7. LANDFILLING

This chapter presents estimates of GHG emissions and carbon storage from landfilling the materials considered in this analysis. For this study, we estimated the CH_4 emissions, transportation-related CO_2 emissions, and carbon storage that will result from landfilling each type of organic waste and mixed MSW. The GHG accounting principles used in the analysis follow.[1]

- When food discards, yard trimmings, paper, and wood are landfilled, anaerobic bacteria degrade the materials, producing CH_4 and CO_2. CH_4 is counted as an anthropogenic GHG, because even though it is derived from sustainably harvested biogenic sources, degradation would not result in CH_4 emissions if not for deposition in landfills. The CO_2 is not counted as a GHG in this context because if it were not emitted from landfills, it would be produced through natural decomposition. Because metals do not contain carbon, they do not generate CH_4 when landfilled. Plastics do not biodegrade, and therefore do not generate any CH_4.
- Transportation of waste materials to a landfill results in anthropogenic CO_2 emissions, due to the combustion of fossil fuels in the vehicles used to haul the wastes.
  Because food discards, yard trimmings, and paper are not completely decomposed by anaerobic bacteria, some of the carbon in these materials is stored in the landfill. Because this carbon storage would not normally occur under natural conditions (virtually all of the organic material would degrade to CO_2, completing the photosynthesis/respiration cycle), this is counted as an anthropogenic sink.[2]

We developed separate estimates of emissions from landfills without gas recovery systems, those that flare CH_4, those that combust CH_4 for energy recovery, and from the national average mix of these three categories. Our national average emission estimate accounts for the extent to which CH_4 will be flared at some landfills and combusted for energy recovery at others.[3]

From the standpoint of post-consumer GHG emissions, landfilling some materials—including magazines/third-class mail, newspaper, phonebooks, dimensional lumber, medium-density fiberboard, leaves, and branches—results in net storage (i.e., carbon storage exceeds CH_4 plus transportation energy emissions) at all landfills, regardless of whether gas recovery is present. At the other extreme, office paper, textbooks, and food discards result in net emissions regardless of landfill gas collection and recovery practices. The remaining materials have net post-consumer emissions that are either very low (aluminum, steel cans, and plastics have transportation-related emissions of 0.01 MTCE per ton, regardless of whether gas collection is present) or borderline, depending on whether the landfill has gas recovery (e.g., mixed MSW has net emissions at landfills without gas recovery, but net carbon storage at landfills with gas recovery).

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[1] These principles are described in broad terms in Section 1.5 of this report.

[2] However, carbon in plastic that remains in the landfill is not counted as stored carbon, because it is of fossil origin.

[3] Currently, most landfill CH_4 recovery in the United States—both for flaring and electricity—is occurring in response to a 1996 EPA rule that requires a well-designed and well-operated landfill gas collection system at landfills that (1) have a design capacity of at least 2.5 million metric tons or 2.5 million cubic meters; (2) are calculated to emit more than 50 metric tons of non-CH_4 organic compounds per year; and (3) received waste on or after November 11, 1987 (Federal Register, Vol. 61, No. 49, p. 9905, March 12, 1996). For the year 2000, an estimated 43 percent of landfill CH_4 was generated at landfills with landfill gas recovery systems subject to these requirements or installed on a voluntary basis.

7.1 EXPERIMENTAL VALUES FOR CH_4 GENERATION AND CARBON STORAGE

To estimate CH_4 emissions and carbon storage from landfilling of specific materials, we used data from laboratory experiments conducted by Dr. Morton Barlaz.[4] The experiments provided data on (1) the amount of CH_4 generated by each type of organic material, when digested by bacteria in anaerobic conditions simulating those in a landfill; and (2) the amount of carbon remaining, undecomposed (i.e., stored) at the end of the experiment.

7.1.1 Experimental Design

Dr. Barlaz placed each type of organic waste and mixed MSW in separate reactor vessels, in which he maintained anaerobic conditions similar to those in a landfill, but controlled to favor maximum CH_4 generation. Dr. Barlaz measured the amount of CH_4 generated in each reactor and the amount of undecomposed carbon remaining in each reactor at the end of the experiment. Each material was tested in four reactors, and the results from each reactor were averaged.[5]

At the start of the experiment, Dr. Barlaz dried a sample of each material and analyzed the amount of cellulose, hemicellulose, and lignin (and, for food discards, protein) in each material. Cellulose, hemicellulose, and protein partly decompose in a landfill, resulting in CH_4 generation. Lignin is relatively stable and non-decomposable under anaerobic conditions.

Portions of each material were weighed, placed in two-liter plastic containers (i.e., reactors), and allowed to decompose anaerobically under warm, moist conditions designed to accelerate decomposition. The reactors were seeded with a small amount of well-decomposed refuse containing an active population of CH_4-producing microorganisms (the "seed"), to ensure that CH_4 generation was not limited due to an insufficient population of microorganisms. To promote degradation, water was cycled through each reactor. Nitrogen and phosphorus were added so that CH_4 generation would not be limited by a lack of these nutrients.

The reactors were allowed to run for periods varying from three months to two years. The experiment ended for each reactor when one of two conditions was met: (1) no measurable CH_4 was being emitted (i.e., any CH_4 that was being emitted was below the detection limits of the analytical equipment); or (2) a curve generated mathematically from an analysis of the reactor's prior CH_4 generation indicated that the reactor had produced at least 95 percent of the CH_4 that it would produce if allowed to run indefinitely.

