

U.S. Environmental Protection Agency
Office of Resource Conservation and Recovery

**Documentation for Greenhouse Gas Emission and
Energy Factors Used in the Waste Reduction Model
(WARM)**

Management Practices Chapters

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Office of Resource Conservation and Recovery

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Table of Contents

| | | |
|---|--------------------------|-----|
| 1 | Source Reduction | 1-1 |
| 2 | Recycling | 2-1 |
| 3 | Anaerobic Digestion..... | 3-1 |
| 4 | Composting | 4-1 |
| 5 | Combustion..... | 5-1 |
| 6 | Landfilling..... | 6-1 |
| 7 | Energy Impacts..... | 7-1 |

1 SOURCE REDUCTION

This chapter describes the development of material-specific emission factors for source reduction in EPA's Waste Reduction Model (WARM). Source reduction, or waste prevention, refers to practices that reduce the amount of materials entering the waste stream, including changes in the design, manufacture, purchase or use of materials. This document provides examples of source reduction and a summary of how EPA estimates the GHG benefits from source reduction of materials.

1.1 TYPES OF SOURCE REDUCTION

Source reduction can result from any activity that reduces the amount of a material or agricultural input needed and therefore used to make products or food.¹ Some specific examples of source reduction practices are:

- Redesigning products to use fewer materials (e.g., lightweighting, material substitution).
- Reusing products and materials (e.g., a refillable water bottle).
- Extending the useful lifespan of products.
- Avoiding using materials in the first place (e.g., reducing junk mail, reducing demand for uneaten food).

In addition to the activities above, there are limited circumstances where the emission factors can be used to estimate GHG benefits of substituting one material or product for another material or product. Section 1.3.2 presents considerations for estimating the GHG effects of material substitution.

1.2 A SUMMARY OF THE GHG IMPLICATIONS OF SOURCE REDUCTION

When a material is source reduced, GHG emissions associated with producing the material and/or manufacturing the product and managing the post-consumer waste are avoided. Consequently, source reduction provides GHG emission benefits by: (1) avoiding the "upstream" GHGs emitted in the raw material acquisition, manufacture or production and transport of the source-reduced material; (2) increasing the amount of carbon stored in forests (when wood and paper products are source reduced); and (3) avoiding the downstream GHG emissions from waste management.

Because many materials are manufactured from a mix of virgin and recycled inputs, the quantity of virgin material production that is avoided is not always equal to the quantity of material source reduced. Therefore, to estimate GHG emissions associated with source reduction, WARM uses a mix of virgin and recycled inputs, based on the national average for each material. However, WARM also allows users to evaluate the benefits of source reducing materials manufactured from 100-percent virgin inputs, instead of a mix of virgin and recycled inputs. For some materials, such as food waste and some wood products, it is either not possible or very uncommon to use recycled inputs during material production, so WARM always assumes material production using 100 percent virgin inputs.

WARM assumes that source reduction of paper and wood products increases the amount of carbon stored in forests by reducing the amount of wood harvested. For more information on the calculations that went into creating the forest carbon storage offset, see the [Forest Carbon Storage](#) chapter.

In order to measure the full GHG impact of source reduction, the user must compare the GHG emissions from source reduction to the GHG emissions of another materials management option. For example, a user could compare the benefits from source reducing one short ton of office paper instead

¹ The source reduction pathway was added for food waste in June 2014 into WARM Version 13.

of sending the paper to the landfill. This approach enables policy-makers to evaluate, on a per-ton basis, the overall difference in GHG emissions between (1) source reducing one short ton of material, and (2) manufacturing and then managing (post-consumer) one short ton of the same material. For most materials, source reduction has lower GHG emissions than the other materials management options.²

1.3 APPLYING EMISSION FACTORS TO SPECIFIC SOURCE REDUCTION STRATEGIES

1.3.1 Calculating the Energy and GHG Emissions Benefits of Reuse

The GHG and energy benefits of reusing non-food materials or products multiple times before they are sent for end-of-life management can be modeled using the source reduction pathway in WARM. The process for calculating the GHG and energy benefits of reuse is as follows:

1. Using the downloadable (i.e., Excel-based) version of WARM, run the model using a baseline scenario of landfilling, recycling, combustion or composting (depending on the likely fate of the material or product if it is not reused), and an alternate scenario of source reduction. For example, if the item was originally destined for a landfill and now will be reused, the baseline scenario is landfilling.
2. Select whether the reused material is manufactured from 100-percent virgin inputs or the current mix of virgin and recycled inputs.³ (The assumption that the material is manufactured from 100-percent virgin inputs indicates an upper bound estimate of the benefits from reuse.)
3. Multiply the GHG emissions reduction result (i.e. “total change in GHG emissions” from WARM) by the number of times the material is reused. The reuse number should equal one less than the number of total uses to account for the production of the initial material.

This methodology for calculating the GHG benefits from reuse is summarized in the following formula. Energy use can be similarly calculated by replacing the GHG emission factors with energy use factors.

$$GHG\ Benefits\ of\ Reuse = (N - 1) \times (A)$$

Where,

N = Number of total uses

A = GHG benefits of the source reduction (alternate) pathway minus the baseline pathway (i.e., “total change in GHG emissions” from WARM)

For example, consider reusable HDPE plastic crates, weighing 1,000 short tons total, used for transporting bread to a grocery store. Assume that the crates are typically recycled after each use, but could be reused up to 20 times before they are recycled. In order to calculate the GHG benefits of reusing the crates, the user can run WARM using a baseline of recycling 1,000 short tons HDPE and an alternate scenario of source reducing 1,000 short tons HDPE. Assuming that reusing the crates offsets the production of HDPE crates that would otherwise have been manufactured from 100-percent virgin

² The most notable exceptions are for aluminum cans and carpet, where recycling benefits are higher. For aluminum cans, source reduction benefits (for the current mix of inputs) are smaller than recycling benefits. This is because of two factors: (1) the large difference in GHG emissions between virgin and recycled manufacture of aluminum cans and (2) the relatively high recycled content (68 percent) in aluminum cans. In this instance, source reduction is relatively less beneficial because of the high recycled content of a “virgin” can. The discrepancy in the carpet emission factors is due to the open-loop recycling process modeled for carpets (see the [Carpet](#) chapter for more details).

³ Some materials modeled in WARM utilize 100% virgin materials in the “current mix” of inputs. This is in cases where information on the share of recycled inputs used in production is unavailable or is not a common practice.

inputs, WARM's results indicate that source reduction of 1,000 short tons of HDPE crates results in a net emissions reduction of 692 MTCO₂E relative to the baseline recycling scenario.⁴

The GHG benefits should then be multiplied by 19 reuses (i.e., 20 total uses – 1 original use). Energy use can be similarly calculated by replacing the GHG emission factors with energy use factors. In equation form:

$$\text{GHG Benefits of Reuse} = 19 \times (\text{source reduction of 1,000 short tons HDPE} - \text{recycling of 1,000 short tons HDPE})$$

100% virgin inputs (upper bound for reductions):

$$\text{GHG Benefits of Reuse} = 19 \times (692 \text{ MTCO}_2\text{E}) = 13,148 \text{ MTCO}_2\text{E}$$

1.3.2 Calculating the Energy and GHG Emissions Benefits of Material Substitution

The analysis of source reduction is based on an assumption that source reduction is achieved by practices such as lightweighting, double-sided copying and material reuse. However, it is also possible to source reduce one type of material by substituting another material. The GHG impact of this type of source reduction is the net GHG benefits from source reduction of the original material and manufacturing and disposing of the substitute material.

Where both the original material and the substitute material are available in WARM, the GHG impacts of source reduction with material substitution may be estimated as long as users verify that the material production and end-of-life pathways in WARM are representative of the materials involved in the substitution. However, for cases where one of the materials in the substitution pair is not in WARM, a quantitative analysis of source reduction with material substitution is beyond the scope of the emission factors described in this documentation. The large number of materials that could be substituted for the materials available in WARM, and the need for specific information on application of material substitution, make such an analysis prohibitive and highly uncertain.

In the case where both the material being replaced and its substitute are in WARM, the GHG benefits can be estimated as described below. Note that this calculation cannot be run in WARM, because WARM requires the user to have the same material in the baseline and alternate scenarios:

1. Calculate the GHG emissions from manufacturing and end-of-life management of the original material that will be replaced by the substitute material (i.e., the baseline scenario; see equations below for an explanation of this calculation).
2. Calculate the GHG emissions from manufacturing and end-of-life management of the substitute material (i.e., the alternate scenario; see equations below for an explanation of this calculation).
3. Calculate the mass substitution rate. The mass substitution rate is the number of tons of substitute material used per ton of original material. In calculating the mass substitution rate, users should also account for any difference in the number of times that a product made from the original material is used prior to waste management, compared to the number of times a product made from the substitute material will be used prior to waste management.
4. Calculate the net GHG benefits by subtracting the GHG emissions that would have been generated to produce the baseline material from the GHG emissions generated by producing an equivalent amount of the substitute materials.

⁴ If reusing the crates offsets crates that would otherwise have been manufactured from the current mix of virgin and recycled inputs, source reduction of 1,000 short tons HDPE would result in a net emissions reduction of 589 MTCO₂E relative to the baseline recycling scenario.

This basic methodology for calculating the GHG benefits of material substitution is summarized in the following formula. Energy use can be similarly calculated by replacing the GHG emission factors with energy use factors.

$$\text{GHG Benefits of Material Substitution} = (EF_{\text{alternate material}} * MS - EF_{\text{baseline material}})$$

Where,

$EF_{\text{alternate material}}$ = GHG emissions from production and end-of-life management of the substitute material per unit of substitute material

$EF_{\text{baseline material}}$ = GHG emissions from production and end-of-life management of the original material per unit of original material

MS = Material substitution rate = Amount of substitute material required to replace a unit of the original material

Because source reduction GHG emission factors represent the benefits of avoided production of materials, the GHG emissions generated by the production of materials can be calculated by taking the absolute value of WARM's source reduction factors. The energy or GHG emissions from end-of-life management can be calculated using the various end-of-life materials management factors in WARM (e.g., recycling, composting, combustion or landfilling). Consequently, the $EF_{\text{alternate material}}$ and $EF_{\text{baseline material}}$ terms are equal to:

$$EF_{\text{alternate material}} = -EF_{\text{source reduction, alternate material}} + EF_{\text{end-of-life management, alternate material}}$$

$$EF_{\text{baseline material}} = -EF_{\text{source reduction, baseline material}} + EF_{\text{end-of-life management, baseline material}}$$

Where,

$EF_{\text{source reduction}}$ = WARM emission factor for source reduction of the baseline and alternative materials

$EF_{\text{end-of-life management}}$ = WARM emission factor for the end-of-life management practice (recycling, composting, combustion or landfilling) used to manage the baseline and alternative materials

1.4 LIMITATIONS

Because the data presented in this chapter were developed using data presented in the raw materials and acquisition section of the [Overview](#) chapter (and the [Forest Carbon Storage](#) chapter), the limitations discussed there also apply to the values presented here. Other limitations include:

- The source reduction factors for food waste materials are meant to capture the emissions avoided through waste reduction. They are the closest pathway available in WARM to approximate the benefits from food reuse and donation, but they likely overstate the benefits. Applying source reduction factors to donated materials assumes that the donation completely offsets the use of new materials, but this may not be the case. For example, edible food can be donated to feed hungry people, and while this may offset the demand for other food, it is unlikely that the donation will entirely offset the production of an equivalent amount of food. Also, food donations could be reused for other purposes such as feed for livestock, which would instead offset the production of traditional livestock feed. EPA is conducting research into how to address food donation and food waste reuse in WARM.

- WARM allows users to model source reduction for several mixed material types: mixed paper (all types), mixed metals, mixed plastics, food waste, food waste (meat only), and food waste (non-meat). For these mixed material categories, all components can be individually source reduced in WARM and users could reasonably implement activities or purchasing practices that would reduce a representative mix of these materials. The other mixed materials in WARM—mixed recyclables, mixed organics, and mixed MSW—cannot be source reduced because they contain a broader mixture of materials at end-of-life where users could not reasonably implement activities or purchasing practices that reduce demand for all components. Additionally, mixed MSW and mixed organics include waste materials for which there is no source reduction pathway in WARM.
- There may be additional GHG impacts from disposal of industrial wastes, particularly paper sludge at paper mills. Because of the complexity of analyzing these second-order effects and the lack of data, EPA did not include them.

2 RECYCLING

This chapter describes the development of material-specific emission factors for recycling in EPA's Waste Reduction Model (WARM). A discussion of forest carbon storage, an important input in calculating the emission benefits of paper product recycling, is also included in this chapter.

2.1 A SUMMARY OF THE GHG IMPLICATIONS OF RECYCLING

EPA defines recycling as “the separation and collection of wastes, their subsequent transformation or remanufacture into usable or marketable products or materials, and the purchase of products made from recyclable materials” (EPA, 2012). WARM considers the recycling of post-consumer materials, which are defined as a “material or finished product that has served its intended use and has been diverted or recovered from waste destined for disposal, having completed its life as a consumer item” (EPA, 2014).

Recycling is a process that takes materials or products that are at end of life and transforms them into either (1) the same product or (2) a secondary product (see discussion of open- and closed-loop recycling). When a material is recycled, it is used in place of virgin inputs in the manufacturing process, rather than being disposed of and managed as waste. Consequently, recycling provides GHG reduction benefits in two ways, depending upon the material recycled: (1) it offsets a portion of “upstream” GHGs emitted in raw material acquisition, manufacture and transport of virgin inputs and materials, and (2) it increases the amount of carbon stored in forests (when wood and paper products are recycled).

In calculating the first source of GHG reduction benefits, WARM assumes that recycling materials does not cause a change in the amount of materials that would otherwise have been manufactured. Since the amount of products manufactured stays the same, and the existing demand for recycled content is the same, an increase in recycling leads to a displacement of virgin-sourced materials.

For more information on the second source of GHG reduction benefits that are provided by forest carbon storage, see the [Forest Carbon Storage](#) chapter.

2.1.1 Open- and Closed-Loop recycling

Recycling processes can be broadly classified into two different categories: open-loop and closed-loop recycling. Most of the materials in WARM are modeled in a closed-loop recycling process, where end-of-life products are recycled into the same product. An example of a closed-loop recycling process is recycling an aluminum can back into another aluminum can. Decisions about whether to model materials in an open-loop or closed-loop process are based on how the material is most often recycled and the availability of data.

For materials recycled in an open loop, the products of the recycling process (secondary product) are not the same as the inputs (primary product). In open-loop emission factors, the GHG benefits of material recycling result from the avoided emissions associated with the virgin manufacture of the *secondary* products that the material is recycled into. Open-loop recycling does not account for avoided emissions from manufacturing the primary material, since recycling the recycled material does not displace manufacturing of the primary material. It only displaces manufacturing of the secondary product. For example, personal computers (PCs) are recycled by dismantling the PC and recovering and processing the raw materials it contains for use in secondary products. WARM models the plastics from PCs as being recycled into asphalt, rather than into new computer casings; the other materials in PCs also are recycled into non-PC products. Consequently, WARM calculates the GHG benefit from recycling PCs based on the emissions displaced from extracting and producing these secondary products from

virgin inputs, rather than on the emissions displaced from manufacturing an entire new PC. In applying this method, EPA considers only the GHG benefit for one generation of recycling (i.e., future benefits from recycling the secondary products into additional products were not included).

The materials modeled as open-loop recycling processes in WARM are: mixed paper, corrugated containers (partial open-loop),⁵ copper wire, carpet, personal computers, concrete, tires, fly ash, asphalt shingles and drywall (partial open-loop).⁶ Corrugated containers and drywall are modeled as partial open-loop because the recycling emission factors for these materials are a weighted average of a closed-loop recycling pathway and an open-loop recycling pathway (e.g., 70 percent of recycled corrugated containers are used in production of more corrugated containers, and 30 percent of corrugated containers are recycled into boxboard). Fly ash is a special case: because it is a byproduct rather than a primary product, it would be impossible to recycle into additional primary product. For more detail on any of the materials mentioned, please refer to the material-specific chapter.

2.1.2 Material Losses

When any material is recovered for recycling, some portion of the recovered material is unsuitable for use as a recycled input. This portion is discarded either in the recovery stage (i.e., at collection and at the materials recovery facility) or in the manufacturing stage. Consequently, more than one short ton of material must be recovered and processed to produce one short ton of new material from the recycling process. Material losses are quantified and translated into loss rates. In this analysis, EPA used estimates of loss rates provided by Franklin Associates, Limited (FAL, 2003), for steel, dimensional lumber and medium-density fiberboard (the same materials for which FAL's energy data were used, as described in the Source Reduction chapter). Loss rates for a number of other materials were based on data compiled by EPA's Office of Research and Development (ORD) and the Research Triangle Institute (RTI, 2004). Material-specific sources were consulted for the remaining materials. These values are shown in Exhibit 2-1.

Exhibit 2-1: Loss Rates for Recovered Materials

| (a) Material | (b) % of Recovered Materials Retained in the Recovery Stage | (c) Short Tons of Product Made per Short Ton of Recycled Inputs In the Manufacturing Stage | (d) Short Tons of Product Made per Short Ton Recovered Materials (d = b × c) | (e) Data Source ^a |
|-----------------------|--|---|---|-------------------------------------|
| Aluminum Cans | 100 | 0.93 | 0.93 | RTI, 2004 |
| Aluminum Ingot | 100 | 0.93 | 0.93 | Aluminum cans used as proxy |
| Steel Cans | 100 | 0.98 | 0.98 | FAL, 2003 |
| Copper Wire | 82 | 0.99 | 0.81 | FAL, 2003 |
| Glass | 90 | 0.98 | 0.88 | FAL, 2003; RTI, 2004 |
| HDPE | 92 | 0.93 | 0.86 | FAL, 2011 |
| PET | 95 | 0.94 | 0.89 | FAL, 2011 |
| Corrugated Containers | 100 | 0.93 | 0.93 | FAL, 2003; RTI, 2004 |

⁵ Note that corrugated containers are modeled using a partial open-loop recycling process. Roughly 70 percent of the recycled corrugated containers are closed-loop (i.e., replaces virgin corrugated) and 30 percent is open-loop (i.e., replaces boxboard).

⁶ Most recycled drywall is used for a variety of agricultural purposes, but can also be recycled back into new drywall. Approximately 20 percent of recycled drywall is closed-loop (i.e., replaces virgin drywall) and 80 percent is open-loop (i.e., used for agricultural purposes).

| (a) Material | (b) % of Recovered Materials Retained in the Recovery Stage | (c) Short Tons of Product Made per Short Ton of Recycled Inputs In the Manufacturing Stage | (d) Short Tons of Product Made per Short Ton Recovered Materials (d = b × c) | (e) Data Source ^a |
|----------------------------|--|---|---|-------------------------------------|
| Magazines/Third-Class Mail | 95 | 0.71 | 0.67 | FAL, 2003; RTI, 2004 |
| Newspaper | 95 | 0.94 | 0.90 | FAL, 2003; RTI, 2004 |
| Office Paper | 91 | 0.66 | 0.60 | FAL, 2003; RTI, 2004 |
| Phone Books | 95 | 0.71 | 0.68 | FAL, 2003; RTI, 2004 |
| Textbooks | 95 | 0.69 | 0.66 | FAL, 2003; RTI, 2004 |
| Dimensional Lumber | 88 | 0.91 | 0.80 | FAL, 2003 |
| Medium-Density Fiberboard | 88 | 0.91 | 0.80 | FAL, 2003 |
| Personal Computers | 100 | 0.71 ^c | 0.71 | FAL, 2002b |
| Concrete | 100 | 1.00 | 1.00 | See note d |
| Fly Ash | 100 | 1.00 | 1.00 | See note d |
| Tires | 90 | 0.86 | 0.78 | Corti & Lombardi, 2004 |
| Asphalt Concrete | 100 | 1.00 | 1.00 | Levis 2008 ^d |
| Asphalt Shingles | 100 | 0.07 | 0.93 | Berenyi, 2007 |
| Drywall | 100 | 1.00 | 1.00 | WRAP, 2008 |

^a Franklin Associates, Ltd. (FAL) provided data for column (b), while the Research Triangle Institute (RTI) provided data for column (c).

^b A 0.5% loss rate was assumed for molded products from carpet recycling, based on data provided by FAL (2002a). No loss was assumed for the carpet pad/cushion and carpet backing. Since molded products make up 25% of the materials recovered from recycling carpet, the loss rate was weighted by this percentage to calculate the overall amount of material retained: $(100\% - 0.05\% \times 25\%) / 100 = 1.00$.

^c Weighted average of the materials that personal computers are assumed to be recycled into in an open-loop recycling process; i.e., asphalt, steel sheet, lead bullion, cathode ray tube (CRT) glass, copper wire and aluminum sheet.

^d Due to the nature of the recycling process for fly ash and concrete, these materials are collected and recycled on a ton-per-ton basis, offsetting the production of portland cement and virgin aggregates, respectively.

^e Loss rates for recycling asphalt concrete are less than 1% by mass. Since the recovered asphalt concrete is extremely valuable and typically recovered on-site, the retention rate for recovered asphalt concrete is quite high.

Explanatory notes: The value in column (b) accounts for losses such as recovered newspapers that were unsuitable for recycling because they were too wet. Column (c) reflects process waste losses at the manufacturing plant or mill. Column (d) is the product of the values in columns (b) and (c).

2.1.3 Calculating the GHG Impacts of recycling

WARM assesses the GHG emission implications of recycling from the point of waste generation (i.e., starting at the point when the material is collected for recycling) through the point where the recycled material or product has been manufactured into a new product for use. This includes all of the GHG emissions associated with collecting, transporting, processing and recycling or manufacturing the recycled material into a new product for use. To account for the emissions associated with virgin manufacture, WARM calculates a “recycled input credit” by assuming that the recycled material avoids—or offsets—the upstream GHG emissions associated with producing the same amount of material from virgin inputs.

The approach for calculating the recycled input credit depends upon whether the material is recycled in a closed- or open-loop process. GHG emission reductions associated with closed-loop manufacture using recycled inputs are calculated by taking the difference between (1) the GHG emissions from manufacturing a material (accounting for loss rates) from 100-percent recycled inputs,

and (2) the GHG emissions from manufacturing an equivalent amount of the material from 100-percent virgin inputs.

For open-loop recycling processes, the emission reductions are calculated by taking the difference between (1) the GHG emissions from manufacturing a secondary product from 100-percent recycled inputs, and (2) the GHG emissions from manufacturing an equivalent amount of the secondary product (accounting for loss rates) from 100-percent virgin inputs.

The methodology for estimating resource acquisition and manufacturing emissions is described in the [WARM Background and Overview](#) chapter. There are separate estimates for manufacturing process emissions for virgin inputs and recycled inputs, and transportation for virgin inputs and recycled inputs. For details on the components of the manufacturing process and transportation inputs, see the [WARM Background and Overview](#) chapter.

The recycling GHG emission factors are provided in the chapters corresponding to each individual material modeled in WARM. These GHG emission factors represent the GHG emissions associated with recycling each material into a new product for use, minus a GHG emission offset for avoiding the manufacture of an equivalent amount of the product from virgin inputs.

In evaluating the relative GHG reduction benefits of recycling compared to an existing materials management practice (i.e., evaluating the benefits of recycling relative to source reduction, composting, combustion or landfilling), the recycling GHG emission factors developed in WARM must be compared against the corresponding emission factors for the existing management practice. For example, to evaluate the GHG emission reductions from recycling one short ton of aluminum cans instead of sending the same quantity to the landfill, the GHG emission factor for landfilling one short ton of aluminum cans must be subtracted from the recycling emission factor for aluminum cans. Please see the [WARM Background and Overview](#) chapter for additional explanation of the comparative aspect of WARM emission factors.

2.2 RESULTS

The national average results of this analysis are shown in Exhibit 2-2. The net GHG emission reductions from recycling of each material are shown in column (f). As stated earlier, these estimates of net GHG emissions are expressed for recycling in absolute terms, and are not values relative to another waste management option, although they must be used comparatively, as all WARM emission factors must be. They are expressed in terms of short tons of waste input (i.e., tons of waste prior to processing).

