44,* 4722–4728

Estimation of Waste Component-Specific Landfill Decay Rates Using Laboratory-Scale Decomposition Data

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Received January 22, 2010. Revised manuscript received April 21, 2010. Accepted April 22, 2010.

The current methane generation model used by the U.S. EPA (Landfill Gas Emissions Model) treats municipal solid waste (MSW) as a homogeneous waste with one decay rate. However, component-specific decay rates are required to evaluate the effects of changes in waste composition on methane generation. Laboratory-scale rate constants, k_{lab}, for the major biodegradable MSW components were used to derive field-scale decay rates (k_{field}) for each waste component using the assumption that the average of the field-scale decay rates for each waste component, weighted by its composition, is equal to the bulk MSW decay rate. For an assumed bulk MSW decay rate of 0.04 yr^{-1}, k_{field} was estimated to be 0.298, 0.171, 0.015, 0.144, 0.033, 0.02, 0.122, and 0.029 yr^{-1}, for grass, leaves, branches, food waste, newsprint, corrugated containers, coated paper, and office paper, respectively. The effect of landfill waste diversion programs on methane production was explored to illustrate the use of component-specific decay rates. One hundred percent diversion of yard waste and food waste reduced the year 20 methane production rate by 45%. When a landfill gas collection schedule was introduced, collectable methane was most influenced by food waste diversion at years 10 and 20 and paper diversion at year 40.

Introduction

Landfills represent the dominant disposal practice for municipal solid waste (MSW) in the United States as well as in many other countries. For example, in the United States, it is estimated that 54% of MSW is buried in landfills (*1*) and the corresponding values for Canada (*2*), Australia and the European Union (*3*) are 77, 54, and 45%, respectively. The anaerobic decomposition of waste in landfills results in methane generation and landfills are estimated to be the second largest source of anthropogenic methane emissions in the United States and on a global level (*4, 5*).

In commonly used predictive models, the quantity of methane produced and its rate of production are governed by two factors, the ultimate methane yield (L_0) and a decay rate (k). These factors appear in different forms in different models. The most common landfill gas model in the United States is the U.S. EPA's Landfill Gas Emissions Model (LandGEM) as given in eq 1 (*6*):

$$Q_n = k \cdot L_0 \cdot \sum_{i=0}^{n} \sum_{j=0}^{0.9} \frac{M_i}{10} \cdot e^{-k \cdot t_{i,j}} \quad (1)$$

where Q_n is the CH_4 generation rate ($m^3\ yr^{-1}$) in year n, k is the waste decay rate (yr^{-1}), L_0 is the CH_4 generation potential (m^3 of CH_4 Mg^{-1} wet waste) (Mg = metric ton), M_i is waste mass placement in year i (Mg), j is the deciyear time increment, and t is time (yr). The form of the model that is used in other countries such as The Netherlands and the United Kingdom is similar (*7, 8*). However, in these countries, the model is referred to as a multiphase model in which total methane production is calculated as the sum of individual implementations of eq 1 for waste components that are classified as slowly, moderately, and rapidly degradable. This contrasts with the approach used in LandGEM where MSW is treated as a single substrate.

The rate at which methane production occurs, which is governed by k, has implications for the fraction of the generated methane that is captured. This is because the fraction captured increases with time after burial as a landfill's gas collection system is installed and then expanded. Estimates of the temporally weighted landfill methane collection efficiency for multiple gas collection scenarios and decay rates have been described (*9*). In general, the fraction of gas that is collected decreases as the decay rate increases.

Over the past several years, there has been increasing interest in the diversion of biodegradable waste from landfills. Diversion programs are most prominent in Europe where the European landfill directive prohibits the landfill disposal of biodegradable waste. Programs to divert food and yard waste, primarily to aerobic composting, are increasing in the United States. The implementation of diversion programs has implications for both the rate and quantity of methane produced from landfills and requires information on both L_0 and k for individual waste components. Data on L_0 for individual waste components have been published but data on k are lacking (*10*).

The objective of this paper is to present a method to estimate a field-scale decay constant for each of the major biodegradable components of MSW using laboratory-scale methane generation data. These decay rates are then used to explore the effect of waste diversion programs and their resulting changes in the mass and composition of landfilled MSW, on methane generation and collection using the LandGEM formulation applied to waste components individually.

Gas Production Modeling and Data Analysis

This study emphasizes the LandGEM formulation because of its pervasive use in both engineering and regulatory practice. The derivation of LandGEM and its relationship to MSW biodegradation is given in the Supporting Information. Critical aspects of eq 1 as used for this study are that it assumes no lag time and its derivation is based on the reactive mass of carbon as opposed to the total mass. As illustrated by eq 1, k is the only parameter that can be adjusted to consider factors such as pH, moisture content, and temperature, all of which will influence the methane production rate.

Previously published methane production data for newsprint (ONP), office paper (OFF), old corrugated containers (OCC), old magazines (OMG), food waste (FW), grass (G), leaves (L), and branches (B) were used to calculate laboratory-scale decay rates ($k_{lab,i}$) as described here (*10*). Waste decomposition can be described by the first-order decay rate in eq 2 in terms of the reactive mass of carbon.

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10.1021/es100240r
Published on Web 05/24/2010

$$\frac{dm}{dt} = -km \quad (2)$$

where m is the reactive mass of C in the refuse present at time t (kg), k is the first-order decay rate (yr^{-1}), and t is time (yr). Integration of eq 2 yields an expression for the amount of refuse remaining in a reactor at time t during decomposition.

$$\ln\left(\frac{m}{m_0}\right) = -kt \quad (3)$$

where m_0 is the initial reactive mass of C in the refuse. Given that the dominant mass loss process is anaerobic decomposition, the mass loss of reactive C at any time can be calculated from the methane yield at that time (m_{CH_4}). The initial reactive mass of carbon, m_0, was calculated from the measured cumulative methane yield. The mass of reactive C remaining at any time is given by eq 4:

$$m = m_0 - (m_{CH_4} + m_{CO_2}) \quad (4)$$

Substituting eq 4 into eq 3 and rearranging results in a linear form of the first-order decay equation:

$$\ln(m_0 - (m_{CH_4} + m_{CO_2})) = -kt + \ln(m_0) \quad (5)$$

Methane production data from 2-L reactors filled with the aforementioned waste components were fit to eq 5 to estimate a first-order decay constant, $k_{lab,i}$, by linear regression. In each case, the decay rate was estimated using the linear part of the curve and lag times were not considered as LandGEM does not consider lag times.

To relate $k_{lab,i}$ to a decay rate that is applicable at field scale, $k_{field,i}$, it was assumed that the weighted average decay rate for a waste mixture is equal to the bulk MSW decay rate ($k_{field,MSW}$). This is illustrated by eq 6. To force the left side of eq 6 to be equal to a constant, a correction factor, f, was introduced. Once f is determined, the field-relevant decay rate for each waste component (i), $k_{field,i}$, can be calculated from eq 7.

$$f \times \sum_{i=1}^{n} k_{lab,i} \times (\text{wt.fraction})_i = k_{field,MSW} \quad (6)$$

$$k_{field,i} = f \times k_{lab,i} \quad (7)$$

where i is the ith waste component.

Initially, eqs 6 and 7 were used with a decay rate of 0.04 and the composition of waste as discarded in 1990 (*11*). This decay rate is the default value given in the U.S. EPA's database (AP-42) for regions that receive greater than 63 cm of precipitation annually (*12*). The 1990 waste composition was selected because it corresponds approximately to the time when the landfill gas data used to develop the AP-42 default values were collected. In the Results and Discussion section, eqs 6 and 7 are applied to a number of alternate waste compositions to develop an estimate of the range of appropriate values for $k_{field,i}$ for an assumed $k_{field,\ MSW}$. In addition, this method was used at bulk MSW decay rates of 0.02 and 0.12 yr^{-1}. The lower value represents landfills in arid regions (<63 cm precipitation per year as defined in AP-42), whereas the higher value is representative of recent estimates for bioreactor landfills (*13*–*15*). For any set of assumptions for waste composition and $k_{field,MSW}$, f, and then $k_{field,i}$ can be calculated.

Results and Discussion

The linearized methane production data for office paper are presented in Figure 1 and the data for other components are presented in Figures S1–S7 in the Supporting Information. The computed decay rates ($k_{lab,i}$) for individual waste components based on laboratory data are presented in Table 1. As expected, food waste and grass have the highest decay rates. The relatively high decay rate for leaves is less intuitive and is a function of the relatively short duration of methane production (Figure S6). Field values estimated using eqs 6 and 7 and 1990 waste composition are presented in Table 2 for assumed overall decay rates of 0.04 and 0.12 yr^{-1}.