Dr. Barlaz measured the amount of CH_4 generated during the experimental period and subtracted the amount of CH_4 attributable to the seed. At the end of the experiment, he opened the reactors, drained the leachate, dried and weighed the contents, and analyzed the percentage composition of cellulose, hemicellulose, and lignin (and, for food discards, protein) in the remaining contents. He then measured the percentage of total volatile solids in the remaining contents. This amount included the cellulose, hemicellulose, lignin, and protein, and any other carbon-containing components such as waxes and tannins.

The experimental results were used to estimate the amount of carbon remaining in the reactor that was attributable to the seed[6] and the amount attributable to the material. The experiment was assumed to reflect actual landfill conditions, and the organic carbon remaining undegraded in the reactors was assumed to remain undegraded over the long term in landfills, i.e., it would be stored.

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[4] Barlaz, M.A. 1997. "Biodegradative Analysis of Municipal Solid Waste in Laboratory-Scale Landfills," EPA 600/R-97-071. Dr. Barlaz's work was funded by EPA's Air and Energy Engineering Research Laboratory.

[5] Barlaz, op. cit.

[6] Dr. Barlaz tested seed alone to be able to control for the amount of CH_4 generation and carbon storage that was attributable to the seed.

Dr. Barlaz's experiment did not specifically test all of the paper grades described in this report. He did evaluate four specific grades: newspaper, corrugated boxes, office paper, and coated paper. We identified proxies for five additional material types for which we had no experimental data. We assumed that magazines placed in a landfill will have characteristics similar to those observed for coated paper. Similarly, we assumed that phonebooks and textbooks would behave in the same way as newspaper and office paper, respectively. Experimental results for branches were used as a proxy for dimensional lumber and medium-density fiberboard.

As discussed in Section 4.2, we included the following three definitions of mixed paper among the materials analyzed in this report:

- Broadly defined mixed paper, which includes almost all printing-writing paper, folding boxes, and most paper packaging;
- Residential mixed paper, which includes the typical mix of papers from residential curbside pick-up (e.g., high-grade office paper, magazines, catalogs, commercial printing, folding cartons, and a small amount of old corrugated containers); and
- Mixed paper from offices, which includes copy and printer paper, stationary and envelopes, and commercial printing.

To develop estimates of CH_4 emissions and carbon storage for these three categories of mixed paper, we used the detailed characterization of mixed paper (shown in Exhibit 4-2) developed by Franklin Associates, Ltd., and we assigned analogs among the four paper grades tested by Dr. Barlaz. Exhibit 7-1 characterizes the composition of the two products made from mixed paper: boxboard (made using either a broad or a residential mix of recycled paper) and paper towels (made from recycled office paper). Emissions were calculated using these characterizations of the mixed paper grades and the values obtained from Dr. Barlaz's experiment for newspaper, corrugated boxes, office paper, and coated paper.[7]

[7] Note that Exhibits 7-2 through 7-4 do not show mixed paper; however, mixed paper is shown in Exhibits 7-6 through 7-8. Exhibits 7-2 through 7-8 appear at the end of the chapter.

Exhibit 7-1

Proxies for Composition Mixed Paper (Percent)

Paper Grade	Broad Definition for Mixed Paper	Mixed Paper from Residential Sources	Mixed Paper from Offices
Newspaper[1]	24	23	21
Corrugated Boxes [2]	48	53	5
Office Paper [3]	20	14	38
Coated Paper [4]	8	10	36
Total	100	100	100

Explanatory Notes:
[1] Includes newspaper, uncoated groundwood paper, recycled folding boxes, and set-up boxes.
[2] Includes virgin and recycled corrugated boxes.
[3] Includes uncoated free sheet paper, cotton fiber paper, bleached bristols, unbleached kraft folding boxes, bleached kraft folding boxes, bleached bags and sacks, unbleached bags and sacks, and unbleached wrapping paper.
[4] Includes coated free sheet paper and coated groundwood paper.

7.1.2 CH_4 Generation: Experimental Data and Adjusted Values

The amount of CH_4 generated by each type of organic material (after deducting the CH_4 attributable to the seed), is shown in column "b" of Exhibit 7-2.

As a check on his experimental results, Dr. Barlaz estimated the amount of CH_4 that would have been produced if all of the cellulose, hemicellulose, and protein from the waste material that was decomposed during the experiment had been converted to equal parts of CH_4 and CO_2 (CH_4-producing microorganisms generate equal amounts, by volume, of CH_4 and CO_2 gas).[8] Dr. Barlaz referred to this amount as the material's "CH_4 potential." He then calculated the percentage of the CH_4 potential for each material accounted for by the sum of (1) the measured CH_4 generation, and (2) the amount of CH_4 that could be formed from the carbon in the leachate that was removed from the reactor and from the carbon in the refuse that remained in the reactor at the end of the experiment.[9] The resulting percentages of the CH_4 potential are shown in column "c" of Exhibit 7-2. CH_4 potential not accounted for could be due to either (1) leaks of CH_4; (2) measurement error; or (3) carbon in the cell mass of microorganisms (which was not measured).