Exhibit 2-2: Emission Factor for Recycling (MTCO₂E/Short Ton of Material Recovered)

| (a) Material | (b) Recycled Input Credit: ^a Process Energy | (c) Recycled Input Credit: ^a Transportation Energy | (d) Recycled Input Credit: ^a Process Non- Energy | (e) Forest Carbon Storage | (f) GHG Reductions from Using Recycled Inputs Instead of Virgin Inputs (f = b + c + d + e) |
|---------------------|--|---|---|------------------------------------|---|
| Aluminum Cans | -5.35 | -0.04 | -3.72 | – | -9.11 |
| Aluminum Ingot | -3.98 | -0.03 | -3.18 | – | -7.19 |
| Steel Cans | -1.77 | -0.04 | 0.00 | – | -1.81 |
| Copper Wire | -4.65 | -0.06 | 0.00 | – | -4.71 |
| Glass | -0.12 | -0.02 | -0.14 | – | -0.28 |
| HDPE | -0.72 | 0.02 | -0.17 | – | -0.87 |
| LDPE | NA | NA | NA | NA | NA |
| PET | -0.88 | 0.11 | -0.34 | 0.00 | -1.12 |
| LLDPE | NA | NA | NA | NA | NA |

| (a) Material | (b) Recycled Input Credit: ^a Process Energy | (c) Recycled Input Credit: ^a Transportation Energy | (d) Recycled Input Credit: ^a Process Non- Energy | (e) Forest Carbon Storage | (f) GHG Reductions from Using Recycled Inputs Instead of Virgin Inputs (f = b + c + d + e) |
|--------------------------------------|--|---|---|--|---|
| PP | NA | NA | NA | NA | NA |
| PS | NA | NA | NA | NA | NA |
| PVC | NA | NA | NA | NA | NA |
| PLA | NA | NA | NA | NA | NA |
| Corrugated Containers | -0.01 | -0.05 | -0.01 | -3.06 | -3.12 |
| Magazines/Third-Class Mail | -0.01 | – | – | -3.06 | -3.07 |
| Newspaper | -0.70 | -0.03 | – | -2.02 | -2.75 |
| Office Paper | 0.21 | – | -0.02 | -3.06 | -2.86 |
| Phone Books | -0.62 | – | – | -2.02 | -2.64 |
| Textbooks | -0.05 | – | – | -3.06 | -3.11 |
| Dimensional Lumber | 0.07 | 0.01 | – | -2.53 | -2.46 |
| Medium-Density Fiberboard | 0.05 | 0.02 | – | -2.53 | -2.47 |
| Food Waste | NA | NA | NA | NA | NA |
| Food Waste (meat only) | NA | NA | NA | NA | NA |
| Food Waste (non-meat) | NA | NA | NA | NA | NA |
| Beef | NA | NA | NA | NA | NA |
| Poultry | NA | NA | NA | NA | NA |
| Grains | NA | NA | NA | NA | NA |
| Bread | NA | NA | NA | NA | NA |
| Fruits and Vegetables | NA | NA | NA | NA | NA |
| Dairy Products | NA | NA | NA | NA | NA |
| Yard Trimmings | NA | NA | NA | NA | NA |
| Grass | NA | NA | NA | NA | NA |
| Leaves | NA | NA | NA | NA | NA |
| Branches | NA | NA | NA | NA | NA |
| Mixed Paper | | | | | |
| Mixed Paper (general) | -0.36 | -0.11 | -0.01 | -3.06 | -3.53 |
| Mixed Paper (primarily residential) | -0.36 | -0.11 | -0.01 | -3.06 | -3.53 |
| Mixed Paper (primarily from offices) | -0.42 | -0.11 | -0.00 | -3.06 | -3.59 |
| Mixed Metals | -3.01 | -0.04 | -1.29 | – | -4.34 |
| Mixed Plastics | -0.82 | 0.07 | -0.28 | – | -1.02 |
| Mixed Recyclables | -0.22 | -0.03 | -0.07 | -2.50 | -2.82 |
| Mixed Organics | NA | NA | NA | NA | NA |
| Mixed MSW | NA | NA | NA | NA | NA |
| Carpet | -1.41 | -0.01 | -0.94 | – | -2.36 |
| Personal Computers | -1.58 | -0.04 | -0.88 | – | -2.50 |
| Clay Bricks | NA | NA | NA | NA | NA |
| Concrete | -0.00 | -0.01 | – | – | -0.01 |
| Fly Ash | -0.42 | – | -0.45 | – | -0.87 |
| Tires | -0.46 | 0.08 | – | – | -0.38 |
| Asphalt Concrete | -0.03 | -0.05 | – | NA | -0.08 |
| Asphalt Shingles | -0.11 | 0.01 | – | NA | -0.09 |
| Drywall | 0.01 | 0.02 | – | – | 0.03 |
| Fiberglass Insulation | NA | NA | NA | NA | NA |
| Vinyl Flooring | NA | NA | NA | NA | NA |
| Wood Flooring | NA | NA | NA | NA | NA |

NA = Not applicable. For the plastic resin material types, only HDPE and PET recycling are modeled in WARM due to LCI data availability.

– = Zero emissions.

Note that totals may not add due to rounding, and more digits may be displayed than are significant. Negative values denote GHG emission reductions or carbon storage.

^a Material that is recycled after use is then substituted for virgin inputs in the production of new products. This credit represents the difference in emissions that results from using recycled inputs rather than virgin inputs. The credit accounts for loss rates in collection, processing and remanufacturing. Recycling credit is based on closed- and open-loop recycling, depending on material.

2.3 LIMITATIONS

The data presented in this document involve GHG emissions associated with the raw materials and acquisition of materials; therefore, the limitations related to raw materials and acquisition for specific material types are provided in respective material type chapters. Other limitations are as follows:

- The recycling results are reported in terms of GHG emissions per short ton of material collected for recycling. Thus, the emission factors incorporate assumptions on loss of material through collection, sorting and remanufacturing. There is uncertainty in the loss rates: some materials recovery facilities and manufacturing processes may recover or use recycled materials more or less efficiently than as estimated here.
- Because the modeling approach assumes closed-loop recycling for most materials, it does not fully reflect the prevalence and diversity of open-loop recycling. Most of the materials in the analysis are recycled into a variety of manufactured products, not just into the original material. Resource limitations prevent an exhaustive analysis of all of the recycling possibilities for each of the materials analyzed.
- For the purpose of simplicity, EPA assumed that increased recycling does not change overall demand for products. In other words, it was assumed that each incremental short ton of recycled inputs would displace virgin inputs in the manufacturing sector. In reality, there may be a relationship between recycling and demand for products with recycled content, since these products become cheaper as the supply of recycled materials increases.

2.4 REFERENCES

- Berenyi, E. B. (2007). *Materials Recycling and Processing in the United States*. Westport, CT: Governmental Advisory Associates, Inc.
- Corti, A., & Lombardi, L. (2004). End life tyres: Alternative final disposal processes compared by LCA. *Energy*. 29 (12–15), 2089–2108. doi:10.1016/j.energy.2004.03.014
- EPA (2014). EPA's Comprehensive Procurement Guideline Glossary. <http://www.epa.gov/wastes/conserves/tools/cpg/resources.htm#glossary>
- EPA (2012). Appendix C: Glossary, RCRA Orientation Manual 2011: Resource Conservation and Recovery Act.
- FAL (2003). Loss rates provided by in-house data from Franklin Associates, Ltd., Prairie Village, KS.
- FAL (2002a). *Energy and Greenhouse Gas Factors for Nylon Broadloom Residential Carpet*. Prairie Village, KS: Franklin Associates Ltd., July 3, 2002.
- FAL (2002b). *Energy and Greenhouse Gas Factors for Personal Computers*. Final Report. Prepared by Franklin Associates Ltd., Prairie Village, KS, for the U.S. Environmental Protection Agency (EPA), August 7, 2002.

- FAL (2011). *Life Cycle Inventory of 100% Postconsumer HDPE and PET Recycled Resin from Postconsumer Containers and Packaging: Revised Final Report*. Prepared by Franklin Associated Ltd. for the Plastics Division of the American Chemistry Council. January 19, 2011.
- ICF Consulting. (1996). Memorandum to EPA Office of Solid Waste: "Methane Generation from Paper Sludge," December.
- Levis, J. W. (2008). *A Life-Cycle Analysis of Alternatives for the Management of Waste Hot-Mix Asphalt, Commercial Food Waste, and Construction and Demolition Waste*. Raleigh: North Carolina State University.
- RTI. (2004). Unpublished database developed jointly by the Research Triangle Institute and the U.S. Environmental Protection Agency Office of Research and Development.
- WRAP. (2008). *Life Cycle Assessment of Plasterboard*. Waste & Resources Action Programme. United Kingdom. April 2008.

3 ANAEROBIC DIGESTION

This chapter describes the development of anaerobic digestion emission factors for EPA's Waste Reduction Model (WARM). Included are estimates of the net greenhouse gas (GHG) emissions from anaerobic digestion of yard trimmings, food waste, and mixed organics waste.

3.1 A SUMMARY OF THE GHG IMPLICATIONS OF ANAEROBIC DIGESTION

During anaerobic digestion, degradable materials, such as yard trimmings and food waste, are digested in a reactor in the absence of oxygen to produce biogas that is between 50-70% methane (CH₄). This biogas is then typically burned on-site for electricity generation.⁷ WARM includes anaerobic digestion as a materials management option for yard trimmings, food waste, and mixed organics (i.e., yard trimmings plus food waste). Although there are many different categories of food waste, including food waste from residential sources, commercial sources, waste from specific types of commercial entities, vegetables, and meat, EPA has not located satisfactory data on how the characteristics of these different types of waste vary when managed at end of life. As a result, all food waste is treated as one material in the anaerobic digestion management practice in WARM. The same assumption was made for the landfilling, composting, and combustion pathways in WARM.

Anaerobic digestion is a biological process in which microorganisms break down organic material in the absence of oxygen. While breaking down this matter, the microorganisms release biogas and leave behind digested solids referred to as digestate. WARM's approach to anaerobic digestion assumes that the biogas is used for electricity generation and to heat the digester while the digestate is ultimately applied to agricultural lands.

There are different types of digesters including wet and dry digesters. Wet digesters involve the addition of water during the digestion process; the liquid resulting from digestion is recovered and returned to the reactor once the process is complete. Dry digesters do not require the addition of water. EPA developed separate estimates of emissions for wet anaerobic digesters and dry anaerobic digesters. Due to the high amount of preprocessing that would be required, EPA assumes that wet digester operators do not use yard trimmings as a feedstock. Therefore dry digestion is the only digestion option for yard trimmings and mixed organics. EPA also modeled two digestate management scenarios: the direct application of digestate to land and the curing of digestate before land application. As modeled in WARM, anaerobic digestion results in carbon dioxide (CO₂) emissions from transportation, preprocessing and digester operations, carbon storage (associated with application of digestate to agricultural soils), nitrogen and phosphorous fertilizer offsets, net electricity offsets, and where applicable, digestate curing. Emissions estimates also include fugitive emissions of CH₄ and nitrous oxide (N₂O) produced during digestate decomposition.

3.2 CALCULATING THE GHG IMPACTS OF ANAEROBIC DIGESTION

The stages of an anaerobic digestion operation that contributed to the WARM anaerobic digestion energy and emission factors include the following processes:

- Transport of materials
- Preprocessing and digester operations
- Biogas collection and utilization
- Curing and land application
- Fugitive CH₄ and N₂O emissions

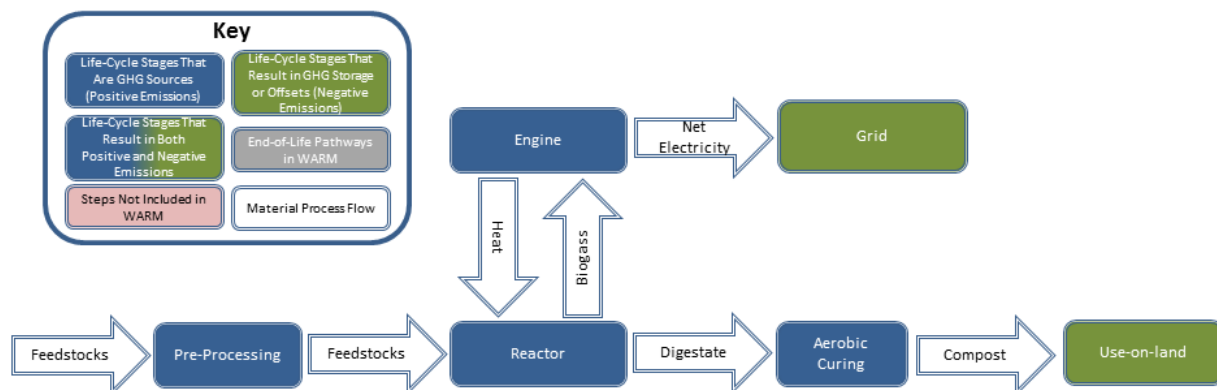
⁷ The generated biogas can be used for other applications such as vehicle fuel or upgrading to pipeline-quality natural gas. These biogas applications are not modeled in WARM.

- Carbon storage
- Avoided fertilizer offsets
- Net electricity offsets

There are numerous configurations of anaerobic digestion facilities. WARM includes the emissions associated with both a continuous single-stage, wet, mesophilic digester and a single-stage, dry, mesophilic digester. Wet digestion is the most widely-used technology in practice (when including the co-digestion of food waste with wastewater sludge or manure). The modeled wet digester is assumed to process only food waste whereas the dry digester may accept food waste, yard trimmings and mixed organics. Dry digestion systems are projected to represent the majority of anaerobic digestion growth in the United States (The Environmental Research & Education Foundation, 2015). Both the wet and dry digesters modeled in WARM may utilize the biogas produced to heat the reactor and to generate electricity on-site. A majority of currently operational facilities beneficially use biogas (The Environmental Research & Education Foundation, 2015). EPA assumes that the generated electricity is used to power the anaerobic digestion facility and excess electricity is sold to the regional electrical grid. Depending on the system type, the digestate removed from the reactor is dewatered and can be aerobically cured. The resulting compost is land applied and assumed to store carbon and offset nitrogen and phosphorus fertilizer use.

Exhibit 3-1 below shows a flow diagram of the different processes within anaerobic digestion. Feedstock materials, such as food waste, are pre-processed. Pre-processing includes grinding, screening and mixing the feedstock before it is fed into the digester. The digester releases biogas which is combusted in an internal combustion engine to generate electricity and heat. The heat is captured and used to heat the reactor while the net electricity generated is exported to the electrical grid, offsetting grid electricity generation. The digestate is removed from the digester and, in the case of a wet digester, dewatered. The digestate is either aerobically cured before land application or directly applied to agricultural lands.

Exhibit 3-1: Flow Diagram of Anaerobic Digestion as Modeled in WARM



The process modeled within WARM results in biogenic CO₂ emissions associated with decomposition after the resulting compost is added to the soil. Because this CO₂ is biogenic in origin, however, it is not counted as a GHG in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* and is not included in this accounting of emissions and sinks.⁸

⁸ For more information on biogenic carbon emissions, see the text box, “CO₂ Emissions from Biogenic Sources” in the [WARM Background and Overview](#) chapter.

The following sections provide additional detail on the data sources and methods used to develop emissions factors. Section 0 describes the material properties required to model anaerobic digestion. Section 3.2.2 describes the diesel used to transfer the solids and feedstocks, transport the digestate and spread the compost during land application. Section 3.2.3 discusses the inputs required for the operation of the anaerobic digester including fuel and electricity use, water requirements and losses. Section 3.2.4 outlines the biogas collection process and the avoided emissions from combusting the methane. Section 3.2.5 describes the curing and land application process. Section 3.2.6 details the fugitive CH₄ and N₂O emissions that occur during digestate curing and after land application. Section 3.2.7 describes the components of carbon storage. Section 3.2.8 discusses the avoided nitrogen and phosphorous fertilizer amounts and emissions from land application of digestate.

3.2.1 Calculating Material Properties

In modeling anaerobic digestion, EPA first determined the amount of carbon contained in degradable materials that will be anaerobically digested. Although a large body of research exists on CH₄ generation from mixed solid wastes, only a few investigators—most notably Dr. Morton Barlaz and colleagues at North Carolina State University—have measured the behavior of specific waste wood, paper, food waste and yard trimming components. The results of their experiments yield data on the inputs—specifically the initial carbon contents, CH₄ generation and carbon stored—that are required for calculating material-specific emission factors for WARM.

The anaerobic digestion process requires eight material properties for each organic feedstock. Net emission values are calculated for mixed yard trimmings and mixed organics based on the weighted average emission factors for the constituent materials (i.e., food waste, branches, grass, and leaves). Exhibit 3-2 shows the material properties based on the work of Dr. Barlaz and are consistent with the methodology used for landfilling in WARM, as described in the [Landfilling](#) Chapter.

Exhibit 3-2: Material Properties by Material Type

| Material | Moisture Content (%) | Initial Carbon Content ^b (%) | Initial Nitrogen Content ^a (%) | Initial Phosphorus Content ^a (%) | Volatile Solids Content ^a (%) | Methane Potential (m ³ /dry metric ton) | Percent of Final Methane Yield Reached ^e (%) | Volatile Solids Destruction ^f (%) |
|------------|----------------------|---|---|---|--|--|---|--|
| Food Waste | 72.2% | 49.5% | 3.8% | 0.51% | 95.6 | 369.0 ^c | 90.0% | 75.0% |
| Branches | 15.9% | 49.4% | 0.8% | 0.20% | 90.6 | 106.4 ^d | 50.0% | 47.5% |
| Grass | 82.0% | 44.9% | 3.4% | 0.20% | 86.4 | 194.8 | 90.0% | 75.0% |
| Leaves | 38.2% | 45.5% | 0.9% | 0.20% | 90.2 | 65.3 ^d | 50.0% | 47.5% |

^a Developed from Riber et al., (2009).

^b Initial carbon content from Barlaz (1998).

^c Mean of literature values reviewed; publication forthcoming.

^d Methane yield calculated from C-loss reported by Barlaz (1998).

^e Varies by process, retention time, and material decay rate. Møller, et al. (2009) used 70% for mixed organics, which was increased to 90% for food waste and grass and reduced to 50% for branches and leaves.

^f Used average for mesophilic reactors reported by EBMUD (2008) for food waste and grass and used average for municipal wastewater solids for branches and leaves due to their higher lignin content.

The methane yield of food waste is the most critical input value, and a review of recent literature shows that it can range from approximately 181 to 544 m³ CH₄/dry ton. The mean of the previous studies is 334 m³ CH₄/ ton. The current version of WARM uses a factor of 369 m³ CH₄/dry ton, which is within one standard deviation of the mean. This higher value was selected for consistency with the current WARM landfill model.

3.2.2 Transport of Materials

WARM accounts for the GHG emissions resulting from fossil fuels used in vehicles collecting and transporting waste to the anaerobic digestion facility. Exhibit 3-3 shows the diesel used for transporting the feedstock and solids to the anaerobic digester and the post-consumer transportation. To calculate the emissions, WARM relies on assumptions NREL's US Life Cycle Inventory Database (USLCI) (NREL 2015). The NREL emission factor assumes a diesel, short-haul truck.

Exhibit 3-3: Diesel Use by Process and by Material Type for Dry Digestion

| Material | Transportation and Spreading (Million Btu) | Post-Consumer Transportation (Million Btu) | Total Energy Required for Wet Anaerobic Digestion (Million Btu) | Total CO ₂ Emissions from Wet Anaerobic Digestion (MTCO ₂ E) |
|----------------|--|--|---|--|
| Food Waste | 0.25 | 0.04 | 0.33 | 0.02 |
| Yard Trimmings | 0.30 | 0.04 | 0.34 | 0.02 |
| Grass | 0.28 | 0.04 | 0.33 | 0.02 |
| Leaves | 0.31 | 0.04 | 0.36 | 0.02 |
| Branches | 0.32 | 0.04 | 0.37 | 0.02 |
| Mixed Organics | 0.29 | 0.04 | 0.34 | 0.02 |

3.2.3 Preprocessing and Digester Operations

WARM models the electricity and diesel consumed during preprocessing and digester operation for both wet and dry digestion based on literature values. Preprocessing includes grinding, screening and mixing the feedstock before they are fed into the reactor. For the electricity used in operations, EPA assumed the upper literature limit for the wet digestion system, as additional electricity is required for pumping and mixing within the system (Moller et al 2009). The lower literature limit was chosen for the dry digestion system (Moller et al 2009). Dry digestion requires more diesel for its operations as it involves the additional use of front-end loaders to move materials. The reactor moisture content of wet digestion systems is assumed to be higher than dry digestion systems. In the wet digestion system, the digestate is dewatered and some liquids are recovered and returned to the reactor, with the remainder being treated in a wastewater treatment plant (WWTP). For dry systems, the digestate is simply removed without dewatering. Electricity is consumed during the dewatering process. Additional operation assumptions are shown below in Exhibit 3-4.

Exhibit 3-4: Pre-processing and Reactor Operations Inputs and Assumptions for Wet and Dry Anaerobic Digestion

| Facility Operation Inputs | Units | Wet Digestion Assumptions | Dry Digestion Assumptions | Source |
|-------------------------------|---------|---------------------------|---------------------------|--|
| Percent methane loss to leaks | % | 2 | 2 | WERF, 2012 Sanscartier et al. 2012 reports (2-5%) |
| House electricity demand | kWh/ton | 45.4 | 18.1 | Boldrin et al. 2011 (48.9 kWh/Mg) Møller, et al. 2009 (20-50 kWh/Mg) Sanscartier et al. 2012 (47-67 kWh/Mg for Dufferin facility) |
| Dewatering electricity use | kWh/ton | 68 | 0 | Niu, D. et al. 2013. |
| House diesel fuel use | L/ton | 0.91 | 5.89 | Boldrin et al. 2011 (0.9 L/Mg) Møller et al. 2009 (1.6 L/Mg) Sanscartier et al. 2012 (0.3 L/Mg for Dufferin facility) WERF, 2012 (6.5 L/Mg) |
| Reactor moisture content | % wet | 95 | 70 | Hansen et al. (2006) |

| | | | | |
|--|--------------|----|----|--|
| | weight | | | |
| Moisture content after dewatering | % wet weight | 76 | NA | Metcalf and Eddy (2003) |
| Percent dry mass Nitrogen loss during AD | % | 8 | 8 | Developed from Hansen et al. (2006) based on initial nitrogen content. |
| Percent dry mass Phosphorus loss during AD | % | 0 | 0 | Assumed. |

3.2.4 Biogas Collection and Avoided Emissions

The methane biogas produced during anaerobic digestion is collected and can be combusted to produce heat and electricity. The recovery of heat and electricity from the combusted biogas offsets the combustion of other fossil fuel inputs. WARM models the recovery of biogas for electricity generation and assumes that this electricity offsets non-baseload electricity generation in the power sector. Electricity generation from combustion of biogas is assumed to be unavailable for 15% of operation time and the process is assumed to be 29% efficient (EPA 2013). These values are consistent with those used for landfill gas combustion in WARM, as described in the [Landfilling](#) Chapter.

WARM estimates the amount of methane that is collected by gas collection equipment. Exhibit 3-5 and Exhibit 3-6 show the mass of methane generated, leaked, flared and combusted for energy by material type for wet and dry digestion. The anaerobic digestion of food waste results in almost twice as much electricity generation compared to yard trimmings and mixed organics due to its higher methane yield. For all feedstocks, the excess heat captured from the engine is more than four times what is needed to heat the digester.

Exhibit 3-5: Methane Generation, Treatment and Use by Material Type for Dry Digestion

| Material | Mass of Methane Generated (kg/ton) | Mass of Methane Leaked (kg/ton) | Mass of Methane Flared (kg/ton) | Mass of Methane Combusted for Energy (kg/ton) | Energy from Combusted Methane (MMBtu/ton) | Electricity Generation (kWh/ton) | Net Electricity to the Grid (kWh/ton) |
|----------------|------------------------------------|---------------------------------|---------------------------------|---|---|----------------------------------|---------------------------------------|
| Food Waste | 60.0 | 1.18 | 8.80 | 50.0 | 2.37 | 201.4 | 183 |
| Yard Trimmings | 20.7 | 0.41 | 3.04 | 17.3 | 0.81 | 69.6 | 51.5 |
| Grass | 20.5 | 0.41 | 2.99 | 17.06 | 0.81 | 68.8 | 50.6 |
| Leaves | 13.1 | 0.26 | 1.91 | 10.9 | 0.52 | 44.0 | 25.9 |
| Branches | 28.9 | 0.58 | 4.26 | 24.1 | 1.14 | 97.1 | 78.9 |
| Mixed Organics | 41.1 | 0.81 | 6.03 | 34.3 | 1.62 | 138 | 120 |

Exhibit 3-6: Methane Generation, Treatment and Use by Material Type for Wet Digestion

| Material | Mass of Methane Generated (kg/ton) | Mass of Methane Leaked (kg/ton) | Mass of Methane Flared (kg/ton) | Mass of Methane Combusted for Energy (kg/ton) | Energy from Combusted Methane (MMBtu/ton) | Electricity Generation (kWh/ton) | Energy Available to Heat Digester (MMBtu/ton) | Net Electricity to the Grid (kWh/ton) | Energy Required to Heat Reactor (MMBtu/ton) |
|------------|------------------------------------|---------------------------------|---------------------------------|---|---|----------------------------------|---|---------------------------------------|---|
| Food Waste | 60.0 | 1.18 | 8.80 | 50.0 | 2.37 | 201.4 | 1.26 | 182.8 | 0.14 |

WARM applies non-baseload electricity emission rates to calculate the emissions offset from gas energy recovery because the model assumes that incremental increases in energy recovery will affect non-baseload power plants (i.e., power plants that are “demand-following” and adjust to marginal changes in the supply and demand of electricity). EPA calculates non-baseload emission rates as the average emissions rate from power plants that combust fuel and have capacity factors less than 0.8

(EPA, 2014a). The methodology used for anaerobic digestion is consistent with landfilling in WARM, as described in the [Landfilling](#) chapter.

The net electricity exported to the grid is the difference between the electricity generated from biogas combustion and the electricity used in the anaerobic digestion process and, if modeled by the user, digestate curing. The majority of the electricity use is due to material pre-processing and mixing. Food waste uses less electricity for dewatering and screening because its higher moisture content results in less solid digestate produced. Exhibit 3-7 illustrates the net electricity exported to the grid by material type.

Exhibit 3-7: Electricity Exported by Material Type for Dry Digestion and Digestate Curing

| Material | Net Electricity to Grid (kWh/ton) | Net Greenhouse Gas Offset ^a (MTCO ₂ e/ton) |
|----------------|-----------------------------------|--|
| Food Waste | 194.8 | 0.15 |
| Yard Trimmings | 55.9 | 0.04 |
| Grass | 53.9 | 0.04 |
| Leaves | 32.0 | 0.02 |
| Branches | 84.0 | 0.06 |
| Mixed Organics | 128.2 | 0.10 |

^a Based on national average grid mix.

3.2.5 Curing and Land Application

For both wet and dry anaerobic digestion systems, WARM estimates the emissions associated with two scenarios for digestate beneficial use: curing the digestate and applying the resulting compost to agricultural lands, or directly applying digestate to agricultural lands without curing.