To evaluate one source of variability in $k_{field,i}$, it was calculated for a range of waste composition data including both the national average composition of waste at different times and statewide waste composition data that were

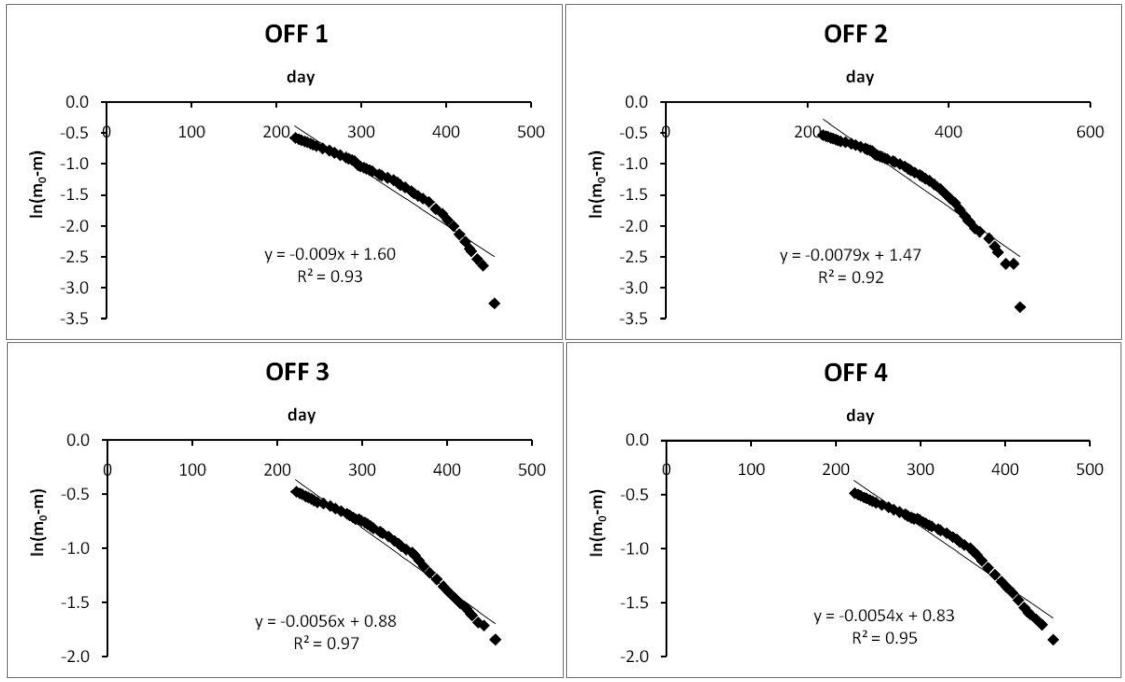

FIGURE 1. Linearized first-order decomposition of office paper (OFF).

TABLE 1. Laboratory-Scale Decay Rates, Methane Yields, and Moisture Contents for MSW Constituents

component	average (yr^{-1})[a]	L_0 (m^3/dry Mg)[b]	moisture (wet wt %)[c]
office paper	3.08(1.03)	217.3	6
grass	31.13(9.32)	144.4	60
branches	1.56(0.30)	62.6	30
newspaper	3.45(0.47)	74.3	6
corrugated containers	2.05(0.07)	152.3	5
food	15.02(0.30)	300.7	70
leaves	17.82(4.28)	30.6	30
coated paper	12.68(4.13)	84.4	6

[a] Data are the average of four replicates except in the cases of leaves and branches where one reactor leaked and was excluded from the data set. The correlation coefficient varied from 0.91 to 0.99 across all regressions. The standard deviation is given parenthetically. [b] L_0 data adopted from ref (*10*). [c] Moisture data adopted from ref (*21*).

recently summarized (*16*). All waste composition data are summarized in Table S1 (*16*). Estimates of $k_{field,i}$ for a range of waste composition data at bulk MSW decay rates of 0.04, 0.02, and 0.12 yr^{-1} are presented in Tables 3 and 4. Only average data are presented in Table 4 as $k_{field,i}$ for each waste composition is directly proportional to the assumed bulk MSW decay rate.

There are several assumptions required to implement the method presented here including (1) knowledge of the initial value of $k_{field,MSW}$, (2) a representative waste composition for use in eq 6, and (3) the absence of interactions between waste components. There is significant uncertainty in the $k_{field,MSW}$ as documented in recent estimates (*13*−*15*) as well as in AP-42. When the AP-42 default parameters for k and L_0 were applied to the data sets used to estimate these parameters, predicted methane collection ranged from 38% to 492% of that measured. The method described here does not reduce the uncertainty in $k_{field,MSW}$, which is the subject of other studies (*13*−*15*). Although the waste component-specific estimates vary with the assumed composition, as illustrated in Tables 3 and 4, the coefficients of variation (std. dev./mean) of the estimated values for $k_{field,i}$ were about 27%.

In the experiments conducted to measure $k_{lab,i}$, waste components were decomposed individually, which leads to questions about whether interactions between waste components are important. However, two aspects of the experimental design mitigate this issue: (1) each component was seeded with decomposed refuse and (2) ammonia and phosphate concentrations were maintained to ensure that methane production was not nutrient-limited. Nonetheless, the values of $k_{field,i}$ are not applicable at the extremes; e.g., a landfill containing 100% newsprint would likely be nutrient-limited.

The values of $k_{field,i}$ derived in this manuscript are compared to values recommended by the Intergovernmental Panel on Climate Change (IPCC) in Figure 2. The $k_{field,i}$ values were calculated at a $k_{field,MSW}$ of 0.05 yr^{-1} to correspond to a value where the IPCC has a published estimate for both bulk MSW and individual waste components (*17*). With the exception of food waste, the component categories used by the IPCC differ somewhat from the categories used in this work. Thus, direct comparisons are imperfect and the waste categories given in Figure 2 are based on the most related waste components. All IPCC default decay rates are given in Table S2 (*17*).

The decay rates for leaves, grass, and branches are 327%, 645%, and −63% of the IPCC value for the garden and park category. The weighted average decay rate for yard waste assuming 30.3% grass, 40.1% leaves, and 29.6% branches (*18*) is 0.20 yr^{-1}, which is a factor of 4 greater than the IPCC value of 0.05 yr^{-1}. The decay rates for textiles, ONP, OFF, and mixed paper calculated in this study are all within 10% of the IPCC value for the paper and textiles category. In contrast, the decay rates for OCC and glossy paper are 280% and 39% greater than the IPCC value, respectively. The decay rate for food waste calculated in this study (0.180 yr^{-1}) is about 200% greater than the IPCC value but comparable to the decay rates of 0.116 and 0.187 yr^{-1} to 0.231 yr^{-1} for rapidly degradable waste that are used in Dutch and British multiphase models (*19*).

TABLE 2. Field-Scale Decay Rates Based on 1990 Waste Composition at Bulk MSW Decay Rates of 0.04 and 0.12 yr^{-1}

MSW component	discarded composition[a] (wet wt %)	k_{lab} (yr^{-1})	comments	$k = 0.04$ $k_{field} = k_{lab} \times f$ (yr^{-1})	$k = 0.12$ $k_{field} = k_{lab} \times f$ (yr^{-1})
textiles (cotton)[b]	0.71	3.08	equal to office paper	0.020	0.059
wood (non-C&D)	7.02	1.56	equal to branches	0.010	0.030
food waste	12.10	15.02		0.096	0.289
leaves	7.18	17.82		0.114	0.343
grass	5.43	31.13		0.200	0.600
branches	5.30	1.56		0.010	0.030
miscellaneous organics	1.40	13.68[b]	equal to average of food, wood, grass, leaves, and branches	0.088	0.263
newspaper	5.17	3.45		0.022	0.066
office paper	4.97	3.08		0.020	0.059
coated paper	1.47	12.68		0.081	0.244
corrugated containers/ Kraft bags	7.26	2.05		0.013	0.040
mixed paper	11.66	3.27	equal to average of office paper and newsprint	0.021	0.063
total biodegradable fraction	69.66[c]				
assumed bulk MSW decay rate				0.040	0.120
correction factor, f				0.0064	0.0192

[a] The composition of the waste discarded was calculated from the difference in waste generation and recovery as given in ref (*11*). [b] Roughly ~23.7% of textiles consumed in the United States from 2001 to 2005 were made of cotton ref (*22*). [c] Other components are inert (e.g., plastic and glass) and therefore the total does not sum 100%.

TABLE 3. Summary of Field-Scale Decay Rates Estimated for Traditional Landfill Scenario (k = 0.04 yr^{-1})[a]

	national						states						
component	1990	1995	2000	2005	CA	DE	GA	MN	OR	PA	WI	avg.	std. dev.
textiles (cotton)	0.020	0.022	0.025	0.024	0.027	0.035	0.034	0.034	0.028	0.030	0.047	0.029	0.008
wood (non-C&D)	0.010	0.011	0.012	0.012	0.014	0.018	0.017	0.017	0.014	0.015	0.024	0.015	0.004
food waste	0.096	0.105	0.120	0.118	0.133	0.170	0.165	0.167	0.135	0.145	0.229	0.144	0.038
yard trimmings, leaves	0.114	0.125	0.143	0.140	0.157	0.202	0.196	0.198	0.160	0.172	0.272	0.171	0.045
yard trimmings, grass	0.200	0.218	0.249	0.244	0.275	0.353	0.342	0.345	0.280	0.300	0.475	0.298	0.078
yard trimmings, branches	0.010	0.011	0.012	0.012	0.014	0.018	0.017	0.017	0.014	0.015	0.024	0.015	0.004
misc. organics	0.088	0.096	0.110	0.107	0.121	0.155	0.150	0.152	0.123	0.132	0.209	0.131	0.034
newspaper	0.022	0.024	0.028	0.027	0.031	0.039	0.038	0.038	0.031	0.033	0.053	0.033	0.009
office paper	0.020	0.022	0.025	0.024	0.027	0.035	0.034	0.034	0.028	0.030	0.047	0.029	0.008
coated paper	0.081	0.089	0.102	0.100	0.112	0.144	0.139	0.141	0.114	0.122	0.194	0.122	0.032
OCC/Kraft bags	0.013	0.014	0.016	0.016	0.018	0.023	0.023	0.023	0.018	0.020	0.031	0.020	0.005
mixed paper	0.021	0.023	0.026	0.026	0.029	0.037	0.036	0.036	0.029	0.031	0.050	0.031	0.008

[a] Waste composition data used to derive the decay rates presented here are given in Table S1.