CH_4 recovery was below 85 percent of the CH_4 potential for five materials: coated paper, office paper, food discards, leaves, and branches. In using Dr. Barlaz's data, we needed to make a choice regarding how to allocate this missing carbon. We chose to assume that some of it had been converted to microorganism cell mass, and the remainder had been degraded. Dr. Barlaz postulated a higher CH_4 yield based on assumptions that (1) 5 percent of the carbon in cellulose and hemicellulose (and protein in the case of food discards) that was degraded was converted into the cell mass of the microbial population; and (2) 90 percent of the carbon-containing compounds that were degraded but not converted to cell mass were converted to equal parts of CH_4 and CO_2. The "corrected yields," based on these assumptions, are shown in column "d" of Exhibit 7-2.

[8] *Ibid.* Lignin was not considered in this check because cellulose, hemicellulose, and protein account for nearly all of the CH_4 generated.

[9] Note that any carbon that was converted to cell mass in microorganisms was not considered in this calculation.

We decided, in consultation with Dr. Barlaz, to use the "corrected yields" for leaves, branches, and office paper because we believed that these values were more realistic than the measured yields.[10, 11]

The CH_4 values that we used for each material (either the measured yield, or the "corrected" yield) are shown again in column "f" of Exhibit 7-2. In order to maintain consistent units with the other parts of our analysis, we converted the units for CH_4 generation from milliliters per dry gram of waste, to MTCE per wet ton of waste.[12] The resulting values are shown in column "g" of Exhibit 7-2. The value for yard trimmings is a weighted average of the values for grass, leaves, and branches, based on an assumption that yard trimmings are composed of 50 percent grass, 25 percent leaves, and 25 percent branches (on a wet weight basis).

7.1.3 Carbon Storage: Experimental Data and Calculations

Carbon storage was estimated by calculating the amount of carbon remaining in each reactor at the end of the experiment and then subtracting the amount of carbon remaining that was attributable to the seed. The difference between the two values is the amount of carbon from the waste material that remained in the reactor, undecomposed, at the end of the experiment. Because the conditions in the reactor simulated landfill conditions (favorable to optimized decomposition), approximately this amount of carbon would be stored if the material were landfilled. Carbon storage for each material is presented in Exhibit 7-3.[13]

7.2 FATES OF LANDFILL CH_4: CONVERSION TO CO_2, EMISSIONS, AND FLARING OR COMBUSTION WITH ENERGY RECOVERY

In this analysis, we accounted for (1) the conversion in the landfill of some portion of landfill CH_4 to CO_2 and (2) the capture of CH_4, either for flaring or for combustion with energy recovery (in either case, the captured CH_4 is converted to CO_2).[14] Exhibit 7-4 presents this analysis.

The exhibit begins with the CH_4 generation per wet ton of each material, which is shown in column "b" (the values were simply copied from the last column of Exhibit 7-2). Columns "c" through "k" calculate net GHG emissions from CH_4 generation for each of three categories of landfills: (1) landfills without landfill gas (LFG) recovery; (2) landfills with LFG recovery that flare LFG; and (3) landfills with LFG recovery, which generate electricity from the LFG. Columns "l" through "n" show the

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[10] The corrected yield was not available for coated paper/magazines. For food discards, even though the CH_4 potential recovery percentage was lower than 85 percent, we used the measured yield, as shown in column "b." We made this choice for food discards because the "corrected yield" for food discards was greater than the maximum possible yield (shown in column "e" of the exhibit). Dr. Barlaz had calculated the maximum possible yield for each material based on the CH_4 yield if all of the cellulose, hemicellulose, and protein in the material (1) decomposed and (2) was converted to equal parts of CH_4 and CO_2.

[11] Note that EPA's Office of Research and Development (ORD) uses the same data as the basis for its estimation of CH_4 yields. In that analysis, ORD does not use "corrected" values for materials with low CH_4 recovery, but rather uses observed experimental values for all materials.

[12] To make the conversion, we used the ratio of dry weight to wet weight for each material and a global warming potential of 21 for CH_4.

[13] The approach for estimating carbon storage is more fully described in, Barlaz, Morton, "Carbon Storage During Biodegradation of Municipal Solid Waste Components in Laboratory-Scale Landfills," paper submitted for publication, Department of Civil Engineering, North Carolina State University, Raleigh, NC, 1997.

[14] The CO_2 that is emitted is not counted as a GHG because it is biogenic in origin (as described in "CO_2 Emissions from Biogenic Sources: in Chapter 1).

estimated percentage of landfills in each category in 2000.[15,16] The final column shows the weighted average GHG emissions from CH_4 generation across all types of landfills.

To estimate MSW CH_4 emissions from each category of landfill, we first estimated the percentage of landfill CH_4 that is oxidized near the surface of the landfill. We estimated that 10 percent of the landfill CH_4 generated is either chemically oxidized or converted by bacteria to CO_2,[17] and the remaining 90 percent is available for atmospheric CH_4 emissions.