In the case in which the digestate is cured, the solids are aerobically cured in turned windrows. The resulting compost is then screened, transported to agriculture lands, and used in place of a portion of the conventional nitrogen and phosphorus fertilizer that would be needed for the same agricultural lands. EPA assumes that there are CH₄ and N₂O emissions released during the curing process. Less N₂O is emitted from the cured compost during land application than from compost that was directly applied due in part to the N₂O released during the curing process. Cured digestate also has a lower mass of carbon stored after 100 years compared to digestate directly applied to agricultural lands. Exhibit 3-8 outlines the digestate curing input values and assumptions used to develop curing GHG emissions within WARM. These inputs are used to calculate the diesel used during curing for mixing and windrow turning and electricity use for screening. Section 3.2.7 and Section 3.2.8 further elaborate on the impact of curing on fugitive emissions and carbon storage calculations.

Exhibit 3-8: Digestate Curing Inputs and Assumptions for Wet and Dry Digestion

| Digestate Curing Parameters | Units | Value | Source |
|--|--------------|-------|--|
| Curing fuel use (mixing windrow turning) | L/ton | 0.91 | Boldrin et al. (2009) Assumed 1/3 of 3L used for curing. |
| Nitrogen loss during curing | % | 38.5 | Average from Beck-Friis et al. (2000) |
| Carbon loss during curing | % | 58 | Average for open biowaste systems from Boldrin et al. (2009) |
| Percent N loss as N ₂ O | % | 1 | Average for open biowaste systems from Boldrin et al. (2009) |
| Percent C loss as CH ₄ | % | 1.3 | Average for open biowaste systems from Boldrin et al. (2009) |
| Screen electricity use | kWh/ton | 0.882 | Komilis and Ham (2004) |
| Mass volatile solids loss per mol C loss | g/mol C loss | 12 | Haug (1993) |
| Finished compost moisture content | % | 45 | Haug (1993) |

3.2.6 Fugitive Emissions of CH₄ and N₂O during curing and After Land Application

In addition to the emissions from curing processes, WARM accounts for the fugitive CH₄ and N₂O emissions that occur during the curing process and after land application. These emissions are dependent on whether the digestate is cured before land application. Exhibit 3-9 summarizes the CH₄ and N₂O emissions by material type. Food waste has greater N₂O emissions and nitrogen fertilizer offsets because it contains more initial nitrogen.

Exhibit 3-9: Methane and Nitrous Oxide Emissions during Curing and After Land Application for Wet and Dry Digestion

| Material | Methane Emitted During Curing (kg CH ₄ /ton) | N ₂ O Emitted During Curing (kg N ₂ O/ton) | N ₂ O Emitted After Land Application when Cured (kg N ₂ O/ton) | N ₂ O Emitted After Land Application when not Cured (kg N ₂ O/ton) |
|----------------|---|--|--|--|
| Food Waste | 0.26 | 0.11 | 0.26 | 0.50 |
| Yard Trimmings | 1.28 | 0.06 | 0.15 | 0.30 |
| Grass | 0.32 | 0.06 | 0.15 | 0.30 |
| Leaves | 1.95 | 0.06 | 0.15 | 0.29 |
| Branches | 2.52 | 0.07 | 0.16 | 0.32 |
| Mixed Organics | 0.75 | 0.09 | 0.21 | 0.41 |

3.2.7 Carbon Storage

Similar to carbon from compost applied to agricultural lands, EPA assumes that carbon from digestate applied to agricultural lands remains stored in the soil through two main mechanisms: direct storage of carbon in depleted soils and carbon stored in non-reactive humus compounds. WARM calculates the carbon storage impact of each carbon storage path separately and then sums them to estimate the carbon storage factor associated with each short ton of organics composted. For more information on carbon storage calculations, see section 2.4 in the [Composting](#) chapter, which includes information on the Century model framework and simulations. EPA uses the Century model to calculate soil carbon storage by simulating soil organic matter pools. Exhibit 3-10 presents the soil carbon storage by material type. The increased solids content of mixed organics causes increased carbon in the compost when compared to compost from just food waste, and thus increased soil carbon storage credits.

Exhibit 3-10: Soil Carbon Storage by Material Type

| Material | Soil Carbon Storage (kg C/ton) |
|----------------|--------------------------------|
| Food Waste | -32.8 |
| Yard Trimmings | -159.0 |
| Grass | -40.1 |
| Leaves | -242.7 |
| Branches | -313.0 |
| Mixed Organics | -93.4 |

3.2.8 Avoided fertilizer offsets

EPA assumes that digestate applied to agricultural land allows for some synthetic fertilizer use to be avoided. WARM includes avoided fertilizer offsets for land application of the digestate generated from anaerobic digestion but not for compost generated from composting due to the difference in feedstocks used for each material management pathway. Food waste is the primary feedstock for anaerobic digestion, and contains significant amounts of nitrogen and phosphorus. Yard waste is the

primary feedstock considered in the compost pathway in WARM and contains significantly smaller amounts of nitrogen and phosphorus. Because the compost from yard trimmings is less nutrient-rich, it is assumed that the compost generated during composting does not offset any synthetic fertilizer use when applied to agricultural land. Given the nutrient loss rates found in reviewed literature, the fertilizer offsets for uncured digestate were larger than those from compost from yard trimmings (Beck-Friis et al. 2000). Based on this information, EPA calculated a nitrogen and phosphorus fertilizer offset for anaerobically digested materials. Further discussion of the fertilizer considerations for composting is found in the [Composting](#) chapter. The literature values used for mineral nutrient equivalence and the emissions intensity of nitrogen and phosphorous fertilizer use and application are shown in Exhibit 3-11.

Exhibit 3-11: Literature Values for Calculating Avoided Fertilizer Offsets

| Use on Land Parameters | Units | Value | Source |
|---|---------------------------|-------|-----------------------|
| Mineral Nutrient Equivalent for Nitrogen | kg N offset/kg N applied | 0.4 | Møller, et al. (2009) |
| Mineral Nutrient Equivalent for Phosphorus | kg N offset/kg P applied | 1.0 | Møller, et al. (2009) |
| GHG intensity of N fertilizer use and application | kg CO ₂ e/kg N | 8.9 | Boldrin et al. (2009) |
| GHG intensity of P fertilizer use and application | kg CO ₂ e/kg N | 1.8 | Boldrin et al. (2009) |

Exhibit 3-12 presents the nitrogen and phosphorous fertilizer offset by material type. Food waste has greater nitrogen fertilizer offsets than yard trimmings and mixed organics as it initially contains more nitrogen.

Exhibit 3-12: Nitrogen and Phosphorous Fertilizer Offset by Material Type

| Material | Nitrogen Fertilizer Offset (kg N/ton) | Phosphorous Fertilizer Offset (kg P/ton) | Nitrogen Fertilizer Offset (MTCO ₂ e/ton) | Phosphorous Fertilizer Offset (MTCO ₂ e/ton) |
|----------------|---------------------------------------|--|--|---|
| Food Waste | 1.084 | 1.286 | 0.009 | 0.002 |
| Yard Trimmings | 0.643 | 0.844 | 0.005 | 0.001 |
| Grass | 0.628 | 0.323 | 0.005 | 0.001 |
| Leaves | 0.626 | 1.218 | 0.005 | 0.002 |
| Branches | 0.691 | 1.511 | 0.006 | 0.002 |
| Mixed Organics | 0.873 | 1.074 | 0.007 | 0.002 |

3.2.9 WARM Anaerobic Digestion Results

The net greenhouse gas emissions resulting from anaerobic digestion are calculated by summing the emissions from the diesel for transportation and land application, fuel and electricity required for operation, biogas collection and combustion of methane, curing and land application, fugitive emissions, carbon storage, avoided fertilizer offsets and avoided electricity offsets. In WARM, the emissions from anaerobic digestion are dependent on the user selection of one of two digestion scenarios (i.e., “Wet Anaerobic Digestion”, and “Dry Anaerobic Digestion”) and one of two curing scenarios (i.e., “Cured Digestate”, and “Direct Application”). Exhibit 3-13 shows the GHG emissions from each sub-process for the dry digestion of food waste and mixed organics with digestate curing. Exhibit 3-14 shows the GHG emissions from dry digestion with direct land application.

Exhibit 3-15 shows the GHG emissions from wet digestion with digestate curing. Exhibit 3-16 shows the GHG emissions from wet digestion with direct land application.

Exhibit 3-13: Components of the Dry Anaerobic Digestion Net Emission Factor by Material Type with Digestate Curing (MTCO₂E/Short Ton)

| Material | Process Energy | Avoided Utility Emissions | Avoided Fertilizer Application | Soil Carbon Storage | Process Non-Energy | Transportation Energy | Net Emissions (Post-Consumer) |
|-----------------------------|----------------|---------------------------|--------------------------------|---------------------|--------------------|-----------------------|-------------------------------|
| Food Waste ^{a,b} | 0.02 | -0.15 | -0.01 | -0.03 | 0.12 | 0.00 | -0.05 |
| Food Waste (meat only) | 0.02 | -0.15 | -0.01 | -0.03 | 0.12 | 0.00 | -0.05 |
| Food Waste (non-meat) | 0.02 | -0.15 | -0.01 | -0.03 | 0.12 | 0.00 | -0.05 |
| Beef | 0.02 | -0.15 | -0.01 | -0.03 | 0.12 | 0.00 | -0.05 |
| Poultry | 0.02 | -0.15 | -0.01 | -0.03 | 0.12 | 0.00 | -0.05 |
| Grains | 0.02 | -0.15 | -0.01 | -0.03 | 0.12 | 0.00 | -0.05 |
| Bread | 0.02 | -0.15 | -0.01 | -0.03 | 0.12 | 0.00 | -0.05 |
| Fruits and Vegetables | 0.02 | -0.15 | -0.01 | -0.03 | 0.12 | 0.00 | -0.05 |
| Dairy Products | 0.02 | -0.15 | -0.01 | -0.03 | 0.12 | 0.00 | -0.05 |
| Yard Trimmings | 0.02 | -0.04 | -0.01 | -0.16 | 0.09 | 0.00 | -0.09 |
| Grass | 0.02 | -0.04 | -0.01 | -0.04 | 0.07 | 0.00 | 0.00 |
| Leaves | 0.02 | -0.02 | -0.01 | -0.24 | 0.10 | 0.00 | -0.14 |
| Branches | 0.02 | -0.06 | -0.01 | -0.31 | 0.13 | 0.00 | -0.23 |
| Mixed Organics ^c | 0.02 | -0.10 | -0.01 | -0.09 | 0.11 | 0.00 | -0.07 |

^a Food waste material properties represent a weighted average of vegetable food waste and non-vegetable food waste

^b Although there are many different categories of food waste, including food waste from residential sources, commercial sources, waste from specific types of commercial entities, vegetables, and meat, EPA has not located satisfactory data on how the characteristics of these different types of waste vary when managed at end of life. As a result, all food waste is treated as one material in the anaerobic digestion management practice in WARM

^c Mixed organics material properties represent a weighted average of branches, grass, leaves, vegetable food waste, and non-vegetable food waste

Exhibit 3-14: Components of the Dry Anaerobic Digestion Net Emission Factor by Material Type with Direct Land Application (MTCO₂E/Short Ton)

| Material | Process Energy | Avoided Utility Emissions | Avoided Fertilizer Application | Soil Carbon Storage | Process Non-Energy | Transportation Energy | Net Emissions (Post-Consumer) |
|-----------------------------|----------------|---------------------------|--------------------------------|---------------------|--------------------|-----------------------|-------------------------------|
| Food Waste ^{a,b} | 0.02 | -0.15 | -0.02 | -0.08 | 0.12 | 0.00 | -0.11 |
| Food Waste (meat only) | 0.02 | -0.15 | -0.02 | -0.08 | 0.12 | 0.00 | -0.11 |
| Food Waste (non-meat) | 0.02 | -0.15 | -0.02 | -0.08 | 0.12 | 0.00 | -0.11 |
| Beef | 0.02 | -0.15 | -0.02 | -0.08 | 0.12 | 0.00 | -0.11 |
| Poultry | 0.02 | -0.15 | -0.02 | -0.08 | 0.12 | 0.00 | -0.11 |
| Grains | 0.02 | -0.15 | -0.02 | -0.08 | 0.12 | 0.00 | -0.11 |
| Bread | 0.02 | -0.15 | -0.02 | -0.08 | 0.12 | 0.00 | -0.11 |
| Fruits and Vegetables | 0.02 | -0.15 | -0.02 | -0.08 | 0.12 | 0.00 | -0.11 |
| Dairy Products | 0.02 | -0.15 | -0.02 | -0.08 | 0.12 | 0.00 | -0.11 |
| Yard Trimmings | 0.02 | -0.04 | -0.01 | -0.38 | 0.06 | 0.00 | -0.35 |
| Grass | 0.02 | -0.04 | -0.01 | -0.10 | 0.06 | 0.00 | -0.06 |
| Leaves | 0.02 | -0.02 | -0.01 | -0.58 | 0.06 | 0.00 | -0.53 |
| Branches | 0.02 | -0.06 | -0.01 | -0.75 | 0.07 | 0.00 | -0.73 |
| Mixed Organics ^c | 0.02 | -0.10 | -0.01 | -0.22 | 0.09 | 0.00 | -0.22 |

^a Food waste material properties represent a weighted average of vegetable food waste and non-vegetable food waste

^b Although there are many different categories of food waste, including food waste from residential sources, commercial sources, waste from specific types of commercial entities, vegetables, and meat, EPA has not located satisfactory data on how the characteristics of these different types of waste vary when managed at end of life. As a result, all food waste is treated as one material in the anaerobic digestion management practice in WARM

^c Mixed organics material properties represent a weighted average of branches, grass, leaves, vegetable food waste, and non-vegetable food waste

Exhibit 3-15: Components of the Wet Anaerobic Digestion Net Emission Factor by Material Type with Digestate Curing (MTCO₂E/Short Ton)

| Material | Process Energy | Avoided Utility Emissions | Avoided Fertilizer Application | Soil Carbon Storage | Process Non-Energy | Transportation Energy | Net Emissions (Post-Consumer) |
|-----------------------------|----------------|---------------------------|--------------------------------|---------------------|--------------------|-----------------------|-------------------------------|
| Food Waste ^{a,b} | 0.01 | -0.12 | -0.02 | -0.03 | 0.10 | 0.00 | -0.06 |
| Food Waste (meat only) | 0.01 | -0.12 | -0.02 | -0.03 | 0.10 | 0.00 | -0.06 |
| Food Waste (non-meat) | 0.01 | -0.12 | -0.02 | -0.03 | 0.10 | 0.00 | -0.06 |
| Beef | 0.01 | -0.12 | -0.02 | -0.03 | 0.10 | 0.00 | -0.06 |
| Poultry | 0.01 | -0.12 | -0.02 | -0.03 | 0.10 | 0.00 | -0.06 |
| Grains | 0.01 | -0.12 | -0.02 | -0.03 | 0.10 | 0.00 | -0.06 |
| Bread | 0.01 | -0.12 | -0.02 | -0.03 | 0.10 | 0.00 | -0.06 |
| Fruits and Vegetables | 0.01 | -0.12 | -0.02 | -0.03 | 0.10 | 0.00 | -0.06 |
| Dairy Products | 0.01 | -0.12 | -0.02 | -0.03 | 0.10 | 0.00 | -0.06 |
| Yard Trimmings | NA | NA | NA | NA | NA | NA | NA |
| Grass | NA | NA | NA | NA | NA | NA | NA |
| Leaves | NA | NA | NA | NA | NA | NA | NA |
| Branches | NA | NA | NA | NA | NA | NA | NA |
| Mixed Organics ^c | NA | NA | NA | NA | NA | NA | NA |

^a Food waste material properties represent a weighted average of vegetable food waste and non-vegetable food waste

^b Although there are many different categories of food waste, including food waste from residential sources, commercial sources, waste from specific types of commercial entities, vegetables, and meat, EPA has not located satisfactory data on how the characteristics of these different types of waste vary when managed at end of life. As a result, all food waste is treated as one material in the anaerobic digestion management practice in WARM

^c Mixed organics material properties represent a weighted average of branches, grass, leaves, vegetable food waste, and non-vegetable food waste

NA = Not applicable

Exhibit 3-16: Components of the Wet Anaerobic Digestion Net Emission Factor by Material Type with Direct Land Application (MTCO₂E/Short Ton)

| Material | Process Energy | Avoided Utility Emissions | Avoided Fertilizer Application | Soil Carbon Storage | Process Non-Energy | Transportation Energy | Net Emissions (Post-Consumer) |
|-----------------------------|----------------|---------------------------|--------------------------------|---------------------|--------------------|-----------------------|-------------------------------|
| Food Waste ^{a,b} | 0.01 | -0.13 | -0.03 | -0.08 | 0.08 | 0.00 | -0.14 |
| Food Waste (meat only) | 0.01 | -0.13 | -0.03 | -0.08 | 0.08 | 0.00 | -0.14 |
| Food Waste (non-meat) | 0.01 | -0.13 | -0.03 | -0.08 | 0.08 | 0.00 | -0.14 |
| Beef | 0.01 | -0.13 | -0.03 | -0.08 | 0.08 | 0.00 | -0.14 |
| Poultry | 0.01 | -0.13 | -0.03 | -0.08 | 0.08 | 0.00 | -0.14 |
| Grains | 0.01 | -0.13 | -0.03 | -0.08 | 0.08 | 0.00 | -0.14 |
| Bread | 0.01 | -0.13 | -0.03 | -0.08 | 0.08 | 0.00 | -0.14 |
| Fruits and Vegetables | 0.01 | -0.13 | -0.03 | -0.08 | 0.08 | 0.00 | -0.14 |
| Dairy Products | 0.01 | -0.13 | -0.03 | -0.08 | 0.08 | 0.00 | -0.14 |
| Yard Trimmings | NA | NA | NA | NA | NA | NA | NA |
| Grass | NA | NA | NA | NA | NA | NA | NA |
| Leaves | NA | NA | NA | NA | NA | NA | NA |
| Branches | NA | NA | NA | NA | NA | NA | NA |
| Mixed Organics ^c | NA | NA | NA | NA | NA | NA | NA |

^a Food waste material properties represent a weighted average of vegetable food waste and non-vegetable food waste

^b Although there are many different categories of food waste, including food waste from residential sources, commercial sources, waste from specific types of commercial entities, vegetables, and meat, EPA has not located satisfactory data on how the characteristics of these different types of waste vary when managed at end of life. As a result, all food waste is treated as one material in the anaerobic digestion management practice in WARM

^c Mixed organics material properties represent a weighted average of branches, grass, leaves, vegetable food waste, and non-vegetable food waste

NA = Not applicable

3.3 LIMITATIONS

Because of data and resource constraints, this chapter does not explore the full range of conditions, technologies, and practices for anaerobic digestion and how this range would affect the results of this analysis. Instead, this study attempts to provide an analysis of GHG emissions and sinks associated with anaerobic digestion of organics under a limited set of scenarios. In addition, the analysis was limited by the scope of WARM, which is intended to present life-cycle GHG emissions of waste management practices for selected material types, including food waste and yard trimmings.

This section compiles the limitations of the anaerobic digestion analysis described in this chapter.

- This analysis did not consider the differences in anaerobic digestion emissions resulting from digesting different food waste types. A future improvement may involve research into developing food type-specific anaerobic digestion factors for WARM.
- WARM assumes that the biogas generated during anaerobic digestion is used in an internal combustion engine to generate electricity. This electricity then offsets grid electricity. Throughout EPA's review of literature and stakeholder engagement, multiple other uses have been identified for the biogas that have not been addressed here. These uses include upgrading the gas to pipeline quality and converting it to either compressed natural gas or liquid natural gas.
- WARM assumes that the digestate generated during anaerobically digesting organic waste is applied to agricultural land, either after curing or without further processing. EPA's review of literature and stakeholder engagement identified other uses for digestate that have not been addressed within WARM. These uses include incinerating it for energy recovery and pelletizing it for sale as a fertilizer substitute.
- The net GHG emissions from anaerobically digesting food waste are quite sensitive to food waste methane yield assumptions. In discussions with stakeholders and in EPA's review of literature, it was indicated that there was little evidence that different anaerobic digestion reactor configurations have significantly different methane yields. Therefore EPA believes that the model presented in this chapter should provide reasonable estimates of the GHG emissions from a wide range of anaerobic digestion configurations.
- This analysis calculates the GHG impacts of the anaerobic digestion of individual substrates as if they were digested by themselves. In practice, food waste may be co-digested with manure or wastewater treatment biosolids. It is assumed that the food waste behaves the same in dedicated and in co-digestion facilities such that the analysis presented here is applicable across many anaerobic digestion scenarios.
- As identified in the Composting Chapter, this analysis does not consider all soil conversation and management pathways and the impact of those practices on carbon storage. Data and resource restraints prevented EPA from using Century to evaluate the variation in carbon storage impacts for a wide range of compost feedstocks (e.g., yard trimmings mixed with food waste, food waste alone). EPA acknowledges that the modeling performed to determine the humus formation for yard trimmings and food discards attempts to provide an analysis of GHG emissions and sinks

that reflect the set of scenarios available. This methodology and its limitations are further explained in the Composting Chapter.

3.4 REFERENCES

- Arsova, L. (2010). Anaerobic digestion of food waste: Current status, problems and an alternative product. Master's Thesis, New York, NY: Department of Earth and Environmental Engineering, Columbia University. http://www.seas.columbia.edu/earth/wtert/sofos/arsova_thesis.pdf
- Berglund, M. & Börjesson, P. (2006). Assessment of energy performance in the life-cycle of biogas production. *Biomass and Bioenergy*, 30,254–266.
- Boldrin, A., Neidel, T. L., Damgaard, A., Bhandar, G. S., Møller, J., & Christensen, T. H. (2011). Modelling of environmental impacts from biological treatment of organic municipal waste in EASEWASTE. *Waste Management (New York, N.Y.)*, 31(4), 619–30. doi:10.1016/j.wasman.2010.10.025
- Bruun, S., Hansen, T.L., Christensen, T.H., Magid, J. & Jensen, L.S. (2006). Application of processed organic municipal solid waste on agricultural land: a scenario analysis. *Environmental Modeling and Assessment*, 11, 251-265.
- The Environmental Research & Education Foundation (2015). Anaerobic Digestion of Municipal Solid Waste: Report on the State of Practice. Retrieved from www.erefdn.org.
- EPA (2015). Advancing Sustainable Materials Management: Facts and Figures 2013. Office of Resource Conservation and Recovery, Washington D.C., EPA530-R-15-002, June 2015.
- EPA (2008). Anaerobic Digestion of Food Waste, Prepared by East Bay Municipal Utility District, Oakland, CA.
- EPA (2000). Biosolids Technology Fact Sheet: Centrifuge Thickening and Dewatering. Office of Water, Washington D.C., EPA 832-F-00-053, September 2000.
- Fruergaard, T., Ekvall, T., Astrup, T. (2009). Energy use and recovery in waste management and implications for accounting of greenhouse gases and global warming contributions. *Waste Management & Research*, 27(8), 724-737.
- IPCC (2011). Moomaw, W., P. Burgherr, G. Heath, M. Lenzen, J. Nyboer, A. Verbruggen, 2011: Annex II: Methodology. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S.
- Hansen, T.L., Bhandar, G.S., Christensen, T.H., Bruun, S. & Jensen, L.S. (2006). Life cycle modelling of environmental impacts of application of processed organic municipal solid waste on agricultural land (EASEWASTE). *Waste Management & Research*, 24, 153-166.
- Haug, R.T. (1993). *The Practical Handbook of Compost Engineering*. CRC Press, Boca Raton, FL, USA.
- Long, J. H. (2012). Environmental, Economic, and Process Evaluation of Anaerobic Co-digestion of Grease Trap Waste with Municipal Wastewater Sludge. North Carolina State University.
- Lopez, V. M. (2015). Commercial Food Waste Feedstock Characterization for Anaerobic Digestion. (MS Thesis), North Carolina State University, Raleigh, NC.
- Møller, J., Boldrin, A., & Christensen, T. H. (2009). Anaerobic digestion and digestate use: accounting of greenhouse gases and global warming contribution. *Waste Management & Research : The Journal of the International Solid Wastes and Public Cleansing Association, ISWA*, 27(8), 813–24. doi:10.1177/0734242X09344876

- National Renewable Energy Laboratory (2015). "U.S. Life Cycle Inventory Database." Retrieved from <https://www.lcacommons.gov>
- Niu, D. et al. (2013). Greenhouse gases emissions accounting for typical sewage sludge digestion with energy utilization and residue land application in China. *Waste Management*, 33(1), pp.123–8. Available at: <http://www.ncbi.nlm.nih.gov/pubmed/22884580>.
- NRAES (1998). *Composting for municipalities: Planning and Design Considerations*; Natural Resource, Agriculture, and Engineering Service: Ithaca, New York, 1998.
- Oshins, C., Block, D. (2000). Feedstock composition at composting sites. *Biocycle*, 41(9), 31-34.
- Riber, C.; Petersen, C.; Christensen, T.H., (2009). Chemical composition of material fractions in Danish household waste. *Waste Manage.*, 29(4), 1251–1257.
- Sanscartier, D., MacLean, H., Saville, B. (2011). Electricity Production from Anaerobic Digestion of Household Organic Waste in Ontario: Techno-Economic and GHG Emission Analyses. *Environ. Sci. Technol.*, 2012, 46 (2), pp 1233–1242 Publication Date (Web): December 14, 2011 (Article) DOI: 10.1021/es2016268
- WERF (2012). *Sustainable Food Waste Evaluation*, Alexandria, VA. OWSO5R07e, <http://www.werf.org/a/ka/Search/ResearchProfile.aspx?ReportId=OWSO5R07e>

4 COMPOSTING

This guidance document describes the development of composting emission factors for EPA's Waste Reduction Model (WARM). Included are estimates of the net greenhouse gas (GHG) emissions from composting of yard trimmings and food waste, as well as mixed organics and polylactide (PLA) biopolymer resin.⁹

4.1 A SUMMARY OF THE GHG IMPLICATIONS OF COMPOSTING

During composting, microbial decomposition aerobically transforms organic substrates into a stable, humus-like material (Brown and Subler 2007). Although small-scale composting, such as backyard composting, occurs across the United States, WARM models composting only in central composting facilities with windrow piles because data for small-scale composting or other large-scale operations are insufficient.¹⁰ WARM includes composting as a materials management option for yard trimmings, food waste, PLA, and mixed organics.