TABLE 4. Summary of Field-Scale Decay Rates Estimated for Dry (k = 0.02) and Bioreactor (k = 0.12) Landfill Scenarios[a]

	k = 0.02 yr^{-1}			k = 0.12 yr^{-1}		
component	avg.	std. dev.	range	avg.	std. dev.	range
textiles (cotton)	0.015	0.004	0.01−0.023	0.088	0.023	0.059−0.141
wood (non-C&D)	0.007	0.002	0.005−0.012	0.045	0.012	0.030−0.071
food waste	0.072	0.019	0.048−0.115	0.432	0.113	0.289−0.688
yard trimmings, leaves	0.085	0.022	0.057−0.136	0.512	0.134	0.343−0.816
yard trimmings, grass	0.149	0.039	0.100−0.238	0.895	0.234	0.599−1.426
yard trimmings, branches	0.007	0.002	0.005−0.012	0.045	0.012	0.030−0.071
misc. organics	0.066	0.017	0.044−0.105	0.393	0.103	0.263−0.627
newspaper	0.017	0.004	0.011−0.026	0.099	0.026	0.066−0.158
office paper	0.015	0.004	0.010−0.023	0.088	0.023	0.059−0.141
coated paper	0.061	0.016	0.004−0.097	0.365	0.095	0.244−0.581
OCC/Kraft bags	0.010	0.003	0.007−0.016	0.059	0.015	0.039−0.094
mixed paper	0.016	0.004	0.010−0.025	0.094	0.025	0.063−0.150

[a] Waste composition data used to derive the decay rates presented here are given in Table S1.

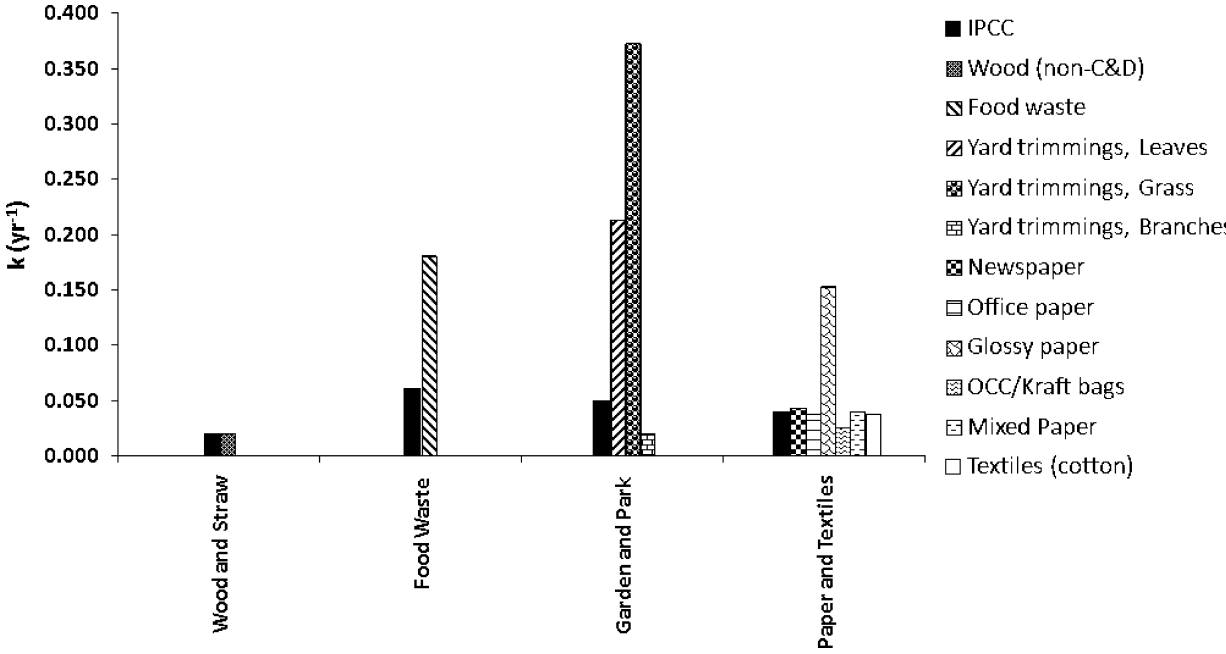

FIGURE 2. Comparison between the IPCC decay rates and the values calculated in this study. The *x*-axis gives the IPCC MSW components categories.

Effect of Changes in Waste Composition on Methane Production

Yard waste is banned from landfills in many states, 60% of the U.S. population has access to curbside recycling programs that are increasingly accepting many types of fiber, and there is increasing interest in the diversion of food waste from landfills (*1*). Five scenarios were analyzed to assess the impact of hypothetical diversion programs

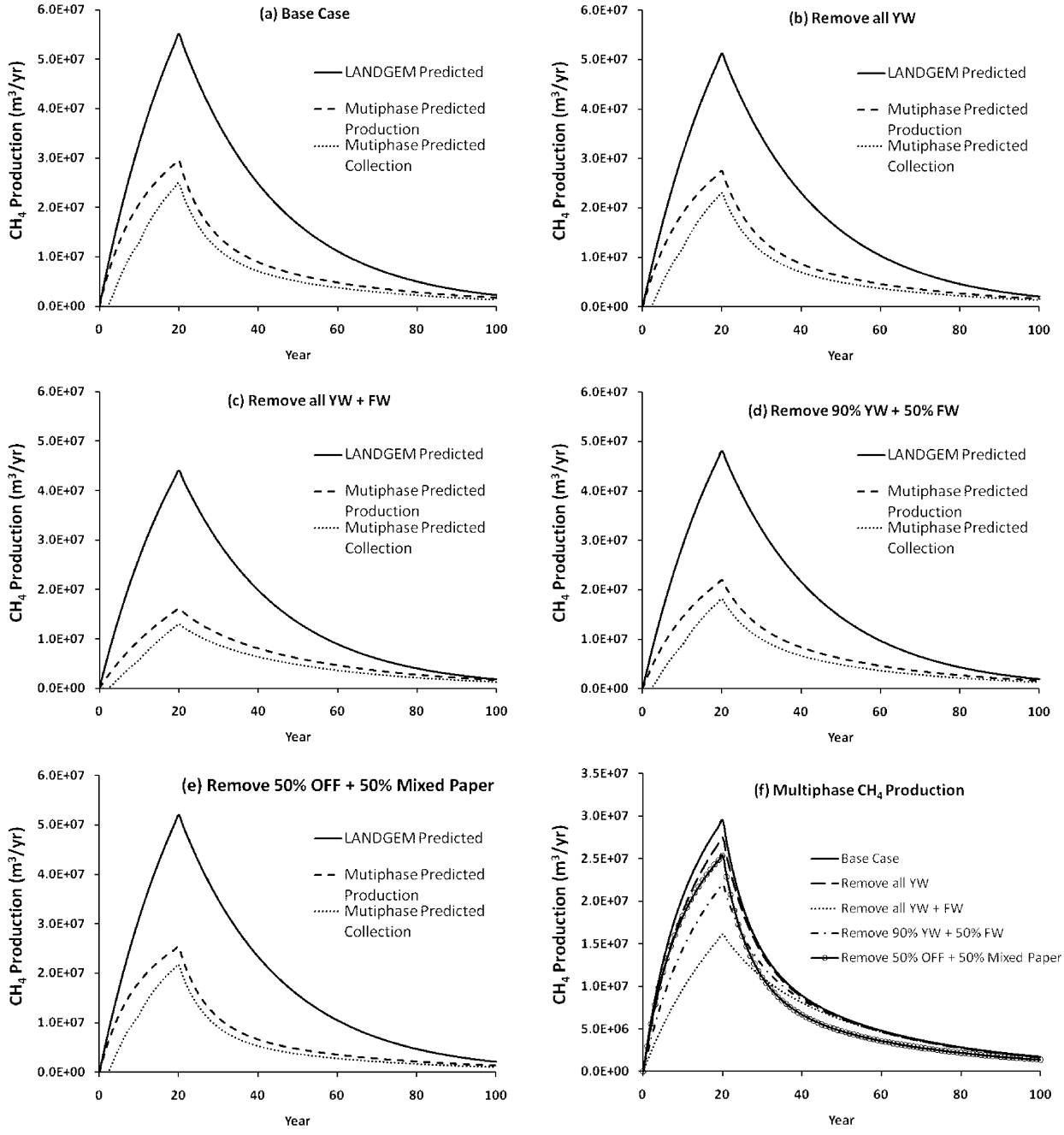

FIGURE 3. Methane production rate for various yard waste (YW), food waste (FW), and paper diversion scenarios. The decay rates for individual waste components are given in Table 3 and assume a bulk MSW decay rate of 0.04. Yard waste includes 30.3% grass, 40.1% leaves, and 29.6% branches based on ref (*18*). The methane collection schedule is given in the text.

and their resulting changes in mass and waste composition on methane production: (1) a base case using the average waste composition from states and EPA (Table S1), (2) all yard waste removed from the discards stream, (3) all yard waste and food waste removed from the discards stream, (4) 90% of yard waste and 50% of food waste removed from the discards stream, and (5) 50% of office paper and 50% of mixed paper removed from the discards stream. In scenario 5, newspaper was not removed from the discards stream because newsprint recycling programs are generally mature and it was assumed that the waste composition data already reflect substantial newsprint recycling. The initial basis was 10^6 Mg of waste buried annually for 20 years. For cases 2, 3, 4, and 5, waste burial was 9.30×10^5, 7.99×10^5, 8.71×10^5, and 9.42×10^5 Mg, annually. Methane production was calculated using a multiphase implementation of eq 1 in which total predicted methane production was the sum of the methane production from individual waste components with unique values of k and L_0. The component-specific L_0's are given in Table 1. For comparison, methane production was also calculated using the LandGEM formulation in which the mass was adjusted for each diversion scenario but the k (0.04 yr^{-1}) and L_0 (100 m^3 of CH_4 Mg^{-1}) remained constant at the AP-42 defaults.