To estimate MSW CH_4 emissions from landfills with LFG recovery, we used the assumption that these landfills have an average LFG recovery efficiency of 75 percent.[18] We then calculated avoided utility GHG emissions from landfills with electricity generation. Because energy recovery systems experience down time, during which CH_4 is flared rather than used to generate electricity, we incorporated a 15 percent system efficiency loss into our estimates for avoided utility emissions.[19]

We also estimated the percentage of MSW disposed in each category of landfill in 2000. According to our estimates, 49 percent of all landfill CH_4 was generated at landfills with recovery systems, and the remaining 51 percent was generated at landfills without LFG recovery.[20] Of the 49 percent of all CH_4 generated at landfills with LFG recovery, 49 percent (or 24 percent of all CH_4) was generated at landfills that use LFG to generate electricity, and 51 percent (or 25 percent of all CH_4) at landfills that flare LFG.[21, 22]

Our results are shown in the final column of Exhibit 7-4. The materials with the highest rates of *net* GHG emissions from CH_4 generation, as shown in column "o"—corrugated boxes, office paper, and textbooks—also have the highest *gross* CH_4 generation, as shown in column "b." The recovery of CH_4 at landfills reduces the CH_4 emissions for each material in proportionate amounts but does not change the

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[15] Draft *U.S. Climate Action Report – 2001* (CAR). At the time of publication of this report, the CAR was still being reviewed; however, EPA expected that these estimates will not change in the final version.

[16] Note that estimates of percent CH_4 generation at landfills with recovery have decreased since the first edition of this report was published (in the first edition, we estimated that 54 percent of CH_4 would be generated at landfills with recovery). This difference is because the first edition relied on 1995 projections of year 2000 generation and recovery, whereas this version uses the most recent estimates of conditions in 2000.

[17] An oxidation rate of 10 percent is cited by Liptay, K., J. Chanton, P. Czepiel, and B. Mosher, "Use of Stable Isotopes to Determine Methane Oxidation in Landfill Cover Soils," *Journal of Geophysical Research*, April 1998, 103(D7), pp. 8243-8250; and Czepiel, P.M., B. Mosher, P.M. Crill, and R.C. Harriss. 1996. "Quantifying the Effects of Oxidation on Landfill Methane Emissions," *Journal of Geophysical Research*, 101, pp. 16721-16729.

[18] Several commenters on the draft version of the first edition of this report suggested a range of values; 75 percent was most often cited as a best estimate. Moreover, EPA has used this figure in its most recent publications [see, for example, *U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions* (Washington, D.C.: U.S. EPA) September 1999].

[19] EPA. 1999. *Landfill Gas-to-Energy Project Opportunities: Background Information on Landfill Profiles*, Office of Air and Radiation, EPA 430-K-99-002, pp. 3-13.

[20] Based on data on (1) year 2000 MSW landfill CH_4 generation of 72.7 million MTCE (from draft *U.S. Climate Action Report – 2001*), (2) year 2000 landfill CH_4 recovery of 26.7 million MTCE (also from draft *U.S. Climate Action Report – 2001*), and (3) estimated landfill CH_4 recovery efficiency of 75 percent (from *U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions*).

[21] Draft *U.S. Climate Action Report – 2001*.

[22] The assumption that 49 percent of landfills recovering CH_4 will use it to generate electricity is subject to change over time based upon changes in the cost of recovery and the potential payback. Additionally, new technologies may arise that use recovered CH_4 for purposes other than generating electricity.

ranking of materials by CH_4 emissions. Leaves, branches, and the two wood products have the lowest rates of net GHG emissions from CH_4 generation.

7.3 UTILITY CO_2 EMISSIONS AVOIDED

Exhibit 7-5 presents a list of conversion factors and physical constants used to convert CH_4 combusted for electricity production to avoided CO_2 emissions. Using data on Btu per cubic feet of CH_4, kwh of electricity generated and delivered per Btu, and kilograms of utility carbon avoided per Btu delivered, we estimated that 0.18 MTCE is avoided per MTCE of CH_4 combusted. This figure then was incorporated into exhibit 7-4 to estimate net GHG emissions from landfills with electricity generation. As mentioned earlier in this chapter, our analysis assumes that 24 percent of landfills in the United States combust landfill CH_4 for electricity generation. We also assume a 15 percent system efficiency loss, reflecting the fact that landfill gas-to-energy facilities incur some system "down time," as shown in column 1.

7.4 NET GHG EMISSIONS FROM LANDFILLING

To determine the net GHG emissions from landfilling each material, we summed the net GHG emissions from CH_4 generation, carbon storage (treated as negative emissions), and transportation CO_2 emissions. The results are shown in Exhibit 7-6. The four columns under section "e" of the exhibit may be used by local MSW planners to estimate GHG emissions from MSW in a given community.

As the exhibit shows, the post-consumer results for organic materials vary widely. For some materials—in particular, magazines/third-class mail, newspaper, phonebooks, dimensional lumber, medium-density fiberboard, and yard trimmings (in particular, leaves and branches)—landfilling results in substantial net GHG reductions. For others—including corrugated cardboard, office paper, textbooks, and food discards—net emissions are significant. For the rest, net emissions and reductions are relatively small.

7.5 LIMITATIONS

Perhaps the most important caveat to the analysis of GHG emissions and storage associated with landfilling is that the results are based on a single set of laboratory experiments, those conducted by Dr. Morton Barlaz. Although researchers other than Dr. Barlaz have conducted laboratory studies that track the degradation of mixed MSW, his experiments were the only ones we identified that rigorously tested materials on an individual basis. Dr. Barlaz is recognized as an expert on the degradation of different fractions of MSW under anaerobic conditions, and his findings with respect to the CH_4 potential of mixed MSW are within the range used by landfill gas developers. Nevertheless, given the sensitivity of the landfill results to estimated CH_4 generation and carbon storage, we recognize that more research is needed in this area.