As modeled in WARM, composting results in some carbon storage (associated with application of compost to agricultural soils), carbon dioxide (CO₂) emissions from transportation and mechanical turning of the compost piles, in addition to fugitive emissions of methane (CH₄) and nitrous oxide (N₂O) produced during decomposition.¹¹ To estimate the carbon storage from compost application, EPA selected point estimates from the range of emission factors covering various compost application rates and time periods. EPA chose the point estimates based on a typical compost application rate of 20 short tons of compost per acre, averaged over four soil-crop scenarios.¹² EPA selected the carbon storage values for the year 2010 to maintain consistency with the forest carbon storage estimates discussed in the Forest Carbon Storage chapter.¹³ Overall, EPA estimates that centralized composting of mixed organics results in net carbon storage of 0.18 MTCO₂E per wet short ton of organic inputs composted and applied to agricultural soil.

4.2 CALCULATING THE GHG IMPACTS OF COMPOSTING

The stages of a composting operation with the potential to affect GHG flux include the following processes:

- Collecting and transporting the organic materials to the central composting site.
- Mechanical turning of the compost pile.
- Non-CO₂ GHG emissions during composting (primarily CH₄ and N₂O).
- Storage of carbon after compost application to soils.

⁹ Composting is not included as a material management pathway for paper because of insufficient information on the GHG implications of composting paper products.

¹⁰ Windrows are a widely used method for composting yard trimmings and municipal solid waste, and they are considered to be the most cost-effective composting technology (EPA, 1994; Coker, 2006).

¹¹ These fugitive emission sources were added in June 2014 to WARM Version 13.

¹² EPA ran the composting simulation on two sites included in CENTURY: an eastern Colorado site with clay loam soil and a southwestern Iowa site with silty clay loam soil. EPA simulated two harvest regimes on each site, one where corn is harvested for silage and 95 percent of the above-ground biomass is removed and the other one where corn is harvested for grain and the stover is left behind to decompose on the field.

¹³ For consistency with the paper recycling/source reduction analysis of forest carbon storage, EPA analyzed the GHG implications of composting at the year 2010. EPA chose 2010 in the paper recycling/source reduction and forest carbon analyses because it represented a delay of 5 to 15 years from the onset of the simulated period of incremental recycling.

Composting also results in biogenic CO₂ emissions associated with decomposition, both during the composting process and after the compost is added to the soil. Because this CO₂ is biogenic in origin, however, it is not counted as a GHG in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* and is not included in this accounting of emissions and sinks.¹⁴

Exhibit 4-1: Components of the Composting Net Emission Factor for Food Waste, Yard Trimmings, and Mixed Organics

| Material Type | Composting of Post-Consumer Material | | | |
|-----------------------------|--------------------------------------|--------------------|---------------------|-------------------------------|
| | Transportation to Composting | Fugitive Emissions | Soil Carbon Storage | Net Emissions (Post-Consumer) |
| PLA | 0.02 | 0.07 | -0.24 | -0.15 |
| Food Waste | 0.02 | 0.05 | -0.24 | -0.18 |
| Food Waste (meat only) | 0.02 | 0.05 | -0.24 | -0.18 |
| Food Waste (non-meat) | 0.02 | 0.05 | -0.24 | -0.18 |
| Beef | 0.02 | 0.05 | -0.24 | -0.18 |
| Poultry | 0.02 | 0.05 | -0.24 | -0.18 |
| Grains | 0.02 | 0.05 | -0.24 | -0.18 |
| Bread | 0.02 | 0.05 | -0.24 | -0.18 |
| Fruits and Vegetables | 0.02 | 0.05 | -0.24 | -0.18 |
| Dairy Products | 0.02 | 0.05 | -0.24 | -0.18 |
| Yard Trimmings ^a | 0.02 | 0.07 | -0.24 | -0.15 |
| Grass | 0.02 | 0.07 | -0.24 | -0.15 |
| Leaves | 0.02 | 0.07 | -0.24 | -0.15 |
| Branches | 0.02 | 0.07 | -0.24 | -0.15 |
| Mixed Organics | 0.02 | 0.07 | -0.24 | -0.16 |

^a Yard trimmings represent a 50-percent, 25-percent, and 25-percent weighted average of grass, leaves and branches, respectively, based on U.S. waste generation data from EPA (2015).

Exhibit 4-1 shows the three components of the net emission factor for food waste, yard trimmings, PLA, and mixed organics. Because of resource and model resolution constraints, the two approaches EPA used in WARM to calculate carbon storage from compost application model only finished compost and do not distinguish between compost feedstocks; therefore, the emission factors for each organic's input are the same. The following sections provide further detail on the sources and methods used to develop these emission factors. Section 4.2.1 describes how WARM accounts for GHG emissions during transportation of composting materials and the physical turning of the compost. Section 4.2.2 describes the estimates of fugitive emissions of CH₄ and N₂O for composting within WARM. Section 4.2.3 details the methodology for calculating the carbon storage resulting from compost application in soils, and Sections 4.2.4 and 4.2.5 describe in greater detail the components of carbon storage.

4.2.1 CO₂ from Transportation of Materials and Turning of Compost

WARM includes emissions associated with transporting and processing of the compost in aerated window piles. Transportation energy emissions occur when fossil fuels are combusted to collect and transport yard trimmings and food waste to the composting facility and then to operate composting equipment that turns the compost.¹⁵ To calculate the emissions, WARM relies on assumptions from FAL (1994) for the equipment emissions and NREL's US Life Cycle Inventory Database (USLCI) (NREL

¹⁴ For more information on biogenic carbon emissions, see the text box, "CO₂ Emissions from Biogenic Sources" in the WARM [Background and Overview](#) chapter.

¹⁵ EPA did not count transportation emissions from delivery of finished compost from the composting facility to its final destination.

2015). The NREL emission factor assumes a diesel, short-haul truck. Exhibit 2 provides the transportation emission factor calculation.

Exhibit 4-2: Emissions Associated with Transporting and Turning Compost

| Material Type | Diesel Fuel Required to Collect and Transport One Short Ton (Million Btu) ^a | Diesel Fuel Required to Turn the Compost Piles (Million Btu) ^b | Total Energy Required for Composting (Million Btu) | Total CO ₂ Emissions from Composting (MTCO ₂ E) |
|---------------|--|---|--|---|
| Organics | 0.04 | 0.22 | 0.26 | 0.02 |

^a Based on estimates from NREL's USLCI Database

^b Based on estimates in Table I-17 in FAL, 1994, p.132.

4.2.2 Fugitive Emissions of CH₄ and N₂O During Composting

4.2.2.1 Background on Fugitive Emissions from Composting

During the composting process, microbial activity decomposes waste into a variety of compounds, some of which are emitted from the compost pile as gases. The amount and type of end products formed during these reactions depends on many factors, including the original nutrient balance and composition of the waste, the temperature and moisture conditions of the compost, and the amount of oxygen present in the pile. These processes result in the generation of small amounts of CH₄ and N₂O gases, which contribute to the net GHG emissions associated with the composting pathway.

The scientific literature suggests that there is a wide range of emissions for fugitive gases generated during composting. Local factors can strongly influence the existence and extent of CH₄ and N₂O emissions from composting piles. These local factors include:

- *Aeration*
- *Density of compost*
- *Frequency of turning*
- *Feedstock composition*
- *Climate (temperature and precipitation)*
- *Size of compost piles*

After reviewing a large number of studies, EPA found that Amlinger et al. (2008) provided the most applicable results for WARM and forms the basis of EPA's estimates of fugitive emissions for composted waste in WARM. The study characterizes CH₄ and N₂O emissions for both biowaste and green waste in well-managed compost windrows across several weeks. Biowaste is composed of separated organic household waste, including food waste. Green waste, or garden waste, is composed primarily of plant waste such as grass and yard trimmings. In WARM, food waste is classified as a bio-waste for the purposes of estimating fugitive emissions, whereas yard trimmings is classified as a green waste. Mixed organics and PLA are considered a representative blend of compostable waste, and use a weighted average of the biowaste and green waste emission factors for the relative shares of each waste type composted within the United States.

The three best data points available from Amlinger et al. (2008) are the 21 week value for green waste and the 12 week values for biowaste. Although composting times vary between facilities, most commercial composting facilities process compost in 6 to 12 weeks (CWMI, 1998), with purely green waste requiring a longer composting time of 14 to 18 weeks (Zanker Road Resource Management, Undated).

4.2.2.2 Methane Generated from Composting

There is a consensus within the scientific literature that CH₄ is emitted in measurable quantities even in well-managed compost piles. Amlinger et al. (2008) conducted an exhaustive review of literature on emissions from composting and supplemented it with their own findings. They found CH₄ emissions occurring across feedstock types even when the piles were managed, although emissions were variable even within the same treatment. In their own experiments, Amlinger et al. (2008) found that CH₄ emissions for green waste feedstock were 0.0139 MTCO₂E per wet ton of fresh matter (FM). The Amlinger study found that CH₄ emissions from biowaste were lower at 0.0066 and 0.0055 MTCO₂E per wet ton of FM, at 9 weeks and 12 weeks, respectively. For biowaste, EPA selected the 12 week value for WARM because the CO₂ equivalent result increases with time of composting and the results stabilized in later weeks of composting.

Exhibit 4-3: Fugitive CH₄ Emissions from Composting Biowaste and Green Waste

| Compost Feedstock | CH ₄ Emissions (MTCO ₂ E/ton) |
|-------------------|---|
| Biowaste | 0.0055 |
| Green waste | 0.0139 |

4.2.2.3 Nitrous Oxide Generated from Composting

Knowledge of the mechanism of N₂O emissions from composting is significantly less developed than that of either CO₂ or CH₄ emissions. N₂O is formed during both incomplete ammonium oxidation and incomplete denitrification processes, but there is debate over which process is most important in composting (Lou and Nair 2009). While CH₄ is usually detected near the bottom of piles where oxygen is absent, N₂O often forms closer to the surface. For green waste, Amlinger recorded a value of 0.0609 MTCO₂E/ton of FM, whereas for biowaste the authors recorded results of 0.0092 and 0.0396 MTCO₂E/ton of FM, at 9 weeks and 12 weeks respectively. For biowaste, EPA selected the 12 week value for WARM because the CO₂ equivalent result increases with time of composting and the results stabilized in later weeks of composting.

Exhibit 4-4: Fugitive N₂O Emissions from Composting Biowaste and Green Waste

| Compost Feedstock | N ₂ O Emissions (MTCO ₂ E/ton) |
|-------------------|--|
| Biowaste | 0.0396 |
| Green waste | 0.0609 |

4.2.2.4 Summary of Fugitive Emissions Generated from Composting

Combining CH₄ and N₂O emissions, the net fugitive emissions from composting comprise 0.0451 and 0.0748 MTCO₂E/ton for biowaste and green waste, respectively. For mixed organics, WARM uses a weighted emission factor that considers the relative amounts of biowaste and green waste composted in the United States.¹⁶ As the composting waste stream is predominantly yard waste, the weighted emission estimate is much closer to the value for green waste, at 0.0724 MTCO₂E/ton. For an overview of fugitive emissions by material type, see Exhibit 4-5.

Exhibit 4-5: Total Fugitive Emissions from Composting, by Material Type

| Material Type | Fugitive Emissions (MTCO ₂ E/ton) |
|----------------|--|
| PLA | 0.0724 |
| Food Waste | 0.0451 |
| Yard Trimmings | 0.0748 |

¹⁶ According to the 2012 EPA MSW Facts and Figures report, 8% of the waste composted in the United States in 2011 was comprised of food waste, whereas the remaining 92% consisted of yard waste (EPA, 2015).

| | |
|----------------|--------|
| Grass | 0.0748 |
| Leaves | 0.0748 |
| Branches | 0.0748 |
| Mixed Organics | 0.0724 |

4.2.3 Carbon Storage Resulting From Compost Application to Soils

4.2.3.1 Background on Carbon Storage in Soils

The stock of carbon in soils is the result of a balance between inputs (usually plant matter) and outputs (primarily CO₂ flux during decomposition of organic matter). The entire portion of carbon held in the soil and undergoing decomposition is collectively referred to as “soil organic matter” (SOM) or “soil organic carbon” (SOC). SOC is a mixture of different organic compounds that decompose at vastly differing rates. Soils contain thousands of different SOC compounds that microbial degradation or abiotic condensation reactions transform into new structures. The more complex of these molecular soil structures tend to have a low decomposition rate and often are identified as humus (Davidson and Janssens, 2006). Strong evidence exists that SOC decomposition decreases with increasing depth (Meersmans et al., 2009). The top layers of soil generally contain organic matter (such as plant residues) that decomposes quickly, meaning that carbon in this portion of the soil is likely to be relatively young. The carbon dynamics in deeper soil layers and the driving factors behind vertical distribution of SOC are poorly understood.

During composting, microbes degrade the original waste materials into organic compounds through a variety of pathways. During this decomposition, approximately 80 percent of the initial organic matter is emitted as CO₂ (Beck-Friis et al., 2000). The remainder of the organic compounds eventually stabilize and become resistant to further rapid microbial decomposition (i.e., recalcitrant) (Francou et al., 2008). Mature compost is characterized as containing a high percentage of these stable, humic substances. When the compost is mature, nearly all of the water-soluble compounds (such as dissolved organic carbon) will have leached out (Bernal et al., 1998).

While EPA is currently researching the mechanisms and magnitude of carbon storage, WARM assumes that carbon from compost remains stored in the soil through two main mechanisms: direct storage of carbon in depleted soils and carbon stored in non-reactive humus compounds. WARM calculates the carbon storage impact of each carbon storage path separately and then adds them together to estimate the carbon storage factor associated with each short ton of organics composted.

4.2.3.2 Soil Carbon Storage Calculation

To calculate soil carbon storage, EPA simulated soil organic matter pools using the Century model, which is described in Section 4.2.4. EPA ran more than 30 scenarios with varied compost application rates and frequency, site characteristics, fertilization rates, and crop residue management. Based on this analysis, EPA concluded that while a single compost application does initially increase soil carbon, the carbon storage rate declines with time after the application. Using a timeframe of 10 years to calculate carbon storage, only a fraction of the initial carbon added remained in the soil at the end of that time period. EPA included this fraction of added carbon per short ton of compost that remained present in the soil after 10 years in the WARM composting emission factor, as shown in Exhibit 4-1.¹⁷

¹⁷ Note that if the time frame is extended to longer periods (and many of the recent discussions of agricultural and forestry offsets in the context of carbon credits would indicate that 10 years is well below the consensus time horizon), the fraction of added carbon per ton of compost that remains present in the soil would be smaller.

4.2.3.3 Alternative Carbon Storage Hypotheses

When EPA first incorporated into WARM composting as a materials management option, the agency conducted research but could not identify sufficient primary data that could be used to develop quantitative estimates of the soil carbon storage benefits of compost. EPA developed modeling approaches to investigate the possible effects of compost application on soil carbon storage. In addition to the humus formation and depleted soils mechanisms mentioned earlier, EPA considered the following two possible mechanisms for the effect of compost on soil carbon:

- Nitrogen in compost may stimulate higher productivity, thus generating more crop residues. This fertilization effect would increase soil carbon because of the larger volume of crop residues, which serves as organic matter input.
- The application of compost produces a multiplier effect by qualitatively changing the dynamics of the carbon cycling system and increasing the retention of carbon from non-compost sources. Some studies of other compost feedstocks (e.g., farmyard manure, legumes) have indicated that the addition of organic matter to soil plots can increase the potential for storage of soil organic carbon. The carbon increase apparently comes not only from the organic matter directly, but also from retention of a higher proportion of carbon from residues of crops grown on the soil. This multiplier effect could enable compost to increase carbon storage by more than its own direct contribution to carbon mass accumulation.

EPA concluded from the Century simulations that a shortage of nitrogen can modestly increase crop productivity with compost application, which results in higher inputs of crop residues into the soil and an increased carbon storage rate. As noted in Section 0, however, our analysis assumes that farmers will supply sufficient synthetic fertilizer to crops to maintain commercial yields, in addition to any compost added, so that the soil carbon effect of nitrogen fertilization resulting from compost is relatively small. Although several of the experts contacted cited persuasive qualitative evidence of the existence of a multiplier effect, EPA was unable to develop an approach to quantify this process. More information on these two hypotheses and why they were not included in the final carbon storage emission factor appears in Section 0.

4.2.4 Century Model Framework and Simulations

4.2.4.1 Evaluating Possible Soil Carbon Models

As mentioned earlier, EPA's composting analysis included an extensive literature review and interviews with experts to consider whether the application of compost leads to long-term storage of carbon in soils. After determining that neither the literature review nor discussions with experts would yield a basis for a quantitative estimate of soil carbon storage, EPA evaluated the feasibility of a simulation modeling approach. EPA initially identified two simulation models with the potential to be applied to the issue of soil carbon storage from compost application: (1) Century and (2) the Rothamsted C (ROTHC-26.3)¹⁸ model. Both are peer-reviewed models that have structure and application that have been described in scores of publications. The models share several features:

- Ability to run multiyear simulations.

Although the selection of an appropriate time frame is not the subject of this documentation, EPA may later revisit the choice of time frame.

¹⁸ This model was developed based on long-term observations of soil carbon at Rothamsted, an estate in the United Kingdom where organic amendments have been added to soils since the 19th century.

- Capability to construct multiple scenarios covering various climate and soil conditions and loading rates.
- Ability to handle interaction of several soil processes, environmental factors, and management scenarios such as carbon: nitrogen (C:N) ratios, aggregate formation, soil texture (e.g., clay content), and cropping regime.

Given the extensive application of Century in the United States, its availability on the Internet, and its ability to address many of the processes important to compost application, EPA decided to use Century rather than RothC-26.3.

4.2.4.2 Century Simulations

For this analysis, EPA developed a basic agricultural scenario in Century where land was converted from prairie to farmland (growing corn) in 1921 and remained growing corn through 2030.¹⁹

Description of the Century Soil Model

Century is a FORTRAN model of plant-soil ecosystems that simulates long-term dynamics of carbon, nitrogen, phosphorus, and sulfur. It tracks the movement of carbon through soil pools—active, slow, and passive—and can show changes in carbon levels as a result of the addition of compost.

In addition to soil organic matter pools, carbon can be found in surface (microbial) pools and in above- and below-ground litter pools. The above-ground and below-ground litter pools are divided into metabolic and structural pools based on the ratio of lignin to nitrogen in the litter. The structural pools contain all of the lignin and have much slower decay rates than the metabolic pools. Carbon additions to the system flow through the various pools and can exit the system (e.g., as CO₂, dissolved carbon, or through crop removals).

The above-ground and below-ground litter pools are split into metabolic and structural pools based on the ratio of lignin to nitrogen in the litter. The structural pools contain all of the lignin and have much slower decay rates than the metabolic pools. The active pool of soil organic matter includes living biomass, some of the fine particulate detritus, most of the non-humic material, and some of the more easily decomposed fulvic acids. The active pool is estimated to have a mean residence time (MRT) of a few months to 10 years (Metherell et al., 1993; Brady and Weil, 1999). The slow pool includes resistant plant material (i.e., high lignin content) derived from the structural pool and other slowly decomposable and chemically resistant components. It has an MRT of 15–100 years. The passive pool of soil organic matter includes very stable materials remaining in the soil for hundreds to thousands of years.

Century does not simulate increased formation of humic substances associated with organic matter additions, nor does it allow for organic matter additions with high humus content to increase the magnitude of the passive pool directly. (Because Century does not account for these processes, EPA developed a separate analysis, described in Section 4.2.4.)

Century contains a submodel to simulate soil organic matter pools. Additional submodels address nitrogen, phosphorus, sulfur, the water budget, leaching, soil temperature, and plant production, as well as individual submodels for various ecosystems (e.g., grassland, cropland). The nitrogen submodel addresses inputs of fertilizer and other sources of nitrogen, mineralization of organic nitrogen, and uptake of nitrogen by plants.

¹⁹ EPA is conducting research into compost markets, and initial findings indicate that compost is not often used in large-scale agricultural applications, but it is often applied in high-end markets, such as landscaping. Century and other widely vetted soil carbon models, however, do not readily model the effects of composting on soil carbon for

Several sets of detailed site characteristics from past modeling applications are available to users in Century. EPA chose two settings: an eastern Colorado site with clay loam soil and a southwestern Iowa site with silty clay loam soil. Both settings represent fairly typical Midwestern corn belt situations where agricultural activities have depleted soil organic carbon levels. EPA then ran more than 30 scenarios to examine the effect of the following variables on soil carbon storage:

- Compost application rate and frequency.
- Site characteristics (rainfall, soil type, irrigation regime).
- Fertilization rate.
- Crop residue management.

EPA adjusted compost application rates using the organic matter (compost) files for each compost application rate included in the analysis. EPA then compared the effect of applying compost annually for 10 years (1996–2005) at seven different application rates: 1.3, 3.2, 6.5, 10, 15, 20, and 40 wet short tons compost per acre (corresponding to 60–1,850 grams of carbon per square meter).²⁰ EPA also investigated the effect of compost application frequency on the soil carbon storage rate and total carbon levels. EPA ran the model to simulate compost applications of 1.3 wet short tons compost/acre and 3.2 wet short tons compost/acre every year for 10 years (1996–2005) and applications of 1.3 wet short tons compost/acre and 3.2 wet short tons compost/acre applied every 5 years (in 1996, 2001, and 2006). The simulated compost was specified as having 33 percent lignin,²¹ 17:1 C:N ratio,²² 60:1 carbon-to-phosphorus ratio, and 75:1 carbon-to-sulfur ratio.²³ EPA also ran a scenario with no compost application for each combination of site-fertilization-crop residue management. This scenario allowed EPA to control for compost application that is, to calculate the change in carbon storage attributable only to the addition of compost.

Finally, EPA simulated two harvest regimes, one where the corn is harvested for silage (where 95 percent of the above-ground biomass is removed) and the other where corn is harvested for grain (where the stover is left behind to decompose on the field). These simulations enabled EPA to isolate

non-agricultural scenarios. Because of this lack of data, EPA chose to simulate composting using the large-scale agricultural scenarios available in Century. EPA is researching methods to improve these assumptions.

²⁰ The model requires inputs in terms of the carbon application rate in grams per square meter. The relationship between the carbon application rate and compost application rate depends on three factors: the moisture content of compost, the organic matter content (as a fraction of dry weight), and the carbon content (as a fraction of organic matter). Inputs are based on values provided by Dr. Harold Keener of Ohio State University, who estimates that compost has a moisture content of 50 percent, an organic matter fraction (as dry weight) of 88 percent, and a carbon content of 48 percent (as a fraction of organic matter). Thus, on a wet weight basis, 21 percent of compost is carbon.

²¹ EPA estimated the percentage of lignin based on the lignin fractions for grass, leaves, and branches specified by compost experts (particularly Dr. Gregory Evanylo at Virginia Polytechnic Institute and State University, and lignin fractions reported in M.A. Barlaz [1997]). FAL provided an estimate of the fraction of grass, leaves, and branches in yard trimmings in a personal communication with ICF Consulting, November 14, 1995. Subsequently, FAL obtained and provided data showing that the composition of yard trimmings varies widely in different states. The percentage composition used here (50 percent grass, 25 percent leaves, and 25 percent branches on a wet weight basis) is within the reported range.

²² The C:N ratio was taken from Brady and Weil (1999).

²³ C:P and C:S ratios were based on the literature and conversations with composting experts, including Dr. Gregory Evanylo at Virginia Polytechnic Institute and State University.

the effect of the carbon added directly to the system in the form of compost, as opposed to total carbon inputs, which include crop residues.

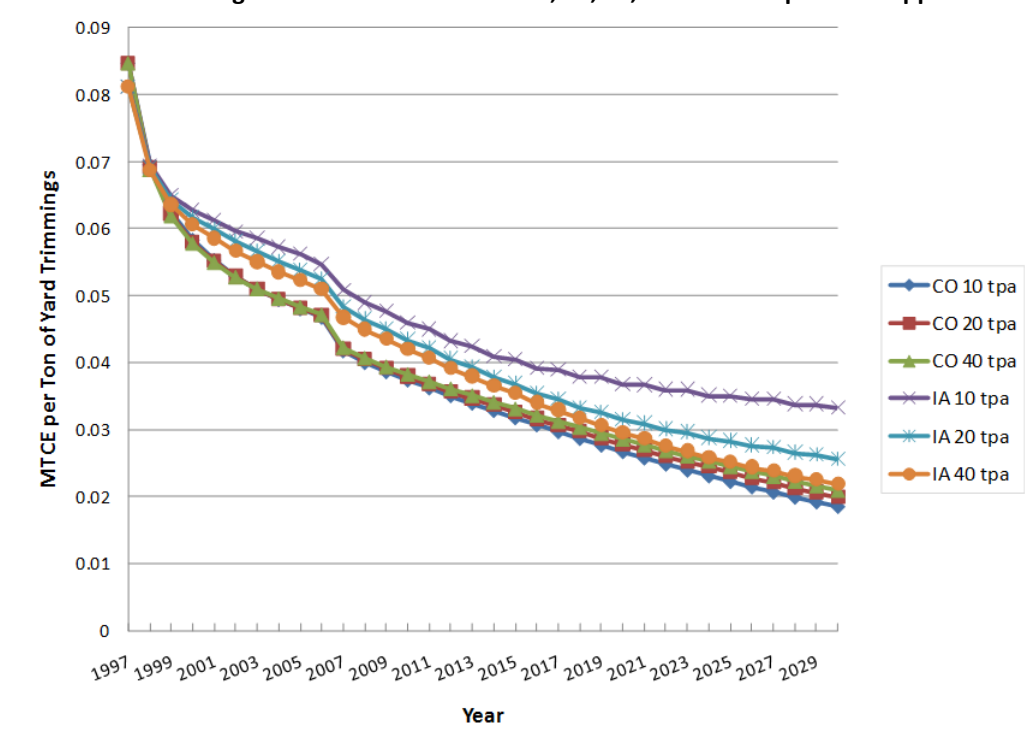
4.2.4.3 Analysis of Compost Application Impacts on Depleted Soils

The output data cover the period from 1900 through 2030. In general, EPA focused on the difference in carbon storage between a baseline scenario where no compost was applied and a with-compost scenario. EPA calculated the difference between the two scenarios to isolate the effect of compost application. EPA converted output data in grams of carbon per square meter to $MTCO_2E$ by multiplying by area in square meters and multiplying by the molecular weight ratio of CO_2 to carbon.