Predicted methane production rates using the LandGEM approach and the multiphase approach with component-specific values of k and L_0 are presented in Figure 3a−e for each scenario. In all cases, the maximum methane production rate is the last year of waste burial as there is no lag time in eq 1. The multiphase approach results in lower methane production rates relative to LandGEM because the LandGEM simulations used an L_0 of 100 m^3 of CH_4 Mg^{-1}, whereas the comparable L_0's for cases 1−5, as calculated using methane

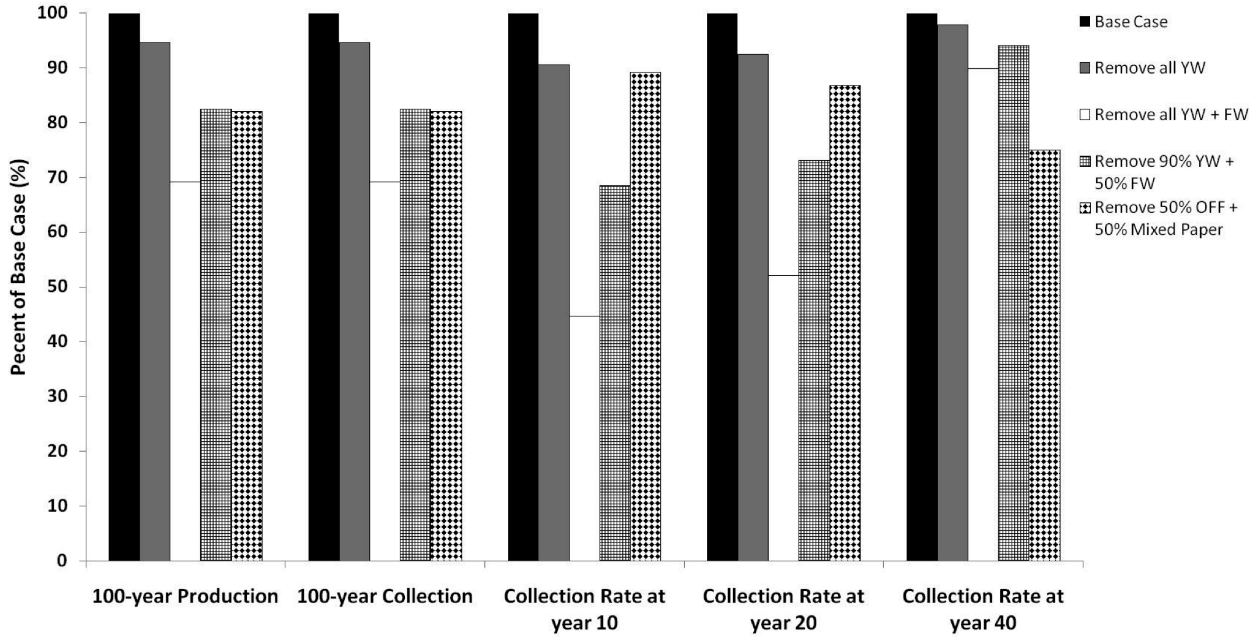

FIGURE 4. Cumulative methane collection and collection rate at different years for various yard waste (YW), food waste (FW), and paper diversion scenarios. All comparisons are based on the multiphase approach.

yields in Table 1, are 50.6, 51.5, 45.1, 48.4, and 44.1 m^3 of CH_4 Mg^{-1}, respectively.

The effect of diversion using the multiphase approach only is presented in Figure 3f. At year 20, the methane production rate is 93%, 55%, 75%, and 86% of the base case for scenarios 2−5, respectively. For cases 3−5, this is well below the mass reductions of 20%, 13%, and 6%, respectively, which emphasizes the need to consider waste composition in estimating methane production. Of course, year 20 is a snapshot and the reduction in methane production changes with time. When the multiphase approach is used, the decreases in cumulative methane over 100 years are 5%, 31%, 18%, and 18% relative to the base case for cases 2−5, respectively. When LandGEM is used, the reductions would be proportional to the mass reductions only and the corresponding reductions in cumulative methane are 7%, 20%, 13%, and 6% for cases 2−5, respectively.

The methane production rates converge at about year 40 for cases 1−4 (Figure 3f). Methane production is affected by both the reduction in tonnage and the removal of degradable materials. Given their relatively high decay rates, food waste, grass, and leaves are the primary substrates for methane production during the early stages of decomposition. Later, paper dominates the methane production curve. The mass of paper does not change among cases 1−4. Thus, the methane production rate curves converge where paper is the dominant contributor to methane production. The opposite trend is observed when paper was removed from the discarded stream (Figure 3f). The significance of removing paper is realized later in the methane curve's life as paper decomposes more slowly and its effects are masked somewhat by rapidly decomposing material in early years of decomposition.

One source of uncertainty is the methane yield attributable to each waste component as the waste component-specific L_0's are based on one set of substrates (*10*). An L_0 of 300.7 m^3 of CH_4·dry Mg of food waste^{-1} was reported initially and used here. However, a second study reported food waste yields of 152.9 and 200.7 m^3 of CH_4·dry Mg^{-1} (*20*). If the average methane yield for food waste is utilized (218.1 m^3 of CH_4·dry Mg^{-1}), then the year 20 methane production rate is 61% and 78% of the base case scenarios for cases 3 and 4, respectively, as opposed to 55% and 75% of the base case at a food waste L_0 of 300.7 m^3 of CH_4·dry Mg^{-1}.

Finally, the effect of various diversion strategies on methane collection is considered. As described previously, the fraction of the generated methane that is collected increases with time as the gas collection system is extended to the youngest waste. A methane collection scenario was adopted from (*9*) in which the collection efficiency was 0% in years 1 and 2, 50% in year 3, 70% in year 4, 75% in years 5−10, and 95% through year 100 based on the assumption that a final cover is placed in year 10. The year refers to waste age as opposed to the landfill's age. This collection schedule results in a 100-year temporally averaged collection efficiency of about 83% (i.e., total collection/total production) for $k = 0.04$ yr^{-1}.

Methane rate curves based on collected gas are presented in Figure 3a−e for cases 1−5, and methane collection is compared in Figure 4. There is a significant reduction in the rate of methane collection relative to base case in years 10 and 20 when the relatively fast degrading food waste is removed (cases 3 and 4). However, in year 40, the reduction in methane collection can be attributed largely to the removal of slowly degrading materials such as paper (case 5). These observations emphasize the need to consider changes in waste mass and composition in landfill gas modeling and have implications for both estimates of fugitive emissions and plans for landfill gas to energy programs. Clearly, LandGEM in its current implementation with one set of parameters to characterize MSW is not useful for exploring the sensitivity of changes in waste composition on methane production; rather, a component-specific approach is required.

Supporting Information Available

The derivation of LandGEM, waste composition data used for this study, IPCC default decay rates, and transformed plots of methane production data. This material is available free of charge via the Internet at http://pubs.acs.org.

Acknowledgments

This research was supported by the Environmental Research and Education Foundation and ICF International. The input of Randall Freed, Deanna Lizas, and Chris Evans of ICF is acknowledged.

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ES100240R

Estimation of Waste Component Specific Landfill Decay Rates Using Laboratory-Scale Decomposition Data

Supporting Information (SI)

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In the first section of this supporting information, the derivation of the first order methane generation model is presented. Table S1 contains the composition data obtained from the U.S. EPA (1-4) and states (5) that were used in the calculation of component-specific decay rate constants. Table S2 includes IPCC decay rate data. Figures S1 to S7 are the transformed plots of methane production data that were used to determine the laboratory-scale component-specific decay rate constants, $k_{lab,i}$ from which the field relevant component-specific decay rates, $k_{field,i}$, were calculated.

Derivation of the U.S. EPA landfill gas generation model based on first-order decay equation (LANDGEM). The development of LANDGEM and its relationship to MSW biodegradation is

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summarized in this section. The gas production rate has been described as being proportional to the rate of decomposition of the reactive carbon as shown in equation 1 (6).

$$\alpha_t = -1.87W\frac{dC}{dt} \quad (1)$$

where α_t is the landfill gas production rate (m^3 yr^{-1}), W is the waste in place, (Mg), 1.87 m^3 landfill gas kg C^{-1} converts a unit weight of C to equimolar volumes of CO_2 and CH_4, C is the amount of reactive carbon, (kg Mg^{-1}) and t is time (yr).