Another important caveat relates to our estimate that 49 percent of MSW landfill CH_4 is generated at landfills with LFG recovery systems. The net GHG emissions from landfilling each material are quite sensitive to the LFG recovery rate. Because of the high global warming potential of CH_4, small changes in the LFG recovery rate (for the national average landfill) could have a large effect on the net GHG impacts of landfilling each material and the ranking of landfilling relative to other MSW management options. The effects of different rates of LFG recovery are shown in Exhibit 7-7. Column "b" of the exhibit shows net GHG emissions if 20 percent of waste was disposed of at landfills with recovery. The remaining columns show net GHG emissions at increasing LFG recovery rates, up to a 60 percent rate. As the exhibit shows, the net post-consumer GHG emissions for landfilling mixed MSW decline significantly as recovery increases. At the local level, the GHG emissions from landfilling MSW depend on whether the local landfill has LFG recovery, as shown in Exhibit 7-6.

Because the national average estimate of emissions is based on estimated year 2000 LFG recovery levels, there are several limitations associated with the use of this emission factor. First, because landfill CH_4 generation occurs over time and has significant timing delays (i.e., CH_4 generation may not begin until a few years after the waste is deposited in the landfill and can continue for many years after the landfill is closed), the values listed in this chapter represent total CH_4 generated, over time, per ton of waste landfilled. To the extent that LFG recovery rates shift dramatically over time, these shifts are not reflected in the analysis. Second, landfills with LFG recovery may be permitted, under EPA regulations, to remove the LFG recovery equipment when three conditions are met: (1) the landfill is permanently closed, (2) LFG has been collected continuously for at least 15 years, and (3) the landfill emits less than 50 metric tons of non-CH_4 organic compounds per year.[23] Although the removal of LFG recovery equipment will permit CH_4 from closed landfills to escape into the atmosphere, the amounts of CH_4 emitted should be relatively small, because of the relatively long time period required for LFG collection before LFG recovery equipment is removed. Third, several methodological issues are associated with applying the CH_4 generation estimates from the Climate Action Report to develop the national average emission factors:

(1) The generation estimates in the CAR include closed landfills (generation is modeled as a function of waste in place), whereas the estimates used in this report apply to ongoing generation (which is routed to open landfills);

(2) Likewise, both the flaring and landfill gas-to-energy estimates also include closed landfills; and

(3) The distribution of waste in place is not a perfect proxy for the destination of ongoing waste generation.

CH_4 oxidation rate and landfill gas collection system efficiency are also important factors driving results. We used values of 10 percent and 75 percent, respectively, as best estimates for these factors. Reviewers who commented on the draft of the first edition of this report and sources in the literature have reported estimates ranging from about 5 percent to 40 percent for oxidation, and from about 60 to 95 percent for collection system efficiency. We investigated the sensitivity of our results to these assumptions, and our results are shown in Exhibit 7-8. We portray the sensitivity as a bounding analysis; i.e., we use the combinations of variables yielding the upper bound emission factor (5 percent oxidation, 60 percent collection efficiency) and the lower bound (40 percent oxidation, 95 percent efficiency).[24] As the exhibit shows, the materials most sensitive to these variables are those with the highest CH_4 generation potential, i.e., corrugated cardboard, office paper, textbooks, food discards, and mixed paper. Sensitivity varies: the difference between upper and lower bounds ranges from 0.06 MTCE/ton for leaves and branches to 0.43 MTCE/ton for office paper and textbooks. The post-consumer emission factors of several materials and mixed material combinations—corrugated cardboard, grass, mixed paper, and mixed MSW—change from having net storage under the lower bound to having net emissions under the upper bound.

Ongoing shifts in the use of landfill cover and liner systems are likely to influence the rate of CH_4 generation and collection. As more landfills install effective covers and implement controls to keep water and other liquids out, conditions will be less favorable for degradation of organic wastes. Over the long term these improvements may result in a decrease in CH_4 generation and an increase in carbon storage. Moreover, Dr. Barlaz believes that the CH_4 yields from his laboratory experiments are likely to be higher than CH_4 yields in a landfill, because the laboratory experiments were designed to generate the maximum

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[23] Federal Register, Vol. 61, No. 49, p. 9907.

[24] The table also reports two intermediate combinations, including the best estimate values.

amount of CH_4 possible. If the CH_4 yields used in this analysis were higher than yields in a landfill, the net GHG emissions from landfilling organic materials would be lower than estimated here.

We assumed that once wastes are disposed in a landfill, they are never removed. In other words, we assumed that landfills are never "mined." A number of communities have mined their landfills—removing and combusting the waste—in order to create more space for continued disposal of waste in the landfill. To the extent that landfills are mined in the future, it is incorrect to assume that carbon stored in a landfill will remain stored. For example, if landfilled wastes are later combusted, the carbon that was stored in the landfill will be oxidized to CO_2 in the combustor.

Our estimate of carbon avoided utility GHG emissions per unit of CH_4 combusted assumes that all landfill gas-to-energy projects are electricity producing. In reality, some projects are "direct gas" projects, in which CH_4 is piped directly to the end user for use as fuel. In these cases, the CH_4 essentially replaces natural gas as a fuel source. Because natural gas use is less GHG-intensive than average electricity production, direct gas projects will tend to offset fewer GHG emissions than electricity projects will—a fact not reflected in our analysis.