To express results in units comparable to those for other sources and sinks, EPA divided the increase in carbon storage by the short tons of organics required to produce the compost.²⁴ That is, the factors are expressed as a carbon storage rate in units of $MTCO_2E$ per wet short ton of organic inputs (not $MTCO_2E$ per short ton of compost).

As Exhibit 4-6 illustrates, EPA’s Century analysis found that the carbon storage rate declines with time after initial application. The rate is similar across application rates and frequencies, and across the site conditions that were simulated. Exhibit 4-6 shows results for the Colorado and Iowa sites, for the 10-, 20-, and 40-ton per acre application rates. As indicated on the graph, the soil carbon storage rate varies from about 0.08 $MTCE$ (0.30 $MTCO_2E$) per wet ton yard trimmings immediately after compost application in 1997 to about 0.02 $MTCE$ (0.07 $MTCO_2E$) per ton in 2030, 24 years after the last application in 2006.

Exhibit 4-6: Soil Carbon Storage—Colorado and Iowa Sites; 10, 20, and 40 Tons-per-Acre Application Rates

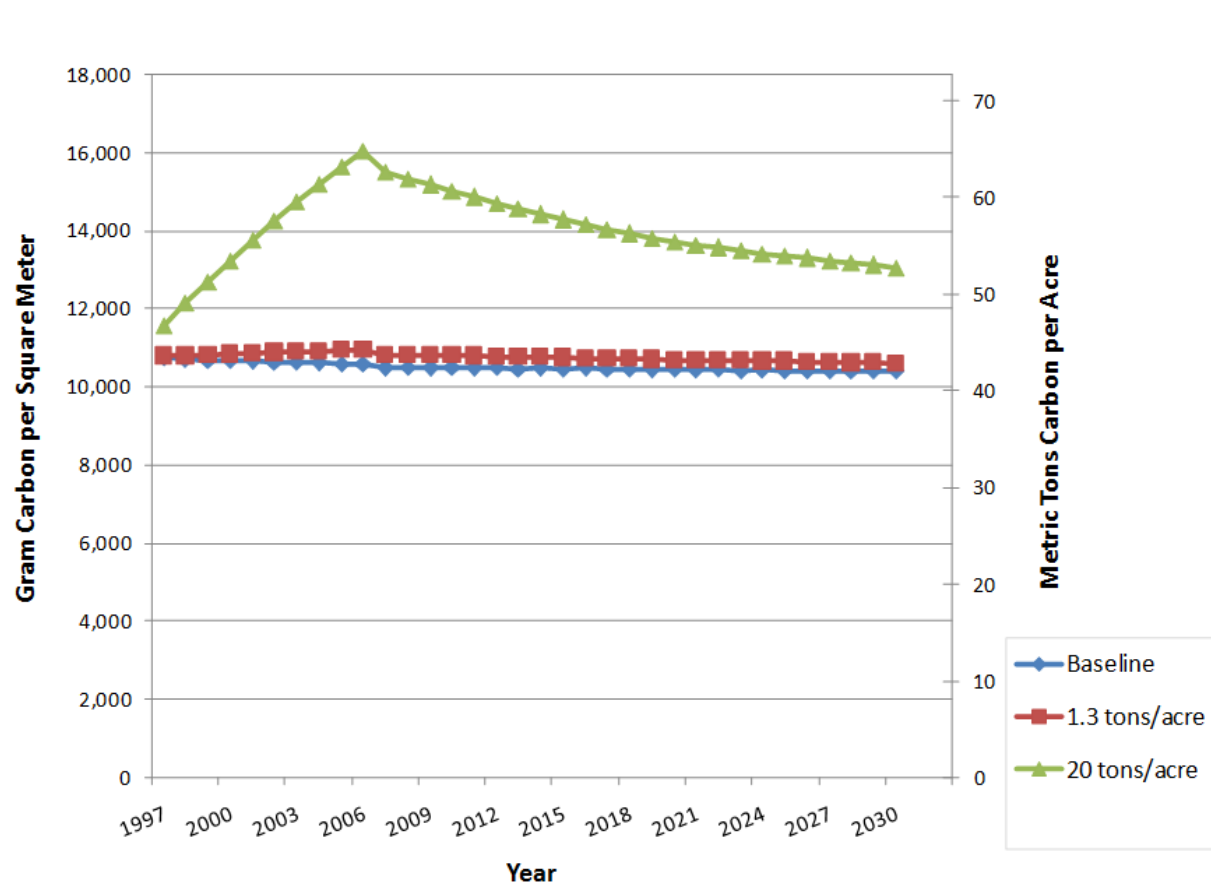


²⁴ EPA assumes 2.1 tons of yard trimmings are required to generate 1 ton of composted yard trimmings; thus, to convert the results in WARM (in $MTCO_2E$ per wet ton yard trimmings) to $MTCO_2E$ per wet ton of compost, multiply by 2.1. To convert to $MTCO_2E$ per dry ton compost, multiply values in WARM by 4.2 (assuming 50 percent moisture content).

The similarity across the various site conditions and application rates reflects the fact that the dominant process controlling carbon retention is the decomposition of organic materials in the various pools. As simulated by Century, this process is governed by first-order kinetics, i.e., the rate is independent of organic matter concentration or the rate of organic matter additions.

When viewed from the perspective of total carbon, rather than as a storage rate per ton of inputs to the composting process, both soil organic carbon concentrations and total carbon stored per acre increase with increasing application rates (see Exhibit 4-7). Soil organic carbon concentrations increase throughout the period of compost application, peak in 2006 (the last year of application), and decline thereafter as a result of decomposition of the imported carbon. Exhibit 4-7 shows total carbon storage (including baseline carbon) in soils on the order of 40 to 65 metric tons per acre. (The range would be higher with higher compost application rates or longer term applications.)

Exhibit 4-7: Total Soil C; Iowa Site, Corn Harvested for Grain



4.2.4.4 Century Simulation of Nitrogen Fertilization Effect

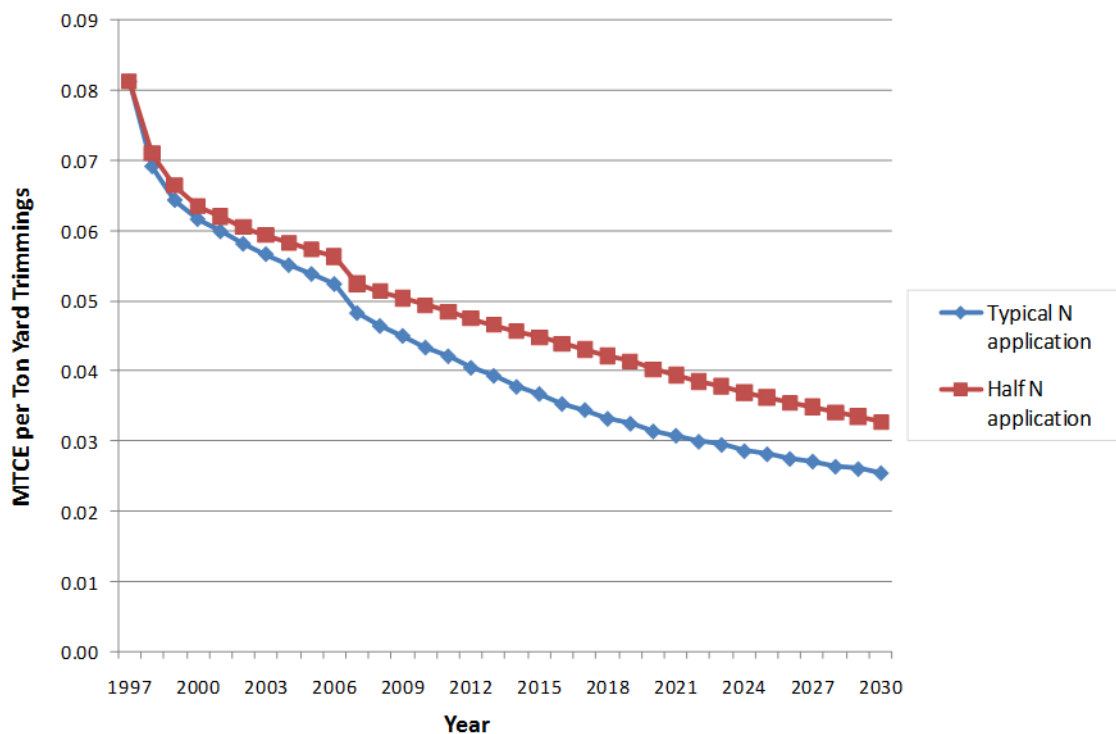
While the decomposition of organic materials is the primary process driving soil carbon retention, EPA’s Century analysis also revealed several secondary effects of compost application, including the effects of compost application on nitrogen availability and moisture retention. EPA performed additional Century simulations to quantify the nitrogen fertilization effect, or the hypothesis that mineralization of nitrogen in compost could stimulate crop growth, leading to production of more organic residues and increased soil organic carbon levels. The strength of this effect varies, depending

on the availability of other sources of nitrogen (N). To investigate this hypothesis, EPA analyzed different rates of synthetic fertilizer addition ranging from zero up to a typical rate to attain average crop yield (Colorado site: 90 lbs. N/acre; Iowa site: 124 lbs. N/per acre). EPA also evaluated fertilizer application at half of these typical rates.

Exhibit 4-8 shows the carbon storage rate for the Iowa site and the effect of nitrogen fertilization. The two curves in the exhibit represent the difference in carbon storage between a with-compost scenario (20 tons per acre) and a baseline, where compost is not applied. The nitrogen application rates differ in the following ways:

- The curve labeled “Typical N application” represents application of 124 lbs. per acre for both the compost and baseline scenarios. Because the nitrogen added through the compost has little effect when nitrogen is already in abundant supply, this curve portrays a situation where the carbon storage is attributable solely to the organic matter additions in the compost.
- The curve labeled “Half N application” represents application of 62 lbs. per acre. In this scenario, mineralization of nitrogen added by the compost has an incremental effect on crop productivity compared to the baseline. The difference between the baseline and compost application runs reflects both organic matter added by the compost and additional biomass produced in response to the nitrogen contributed by the compost.

Exhibit 4-8: Incremental Carbon Storage as a Function of Nitrogen Application Rate at the Iowa Site



The difference in incremental carbon storage rates between the two fertilization scenarios is less than 0.01 MTCE (0.03 MTCO₂E) per ton, indicating that the nitrogen fertilization effect is relatively small. Note that this finding is based on the assumption that farmers applying compost also will apply sufficient synthetic fertilizer to maintain economic crop yields. The effect would be larger if this

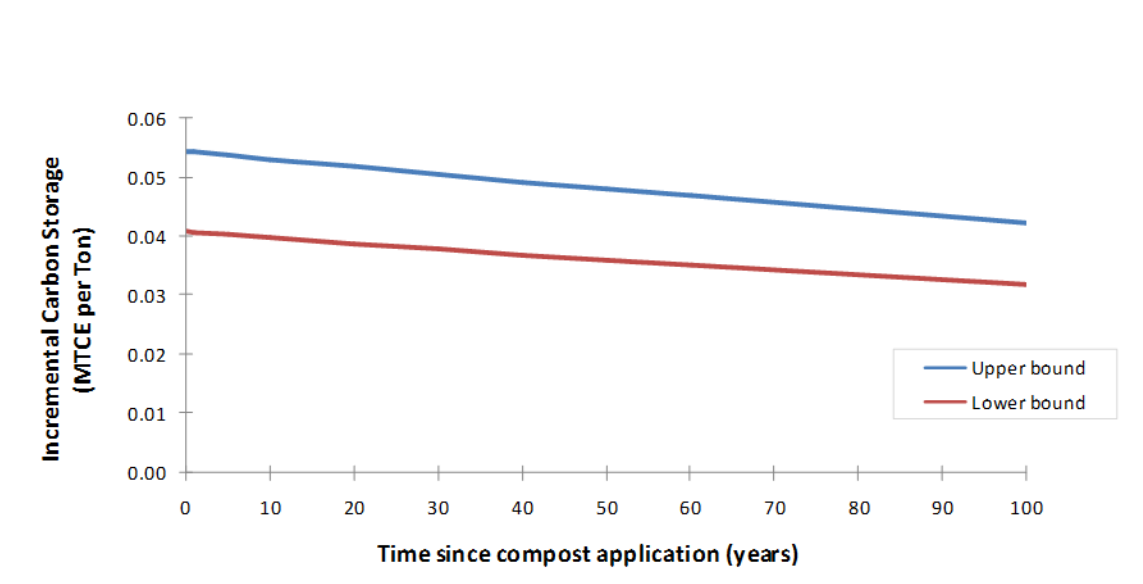
assumption is not well-founded or in situations where compost is applied as a soil amendment for road construction, landfill cover, or similar situations.

4.2.5 Humus Formation Carbon Storage

Significant evidence exists that compost contains stable compounds, such as humus, and that the carbon stored in that humus should be considered passive when added to the soil because it breaks down much more slowly than crop residues. As mentioned earlier, the Century model does not allow carbon inputs to flow directly into the passive pools; therefore, EPA used a bounding analysis to estimate the upper and lower limits of this humus formation mechanism of carbon storage. This bounding analysis rested on two primary variables: (1) the fraction of carbon in compost that is considered very stable and (2) the rate at which passive carbon is degraded to CO₂. Based on the expert judgment of Dr. Michael Cole from the University of Illinois, EPA found that between 4 to 20 percent of the carbon in compost degrades very quickly, and the remainder can be considered either slow or passive. Dr. Cole found 400 years to be the average of the reported sequestration times of carbon in the soil. The upper and lower bounds of the rate of carbon storage in soils resulting from the humus effect are shown in Exhibit 4-9. EPA took an average value of the upper and lower bounds after 10 years to estimate the carbon storage per short ton of compost that was stored in the passive carbon pool after year 10.

In WARM’s final calculation, EPA weighed the carbon values from the two carbon storage mechanisms according to the estimated percentage of compost that is passive (assumed to be 52 percent), and then used the total to estimate the sequestration value associated with composting, as shown in Exhibit 4-11.

Exhibit 4-9: Carbon Storage Resulting from Humus Effect, Bounding Estimate

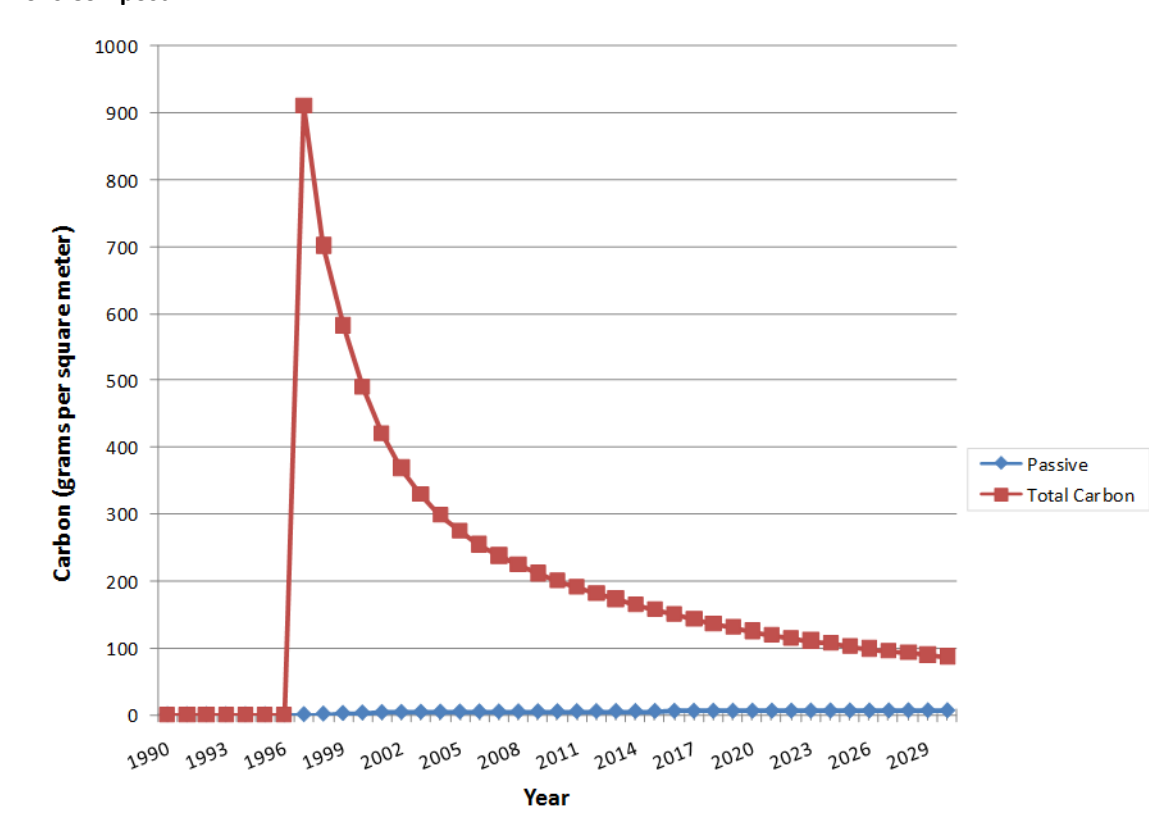


4.2.5.1 Eliminating the Possibility of Double-Counting

EPA adopted the approach of adding the humus formation effect to the direct carbon storage effect to capture the range of carbon storage benefits associated with compost application; however, this dual approach creates the possibility of double counting because the Century simulation may include both the direct carbon storage and humus formation effects. In an effort to eliminate double counting, EPA evaluated the way that Century partitions compost carbon after it is applied to the soil.

To do so, EPA ran a Century model simulation of compost addition during a single year and compared the results to a corresponding reference case without compost. EPA calculated the difference in carbon in each of the Century pools for the two simulations and found that the change in the passive pool represented less than 0.01 percent of the change in total carbon; therefore, Century is not adding recalcitrant carbon directly to the passive pool. Next, EPA graphed the change in the passive pool over time to ensure that the recalcitrant compost carbon was not being cycled from the faster pools into the passive pool several years after the compost is applied. As Exhibit 4-10 shows, Century does not introduce significant increments over the base case of recalcitrant carbon into the passive pool at any time.

Exhibit 4-10: Difference in Carbon Storage Between Compost Addition and Base Case Yearly Application with 20 Tons Compost



Based on the analysis, it appears that Century is appropriately simulating carbon cycling and storage for all but the passive carbon introduced by compost application. Because passive carbon represents approximately 52 percent of carbon in compost (the midpoint of 45 percent and 60 percent), EPA scaled the Century results by 48 percent to reflect the proportion of carbon that can be classified as fast or slow (i.e., not passive).

4.2.5.2 WARM Composting Results

Exhibit 4-11 shows the two carbon storage mechanisms included in WARM’s analysis of the GHGs associated with composting. The resulting net storage value relies on three main input values: the direct carbon storage, the carbon stored resulting from humus formation, and the percentage of carbon in compost assumed to be passive, or resistant to degradation.

Exhibit 4-11: The Soil Carbon Restoration Effect, the Increased Humus Formation Effect, and the Transportation Emissions for the Typical Compost Application Rate of 20 Short Tons per Acre

| Scenario | Soil Carbon Restoration | | | Increased Humus Formation | Transportation Emissions | Net Carbon Flux |
|---|-------------------------|---|-------------------|---------------------------|--------------------------|-----------------|
| | Unweighted | Proportion of C that Is Not Passive (%) | Weighted Estimate | | | |
| Annual application of 20 short tons of compost per acre | -0.04 | 0.48 | -0.07 | -0.17 | 0.04 | -0.20 |

4.3 LIMITATIONS

Because of data and resource constraints, this chapter does not explore the full range of conditions under which compost is managed and applied and how these conditions would affect the results of this analysis. Instead, this study attempts to provide an analysis of GHG emissions and sinks associated with centralized composting of organics under a limited set of scenarios. The lack of primary research on carbon storage associated with composting limited EPA's analysis. The limited availability of data forced EPA to rely on two modeling approaches, each with its own set of limitations. In addition, the analysis was limited by the scope of WARM, which is intended to present life-cycle GHG emissions of waste management practices for selected material types, including food discards and yard trimmings.

4.3.1 Limitations of Modeling Approaches

Because of data and resource constraints, EPA was unable to use Century to evaluate the variation in carbon storage impacts for a wide range of compost feedstocks (e.g., yard trimmings mixed with food discards, food discards alone). As noted earlier, resource constraints limited the number of soil types, climates, and compost applications simulated. The Century results also incorporate the limitations of the model itself, which have been well documented elsewhere. Perhaps most important, the model's predictions of soil organic matter levels are driven by four variables: annual precipitation, temperature, soil texture, and plant lignin content. Beyond these, the model is limited by its sensitivity to several factors for which data are difficult or impossible to obtain (e.g., presettlement grazing intensity, nitrogen input during soil development) (Parton et al., 1987). The model's monthly simulation intervals limit its ability to fully address potential interactions between nitrogen supply, plant growth, soil moisture, and decomposition rates, which may be sensitive to conditions that vary on a shorter time scale (Paustian et al., 1992). In addition, the model is not designed to capture the hypothesis that, because of the compost application, soil ecosystem dynamics change and more carbon is stored than is added to the soil (i.e., the multiplier effect).

Century simulates carbon movement through organic matter pools. Although the model is designed to evaluate additions of organic matter in general, EPA does not believe that it has been applied in the past to evaluate the application of organics compost. Century is parameterized to partition carbon to the various pools based on ratios of lignin to nitrogen and lignin to total carbon, not on the amount of organic material that has been converted to humus already. EPA addressed this limitation by developing an add-on analysis to evaluate humus formation in the passive pool, scaling the Century results, and summing the soil carbon storage values. There is some potential for double counting, to the extent that Century is routing some carbon to various pools that is also accounted for in the incremental humus analysis. EPA believes that this effect is likely to be minor.

The bounding analysis used to analyze increased humus formation is limited by the lack of data specifically dealing with composts composed of yard trimmings or food discards. This analysis is also

limited by the lack of data on carbon in compost that is passive. The approach of taking the average value from the two scenarios is simplistic, but it appears to be the best available option.

4.3.2 Limitations Related to the Scope of the Emission Factors

As indicated earlier, this chapter describes EPA's estimates of the GHG-related impacts of composting organics. EPA developed these estimates within the framework of the larger WARM development effort; therefore, the presentation of results, estimation of emissions and sinks, and description of ancillary benefits is not comprehensive. The remainder of this section describes specific limitations of the compost analysis.

As noted in the other documentation chapters, the GHG impacts of composting reported in this chapter are calculated using a methodology that facilitates comparison between composting and other possible disposal options for yard trimmings (i.e., landfilling and combustion). To present absolute GHG emission factors for composted yard trimmings that could be used to compare composting to a baseline of leaving yard trimmings on the ground where they fall, EPA would need to analyze the home soil. In particular, the carbon storage benefits of composting would need to be compared to the impact of removal of yard trimmings on the home soil.

As mentioned in Section 4.2, the lack of data and resources constrained EPA's analysis and, therefore, the analysis considers a small sampling of feedstocks and a specific application scenario (i.e., degraded agricultural soil). EPA analyzed two types of compost feedstocks—yard trimmings and food discards—although sewage sludge, animal manure, and several other compost feedstocks also may have significant GHG implications. Similarly, it was assumed that compost was applied to degraded agricultural soils, despite widespread use of compost in land reclamation, silviculture, horticulture, and landscaping.

This analysis did not consider the full range of soil conservation and management practices that could be used in combination with compost and the impacts of those practices on carbon storage. Some research indicates that adding compost to agricultural soils in conjunction with various conservation practices enhances the generation of soil organic matter to a much greater degree than applying compost alone. Examples of these conservation practices include conservation tillage, no tillage, residue management, crop rotation, wintering, and summer fallow elimination. Research also suggests that allowing crop residues to remain on the soil rather than turning them over helps to protect and sustain the soil while simultaneously enriching it. Alternatively, conventional tillage techniques accelerate soil erosion, increase soil aeration, and hence lead to greater GHG emissions (Lal et al., 1998). Compost use also has been shown to increase soil water retention; moister soil gives a number of ancillary benefits, including reduced irrigation costs and reduced energy used for pumping water. Compost can also play an important role in the adaptation strategies that will be necessary as climate zones shift and some areas become more arid.

As is the case in other chapters, the methodology EPA used to estimate GHG emissions from composting did not allow for variations in transportation distances. EPA recognizes that the density of landfills versus composting sites in any given area would have an effect on the extent of transportation emissions derived from composting. For example, in states that have a higher density of composting sites, the hauling distance to such a site would be smaller and thus require less fuel than transportation to a landfill. Alternatively, transporting compost from urban areas, where compost feedstocks may be collected, to farmlands, where compost is typically applied, could require more fuel because of the large distance separating the sites.

In addition to the carbon storage benefits of adding compost to agricultural soils, composting can lead to improved soil quality, improved productivity, and cost savings. For example, nutrients in compost tend to foster soil fertility (Brady and Weil, 1999). In fact, composts have been used to establish plant growth on land previously unable to support vegetation.

4.3.3 Ongoing Research to Improve Composting Estimates

EPA is researching several aspects of the composting analysis to improve existing assumptions based on updated research that is emerging. EPA's literature review focused on the following key topics: potential end uses and markets for compost, the shares of compost currently used in different applications in the United States, humus formation, the carbon storage timeframe, the multiplier effect, and other environmental benefits of composting.