Gas production is typically modeled assuming first order decomposition as in equation 2, the integrated form of which is given in equation 3.

$$-\frac{dC}{dt} = kC \quad (2)$$

$$\frac{C}{C_0} = e^{-kt} \quad (3)$$

where C_0 is the initial mass of reactive carbon in the refuse. Substituting equations 2 and 3 into 1, results in equation 4:

$$\alpha_t = 1.87WkC_0e^{-kt} \quad (4)$$

Cellulose and hemicellulose are the major biodegradable constituents of refuse (7). The stoichiometry of cellulose and hemicellulose conversion to methane is presented in equations 5 and 6, respectively. Since the biodegradation of cellulose and hemicellulose both yield equimolar amounts of CH_4 and CO_2, the amount of landfill gas (LFG) can be estimated by equation 7.

$$(C_6H_{10}O_5)_n + nH_2O \rightarrow 3nCO_2 + 3nCH_4 \quad (5)$$

$$(C_5H_8O_4)_n + nH_2O \rightarrow 2.5nCO_2 + 2.5nCH_4 \quad (6)$$

$$1.87\left(\frac{m^3 LFG}{kg\ reactive\ C}\right)C_0\left(\frac{kg\ reactive\ C}{Mg}\right) = 2L_0\left(\frac{m^3 LFG}{Mg}\right) \quad (7)$$

Thus, the rate of methane production (Q_{CH_4}) can be written in equation 8 which is equivalent to the LANDGEM formulation for a specific waste quantity.

$$Q_{CH_4} = \frac{\alpha_t}{2} = L_0 W k e^{-kt} \quad (8)$$

Table S1. National and state average composition data used for the estimation of field-scale decay rate from laboratory data[a]

	National Average				States Average								
	1990	1995	2000	2005	CA	DE	GA	MN	OR	PA	WI	Average	Standard Deviation
Textiles (cotton)[b]	0.71	0.98	1.19	1.35	2.40	2.50	4.00	2.70	3.10	3.80	2.50	2.3	1.1
Wood (non-C&D)	7.02	6.39	7.54	7.57	0.30	0.20	1.90	7.50	4.10	2.50	1.80	4.3	3.0
Food waste	12.10	13.53	15.57	17.12	14.80	9.30	12.00	12.40	15.70	12.10	10.30	13.2	2.4
Yard trimmings, Leaves[c]	7.18	5.30	2.96	2.94	2.65	2.61	1.08	0.92	2.53	2.09	0.48	2.8	1.9
Yard trimmings, Grass[c]	5.43	4.01	2.24	2.22	2.00	1.97	0.82	0.70	1.91	1.58	0.36	2.1	1.5
Yard trimmings, Branches[c]	5.30	3.91	2.19	2.17	1.95	1.92	0.80	0.68	1.86	1.54	0.36	2.1	1.4
Misc. organics	1.40	1.85	1.98	2.04	4.40	2.40	1.30	1.30	2.00	2.70	2.00	2.1	0.9
Newspaper	5.17	4.19	4.25	1.13	2.20	3.30	4.80	4.10	2.20	4.20	2.00	3.4	1.3
Office paper	4.97	4.79	4.69	4.05	2.00	1.80	3.40	3.10	1.80	3.70	1.40	3.2	1.3
Coated paper	1.47	1.20	0.90	0.93	0.80	1.50	2.70	2.50	1.30	2.70	1.00	1.5	0.7
OCC/Kraft bags	7.26	6.60	5.46	5.30	6.80	7.80	11.00	6.90	3.30	8.40	4.20	6.6	2.1
Mixed Paper	11.66	14.52	13.95	13.78	3.70	3.00	6.40	8.50	6.50	4.60	5.00	8.3	4.4

a. The state composition data were adopted from a published study (5).

b. Only biodegradable components are listed so components do not sum to 100%. Roughly ~23.7% of textiles consumed in the U.S. from 2001-05 were made of cotton (8).

c. Based on relative contribution of grass (30.3%), leaves (40.1%) and brush (29.6%) in yard waste (9).

Table S2. Default k-values for various climate zones and organic waste fractions adopted from reference (10).

	Non-tropical (MAT < 20°C)		**Tropical (MAT > 20 °C)**	
	MAP/PET<1	MAP/PET>1	MAP< 1m	MAP> 1m
Slowly degradable				
• Paper and textile	0.04	0.06	0.045	0.07
• Wood and straw	0.02	0.03	0.025	0.035
Moderately degradable				
• Other non-food	0.05	0.10	0.065	0.17
• Garden and park	0.05	0.10	0.065	0.17
Rapidly degradable				
• Food waste	0.06	0.185	0.085	0.4
Bulk Waste	0.05	0.09	0.065	0.17

MAT: mean annual temperature

MAP: mean annual precipitation

PET: potential evapotranspiration

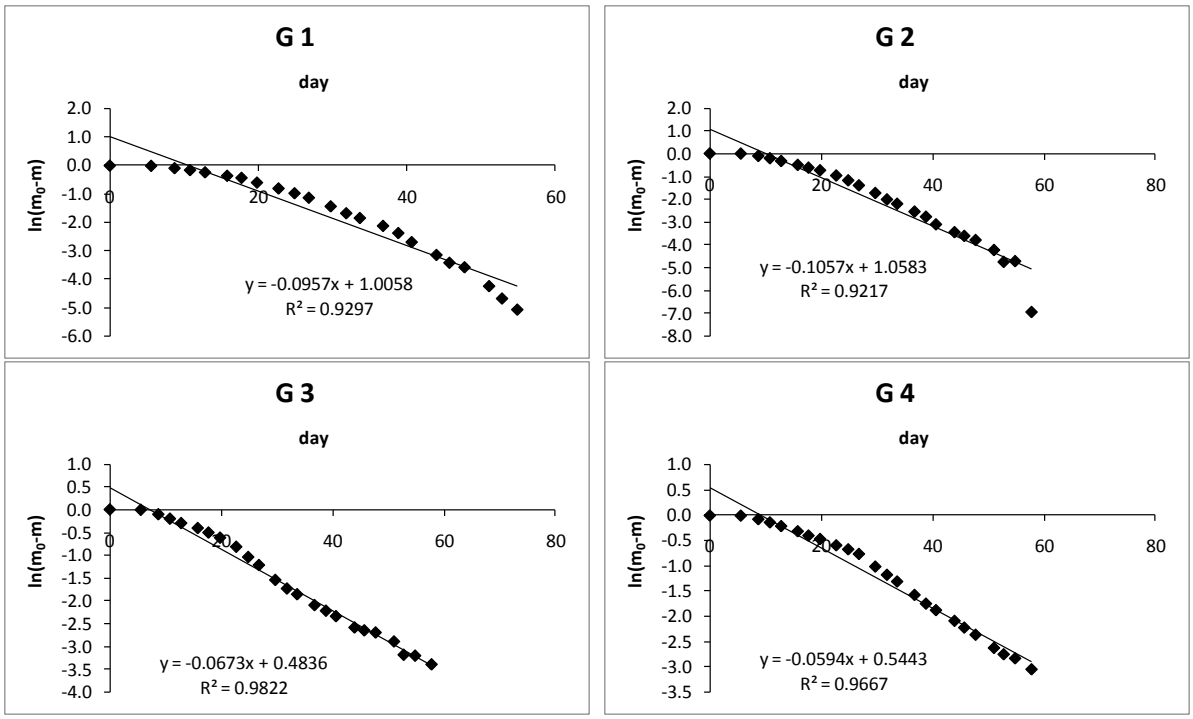

Figure S1. Linearized first-order decomposition of grass (G).

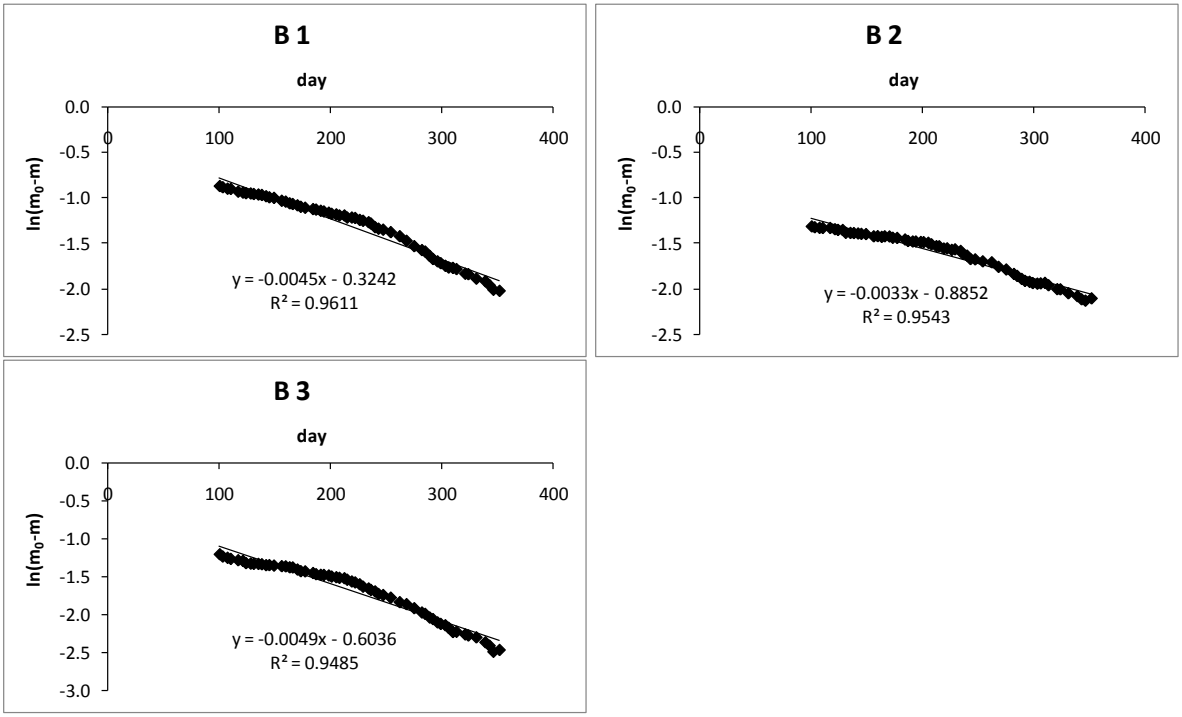

Figure S2. Linearized first-order decomposition of branches (B).