For landfilling of yard trimmings (and other organic materials), we assumed that all carbon storage in a landfill environment is incremental to the storage that occurs in a non-landfill environment. In other words, we assumed that in a baseline where yard trimmings are returned to the soil (i.e., in a non-landfill environment), all of the carbon is decomposed relatively rapidly (i.e., within several years) to CO_2, and there is no long-term carbon storage. To the extent that long-term carbon storage occurs in the baseline, the estimates of carbon storage reported here are overstated, and the net post-consumer GHG emissions are understated.

Finally, our spreadsheet analysis is limited by the assumptions that were made at various steps in the analysis, as described throughout this chapter. The key assumptions that have not already been discussed as limitations are the assumptions used in developing "corrected" CH_4 yields for organic materials in MSW. Because of the high global warming potential of CH_4, a small difference between estimated and actual CH_4 generation values would have a large effect on the GHG impacts of landfilling and the ranking of landfilling relative to other MSW management options.

Exhibit 7-2
Methane Yield for Solid Waste Components

(a) Material	(b) Average Measured Methane Yield (ml per dry gm)	(c) Percentage of "Methane Potential" Accounted for	(d) "Corrected" Methane Yield (ml per dry gram)	(e) Maximum Possible Methane Yield (ml per dry gram)	(f) Selected Methane Yield (ml per dry gm)	(g) Selected Methane Yield (MTCE/Wet Ton)
Corrugated Cardboard	152.3	87.7	NA	279.7	152.3	0.537
Magazines/Third-class Mail	84.4	83.7	NA	NA	84.4	0.294
Newspaper	74.2	98.0	NA	239.4	74.2	0.259
Office Paper	217.3	55.5	346.0	398.2	346.0	1.207
Food Discards	300.7	77.4	386.2	357.6	300.7	0.335
Yard Trimmings						0.191
Grass	144.3	89.3	NA	153.2	144.3	0.214
Leaves	30.5	75.2	56.0	108.0	56.0	0.166
Branches	62.6	82.8	76.3	224.9	76.3	0.170
Mixed MSW	92.0	97.6	NA	157.6	92.0	0.286

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

Note that Exhibits 7-1 to 7-3 show coated paper but not mixed paper; mixed paper is shown in Exhibits 7-5 and 7-6. The values for the different types of mixed paper are based on the proportion of the four paper types (newspaper, office paper, corrugated cardboard, and coated paper) that comprise the different "mixed paper" definitions.

Exhibit 7-3
Carbon Storage for Solid Waste Components

(a) Material	(b) Ratio of Carbon Storage to Dry Weight (gm C/dry gm)	(c) Ratio of Dry Weight to Wet Weight	(d) (d = b * c) Ratio of Carbon Storage to Wet Weight (gm C/wet gm)	(e) Amount of Carbon Stored (MTCE per Wet Ton)
Corrugated Cardboard	0.26	0.95	0.25	0.22
Magazines/Third-class Mail	0.34	0.94	0.32	0.29
Newspaper	0.42	0.94	0.39	0.36
Office Paper	0.05	0.94	0.05	0.04
Food Discards	0.08	0.30	0.02	0.02
Yard Trimmings			0.23	0.21
Grass	0.32	0.40	0.13	0.12
Leaves	0.54	0.80	0.43	0.39
Branches	0.38	0.60	0.23	0.21
Mixed MSW	0.13	0.84	0.11	0.10

Note that more digits may be displayed than are significant.

Explanatory Notes for Exhibit 7-3:
(1) Because MSW is typically measured in terms of its wet weight, we needed to convert the ratios for carbon stored as a fraction of dry weight to carbon stored as a fraction of wet weight. To do this, we used the estimated ratio of dry weight to wet weight for each material. These ratios are shown in column “c” of the exhibit. For most of the materials, we used data from an engineering handbook.[25] For grass, leaves, and branches, we used data provided by Dr. Barlaz.

(2) For consistency with the overall analysis, we converted the carbon storage values for each material to units of MTCE stored per short ton of waste material landfilled. The resulting values are shown in column “e” of the exhibit.

[25] Tchobanoglous, George, Hilary Theisen, and Rolf Eliassen. 1977. *Solid Wastes: Engineering Principles and Management Issues* (New York: McGraw-Hill Book Co.), pp. 58 and 60.