Research on the potential end uses and markets for compost suggested that the horticultural/landscaping markets appear to be the most popular markets for compost in the United States. While data quantifying the size of these markets are limited, this finding suggests that the assumptions underlying the current WARM modeling may need to be re-examined. Further research into this subject may be warranted to determine exactly how compost is used in these urban or higher-end markets.

During EPA's research on carbon storage mechanisms, the agency uncovered new field research that may provide a basis for using primary data to quantify the carbon storage emission factor. If EPA decides to calculate a new carbon sequestration value based on field data, both the Century and bounding analyses will be superseded by this approach. EPA has also conducted extensive research into potential GHG emissions from composting. Preliminary research indicates that small amounts of both CH₄ and N₂O emissions are released during composting, even in well-managed piles.

Addressing the possible GHG emission reductions and other environmental benefits achievable by applying compost instead of chemical fertilizers, fungicides, and pesticides was beyond the scope of this documentation. Manufacturing those agricultural products requires energy. To the extent that compost may replace or reduce the need for these substances, composting may result in reduced energy-related GHG emissions. Although EPA understands that generally compost is applied for its soil amendment properties rather than for pest control, compost has been effective in reducing the need for harmful or toxic pesticides and fungicides.²⁵ Analyses of these benefits, however, are highly sensitive to assumptions about composting and fertilizer application rates, and information on the typical applications of these two soil additions is lacking.

4.4 REFERENCES

- Amlinger, F., P. Stefan, and C. Cuhls. 2008. *Greenhouse gas emissions from composting and mechanical biological treatment*. Waste Management & Research. 26: 47-60.
- Barlaz, M.A. (1997). *Biodegradative Analysis of Municipal Solid Waste in Laboratory-Scale Landfills*. 600/R-97-071. U.S. Environmental Protection Agency. Washington, DC.
- Beck-Friis, B., Pell, M., Sonesson, U., Jonsson, H., and Kirchmann, H. (2000). Formation and Emission of N₂O and CH₄ from Compost Heaps of Organic Household Waste. *Environmental Monitoring and Assessment*. 62: 317–331.

²⁵ For example, the use of compost may reduce or eliminate the need for soil fumigation with methyl bromide (an ozone-depleting substance) to kill plant pests and pathogens.

- Bernal, M., Sanchez-Montero, M., Paredes, C., and Roig, A. (1998). Carbon mineralization from organic wastes at different composting stages during their incubation with soil. *Agriculture, Ecosystems & Environment*. 69 (3): 175–189.
- Brady, N., & Weil, R. (1999). *The Nature and Properties of Soils*. Upper Saddle River, NJ: Prentice Hall.
- Brown, S. & Subler, S. (2007). Composting and Greenhouse Gas Emissions: A Producer's Perspective. *BioCycle*. 48(3): 37–41.
- Coker, C. (2006). Environmental Remediation by Composting. *BioCycle* 47(12):18. Retrieved from <http://www.biocycle.net/2006/12/14/environmental-remediation-by-composting/>
- Cornell Waste Management Institute (CWMI). (1998). Master Composter Resource Manual. <http://cwmi.css.cornell.edu/mastercompostermanual.pdf>
- Davidson, E.A., & Janssens, E.A. (2006). Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature*. 440: 165–173.
- EPA. (2015). *Advancing Sustainable Materials Management: Facts and Figures 2013*. (EPA530-R-15-002). Washington, DC: U.S. Government Printing Office. Retrieved from http://www.cta.tech/CorporateSite/media/environment/eCycle/2013_advncng_smm_rpt.pdf.
- EPA. (1994). *Composting Yard Trimmings and Municipal Solid Waste* (EPA document number EPA530-R-94-003). Washington, DC: U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response.
- Francou, C., Lineres, M., Derenne, S., Willio-Poitrenaud, M., and Houot, S. (2008). Influence of green waste, biowaste and paper-cardboard initial ratios on organic matter transformations during composting. *Bioresource Technology*, 99(18): 8926–8934.
- FAL. (1994). *The Role of Recycling in Integrated Solid Waste Management for the Year 2000*. Franklin Associates, Ltd. (Stamford, CT: Keep America Beautiful, Inc.), September, pp. 1–27, 30, and 31.
- Lal, R., et al. (1998). *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect* (Ann Arbor, MI: Sleeping Bear Press, Inc).
- Lou, W.F., and J. Nair. 2009. The impact of landfilling and composting on greenhouse gas emissions – A review. *Bioresource Technology*. 100 (16): 3792-3798.
- Meersmans, J., van Wesemael, B., de Ridder, F., Fallas Dotti, M., de Baets, S., and van Molle, M. (2009). Changes in organic carbon distribution with depth in agricultural soils in northern Belgium, 1960–2006. *Global Change Biology*: 1–12.
- Metherell, A., Harding, L., Cole, C., and Parton, W. (1993). Century Agroecosystem Version 4.0, Great Plains System Research Unit Technical Report No. 4, USDA-ARS Global Climate Change Research Program (Colorado State University: Fort Collins, CO).
- National Renewable Energy Laboratory (2015). "U.S. Life Cycle Inventory Database." Retrieved from <https://www.lcacommons.gov/nrel/search>
- Parton, W., Schimel, D., Cole, C., and Ojima, D. (1987). Analysis of Factors Controlling Soil Organic Matter Levels in Great Plains Grasslands. *Soil Sci. Soc. Am. J.*, 51:1173–1179.
- Paustian, K., Parton, W., and Persson, J. (1992). Modeling Soil Organic Matter in Organic-Amended and Nitrogen-Fertilized Long-Term Plots. *Soil Sci. Soc. Am. J.*, 56:476–488.

Zanker Road Resource Management, Ltd. Undated. Z-Best Compost Facility.

5 COMBUSTION

This document presents an overview of combustion as a waste management strategy in relation to the development of material-specific emission factors for EPA's Waste Reduction Model (WARM). Included are estimates of the net greenhouse gas (GHG) emissions from combustion of most of the materials considered in WARM and several categories of mixed waste.

5.1 A SUMMARY OF THE GHG IMPLICATIONS OF COMBUSTION

Combustion of municipal solid waste (MSW) results in emissions of CO₂ and N₂O. Note that CO₂ from combustion of biomass (such as paper products and yard trimmings) is not counted because it is biogenic (as explained in the WARM Background and Overview chapter). WARM estimates emissions from combustion of MSW in waste-to-energy (WTE) facilities. WARM does not consider any recovery of materials from the MSW stream that may occur before MSW is delivered to the combustor.

In the United States, about 80 WTE facilities process more than 30 million tons of MSW annually (ERC, 2014). WTE facilities can be divided into three categories: (1) mass burn, (2) modular and (3) refuse-derived fuel (RDF). A mass burn facility generates electricity and/or steam from the combustion of mixed MSW. Most of the facilities (76 percent) employ mass burn technology. Modular WTE plants are generally smaller than mass burn plants, and are prefabricated off-site so that they can be assembled quickly where they are needed. Because of their similarity to mass burn facilities, modular facilities are treated as part of the mass burn category for the purposes of this analysis.

An RDF facility combusts MSW that has undergone varying degrees of processing, from simple removal of bulky and noncombustible items to more complex processes (such as shredding and material recovery) that result in a finely divided fuel. Processing MSW into RDF yields a more uniform fuel that has a higher heating value than that used by mass burn or modular WTE. MSW processing into RDF involves both manual and mechanical separation to remove materials such as glass and metals that have little or no fuel value. In the United States, approximately 14 facilities combust RDF (ERC, 2010).

This study analyzed the net GHG emissions from combustion of all individual and mixed waste streams in WARM at mass burn and RDF facilities, with the exception of asphalt concrete, drywall and fiberglass insulation. These three materials were excluded because EPA determined that they are not typically combusted at end of life. Note that **WARM incorporates only the emission factors for mass burn facilities**, due to (1) the relatively small number of RDF facilities in the United States and (2) the fact that the RDF emission factors are based on data from only one RDF facility.

Net emissions consist of (1) emissions from the transportation of waste to a combustion facility, (2) emissions of non-biogenic CO₂, and (3) emissions of N₂O minus (4) avoided GHG emissions from the electric utility sector and (5) avoided GHG emissions due to the recovery and recycling of ferrous metals at the combustor. There is some evidence that as combustor ash ages, it absorbs CO₂ from the atmosphere. However, EPA did not count absorbed CO₂ because the quantity is estimated to be less than 0.02 MTCO₂E per ton of MSW combusted.²⁶ The results of this analysis for the materials contained in WARM and the explanations for each of these results are discussed in section 5.3.²⁷

²⁶ Based on data provided by Dr. Jürgen Vehlow of the Institut für Technische Chemie in Karlsruhe, Germany, EPA estimated that the ash from one ton of MSW would absorb roughly 0.004 MTCE of CO₂.

²⁷ Note that Exhibit 5-1, Exhibit 5-2, and Exhibit 5-6 do not show mixed paper. Mixed paper is shown in the summary exhibit. The summary values for mixed paper are based on the proportions of the four paper types (newspaper, office paper, corrugated containers, and magazines/third-class mail) that make up the different "mixed paper" definitions.

5.2 CALCULATING THE GHG IMPACTS OF COMBUSTION

This study's general approach was to estimate (1) the gross emissions of CO₂ and N₂O from MSW combustion (including emissions from transportation of waste to the combustor and ash from the combustor to a landfill) and (2) the CO₂ emissions avoided because of displaced electric utility generation and decreased energy requirements for production processes using recycled inputs. A comprehensive evaluation would also consider the fate of carbon remaining in combustor ash. Depending on its chemical form, carbon may be aerobically degraded to CO₂, anaerobically degraded to CH₄, or remain in a relatively inert form and be stored. Unless the ash carbon is converted to CH₄ (which EPA considers unlikely), the effect on the net GHG emissions will be very small. To obtain an estimate of the *net* GHG emissions from MSW combustion, the GHG emissions avoided were subtracted from the direct GHG emissions. EPA estimated the net GHG emissions from waste combustion per ton of mixed MSW and per ton of each selected material in MSW. The remainder of this section describes how EPA developed these estimates.

5.2.1 Emissions of CO₂ from WTE Facilities

The carbon in MSW has two distinct origins: some of it is derived from sustainably harvested biomass (i.e., carbon in plant matter that was converted from CO₂ in the atmosphere through photosynthesis), and the remainder is from non-biomass sources, e.g., plastic and synthetic rubber derived from petroleum.

As explained in the [WARM Background and Overview](#) chapter, WARM considers only CO₂ that derives from fossil sources and does not consider biogenic CO₂ emissions. Therefore, only CO₂ emissions from the combustion of non-biomass components of MSW—plastic, textiles and rubber—were counted. These components make up a relatively small share of total MSW, so only a small portion of the total CO₂ emissions from combustion are considered in WARM.

To estimate the non-biogenic carbon content of the plastics, textiles, rubber and leather contained in one ton of mixed MSW, EPA first establishes assumptions for the non-biogenic share of carbon in these materials. For plastics in products in MSW, EPA assumes that all carbon is non-biogenic carbon, because biogenic plastics likely make up a small but unknown portion of products. For rubber and leather products in MSW, EPA assumes that the non-biogenic share of carbon contained in clothing and footwear is 25 percent; this assumption is based on expert judgment. The non-biogenic share of carbon in containers, packaging, and other durables is 100 percent; and the non-biogenic share of carbon in other nondurables is 75 percent (EPA, 2010). For textile products in MSW, EPA assumes that the non-biogenic share of carbon is 55 percent (DeZan, 2000). EPA then calculates the non-biogenic carbon content of each of these material groups. For plastics in products in MSW, EPA uses the molecular formula of each resin type to assume that PET is 63 percent carbon; PVC is 38 percent carbon; polystyrene is 92 percent carbon; HDPE, LDPE, and polypropylene are 86 percent carbon; and a weighted average of all other resins is 66 percent carbon (by weight). Based on the amount of each plastic discarded in 2013 (EPA, 2015c), EPA calculates a weighted carbon content of 80 percent for plastics in mixed MSW. For rubber and leather products, EPA uses the weighted average carbon content of rubbers consumed in 2002 to estimate a carbon content of 85 percent (by weight) for rubber and leather products in mixed MSW. For textiles, EPA uses the average carbon content of the four main synthetic fiber types to estimate a carbon content of 70 percent (by weight) for textiles in mixed MSW. Next, using data from BioCycle's *The State of Garbage in America* (Van Haaren et al., 2010), EPA assumes that 7 percent of discards are combusted in the United States. Data from BioCycle is used instead of EPA's *Advancing Sustainable Materials Management: Facts and Figures* report (EPA, 2015c), because it is based off of direct reporting, and provides a more accurate representation of the amount of materials

discarded at WTE facilities. Additionally, these data are also used in order to maintain consistency with the data source used in EPA's annual *Inventory of U.S. Greenhouse Gas Emissions and Sinks* report. Based on these assumptions, EPA estimates that there are 0.10 tons of non-biogenic carbon in the plastic, textiles, rubber and leather contained in one ton of mixed MSW (EPA, 2015c; Van Haaren et al., 2010).

The 10 percent non-biomass carbon content of mixed MSW was then converted to units of MTCO₂E per short ton of mixed MSW combusted. The resulting value for mixed MSW is shown in Exhibit 5-1. Note that if EPA had used a best-case assumption for textiles (i.e., assuming that they have no petrochemical-based fibers), the resulting value for mixed MSW would have been slightly lower. The values for CO₂ emissions are shown in column (b) of Exhibit 5-1.

Exhibit 5-1: Gross GHG Emissions from MSW Combustion (MTCO₂E/Short Ton of Material Combusted)

| (a) Material | (b) Combustion CO ₂ Emissions From Non- Biomass per Short Ton Combusted | (c) Combustion N ₂ O Emissions per Short Ton Combusted | (d) Transportation CO ₂ Emissions per Short Ton Combusted | (e) Gross GHG Emissions per Short Ton Combusted (e = b + c + d) |
|-------------------------------------|--|---|--|---|
| Aluminum Cans | – | – | 0.01 | 0.01 |
| Aluminum Ingot | – | – | 0.01 | 0.01 |
| Steel Cans | – | – | 0.01 | 0.01 |
| Copper Wire | – | – | 0.01 | 0.01 |
| Glass | – | – | 0.01 | 0.01 |
| HDPE | 2.79 | – | 0.01 | 2.80 |
| LDPE | 2.79 | – | 0.01 | 2.80 |
| PET | 2.04 | – | 0.01 | 2.05 |
| LLDPE | 2.79 | – | 0.01 | 2.80 |
| PP | 2.79 | – | 0.01 | 2.80 |
| PS | 3.01 | – | 0.01 | 3.02 |
| PVC | 1.25 | – | 0.01 | 1.26 |
| PLA | – | – | 0.01 | 0.01 |
| Corrugated Containers | – | 0.04 | 0.01 | 0.05 |
| Magazines/Third-Class Mail | – | 0.04 | 0.01 | 0.05 |
| Newspaper | – | 0.04 | 0.01 | 0.05 |
| Office Paper | – | 0.04 | 0.01 | 0.05 |
| Phone Books ^a | – | 0.04 | 0.01 | 0.05 |
| Textbooks ^a | – | 0.04 | 0.01 | 0.05 |
| Dimensional Lumber | – | 0.04 | 0.01 | 0.05 |
| Medium-Density Fiberboard | – | 0.04 | 0.01 | 0.05 |
| Food Waste | – | 0.04 | 0.01 | 0.05 |
| Food Waste (meat only) | – | 0.04 | 0.01 | 0.05 |
| Food Waste (non-meat) | – | 0.04 | 0.01 | 0.05 |
| Beef | – | 0.04 | 0.01 | 0.05 |
| Poultry | – | 0.04 | 0.01 | 0.05 |
| Grains | – | 0.04 | 0.01 | 0.05 |
| Bread | – | 0.04 | 0.01 | 0.05 |
| Fruits and Vegetables | – | 0.04 | 0.01 | 0.05 |
| Dairy Products | – | 0.04 | 0.01 | 0.05 |
| Yard Trimmings | – | 0.04 | 0.01 | 0.05 |
| Grass | – | 0.04 | 0.01 | 0.05 |
| Leaves | – | 0.04 | 0.01 | 0.05 |
| Branches | – | 0.04 | 0.01 | 0.05 |
| Mixed Paper (general) | – | 0.04 | 0.01 | 0.05 |
| Mixed Paper (primarily residential) | – | 0.04 | 0.01 | 0.05 |

| (a) Material | (b) Combustion CO ₂ Emissions From Non- Biomass per Short Ton Combusted | (c) Combustion N ₂ O Emissions per Short Ton Combusted | (d) Transportation CO ₂ Emissions per Short Ton Combusted | (e) Gross GHG Emissions per Short Ton Combusted (e = b + c + d) |
|--------------------------------------|--|---|--|---|
| Mixed Paper (primarily from offices) | – | 0.04 | 0.01 | 0.05 |
| Mixed Metals | – | – | 0.01 | 0.01 |
| Mixed Plastics | 2.33 | – | 0.01 | 2.34 |
| Mixed Recyclables | 0.07 | 0.03 | 0.01 | 0.11 |
| Mixed Organics | – | 0.04 | 0.01 | 0.05 |
| Mixed MSW | 0.32 | 0.04 | 0.01 | 0.37 |
| Carpet | 1.67 | – | 0.01 | 1.68 |
| Personal Computers | 0.38 | – | 0.01 | 0.39 |
| Clay Bricks | NA | NA | NA | NA |
| Concrete | NA | NA | NA | NA |
| Fly Ash | NA | NA | NA | NA |
| Tires | 2.20 | – | 0.01 | 2.21 |
| Asphalt Concrete | NA | NA | NA | NA |
| Asphalt Shingles | 0.65 | 0.04 | 0.01 | 0.70 |
| Drywall | NA | NA | NA | NA |
| Fiberglass Insulation | NA | NA | NA | NA |
| Vinyl Flooring | 0.28 | – | 0.01 | 0.29 |
| Wood Flooring | – | 0.04 | 0.05 | 0.09 |

– = Zero emissions.

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

^aThe values for phone books and textbooks are proxies, based on newspaper and office paper, respectively.

5.2.2 Emissions of N₂O from WTE Facilities

Studies compiled by the Intergovernmental Panel on Climate Change (IPCC) show that MSW combustion results in measurable emissions of N₂O, a GHG with a global warming potential (GWP) 298 times that of CO₂ (EPA, 2015a; IPCC, 2007; IPCC, 2006). The IPCC compiled reported ranges of N₂O emissions, per metric ton of waste combusted, from six classifications of MSW combustors. This study averaged the midpoints of each range and converted the units to MTCO₂E of N₂O per ton of MSW. The resulting estimate is 0.04 MTCO₂E of N₂O emissions per ton of mixed MSW combusted. Because the IPCC did not report N₂O values for combustion of individual components of MSW, EPA used the 0.04 value not only for mixed MSW, but also as a proxy for all components of MSW, except for aluminum cans, steel cans, glass, HDPE, LDPE and PET. This exception was made because at the relatively low combustion temperatures found in MSW combustors, most of the nitrogen in N₂O emissions is derived from the waste, not from the combustion air. Because aluminum and steel cans, glass, and plastics do not contain nitrogen, EPA concluded that running these materials through an MSW combustor would not result in N₂O emissions.

5.2.3 Emissions of CO₂ from Transportation of Waste and Ash

WARM includes emissions associated with transporting of waste and the subsequent transportation of the residual waste ash to the landfill. Transportation energy emissions occur when fossil fuels are combusted to collect and transport material to the combustion facility and then to operate on-site equipment. Transportation of any individual material in MSW is assumed to use the same amount of energy as transportation of mixed MSW. To calculate the emissions, WARM relies on assumptions from FAL (1994) for the equipment emissions and NREL's US Life Cycle Inventory Database (USLCI) (NREL 2015). The NREL emission factor assumes a diesel, short-haul truck.

5.2.4 Estimating Utility CO₂ Emissions Avoided

Most WTE plants in the United States produce electricity. Only a few cogenerate electricity and steam. In this analysis, EPA assumes that the energy recovered with MSW combustion would be in the form of electricity, with the exception of two materials that are not assumed to be combusted at WTE plants. For tires, the avoided utility CO₂ emissions per ton of tires combusted is based on the weighted average of three tire combustion pathways: combustion at cement kilns, power plants, and pulp and paper mills. For asphalt shingles, the avoided utility CO₂ emissions per ton of shingles combusted is equal to the amount of avoided refinery gas combusted at cement kilns where asphalt shingles are combusted. The avoided utility CO₂ emissions analysis is shown in Exhibit 5-2. EPA uses three data elements to estimate the avoided electric utility CO₂ emissions associated with combustion of waste in a WTE plant: (1) the energy content of mixed MSW and of each separate waste material considered, (2) the combustion system efficiency in converting energy in MSW to delivered electricity, and (3) the electric utility CO₂ emissions avoided per kilowatt-hour (kWh) of electricity delivered by WTE plants.

Exhibit 5-2: Avoided Utility GHG Emissions from Combustion at WTE Facilities

| (a) Material Combusted | (b) Energy Content (Million Btu Per Ton) | (c) Mass Burn Combustion System Efficiency (%) | (d) RDF Combustion System Efficiency (%) | (e) Emission Factor for Utility- Generated Electricity ^a (MTCO ₂ E/ Million Btu of Electricity Delivered) | (f) Avoided Utility GHG Emissions per Ton Combusted at Mass Burn Facilities ^a (MTCO ₂ E) (f = b × c × e) | (g) Avoided Utility CO ₂ per Ton Combusted at RDF Facilities (MTCO ₂ E) (g = b × d × e) |
|----------------------------------|--|--|--|--|--|---|
| Aluminum Cans | -0.67 ^b | 17.8% | 16.3% | 0.22 | -0.03 | -0.02 |
| Aluminum Ingot | -0.67 | 17.8% | 16.3% | 0.22 | -0.03 | -0.02 |
| Steel Cans | -0.42 ^b | 17.8% | 16.3% | 0.22 | -0.02 | -0.02 |
| Copper Wire | -0.55 ^c | 17.8% | 16.3% | 0.22 | -0.02 | -0.02 |
| Glass | -0.47 ^b | 17.8% | 16.3% | 0.22 | -0.02 | -0.02 |
| HDPE | 40.0 ^d | 17.8% | 16.3% | 0.22 | 1.58 | 1.44 |
| LDPE | 39.8 ^d | 17.8% | 16.3% | 0.22 | 1.57 | 1.43 |
| PET | 21.2 | 17.8% | 16.3% | 0.22 | 0.84 | 0.76 |
| LLDPE | 39.9 | 17.8% | 16.3% | 0.22 | 1.57 | 1.43 |
| PP | 39.9 | 17.8% | 16.3% | 0.22 | 1.57 | 1.43 |
| PS | 36.0 | 17.8% | 16.3% | 0.22 | 1.42 | 1.29 |
| PVC | 15.8 | 17.8% | 16.3% | 0.22 | 0.62 | 0.57 |
| PLA | 16.7 | 17.8% | 16.3% | 0.22 | 0.66 | 0.60 |
| Corrugated Containers | 14.1 ^d | 17.8% | 16.3% | 0.22 | 0.56 | 0.51 |
| Magazines/Third- Class Mail | 10.5 ^d | 17.8% | 16.3% | 0.22 | 0.41 | 0.38 |
| Newspaper | 15.9 ^d | 17.8% | 16.3% | 0.22 | 0.63 | 0.57 |
| Office Paper | 13.6 ^d | 17.8% | 16.3% | 0.22 | 0.54 | 0.49 |
| Phone Books | 15.9 ^d | 17.8% | 16.3% | 0.22 | 0.63 | 0.57 |
| Textbooks | 13.6 ^d | 17.8% | 16.3% | 0.22 | 0.54 | 0.49 |
| Dimensional Lumber | 16.6 ^f | 17.8% | 16.3% | 0.22 | 0.65 | 0.60 |
| Medium-Density Fiberboard | 16.6 ^f | 17.8% | 16.3% | 0.22 | 0.65 | 0.60 |
| Food Waste | 4.7 ^d | 17.8% | 16.3% | 0.22 | 0.19 | 0.17 |
| Food Waste (meat only) | 4.7 ^d | 17.8% | 16.3% | 0.22 | 0.19 | 0.17 |
| Food Waste (non- | 4.7 ^d | 17.8% | 16.3% | 0.22 | 0.19 | 0.17 |

| (a) | (b) | (c) | (d) | (e) | (f) | (g) |
|--------------------------------------|--------------------------------------|--|--------------------------------------|--|--|---|
| Material Combusted | Energy Content (Million Btu Per Ton) | Mass Burn Combustion System Efficiency (%) | RDF Combustion System Efficiency (%) | Emission Factor for Utility-Generated Electricity ^a (MTCO ₂ E/ Million Btu of Electricity Delivered) | Avoided Utility GHG Emissions per Ton Combusted at Mass Burn Facilities ^a (MTCO ₂ E) (f = b × c × e) | Avoided Utility CO ₂ per Ton Combusted at RDF Facilities (MTCO ₂ E) (g = b × d × e) |
| meat) | | | | | | |
| Beef | 4.7 ^d | 17.8% | 16.3% | 0.22 | 0.19 | 0.17 |
| Poultry | 4.7 ^d | 17.8% | 16.3% | 0.22 | 0.19 | 0.17 |
| Grains | 4.7 ^d | 17.8% | 16.3% | 0.22 | 0.19 | 0.17 |
| Bread | 4.7 ^d | 17.8% | 16.3% | 0.22 | 0.19 | 0.17 |
| Fruits and Vegetables | 4.7 ^d | 17.8% | 16.3% | 0.22 | 0.19 | 0.17 |
| Dairy Products | 4.7 ^d | 17.8% | 16.3% | 0.22 | 0.19 | 0.17 |
| Yard Trimmings | 5.6 ^g | 17.8% | 16.3% | 0.22 | 0.22 | 0.20 |
| Grass | 5.6 ^g | 17.8% | 16.3% | 0.22 | 0.22 | 0.20 |
| Leaves | 5.6 ^g | 17.8% | 16.3% | 0.22 | 0.22 | 0.20 |
| Branches | 5.6 ^g | 17.8% | 16.3% | 0.22 | 0.22 | 0.20 |
| Mixed Paper (general) | NA | 17.8% | 16.3% | 0.22 | 0.56 | NA |
| Mixed Paper (primarily residential) | NA | 17.8% | 16.3% | 0.22 | 0.56 | NA |
| Mixed Paper (primarily from offices) | NA | 17.8% | 16.3% | 0.22 | 0.51 | NA |
| Mixed Metals | NA | 17.8% | 16.3% | 0.22 | -0.02 | NA |
| Mixed Plastics | NA | 17.8% | 16.3% | 0.22 | 1.12 | NA |
| Mixed Recyclables | NA | 17.8% | 16.3% | 0.22 | 0.51 | NA |
| Mixed Organics | NA | 17.8% | 16.3% | 0.22 | 0.20 | NA |
| Mixed MSW | 10.0 ^h | 17.8% | 16.3% | 0.22 | 0.39 | 0.36 |
| Carpet | 15.2 ⁱ | 17.8% | 16.3% | 0.22 | 0.60 | 0.55 |
| Personal Computers | 3.1 ^j | 17.8% | 16.3% | 0.22 | 0.12 | 0.11 |
| Clay Bricks | NA | NA | NA | NA | NA | NA |
| Concrete | NA | NA | NA | NA | NA | NA |
| Fly Ash | NA | NA | NA | NA | NA | NA |
| Tires | 27.8 ^k | NA | NA | NA | 1.57 | 1.57 |
| Asphalt Concrete | NA | NA | NA | NA | NA | NA |
| Asphalt Shingles | 8.8 | NA ^l | NA ^l | NA ^l | 1.05 ^m | 1.05 ^m |
| Drywall | NA | NA | NA | NA | NA | NA |
| Fiberglass Insulation | NA | NA | NA | NA | NA | NA |
| Vinyl Flooring | 15.8 | 17.8% | 16.3% | 0.22 | 0.62 | 0.57 |
| Wood Flooring | 18.0 ⁿ | 21.5% ^o | 16.3% | 0.22 | 0.86 | 0.65 |

NA = Not applicable.