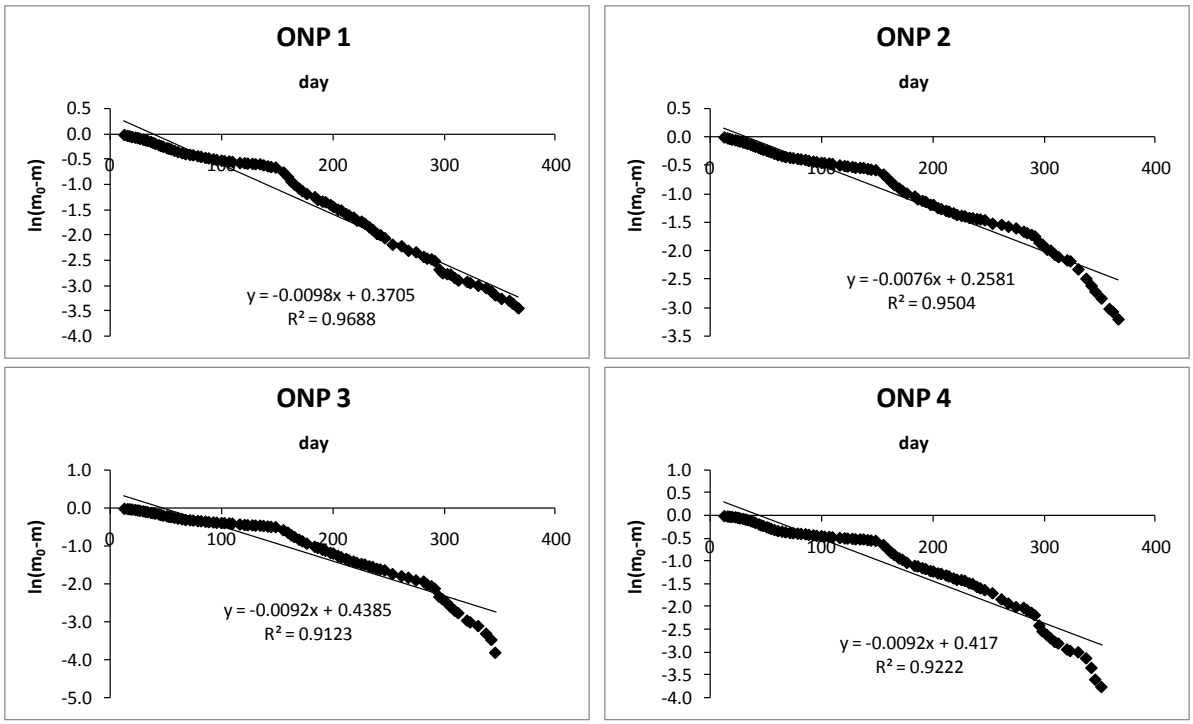

Figure S3. Linearized first-order decomposition of old newsprint (ONP).

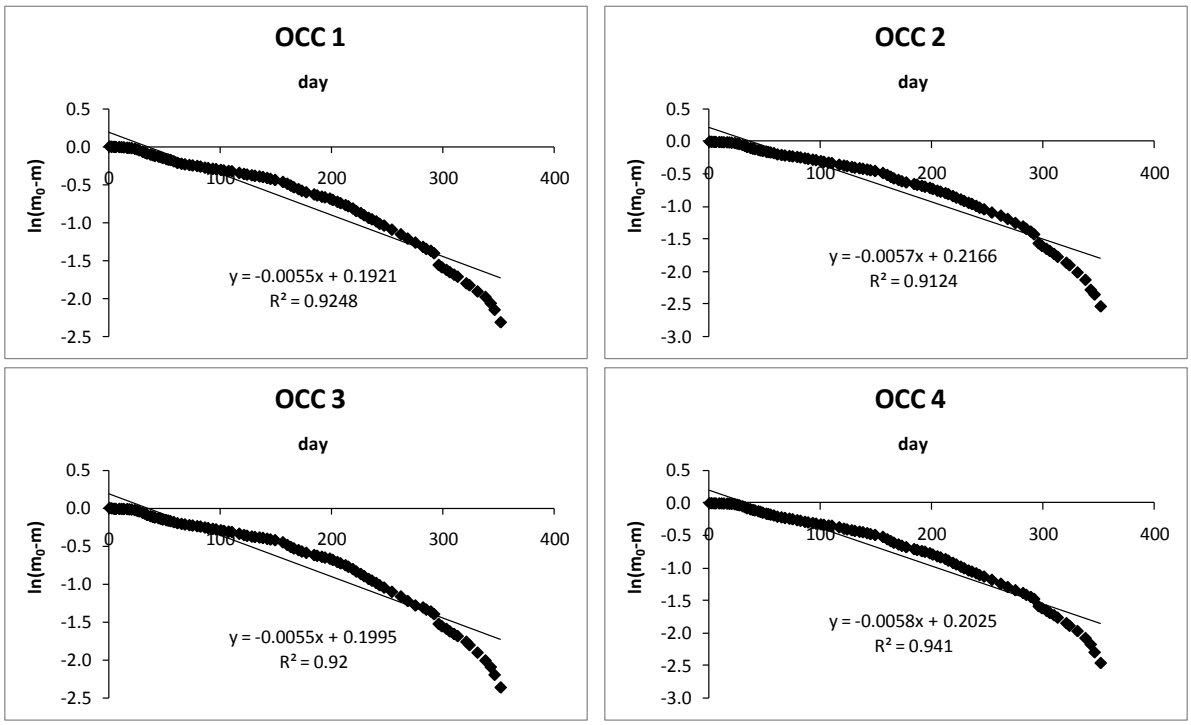

Figure S4. Linearized first-order decomposition of old corrugated cardboard (OCC).

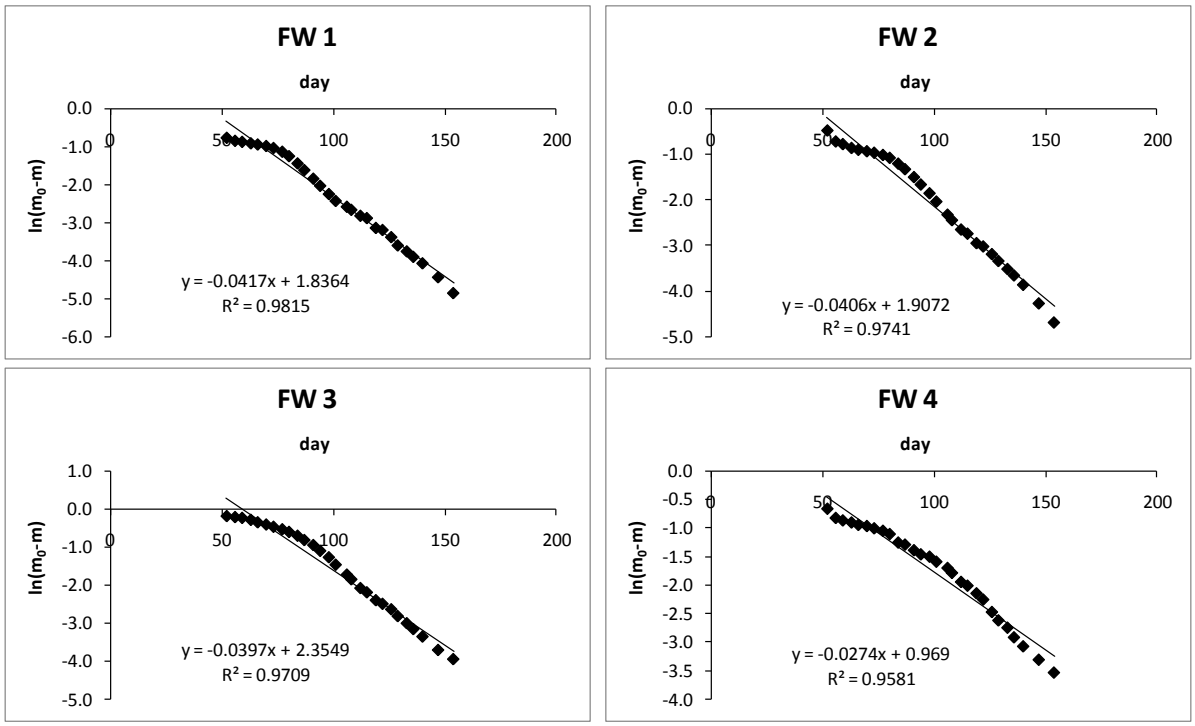

Figure S5. Linearized first-order decomposition of food waste (FW).