Exhibit 7-4
Net GHG Emissions from CH_4 Generation

		Methane from Landfills Without Methane Recovery		Methane from Landfills With LFG Recovery and: Flaring			Electricity Generation			Percentage of Methane from Each Type of Landfill in 2000			Net Methane Generation	Avoided CO_2 from Energy Recovery	TOTAL
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(l)	(m)	(n)	(o)	(p)	(q)
Material	CH_4 Generation (MTCE/Wet Ton)	Percentage of CH_4 Not Oxidized to CO_2	Net GHG Emissions From CH_4 Generation (MTCE/Wet Ton)	Percentage of CH_4 Not Recovered (100% Minus LFG Collection System Efficiency)	Percentage of CH_4 Not Recovered That Is Not Oxidized to CO_2	Net GHG Emissions From CH_4 Generation (MTCE/Wet Ton)	Utility CO_2 Emissions Avoided per MTCE CH_4 Combusted (MTCE)	Percentage of CH_4 Recovered for Electricity Generation Not Utilized Due to System "Down Time"	Utility CO_2 Emissions Avoided (MTCE/Wet Ton)	Percentage of CH_4 From Landfills Without LFG Recovery in 2000	Percentage of CH_4 From Landfills With LFG Recovery And Flaring in 2000	CH_4 From Landfills With LFG Recovery and Electricity Generation in 2000	Net CH_4 Emissions from Landfilling (MTCE/Wet Ton)	Net Avoided CO_2 Emissions from Landfilling (MTCE/Wet Ton)	Net GHG Emissions From Landfilling (MTCE/Wet Ton)
Corrugated Cardboard	0.537	90%	0.48	25%	90%	0.12	-0.18	0.15	-0.06	51%	25%	24%	0.31	-0.01	0.29
Magazines/Third-class Mail	0.294	90%	0.26	25%	90%	0.07	-0.18	0.15	-0.03	51%	25%	24%	0.17	-0.01	0.16
Newspaper	0.259	90%	0.23	25%	90%	0.06	-0.18	0.15	-0.03	51%	25%	24%	0.15	-0.01	0.14
Office Paper	1.207	90%	1.09	25%	90%	0.27	-0.18	0.15	-0.14	51%	25%	24%	0.69	-0.03	0.66
Phonebooks	0.259	90%	0.23	25%	90%	0.06	-0.18	0.15	-0.03	51%	25%	24%	0.15	-0.01	0.14
Textbooks	1.207	90%	1.09	25%	90%	0.27	-0.18	0.15	-0.14	51%	25%	24%	0.69	-0.03	0.66
Dimensional Lumber	0.170	90%	0.15	25%	90%	0.04	-0.18	0.15	-0.02	51%	25%	24%	0.10	0.00	0.09
Medium-density Fiberboard	0.170	90%	0.15	25%	90%	0.04	-0.18	0.15	-0.02	51%	25%	24%	0.10	0.00	0.09
Food Discards	0.335	90%	0.30	25%	90%	0.08	-0.18	0.15	-0.04	51%	25%	24%	0.19	-0.01	0.18
Yard Trimmings	0.191	90%	0.17	25%	90%	0.04	-0.18	0.15	-0.02	51%	25%	24%	0.11	-0.01	0.10
Grass	0.214	90%	0.19	25%	90%	0.05	-0.18	0.15	-0.02	51%	25%	24%	0.12	-0.01	0.12
Leaves	0.166	90%	0.15	25%	90%	0.04	-0.18	0.15	-0.02	51%	25%	24%	0.09	0.00	0.09
Branches	0.170	90%	0.15	25%	90%	0.04	-0.18	0.15	-0.02	51%	25%	24%	0.10	0.00	0.09
Mixed MSW	0.28601	90%	0.26	25%	90%	0.06	-0.18	0.15	-0.03	51%	25%	24%	0.16	-0.01	0.16

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

Exhibit 7-5
Calculation to Estimate Utility GHGs Avoided through Combustion of Landfill CH_4

Step	Value	Source
Metric tons CH_4/MTCE CH_4	0.17	1/((12/44)*Global warming potential of CH_4)
Grams CH_4/metric ton CH_4	1.00E+06	Physical constant
Cubic ft. CH_4/gram CH_4	0.05	1/20: 20 grams per cubic foot of methane at standard temperature and pressure
Btu/cubic ft. CH_4	1,000	"Opportunity for LF Gas Energy Recovery in Kentucky," OAR September 97, pp. 2-12
kwh Electricity generated/Btu	0.00008	1/13,000: from "Opportunity" report p. 2-11, assumes use of internal combustion engines
kwh electricity delivered/kwh electricity generated	0.95	Telephone conversation among IWSA, American Ref-Fuel, and ICF Consulting, October 28, 1997.
Btu/kwh electricity delivered	3,412	Physical constant
Kg utility C avoided/Btu delivered electricity	8.060E-05	0.08349 MTCE/mmBtu delivered electricity, from Exhibit 6-3. This assumes that LFG energy recovery displaces fossil fuel generation.
Metric Tons avoided utility C/kg utility C	0.001	1000 kg per metric ton
Ratio of MTCE avoided utility C per MTCE CH_4	0.18	Product from multiplying all factors