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

^a The values in this column are based on national average emissions from utility-generated electricity. The Excel version of WARM also allows users to choose region-specific utility-generated factors, which are contained in Exhibit 5-4.

^b EPA developed these estimates based on data on the specific heat of aluminum, steel and glass and calculated the energy required to raise the temperature of aluminum, steel and glass from ambient temperature to the temperature found in a combustor (about 750° Celsius), based on Incropera and DeWitt (1990).

^c Average of aluminum and steel.

^d Source: EPA (1995). "Magazines" used as proxy for magazines/third-class mail; "mixed paper" used as a proxy for the value for office paper and textbooks; "newspapers" used as a proxy for phone books.

^e Source: Gaines and Stodolsky (1993).

^f EPA used the higher end of the MMBtu factor for basswood from the USDA-FS. Basswood is a relatively soft wood, so its high-end MMBtu content should be similar to an average factor for all wood types (Fons et al., 1962).

^g Procter and Redfern, Ltd. and ORTECH International (1993).

^h Source: IWSA and American Ref-Fuel (personal communication, October 28, 1997). Mixed MSW represents the entire waste stream as disposed of.

ⁱ Source: Realf, M. (2010).

^j Source: FAL (2002b).

^k Tires used as tire-derived fuel substitute for coal in cement kilns and electric utilities; used as a substitute for natural gas in pulp and paper facilities. Therefore, columns (d) through (h) are a weighted average of multiple tire combustion pathways, and are not calculated in the same manner as the other materials and products in the table.

^l The avoided utility GHG emissions are assumed to equal avoided cement kiln refinery gas combustion, so this factor is not used.

^m Assumes avoided cement kiln refinery gas combustion.

ⁿ Bergman and Bowe (2008), Table 3, p. 454. Note that this is in good agreement with values already in WARM for lumber and medium-density fiberboard.

^o Based on average heat rate of U.S. dedicated biomass electricity plants.

5.2.4.1 Energy Content

The energy content of each of the combustible materials in WARM is contained in column (b) of Exhibit 5-2. For the energy content of mixed MSW, EPA used a value of 10.0 million Btu (MMBtu) per short ton of mixed MSW combusted, which is a value commonly used in the WTE industry (IWSA and American Ref-Fuel, 1997). This estimate is within the range of values (9.0 to 13.0 MMBtu per ton) reported by FAL (1994) and is slightly higher than the 9.6 MMBtu per ton value reported in EPA's *MSW Fact Book* (EPA, 1995). For the energy content of RDF, a value of 11.4 MMBtu per ton of RDF combusted was used (Harrington 1997). This estimate is within the range of values (9.6 to 12.8 MMBtu per ton) reported by the DOE's National Renewable Energy Laboratory (NREL, 1992). For the energy content of specific materials in MSW, EPA consulted three sources: (1) EPA's *MSW Fact Book* (1995), a compilation of data from primary sources, (2) a report by Environment Canada (Procter and Redfern, Ltd. and ORTECH International, 1993), and (3) a report by Argonne National Laboratories (Gaines and Stodolsky, 1993). EPA assumes that the energy contents reported in the first two of these sources were for materials with moisture contents typically found for the materials in MSW (the sources imply this but do not explicitly state it). The Argonne study reports energy content on a dry weight basis.

5.2.4.2 Combustion System Efficiency

To estimate the combustion system efficiency of mass burn plants, EPA uses a net value of 550 kWh generated by mass burn plants per ton of mixed MSW combusted (Zannes, M. 1997).

To estimate the combustion system efficiency of RDF plants, EPA evaluated three sources: (1) data supplied by an RDF processing facility located in Newport, MN (Harrington, 1997); (2) the Integrated Waste Services Association report, *The 2000 Waste-to-Energy Directory: Year 2000* (IWSA, 2000); and (3) the National Renewable Energy Laboratory (NREL, 1992). EPA uses the Newport Processing Facility's reported net value of 572 kWh generated per ton of RDF for two reasons. First, this value is within the range of values reported by the other sources. Second, the Newport Processing Facility provides a complete set of data for evaluating the overall system efficiency of an RDF plant. The net energy value reported accounts for the estimated energy required to process MSW into RDF and the estimated energy consumed by the RDF combustion facility. The dataset includes estimates on the composition and amount of MSW delivered to the processing facility, as well as estimates for the heat value of RDF, the amount of energy required to process MSW into RDF, and the amount of energy used to operate the RDF facility.

Next, EPA considers losses in transmission and distribution of electricity specific to WTE combustion facilities. The U.S. average transmission and distribution ("line") loss rate is about 9 percent, although for some facilities or cities, this rate may be lower. According to IWSA and American Ref-Fuel (1997), this rate could be as low as 4 percent. IWSA supports a 5-percent line loss rate, and for purposes of this analysis, we assume this value. Using the 5-percent loss rate, EPA estimates that 523 kWh are delivered per ton of waste combusted at mass burn facilities, and 544 kWh are delivered per ton of waste input at RDF facilities.

EPA then uses the value for the delivered kWh per ton of waste combusted to derive the implicit combustion system efficiency (i.e., the percentage of energy in the waste that is ultimately delivered in the form of electricity). To determine this efficiency, we estimate the MMBtu of MSW needed to deliver 1 kWh of electricity. EPA divides the MMBtu per ton of waste by the delivered kWh per ton of waste to obtain the MMBtu of waste per delivered kWh. The result is 0.0191 MMBtu per kWh for mass burn and 0.0210 MMBtu per kWh for RDF. The physical constant for the energy in 1 kWh (0.0034 MMBtu) is then divided by the MMBtu of MSW and RDF needed to deliver 1 kWh, to estimate the total system efficiency at 17.8 percent for mass burn and 16.3 percent for RDF (see Exhibit 5-2, columns (d) and (e)). Note that the total system efficiency is the efficiency of translating the energy content of the fuel into the energy content of delivered electricity. The estimated system efficiencies of 17.8 and 16.3 percent reflect losses in (1) converting energy in the fuel into steam, (2) converting energy in steam into electricity, and (3) delivering electricity.

5.2.4.3 Electric Utility Carbon Emissions Avoided

To estimate the avoided utility GHG emissions from waste combustion, EPA uses "non-baseload" emission factors from EPA's Emissions and Generation Resource Integrated Database (eGRID). EPA made the decision to use non-baseload factors rather than a national average of only fossil-fuel plants²⁸ because the non-baseload emission rates provide a more accurate estimate of the marginal emissions rate. The non-baseload rates scale emissions from generating units based on their capacity factor. Plants that run at more than 80 percent capacity are considered "baseload" generation and not included in the "non-baseload" emission factor; a share of generation from plants that run between 80 percent and 20 percent capacity is included in the emission factor based on a "linear relationship," and all plants with capacity factors below 20 percent are included (E.H. Pechan & Associates, 2006).

In order to capture the regional differences in the emissions rate due to the variation in sources of electricity generation, WARM first uses state-level eGRID non-baseload emission factors and aggregates them into weighted average regional emission factors based on fossil-fuel-only state electricity generation. The geographic regions are based on U.S. Census Bureau-designated areas. Exhibit 5-3 contains a map, prepared by the U.S. Census Bureau, of the nine regions. Exhibit 5-4 shows the national average eGRID emission factor and the factors for each of the nine geographic regions. In addition to the calculated regional non-baseload emission factors, EPA also utilizes eGRID's national non-baseload emission factor to represent the national average non-baseload avoided utility emission factor. The resulting non-baseload regional and national average estimates for utility carbon emissions avoided for each material at mass burn facilities are shown in Exhibit 5-5. Columns (g) and (h), respectively, of Exhibit 5-2 show the national average estimates for mass burn and RDF facilities.

²⁸ While coal accounts for 48 percent of U.S. primary energy consumption—and 70 percent of fossil-fuel consumption—in the electricity sector, these plants may serve as baseload power with marginal changes in electricity supply met by natural gas plants in some areas (EIA, 2015). Natural gas plants have a much lower emissions rate than the coal-dominated national average of fossil-fuel plants.

Exhibit 5-3: Electric Utility Regions Used in WARM



Source: U.S. Census Bureau (2009).

Exhibit 5-4: Avoided Utility Emission Factors by Region

| Region | Emission Factors for Utility-Generated Electricity ^a (MTCO ₂ E/Million Btu of Electricity Delivered) |
|--------------------|---|
| National Average | 0.221 |
| Pacific | 0.151 |
| Mountain | 0.230 |
| West-North Central | 0.294 |
| West-South Central | 0.193 |
| East-North Central | 0.265 |
| East-South Central | 0.237 |
| New England | 0.156 |
| Middle Atlantic | 0.203 |
| South Atlantic | 0.231 |

^a Includes transmission and distributions losses, which are assumed to be 7% (EIA, 2015).

Exhibit 5-5: Avoided Utility GHG Emissions at Mass Burn Facilities by Region (MTCO₂E/Short Ton of Material Combusted)

| Material Combusted | National Average | Pacific | Mountain | West-North Central | West-South Central | East-North Central | East-South Central | New England | Middle Atlantic | South Atlantic |
|--------------------|------------------|---------|----------|--------------------|--------------------|--------------------|--------------------|-------------|-----------------|----------------|
| Aluminum Cans | -0.03 | -0.02 | -0.03 | -0.04 | -0.02 | -0.03 | -0.03 | -0.02 | -0.03 | -0.03 |
| Aluminum Ingot | -0.03 | -0.02 | -0.03 | -0.04 | -0.02 | -0.03 | -0.03 | -0.02 | -0.03 | -0.03 |
| Steel Cans | -0.02 | -0.01 | -0.02 | -0.02 | -0.01 | -0.02 | -0.02 | -0.01 | -0.02 | -0.02 |
| Copper Wire | -0.02 | -0.01 | -0.02 | -0.03 | -0.02 | -0.03 | -0.02 | -0.02 | -0.02 | -0.02 |
| Glass | -0.02 | -0.01 | -0.02 | -0.02 | -0.02 | -0.02 | -0.02 | -0.01 | -0.02 | -0.02 |
| HDPE | 1.58 | 1.08 | 1.64 | 2.10 | 1.37 | 1.89 | 1.69 | 1.11 | 1.44 | 1.65 |
| LDPE | 1.57 | 1.07 | 1.63 | 2.08 | 1.37 | 1.88 | 1.68 | 1.11 | 1.44 | 1.64 |
| PET | 0.84 | 0.57 | 0.87 | 1.11 | 0.73 | 1.00 | 0.90 | 0.59 | 0.77 | 0.87 |
| LLDPE | 1.57 | 1.08 | 1.64 | 2.09 | 1.37 | 1.89 | 1.69 | 1.11 | 1.44 | 1.64 |
| PP | 1.57 | 1.08 | 1.64 | 2.09 | 1.37 | 1.89 | 1.69 | 1.11 | 1.44 | 1.64 |
| PS | 1.42 | 0.97 | 1.48 | 1.89 | 1.24 | 1.70 | 1.52 | 1.00 | 1.30 | 1.48 |

| Material Combusted | National Average | Pacific | Mountain | West-North Central | West-South Central | East-North Central | East-South Central | New England | Middle Atlantic | South Atlantic |
|-------------------------------|------------------|---------|----------|--------------------|--------------------|--------------------|--------------------|-------------|-----------------|----------------|
| PVC | 0.62 | 0.39 | 0.65 | 0.83 | 0.54 | 0.74 | 0.67 | 0.44 | 0.57 | 0.65 |
| PLA | 0.66 | 0.45 | 0.69 | 0.88 | 0.57 | 0.79 | 0.71 | 0.47 | 0.61 | 0.69 |
| Corrugated Containers | 0.56 | 0.38 | 0.58 | 0.74 | 0.48 | 0.67 | 0.60 | 0.39 | 0.51 | 0.58 |
| Magazines/Third-Class Mail | 0.41 | 0.28 | 0.43 | 0.55 | 0.36 | 0.50 | 0.44 | 0.29 | 0.38 | 0.43 |
| Newspaper | 0.63 | 0.43 | 0.65 | 0.83 | 0.55 | 0.75 | 0.67 | 0.44 | 0.57 | 0.65 |
| Office Paper | 0.54 | 0.37 | 0.56 | 0.71 | 0.47 | 0.64 | 0.58 | 0.38 | 0.49 | 0.56 |
| Phone Books | 0.63 | 0.43 | 0.65 | 0.83 | 0.55 | 0.75 | 0.67 | 0.44 | 0.57 | 0.65 |
| Textbooks | 0.54 | 0.37 | 0.56 | 0.71 | 0.47 | 0.64 | 0.58 | 0.38 | 0.49 | 0.56 |
| Dimensional Lumber | 0.65 | 0.45 | 0.68 | 0.87 | 0.57 | 0.78 | 0.70 | 0.46 | 0.60 | 0.68 |
| Medium-Density Fiberboard | 0.65 | 0.45 | 0.68 | 0.87 | 0.57 | 0.78 | 0.70 | 0.46 | 0.60 | 0.68 |
| Food Waste | 0.19 | 0.13 | 0.19 | 0.25 | 0.16 | 0.22 | 0.20 | 0.13 | 0.17 | 0.20 |
| Food Waste (meat only) | 0.19 | 0.13 | 0.19 | 0.25 | 0.16 | 0.22 | 0.20 | 0.13 | 0.17 | 0.20 |
| Food Waste (non-meat) | 0.19 | 0.13 | 0.19 | 0.25 | 0.16 | 0.22 | 0.20 | 0.13 | 0.17 | 0.20 |
| Beef | 0.19 | 0.13 | 0.19 | 0.25 | 0.16 | 0.22 | 0.20 | 0.13 | 0.17 | 0.20 |
| Poultry | 0.19 | 0.13 | 0.19 | 0.25 | 0.16 | 0.22 | 0.20 | 0.13 | 0.17 | 0.20 |
| Grains | 0.19 | 0.13 | 0.19 | 0.25 | 0.16 | 0.22 | 0.20 | 0.13 | 0.17 | 0.20 |
| Bread | 0.19 | 0.13 | 0.19 | 0.25 | 0.16 | 0.22 | 0.20 | 0.13 | 0.17 | 0.20 |
| Fruits and Vegetables | 0.19 | 0.13 | 0.19 | 0.25 | 0.16 | 0.22 | 0.20 | 0.13 | 0.17 | 0.20 |
| Dairy Products | 0.19 | 0.13 | 0.19 | 0.25 | 0.16 | 0.22 | 0.20 | 0.13 | 0.17 | 0.20 |
| Yard Trimmings | 0.22 | 0.15 | 0.23 | 0.29 | 0.19 | 0.26 | 0.24 | 0.16 | 0.20 | 0.23 |
| Mixed MSW | 0.39 | 0.27 | 0.41 | 0.52 | 0.34 | 0.47 | 0.42 | 0.28 | 0.36 | 0.41 |
| Carpet | 0.60 | 0.41 | 0.62 | 0.80 | 0.52 | 0.72 | 0.64 | 0.42 | 0.55 | 0.63 |
| Personal Computers | 0.12 | 0.08 | 0.13 | 0.16 | 0.11 | 0.15 | 0.13 | 0.09 | 0.11 | 0.13 |
| Tires ^a | 1.57 | 1.57 | 1.57 | 1.57 | 1.57 | 1.57 | 1.57 | 1.57 | 1.57 | 1.57 |
| Asphalt Shingles ^b | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 |
| Vinyl Flooring | 0.62 | 0.42 | 0.65 | 0.83 | 0.54 | 0.74 | 0.67 | 0.44 | 0.57 | 0.65 |
| Wood Flooring | 0.86 | 0.55 | 0.89 | 1.14 | 0.75 | 1.03 | 0.92 | 0.60 | 0.79 | 0.89 |

Note that the "National Average" column is also represented in column (g) of Exhibit 5-2.

^a Assumes weighted average avoided utility GHG emissions for multiple tire combustion pathways.

^b Assumes avoided cement kiln refinery gas combustion.

5.2.5 Avoided CO₂ Emissions due to Steel Recycling

WARM estimates the avoided CO₂ emissions from increased steel recycling made possible by steel recovery from WTE plants for steel cans, mixed MSW, personal computers and tires. Most MSW combusted with energy recovery in the United States is combusted at WTE plants that recover ferrous metals (e.g., iron and steel).²⁹ Note that EPA does not credit increased recycling of nonferrous materials due to a lack of data on the proportions of those materials being recovered. Therefore, the result tends to overestimate net GHG emissions from combustion.

²⁹ EPA did not consider any recovery of materials from the MSW stream that might occur before MSW is delivered to the combustor. EPA considered such prior recovery to be unrelated to the combustion operation—unlike the recovery of steel from combustor ash, an activity that is an integral part of the operation of many combustors.

For mixed MSW, EPA estimates the amount of steel recovered per ton of mixed MSW combusted, based on (1) the amount of MSW combusted in the United States, and (2) the amount of steel recovered, post-combustion. Ferrous metals are recovered at approximately 98 percent of WTE facilities in the United States (Bahor, 2010) and at five RDF processing facilities that do not generate power on-site. These facilities recovered a total of nearly 706,000 short tons per year of ferrous metals in 2004 (IWSA, 2004). By dividing 706,000 short tons (total U.S. steel recovery at combustors) by total U.S. combustion of MSW, which is 28.5 million tons (Van Haaren al., 2010), EPA estimates that 0.02 short tons of steel are recovered per short ton of mixed MSW combusted (as a national average).

For steel cans, EPA first estimates the national average proportion of steel cans entering WTE plants that would be recovered. As noted above, approximately 98 percent of MSW destined for combustion goes to facilities with a ferrous recovery system. At these plants, approximately 90 percent of steel is recovered (Bahor, 2010). EPA multiplies these percentages to estimate the weight of steel cans recovered per ton of MSW combusted—about 0.88 tons recovered per ton combusted.

Finally, to estimate the avoided CO₂ emissions due to increased recycling of steel, EPA multiplies (1) the weight of steel recovered by (2) the avoided CO₂ emissions per ton of steel recovered. The estimated avoided CO₂ emissions results are in column (d) of Exhibit 5-6. For more information on the GHG benefits of recycling, see the [Recycling](#) and [Metals](#) chapters.

Exhibit 5-6: Avoided GHG Emissions Due to Increased Steel Recovery from MSW at WTE Facilities

| (a) Material Combusted | (b) Short Tons of Steel Recovered per Short Ton of Waste Combusted (Short Tons) | (c) Avoided CO ₂ Emissions per Short Ton of Steel Recovered (MTCO ₂ E/Short Ton) | (d) Avoided CO ₂ Emissions per Short Ton of Waste Combusted (MTCO ₂ E/Short Ton) ^a |
|----------------------------|--|---|--|
| Aluminum Cans | – | – | – |
| Aluminum Ingot | – | – | – |
| Steel Cans | 0.88 | 1.81 | -1.60 |
| Copper Wire | – | – | – |
| Glass | – | – | – |
| HDPE | – | – | – |
| LDPE | – | – | – |
| PET | – | – | – |
| LLDPE | – | – | – |
| PP | – | – | – |
| PS | – | – | – |
| PVC | – | – | – |
| PLA | – | – | – |
| Corrugated Containers | – | – | – |
| Magazines/Third-Class Mail | – | – | – |
| Newspaper | – | – | – |
| Office Paper | – | – | – |
| Phone Books | – | – | – |
| Textbooks | – | – | – |
| Dimensional Lumber | – | – | – |
| Medium-Density Fiberboard | – | – | – |
| Food Waste | – | – | – |
| Food Waste (meat only) | – | – | – |
| Food Waste (non-meat) | – | – | – |
| Beef | – | – | – |
| Poultry | – | – | – |
| Grains | – | – | – |
| Bread | – | – | – |
| Fruits and Vegetables | – | – | – |

| (a) Material Combusted | (b) Short Tons of Steel Recovered per Short Ton of Waste Combusted (Short Tons) | (c) Avoided CO ₂ Emissions per Short Ton of Steel Recovered (MTCO ₂ E/Short Ton) | (d) Avoided CO ₂ Emissions per Short Ton of Waste Combusted (MTCO ₂ E/Short Ton) ^a |
|--------------------------------------|--|---|--|
| Dairy Products | - | - | - |
| Yard Trimmings | - | - | - |
| Mixed Paper (general) | - | - | - |
| Mixed Paper (primarily residential) | - | - | - |
| Mixed Paper (primarily from offices) | - | - | - |
| Mixed Metals | - | - | -1.04 |
| Mixed Plastics | - | - | - |
| Mixed Recyclables | - | - | -0.04 |
| Mixed Organics | - | - | - |
| Mixed MSW | 0.02 | 1.81 | -0.04 |
| Carpet | - | - | - |
| Personal Computers | 0.25 | 1.81 | -0.46 |
| Clay Bricks | - | - | - |
| Concrete | - | - | - |
| Fly Ash | - | - | - |
| Tires | 0.06 | 1.80 | -0.13 |
| Asphalt Concrete | - | - | - |
| Asphalt Shingles | - | - | - |
| Drywall | - | - | - |
| Fiberglass Insulation | - | - | - |
| Vinyl Flooring | - | - | - |
| Wood Flooring | - | - | - |

- = Zero emissions.

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

^aThe value in column (d) is a national average and is weighted to reflect 90 percent recovery at the 98 percent of facilities that recover ferrous metals.

^bAssumes that only 68 percent of facilities that use TDF recover ferrous metals.

5.3 RESULTS

The national average results of this analysis are shown in Exhibit 5-7. The results from the last column of Exhibit 5-1, the last two columns of Exhibit 5-2, and the last column of Exhibit 5-6 are shown in columns (b) through (e) in Exhibit 5-7. The net GHG emissions from combustion of each material at mass burn and RDF facilities are shown in columns (f) and (g), respectively. These net values represent the gross GHG emissions (column (b)), minus the avoided GHG emissions (columns (c), (d) and (e)). As stated earlier, these estimates of net GHG emissions are expressed for combustion in absolute terms, and are not values relative to another waste management option, although they must be used comparatively, as all WARM emission factors must be. They are expressed in terms of short tons of waste input (i.e., tons of waste prior to processing).