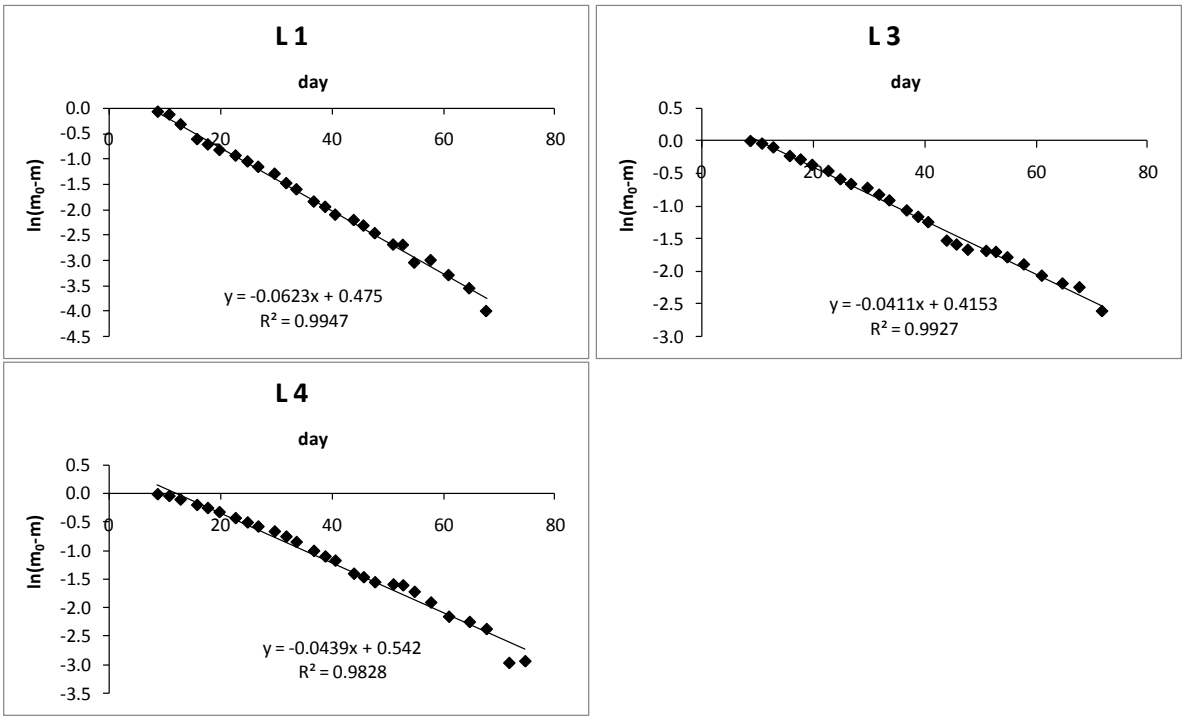

Figure S6. Linearized first-order decomposition of leaves (L).

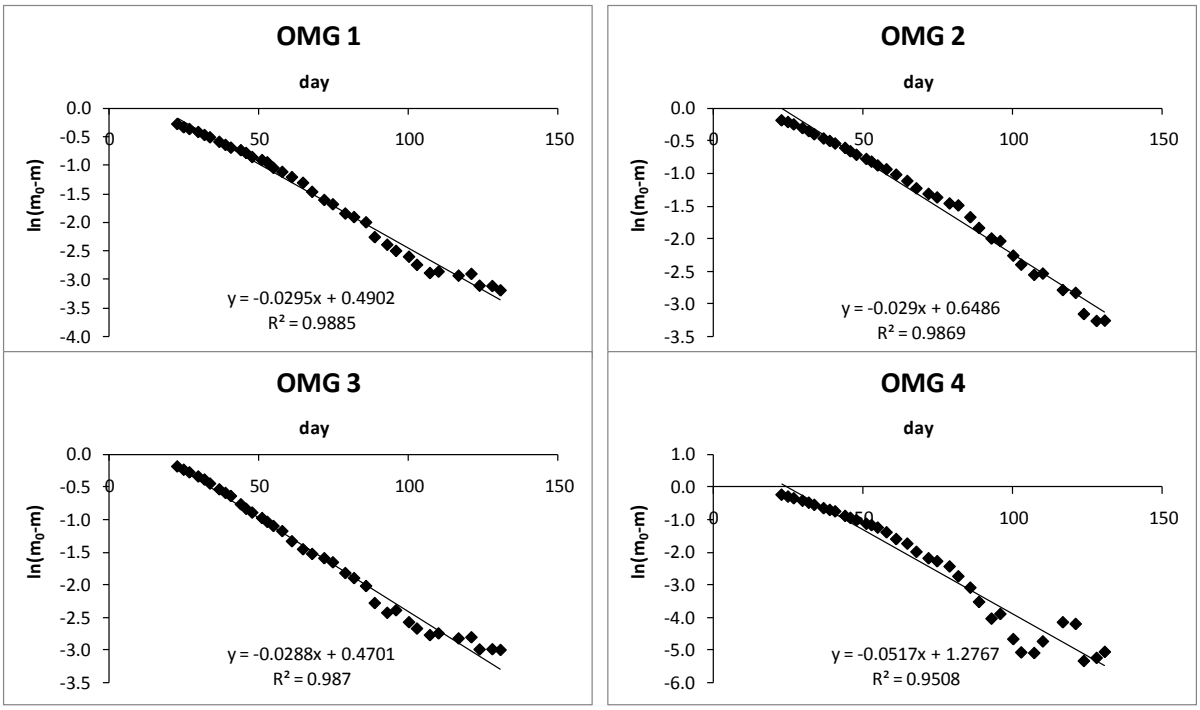

Figure S7. Linearized first-order decomposition of old magazines (OMG).

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Dr. Jhih-Shyang Shih,

Resources for the Future

Review Comments on the EPA LFGcost-Web model

Thank you for the opportunity to review the EPA LFGcost-Web model. This model provides a useful framework for EPA to conduct landfill regulatory cost-benefit analysis and for landfill owners and landfill gas-to-energy project developers to conduct a project feasibility analysis. My comments to EPA's questions are provided below.

A. Model Methods

1. Does LFGCost-Web include a reasonable range of energy recovery project types? Are there any other existing or emerging LFG utilization technologies that warrant consideration in future versions of the model?

   Yes, there are other emerging LFG utilization technologies that warrant consideration in addition to electricity generation, such as gas-to-liquid technology, which could covert biogas produced from landfills into liquid methanol. Methanol has a higher economic value and is widely used as a feedstock for industrial chemicals.

2. Are the estimated costs reasonable for typical project types and sizes (emphasis on review of Collection and Flaring System (C&F) and Standard Reciprocating Engine-Generator Set (ENG) modules)?

   The estimated costs are for the most part reasonable; however, there is much uncertainty and variability associated with the cost and LFG production parameters. Whenever possible, the model should provide uncertainty bounds/ranges for the model parameters, including gas production and cost parameters. For example, LFGCost could provide a range to the economy of scale parameter, which is currently a fixed number of 0.61 in the capital cost equation for the blower and flaring system.

3. Are default input parameters appropriate?

   The assumption of one well per acre seems very restrictive. The number of extraction wells needed depends on the gas production, well size and density, and the size of the blower. Assuming a fixed gas production rate, the higher the well density, the smaller the size of the blower, and vice versa. Since the extraction well is one of the most expensive components, the developer could use a smaller well density and a bigger blower, instead of a higher well density and a smaller blower. There is a trade-off between the number of wells and the size of the blower. Building this relationship into the model would allow for the optimal choice of well density and blower size.

   The default engine capacity factor of 93% seems too high. According to EIA, in 2011, the average capacity factor for generators at industrial CHP plants was only about 57%.
   (http://www.eia.gov/todayinenergy/detail.cfm?id=8250)

4. Are there any other aspects of the model that need to be changed or improved before using the results in project analysis or benefit cost analysis?

   Based on our conversation with the LFGE project developer, for the electricity project, the developer/landfill owner is likely to be responsible for the cost of connecting an electricity generation unit to the power grid. The cost of grid connection could be substantial and is usually overlooked. This cost component is not currently available in the LFGCost model, but it something that the EPA might want to include.

Some states have renewable energy policies such as production tax credits, investment tax credits and feed-in-tariffs, which could subsidize a LFGE project. It seems that the model has the capability to consider these policy instruments through the "Direct Credits" component. That is very good!

The EPA may want to incorporate the social benefit of methane offsets based on or using the social cost of carbon.

B. Model Functionality

1. Does the model provide a useful and sensible structure for estimating project-level costs?

   This model is a valuable tool that provides a useful framework and guidance for landfill owners and LFGE project developers to estimate project-level costs.

2. Does the model itemize cost components and present them in the REPORT worksheet in an appropriate manner?

   Yes, the REPORT spreadsheet provides the estimated cost components in a clear manner.

   However, it seems that there is a bug in the energy project type of "Microturbine." When changing the energy project type, but keeping all other inputs the same, I got a different design project size for Microturbine. Other energy project types all have the same numbers.