Exhibit 7-6

Net GHG Emissions from Landfilling

(a)	(b) Net GHG Emissions from CH_4 Generation (MTCE/Wet Ton)				(c)	(d)	(e) (e = b + c + d) Net GHG Emissions from Landfilling (MTCE/Wet Ton)			
Material	Landfills Without LFG Recovery	Landfills With LFG Recovery and Flaring	Landfills With LFG Recovery and Electric Generation	Year 2000 National Average	Net Carbon Storage (MTCE/Wet Ton)	GHG Emissions From Transportation (MTCE/Wet Ton)	Landfills Without LFG Recovery	Landfills With LFG Recovery and Flaring	Landfills With LFG Recovery and Electric Generation	Year 2000 National Average
Aluminum Cans	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Steel Cans	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Glass	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
HDPE	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
LDPE	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
PET	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Corrugated Cardboard	0.48	0.12	0.06	0.29	-0.22	0.01	0.27	-0.09	-0.15	0.08
Magazines/Third-class Mail	0.26	0.07	0.03	0.16	-0.29	0.01	-0.02	-0.21	-0.25	-0.12
Newspaper	0.23	0.06	0.03	0.14	-0.36	0.01	-0.12	-0.29	-0.32	-0.21
Office Paper	1.09	0.27	0.14	0.66	-0.04	0.01	1.05	0.24	0.10	0.62
Phonebooks	0.23	0.06	0.03	0.14	-0.36	0.01	-0.12	-0.29	-0.32	-0.21
Textbooks	1.09	0.27	0.14	0.66	-0.04	0.01	1.05	0.24	0.10	0.62
Dimensional Lumber	0.15	0.04	0.02	0.09	-0.21	0.01	-0.04	-0.16	-0.18	-0.10
Medium-density Fiberboard	0.15	0.04	0.02	0.09	-0.21	0.01	-0.04	-0.16	-0.18	-0.10
Food Discards	0.30	0.08	0.04	0.18	-0.02	0.01	0.29	0.06	0.03	0.17
Yard Trimmings	0.17	0.04	0.02	0.10	-0.21	0.01	-0.03	-0.15	-0.18	-0.09
Grass	0.19	0.05	0.02	0.12	-0.12	0.01	0.09	-0.06	-0.08	0.01
Leaves	0.15	0.04	0.02	0.09	-0.39	0.01	-0.23	-0.34	-0.36	-0.29
Branches	0.15	0.04	0.02	0.09	-0.21	0.01	-0.04	-0.16	-0.18	-0.10
Mixed Paper										
Broad Definition	0.53	0.13	0.07	0.32	-0.23	0.01	0.31	-0.08	-0.15	0.10
Residential Definition	0.49	0.12	0.06	0.29	-0.24	0.01	0.26	-0.10	-0.16	0.07
Office Paper Definition	0.58	0.15	0.07	0.35	-0.21	0.01	0.38	-0.05	-0.12	0.15
Mixed MSW	0.26	0.06	0.03	0.16	-0.10	0.01	0.17	-0.02	-0.06	0.07

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

Exhibit 7-7
Net GHG Emissions from CH_4 Generation at Landfills

Sensitivity Analysis: Varying the Percentage of Waste Disposed at Landfills with Methane Recovery

(a) Material	(b) 17% of Waste Disposed At Landfills With LFG Recovery	(c) 20% of Waste Disposed At Landfills With LFG Recovery	(d) 49% of Waste Disposed At Landfills With LFG Recovery	(e) 55% of Waste Disposed At Landfills With LFG Recovery	(f) 60% of Waste Disposed at Landfills With LFG Recovery
Corrugated Cardboard	0.20	0.19	0.06	0.04	0.02
Magazines/Third-class Mail	-0.05	-0.06	-0.13	-0.14	-0.15
Newspaper	-0.15	-0.16	-0.21	-0.23	-0.24
Office paper	0.89	0.87	0.59	0.54	0.49
Phonebooks	-0.15	-0.16	-0.21	-0.23	-0.24
Textbooks	0.89	0.87	0.59	0.54	0.49
Dimensional Lumber	-0.07	-0.07	-0.11	-0.12	-0.12
Medium-density Fiberboard	-0.07	-0.07	-0.11	-0.12	-0.12
Food Discards	0.25	0.24	0.16	0.15	0.13
Yard Trimmings	-0.05	-0.06	-0.10	-0.11	-0.11
Grass	0.06	0.05	0.01	0.00	-0.01
Leaves	-0.25	-0.26	-0.30	-0.30	-0.31
Branches	-0.07	-0.07	-0.11	-0.12	-0.12
Mixed Paper					
Broad Definition	0.23	0.22	0.09	0.06	0.04
Residential Definition	0.19	0.18	0.06	0.03	0.01
Office Paper Definition	0.30	0.28	0.14	0.11	0.08
Mixed MSW	0.13	0.12	0.06	0.05	0.03

Exhibit 7-8
Net GHG Emissions from CH_4 Generation at Landfills

Sensitivity Analysis: Varying Oxidation and Gas Collection Efficiency Rates. Based on Estimated National Mix of Landfill Gas Recovery Systems in 2000.

Oxidation Rate:	40%	25%	10%	5%
Collection Efficiency:	95%	85%	75%	60%
Material	Lower-bound Emissions	Conservative (High) Emissions	Best Estimate	Upper-bound Emissions
Corrugated Cardboard	0.15	0.22	0.29	0.35
Magazines/Third-class Mail	0.08	0.12	0.16	0.19
Newspaper	0.07	0.11	0.14	0.17
Office Paper	0.35	0.49	0.66	0.78
Phonebooks	0.07	0.11	0.14	0.17
Textbooks	0.35	0.49	0.66	0.78
Dimensional Lumber	0.05	0.07	0.09	0.11
Medium-density Fiberboard	0.05	0.07	0.09	0.11
Food Discards	0.10	0.14	0.18	0.22
Yard Trimmings	0.05	0.08	0.10	0.12
Grass	0.06	0.09	0.12	0.14
Leaves	0.05	0.07	0.09	0.11
Branches	0.05	0.07	0.09	0.11
Mixed Paper				
Broad Definition	0.17	0.24	0.32	0.38
Residential Definition	0.16	0.22	0.29	0.35
Office Paper Definition	0.19	0.26	0.35	0.42
Mixed MSW	0.08	0.12	0.16	0.19