   I would suggest that the model could consider quantifying the environmental benefit in monetary value using social cost of carbon and then reporting it in the environmental benefit section of the REPORT spreadsheet.

3. Are there any specific features that could be improved or added to the model to strengthen the usefulness of this tool?

   In the INST spreadsheet, please add "Back to the top" at the end of every table.

   In the WASTE spreadsheet, the program allows me to change the numbers, but doesn't allow me to delete the numbers I have entered previously in the "waste-in-place" and "Annual Waste Acceptance" columns.

4. Does the model conduct a reasonable level of error checking?

   The model has done an excellent job in error checking. There are still some minor bugs, such as the one I mentioned above.

C. Documentation (User's Manual)

1. Does the User's Manual clearly explain how to use the model?

   Yes, the User's Manual is very well written.

2. Does the documentation clearly explain the assumptions and methodology incorporated in the model?

   Yes.

3. Does the documentation clearly and appropriately explain the uncertainty, caveats, and limitations to consider when using the model? Please fully explain. What additional recommendations would you make to better address these factors?

   As mentioned earlier, there exists much uncertainly and variability in the gas production and economic cost parameters. Whenever possible, the model should provide uncertainty bounds/ranges for the model parameters, including those for gas production and cost.

D. Application of LFGcost-Web to regulatory benefit-cost analysis

1. Does the reviewer have any comments on EPA's approach of using cost equations derived from the model to estimate overall costs for the proposed regulations? Would you make any suggestions to improve this approach?

   The model focuses mostly on private costs. If feasible, EPA should consider and allow the modeling tool to account for the social costs and benefits in the regulatory analysis.

   Reciprocating engines could potentially become a source of NO_x emissions. To meet future NO_x emission standards, the LFGcost model may want to include NO_x control technologies and associated cost components to align with Clean Air Act regulations.

2. Are there any model implementation issues not addressed in the June 2015 memo that should be considered in when using LFGCost in regulatory benefit-cost analysis?

   The same as mentioned above.

3. Are there other models that could be used in lieu of LFGCost-Web or could complement components of LFGCost-Web when calculating the regulatory costs of controlling LFG emissions from municipal solid waste landfills?

   I am not aware of any models that could be used in lieu of or complement LFGCost.

Dr. Sarah Stafford,

William and Mary

Comments on the Overview of Landfill Gas Energy Cost Model Version 3.0 (LFGcost-Web V3.0) from Sarah L. Stafford

A. Model Methods

1. Does LFGCost-Web include a reasonable range of energy recovery project types? Are there any other existing or emerging LFG utilization technologies that warrant consideration in future versions of the model?

Beyond my area of expertise to answer.

2. Are the estimated costs reasonable for typical project types and sizes (emphasis on review of Collection and Flaring System (C&F) and Standard Reciprocating Engine-Generator Set (ENG) modules)?

Beyond my area of expertise to answer.

3. Are default input parameters appropriate?

Many of the input parameters are in areas beyond my area of expertise. However, I do think that those that deal with economics of the model (inflation, discounting, interest rate, etc.) are appropriate and adequately justified.

4. Are there any other aspects of the model that need to be changed or improved before using the results in project analysis or benefit cost analysis?

I have some minor suggestions which I discuss in sections B and D below, but these are all suggestions for modest improvements would not significantly change the working of the model or the primary results of the cost benefit analysis.

B. Model Functionality

1. Does the model provide a useful and sensible structure for estimating project-level costs?

I think the spreadsheet is well set up for use by a novice user of excel. I particularly like the collection of the input parameters and key outputs on one page and the provision of the glossary of terms. I also like the transparency of the model so that one who is familiar with excel can see exactly how the estimates are developed.

2. Does the model itemize cost components and present them in the REPORT worksheet in an appropriate manner?

I think that the Report worksheet provides a nice, high level accounting of the costs and benefits for the inputted project. The RPT- Cashflow worksheet provides a useful breakdown by

year and cost category. I also appreciate that one can get more detail by looking at the particular worksheet for each project type.

3. Are there any specific features that could be improved or added to the model to strengthen the usefulness of this tool?

I had a number of comments/suggestions about the tool. There is no particular order to these comments.

- Why is there an option to pick the GWP of methane – shouldn't the IPCC number always be used, and if not, why would any user of this model need to change it? If the option to change the number remains, perhaps an explanation should be added to Appendix A as to why someone might choose the non-IPCC number.
- I think it would be helpful to provide alternative energy product prices based on region or at least a link to a website where users could go to find better estimates for the energy costs for their particular area, given that differences in energy price can be quite large and may make a difference to the bottom line.
- I would like to see an option to change the "Total lifetime carbon dioxide from avoided energy generation" and "Average annual carbon dioxide from avoided energy generation" driver (Avg. U.S. Power emissions factor on the ENV sheet) for electricity projects – i.e. allow the user to input the fuel being replaced. One again, this may make a significant difference depending on where the project is located.

4. Does the model conduct a reasonable level of error checking?

The worksheet allowed me to do the following which I would think should not be possible:

- Enter a landfill closure year earlier than the landfill opening year.
- Enter a year for waste in place earlier than the landfill opening year.

Otherwise the error checking is very well done.

C. Documentation (User's Manual)

1. Does the User's Manual clearly explain how to use the model?

The manual needs to clearly state at the beginning, and ideally as a disclaimer on all materials connected to the model, that some of the macros do not work in Microsoft Excel for Mac. (At least they did not work on any of the three Mac computers I tried with varying versions of MS Excel for Mac.) Otherwise I generally found the manual straightforward to use and it did walk me through the Excel spreadsheet in a nice way.

2. Does the documentation clearly explain the assumptions and methodology incorporated in the model?

I had the following questions about the assumptions/methodology when I read the manual. (Note that some of these questions were answered by looking at the spreadsheet, but I think they should be in the manual as well.):

- What is the discount rate used to calculate NPV? (It should be upfront, not just in Appendix A since there is no reference to App A on page 4.)
- I assume that the energy price escalation rates are increases in real prices. If so, I think that should be indicated as a naïve user may use nominal prices. If not, what inflation rate is used for energy prices, as that is not spelled out? (I would be troubled if there were a negative real energy price factor.)
- Perhaps if I were a government entity using the model I would know why the inputs need to be adjusted as shown in Table D-1, but perhaps not. I think additional discussion as to why these changes need to be made and how a particular government owned project should be represented would be helpful.

Other minor comments:

- I think the definition offered for "Net present value at year of construction" is really bad. If I didn't know what NPV was, this definition would certainly not make it any clearer.
- I'm not sure the term "Net present value payback (years after operation begins)" is the correct one – I prefer "Years to Breakeven".

3. Does the documentation clearly and appropriately explain the uncertainty, caveats, and limitations to consider when using the model? Please fully explain. What additional recommendations would you make to better address these factors?

The uncertainty level is an issue. The manual states that the estimates provided have a ± 30-50 percent accuracy rate. It would be helpful to have more clarification on this. From the 2014 Memo we were sent, it is clear that the cost estimates are upperbound estimates. What might make the numbers underestimates? I think it would be helpful to know things that generally increase costs and things that decrease costs. Page 5 does provide a short list, but could this be expanded on in an appendix? Given that region affects the estimates, can you provide anything about which regions will have higher/lower costs? I know that the model can't fully capture the magnitude of the range of costs, but just knowing directions would be helpful.

Given the uncertainty of the model, it's not clear to me why you allow the user to add a cost uncertainty factor of ± 20 percent. Since the underlying uncertainty ± 30-50 percent, providing for calculations of ± 20 percent could make users think that they had fully captured the uncertainty by using that factor when in fact significant uncertainty remains. Would it make sense to present the ± 30-50 percent numbers somewhere instead of allowing users to adjust by only ± 20 percent? At a minimum when this adjustment factor is presented in the manual I think you need to say something to reiterate the inherent uncertainty that already exists in the estimates.

D. Application of LFGcost-Web to regulatory benefit-cost analysis

1. Does the reviewer have any comments on EPA's approach of using cost equations derived from the model to estimate overall costs for the proposed regulations? Would you make any suggestions to improve this approach?

Overall the methodology for the cost analysis is straightforward and sensible. I do have a couple of minor comments on the approach.

First, I wonder if the approach is not overly conservative. According to the 2014 memo provided to us, for each cost element the estimates were rounded up – often significantly (particularly when there were multiple components that were each rounded before being summed). Second, when estimating which landfills will be able to reduce costs through electricity generation, the decision rule is pretty conservative, as it assumes a facility has to operate at capacity for 15 years even if operating at capacity for less than 50 years would be profitable. For example, a landfill in a region with a particularly high electricity buy back rate could be profitable if it operates at full capacity for only 10 years and partial capacity after that.

Additionally, the write up does not make it clear how electricity prices are modeled in the future – I assume that the default 1% energy price increase used in the model is also used in the cost-benefit analysis and that this is a real price increase.

2. Are there any model implementation issues not addressed in the June 2015 memo that should be considered in when using LFGCost in regulatory benefit-cost analysis?

I did wonder how the specifications for "future" landfills were developed. It would have been helpful to know more about those since presumably the details such as location, capacity and AWAR will drive the costs for those landfills.

3. Are there other models that could be used in lieu of LFGCost-Web or could complement components of LFGCost-Web when calculating the regulatory costs of controlling LFG emissions from municipal solid waste landfills?

None of which I am aware.