Exhibit 5-7: Net National Average GHG Emissions from Combustion at WTE Facilities

| (a) | (b) | (c) | (d) | (e) | (f = b - c - e) | (g = b - d - e) |
|----------------------------|---|--|---|---|---|---|
| Material Combusted | Gross GHG Emissions per Ton Combusted (MTCO ₂ E / Short Ton) | Avoided Utility GHG Emissions per Ton Combusted at Mass Burn Facilities (MTCO ₂ E / Short Ton) ^a | Avoided Utility GHG Emissions per Ton Combusted at RDF Facilities (MTCO ₂ E / Short Ton) | Avoided CO ₂ Emissions per Ton Combusted Due to Steel Recovery (MTCO ₂ E / Short Ton) | Net GHG Emissions from Combustion at Mass Burn Facilities (MTCO ₂ E / Short Ton) | Net GHG Emissions from Combustion at RDF Facilities (MTCO ₂ E / Short Ton) |
| Aluminum Cans | 0.01 | -0.03 | -0.02 | - | 0.04 | 0.03 |
| Aluminum Ingot | 0.01 | -0.03 | -0.02 | - | 0.04 | 0.03 |
| Steel Cans | 0.01 | -0.02 | -0.02 | 1.60 | -1.57 | -1.57 |
| Copper Wire | 0.01 | -0.02 | -0.02 | - | 0.03 | 0.03 |
| Glass | 0.01 | -0.02 | -0.02 | - | 0.03 | 0.03 |
| HDPE | 2.80 | 1.58 | 1.44 | - | 1.23 | 1.36 |
| LDPE | 2.80 | 1.57 | 1.43 | - | 1.24 | 1.37 |
| PET | 2.05 | 0.84 | 0.76 | - | 1.21 | 1.29 |
| LLDPE | 2.80 | 1.57 | 1.43 | - | 1.23 | 1.37 |
| PP | 2.80 | 1.57 | 1.43 | - | 1.23 | 1.37 |
| PS | 3.02 | 1.42 | 1.29 | - | 1.60 | 1.73 |
| PVC | 1.26 | 0.62 | 0.57 | - | 0.64 | 0.69 |
| PLA | 0.01 | 0.66 | 0.60 | - | -0.65 | -0.59 |
| Corrugated Containers | 0.05 | 0.56 | 0.51 | - | -0.51 | -0.46 |
| Magazines/Third-Class Mail | 0.05 | 0.41 | 0.38 | - | -0.37 | -0.33 |
| Newspaper | 0.05 | 0.63 | 0.57 | - | -0.58 | -0.52 |
| Office Paper | 0.05 | 0.54 | 0.49 | - | -0.49 | -0.44 |
| Phone Books | 0.05 | 0.63 | 0.57 | - | -0.58 | -0.52 |
| Textbooks | 0.05 | 0.54 | 0.49 | - | -0.49 | -0.44 |
| Dimensional Lumber | 0.05 | 0.65 | 0.60 | - | -0.61 | -0.55 |
| Medium-Density Fiberboard | 0.05 | 0.65 | 0.60 | - | -0.61 | -0.55 |
| Food Waste | 0.05 | 0.19 | 0.17 | - | -0.14 | -0.12 |
| Food Waste (meat only) | 0.05 | 0.19 | 0.17 | - | -0.14 | -0.12 |
| Food Waste (non-meat) | 0.05 | 0.19 | 0.17 | - | -0.14 | -0.12 |
| Beef | 0.05 | 0.19 | 0.17 | - | -0.14 | -0.12 |
| Poultry | 0.05 | 0.19 | 0.17 | - | -0.14 | -0.12 |
| Grains | 0.05 | 0.19 | 0.17 | - | -0.14 | -0.12 |
| Bread | 0.05 | 0.19 | 0.17 | - | -0.14 | -0.12 |
| Fruits and Vegetables | 0.05 | 0.19 | 0.17 | - | -0.14 | -0.12 |
| Dairy Products | 0.05 | 0.19 | 0.17 | - | -0.14 | -0.12 |

| | | | | | | |
|---|------|-------------------|-------------------|------|-------|-------|
| Yard Trimmings | 0.05 | 0.22 | 0.20 | - | -0.18 | -0.15 |
| Grass | 0.05 | 0.22 | 0.20 | - | -0.18 | -0.15 |
| Leaves | 0.05 | 0.22 | 0.20 | - | -0.18 | -0.15 |
| Branches | 0.05 | 0.22 | 0.20 | - | -0.18 | -0.15 |
| Mixed Paper (general) ^b | 0.05 | 0.55 | NA | - | -0.51 | -0.44 |
| Mixed Paper (primarily residential) ^b | 0.05 | 0.55 | NA | - | -0.51 | -0.44 |
| Mixed Paper (primarily from offices) ^b | 0.05 | 0.51 | NA | - | -0.47 | -0.40 |
| Mixed Metals | 0.01 | -0.02 | NA | 1.04 | -1.02 | -1.06 |
| Mixed Plastics | 2.34 | 1.11 | NA | - | 1.22 | 1.36 |
| Mixed Recyclables | 0.11 | 0.51 | NA | 0.04 | -0.44 | -0.38 |
| Mixed Organics | 0.05 | 0.20 | NA | - | -0.16 | -0.12 |
| Mixed MSW | 0.37 | 0.39 | 0.36 | 0.04 | -0.07 | -0.03 |
| Carpet | 1.68 | 0.60 | 0.55 | - | 1.08 | 1.13 |
| Personal Computers | 0.39 | 0.12 | 0.11 | 0.46 | -0.19 | -0.18 |
| Clay Bricks | NA | NA | NA | NA | NA | NA |
| Concrete | NA | NA | NA | NA | NA | NA |
| Fly Ash | NA | NA | NA | NA | NA | NA |
| Tires ^c | 2.21 | 1.57 | 1.57 | 0.13 | 0.51 | 2.11 |
| Asphalt Concrete | NA | NA | NA | NA | NA | NA |
| Asphalt Shingles | 0.70 | 1.05 ^m | 1.05 ^m | - | -0.35 | -0.35 |
| Drywall | NA | NA | NA | - | NA | NA |
| Fiberglass Insulation | NA | NA | NA | - | NA | NA |
| Vinyl Flooring | 0.29 | 0.62 | 0.57 | - | -0.33 | -0.28 |
| Wood Flooring | 0.09 | 0.86 | 0.65 | - | -0.77 | -0.56 |

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

^a The values in this column represent the national average avoided utility GHG emissions. WARM also allows users to use region-specific avoided utility emissions, which are contained in Exhibit 5-5.

^b The summary values for mixed paper are based on the proportions of the four paper types (corrugated containers, magazines/third-class mail, newspaper and office paper) that constitute the different "mixed paper" definitions.

^c Tires used as TDF substitute for coal in cement kilns and utility boilers and as a substitute for natural gas, coal and biomass in pulp and paper facilities.

In the Excel version of WARM, the user can select the state where the waste is being disposed of to determine the combustion emissions based on regional avoided utility emission factors. This functionality is not available in the online version of WARM, which only allows for national average emissions calculations.

Net GHG emissions are estimated to be negative for all biogenic sources of carbon (paper and wood products, organics) because CO₂ emissions from these sources are not counted, as discussed earlier.

As shown in Exhibit 5-7, combustion of plastics results in substantial net GHG emissions. This result is primarily because of the high content of non-biomass carbon in plastics. Also, when combustion of plastics results in electricity generation, the utility carbon emissions avoided (due to displaced utility fossil fuel combustion) are much lower than the carbon emissions from the combustion of plastics. This result is largely due to the lower system efficiency of WTE plants compared with electric utility plants. Recovery of ferrous metals at combustors results in negative net GHG emissions for steel cans, due to the increased steel recycling made possible by ferrous metal recovery at WTE plants. Combustion of mixed MSW results in slightly negative GHG emissions because of the high proportion of biogenic carbon and steel.

5.4 LIMITATIONS

The certainty of the analysis presented in this chapter is limited by the reliability of the various data elements used. The most significant limitations are as follows:

- Combustion system efficiency of WTE plants may be improving. If efficiency improves, more utility CO₂ will be displaced per ton of waste combusted (assuming no change in utility emissions per kWh), and the net GHG emissions from combustion of MSW will decrease.
- Data for the RDF analysis were provided by the Minnesota Office of Environmental Assistance and were obtained from a single RDF processing facility and a separate RDF combustion facility. Research indicates that each RDF processing and combustion facility is different. For example, some RDF combustion facilities may generate steam for sale off-site, which can affect overall system efficiency. In addition, the amount of energy required to process MSW into RDF and the amount of energy used to operate RDF combustion facilities can be difficult to quantify and can vary among facilities on daily, seasonal and annual bases. This is one of the reasons that RDF factors are not included in WARM.
- The reported ranges for N₂O emissions were broad. In some cases, the high end of the range was 10 times the low end of the range. Research has indicated that N₂O emissions vary with the type of waste burned. Thus, the average value used for mixed MSW and for all MSW components should be interpreted as approximate values.
- For mixed MSW, the study assumes that all carbon in textiles is from synthetic fibers derived from petrochemicals (whereas, in fact, some textiles are made from cotton, wool and other natural fibers). Because EPA assumed that all carbon in textiles is non-biogenic, all of the CO₂ emissions from combustion of textiles as GHG emissions were counted. This assumption will slightly overstate the net GHG emissions from combustion of mixed MSW, but the magnitude of the error is small because textiles represent only a small fraction of the MSW stream. Similarly, the MSW category of “rubber and leather” contains some biogenic carbon from leather and natural rubber. By not considering this small amount of biogenic carbon, the analysis slightly overstates the GHG emissions from MSW combustion.

- Because the makeup of a given community's mixed MSW may vary from the national average, the energy content also may vary from the national average energy content used in this analysis. For example, MSW from communities with a higher- or lower-than-average recycling rate may have a different energy content, and MSW with more than the average proportion of dry leaves and branches will have a higher energy content.
- In this analysis, EPA used the national average recovery rate for steel. Where waste is sent to a WTE plant with steel recovery, the net GHG emissions for steel cans will be slightly lower (i.e., more negative). Where waste is sent to a WTE plant without steel recovery, the net GHG emissions for steel cans will be the same as for aluminum cans (i.e., close to zero). EPA did not credit increased recycling of nonferrous materials, because of a lack of information on the proportions of those materials. This assumption tends to result in overstated net GHG emissions from combustion.
- This analysis uses the "non-baseload" emission factors for electricity as the proxy for fuel displaced at the margin when WTE plants displace utility electricity. These non-baseload emission factors vary depending on the state where the waste is assumed to be combusted. If some other fuel or mix of fuels is displaced at the margin (e.g., a more coal-heavy fuel mix), the avoided utility CO₂ would be different.

5.5 REFERENCES

- Bahor, B. (2010). Personal communications between Victoria Thompson, ICF International, and Brian Bahor, Covanta Energy. May 24, 2010; June 7, 2010; and July 14, 2010.
- Bergman, R., & Bowe, S. A. (2008). Environmental impact of producing hardwood lumber using life-cycle inventory. *Wood and Fiber Science*, 40(3), 448-458. Retrieved October 20, 2009 from <http://www.treesearch.fs.fed.us/pubs/31113>.
- DeZan, D. (2000). Personal communication between Diane DeZan, Fiber Economics Bureau and Joe Casola, ICF Consulting. 4 August 2000.
- EIA. (2015). *U.S. Coal Flow, 2014*.
- EPA. (1995). *The EPA Municipal Solid Waste Fact Book, Version 2.0*. Washington, D.C.: U.S. Environmental Protection Agency, Office of Solid Waste.
- EPA. (2015a). *Advancing Sustainable Materials Management: Facts and Figures 2013*. (EPA530-R-15-002). Washington, DC: U.S. Government Printing Office. Retrieved from http://www.cta.tech/CorporateSite/media/environment/eCycle/2013_advncng_smm_rpt.pdf.
- EPA. (2015b). *Emissions & Generation Resource Integrated Database (eGRID)*. Available from EPA at <http://www.epa.gov/energy/egrid>.
- EPA. (2015c). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2013*. (EPA 430-R-15-004). Washington, DC: U.S. Government Printing Office. Retrieved from <http://www3.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2015-Main-Text.pdf>. EPA.
- ERC. (2014). *The 2014 ERC Directory of Waste-to-Energy Plants*. Washington, DC. Energy Recovery Council.

- FAL. (2002a). *Energy and Greenhouse Gas Factors for Nylon Broadloom Residential Carpet*. Prairie Village, KS: Franklin Associates, Ltd., July 3, 2002.
- FAL. (2002b). *Energy and Greenhouse Gas Factors for Personal Computers*. Final Report. Prairie Village, KS: Franklin Associates, Ltd., August 7, 2002.
- FAL. (1994). *The Role of Recycling in Integrated Solid Waste Management to the Year 2000*. Franklin Associates, Ltd. (Stamford, CT: Keep America Beautiful, Inc.), September, pp. I-24.
- Fons, W. L., Clements, H. B., Elliott, E. R., & George, P. M. (1962). *Project Fire Model. Summary Progress Report-II. Period May 1, 1960 to April 30, 1962*. Macon, GA: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Southern Forest Fire Laboratory. 58 pp. [16824].
- Gaines, L., and Stodolsky, F. (1993). *Mandated Recycling Rates: Impacts on Energy Consumption and Municipal Solid Waste Volume*. Argonne, IL: Argonne National Laboratory, pp. 11 and 85.
- Harrington, K. (1997). Personal communication by facsimile with Karen Harrington, principal planner for the Minnesota Office of Environmental Assistance. October 1997.
- ICF Consulting. (1995). Memorandum for Work Assignment 239, Task 2: Carbon Sequestration in Landfills. April 28, 1995. Exhibit 2-A, column (o).
- Incropera, F. P., & DeWitt, D. P. (1990). *Introduction to Heat Transfer*, Second Edition. New York: John Wiley & Sons, pp. A3-A4.
- IPCC. (2007). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- IPCC. (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Hayama, Japan: Intergovernmental Panel on Climate Change.
- IWSA. (2007). *The 2007 IWSA Waste-To-Energy Directory of United States Facilities*. Washington DC: Integrated Waste Services Association.
- IWSA. (2004). *The 2004 IWSA Waste-To-Energy Directory of United States Facilities*. Washington, DC: Integrated Waste Services Association.
- IWSA. (2000). *The 2000 IWSA Waste-To-Energy Directory of United States Facilities*. Washington, DC: Integrated Waste Services Association.
- IWSA & American Ref-Fuel (1997). Telephone conversation among representatives of Integrated Waste Services Association, American Ref-Fuel, and ICF Consulting, October 28, 1997.
- National Renewable Energy Laboratory (2015). "U.S. Life Cycle Inventory Database." Retrieved from <https://www.lcacommons.gov/nrel/search>
- NREL. (1992). *Data Summary of Municipal Solid Waste Management Alternatives, Volume IV: Appendix B - RDF Technologies*. Springfield, VA: National Technical Information Service, National Renewable Energy Laboratory/TP-431-4988D), p. B-5.
- Procter and Redfern, Ltd. & ORTECH International. (1993). *Estimation of the Effects of Various Municipal Waste Management Strategies on Greenhouse Gas Emissions, Part II*. Ottawa, Canada: Environment Canada, Solid Waste Management Division, and Natural Resources Canada, Alternative Energy Division.

Realf, M. (2010). "The role of using carpet as a fuel in carpet recovery system development." Delivered to ICF International via email on September 9, 2010.

U.S. Census Bureau. (2009). Census Regions and Divisions of the United States. Washington, DC: U.S. Census Bureau, Geography Division.

Van Haaren, R., Goldstein, N., & Themelis, N.J. (2008). The State of Garbage in America. *BioCycle*, 51 (10), 16.

Zannes, M. (1997). Personal communication with Maria Zannes of Integrated Waste Services Association, Washington, DC. August 25, 1997.

6 LANDFILLING

This chapter presents an overview of landfilling as a waste management strategy in relation to the development of material-specific emission factors for EPA's Waste Reduction Model (WARM). Estimates of the net greenhouse gas (GHG) emissions from landfilling most of the materials considered in WARM and several categories of mixed waste streams (e.g., mixed paper, mixed recyclables and mixed municipal solid waste (MSW)) are included in the chapter.

6.1 A SUMMARY OF THE GHG IMPLICATIONS OF LANDFILLING

When food waste, yard trimmings, paper and wood are landfilled, anaerobic bacteria degrade the materials, producing methane (CH₄) and carbon dioxide (CO₂). CH₄ is counted as an anthropogenic GHG because, even if it is derived from sustainably harvested biogenic sources, degradation would not result in CH₄ emissions if not for deposition in landfills. The CO₂ is not counted as a GHG because it is considered part of the natural carbon cycle of growth and decomposition; for more information, see the text box on biogenic carbon in the [WARM Background and Overview](#) chapter. The other materials in WARM either do not contain carbon or do not biodegrade measurably in anaerobic conditions, and therefore do not generate any CH₄.

In addition to carbon emissions, some of the carbon in these materials (i.e., food waste, yard trimmings, paper and wood) is stored in the landfill because these materials are not completely decomposed by anaerobic bacteria. Because this carbon storage would not normally occur under natural conditions (virtually all of the biodegradable material would degrade to CO₂, completing the photosynthesis/respiration cycle), this is counted as an anthropogenic sink. However, carbon in plastics and rubber that remains in the landfill is not counted as stored carbon because it is of fossil origin. Fossil carbon (e.g., petroleum, coal) is already considered "stored" in its natural state; converting it to plastic or rubber and putting it in a landfill only moves the carbon from one storage site to another.

EPA developed separate estimates of emissions from (1) landfills without gas recovery systems, (2) those that flare CH₄, (3) those that combust CH₄ for energy recovery, and (4) the national average mix of these three categories. The national average emission estimate accounts for the extent to which CH₄ will not be managed at some landfills, flared at some landfills, and combusted onsite for energy recovery at others.³⁰ The assumed mix of the three landfill categories that make up the national average for all material types are presented in Exhibit 6-1. These estimates are based on the amount of CH₄ recovered by U.S. landfills, as cited in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-2012* (EPA, 2014b). WARM assumes that construction and demolition landfills do not flare or collect CH₄.

Exhibit 6-1: Percentage of CH₄ Generated from Each Type of Landfill

| Material | Percentage of CH ₄ from Landfills without LFG Recovery | Percentage of CH ₄ from Landfills with LFG Recovery and Flaring | CH ₄ from Landfills with LFG Recovery and Electricity Generation (%) |
|---------------------------------------|---|--|---|
| Construction and Demolition Materials | 100% | – | – |
| All Other Materials | 18% | 38% | 44% |

– = Zero Emissions.

³⁰ Although gas from some landfills is piped to an offsite power plant and combusted there, for the purposes of WARM, the simplifying assumption was that all gas for energy recovery was combusted onsite. This assumption was made due to the lack of information about the frequency of offsite power generation, piping distances and losses from pipelines.

6.2 CALCULATING THE GHG IMPACTS OF LANDFILLING

The landfilling emission factors are made up of the following components:

1. CH₄ emissions from anaerobic decomposition of biogenic carbon compounds;
2. Transportation CO₂ emissions from landfilling equipment;
3. Biogenic carbon stored in the landfill; and
4. CO₂ emissions avoided through landfill gas-to-energy projects.

As mentioned above, WARM does not calculate CH₄ emissions, stored carbon or CO₂ avoided for materials containing only fossil carbon (e.g., plastics, rubber). These materials have net landfilling emissions that are very low because they include only the transportation-related emissions from landfilling equipment. Some materials (e.g., newspaper and dimensional lumber) result in net storage (i.e., carbon storage exceeds CH₄ plus transportation energy emissions) at all landfills, regardless of whether gas recovery is present, while others (e.g., food waste) result in net emissions regardless of landfill gas collection and recovery practices. Whether the remaining materials result in net storage or net emissions depends on the landfill gas recovery scenario.

6.2.1 Carbon Stocks and Flows in Landfills

Exhibit 6-2 shows the carbon flows within a landfill system. Carbon entering the landfill can have one of several fates: exit as CH₄, exit as CO₂, exit as volatile organic compounds (VOCs), exit dissolved in leachate, or remain stored in the landfill.³¹

After entering landfills, a portion of the biodegradable material decomposes and eventually is transformed into landfill gas and/or leachate. Aerobic bacteria initially decompose the waste until the available oxygen is consumed. This stage usually lasts less than a week and is followed by the anaerobic acid state, in which carboxylic acids accumulate, the pH decreases, and some cellulose and hemicellulose decomposition occurs. Finally, during the methanogenic state, bacteria further decompose the biodegradable material into CH₄ and CO₂.

The rate of decomposition in landfills is affected by a number of factors, including: (1) waste composition; (2) factors influencing microbial growth (moisture, available nutrients, pH, temperature); and (3) whether the operation of the landfill retards or enhances waste decomposition. Most studies have shown that the amount of moisture in the waste, which can vary widely within a single landfill, is a critical factor in the rate of decomposition (Barlaz et al., 1990).

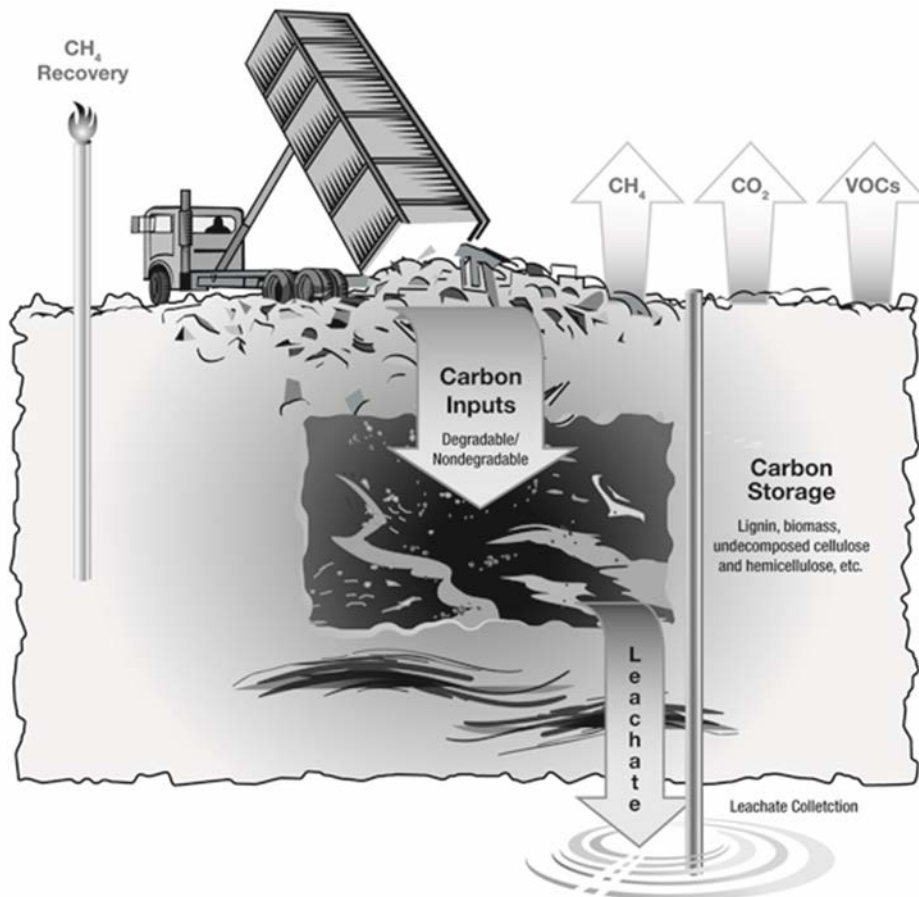
Among the research conducted on the various components of the landfill carbon system, by far the most to date has focused on the transformation of landfill carbon into CH₄. This interest has been spurred by a number of factors, including EPA's 1996 rule requiring large landfills to control landfill gas emissions (40 Code of Federal Regulations Part 60, Subparts Cc and WWW), the importance of CH₄ emissions in GHG inventories, and the market for CH₄ as an energy source. CH₄ production occurs in the methanogenic stage of decomposition, as methanogenic bacteria break down the fermentation products from earlier decomposition processes. Since CH₄ emissions result from waste decomposition, the quantity and duration of the emissions is dependent on the same factors that influence waste degradability (e.g., waste composition, moisture). The CH₄ portion of each material type's emission factor is discussed further in section 6.2.2.

Carbon dioxide is produced in the initial aerobic stage and in the anaerobic acid stage of decomposition. However, relatively little research has been conducted to quantify CO₂ emissions during these stages. Emissions during the aerobic stage are generally assumed to be a small proportion of total

³¹ The exhibit and much of the ensuing discussion are taken directly from Freed et al. (2004).

organic carbon inputs, and a screening-level analysis indicates that less than 1 percent of carbon is likely to be emitted through this pathway (Freed et al., 2004). Once the methanogenic stage of decomposition begins, landfill gas *as generated* is composed of approximately 50 percent CH₄ and 50 percent CO₂ (Bingemer and Crutzen, 1987). However, landfill gas *as collected* generally has a higher CH₄ concentration than CO₂ concentration (sometimes as much as a 60 percent: 40 percent ratio), because some of the CO₂ is dissolved in the leachate as part of the carbonate system (CO₂ ↔ H₂CO₃ ↔ HCO₃⁻ ↔ CO₃²⁻).

Exhibit 6-2: Landfill Carbon Mass Balance



Source: Freed et al. (2004).

To date, very little research has been conducted on the role of VOC emissions in the landfill carbon mass balance. Given the thousands of compounds entering the landfill environment, tracking the biochemistry by which these compounds ultimately are converted to VOC is a complex undertaking. Existing research indicates that ethane, limonene, *n*-decane, *p*-dichlorobenzene and toluene may be among the most abundant landfill VOCs (Eklund et al., 1998). Hartog (2003) reported non-CH₄ volatile organic compound concentrations in landfill gas at a bioreactor site in Iowa, averaging 1,700 parts per million (ppm) carbon by volume in 2001 and 925 ppm carbon by volume in 2002. If the VOC concentrations in landfill gas are generally of the order of magnitude of 1,000 ppm, VOCs would have a small role in the overall carbon balance, as concentrations of CH₄ and CO₂ will both be hundreds of times larger.

Leachate is produced as water percolates through landfills. Factors affecting leachate formation include the quantity of water entering the landfill, waste composition, and the degree of decomposition.

Because it may contain materials capable of contaminating groundwater, leachate (and the carbon it contains) is typically collected and treated before being released to the environment, where it eventually degrades into CO₂. However, leachate is increasingly being recycled into the landfill as a means of inexpensive disposal and to promote decomposition, increasing the mass of biodegradable materials collected by the system and consequently enhancing aqueous degradation (Chan et al., 2002; Warith et al., 1999). Although a significant body of literature exists on landfill leachate formation, little research is available on the carbon implications of this process. Based on a screening analysis, Freed et al. (2004) found that loss as leachate may occur for less than 1 percent of total carbon inputs to landfills.

In mass balance terms, carbon storage can be characterized as the carbon that remains after accounting for the carbon exiting the system as landfill gas or dissolved in leachate. On a dry weight basis, municipal refuse contains 30–50 percent cellulose, 7–12 percent hemicellulose and 15–28 percent lignin (Hilger and Barlaz, 2001). Although the degradation of cellulose and hemicellulose in landfills is well documented, lignin does not degrade to a significant extent under anaerobic conditions (Colberg, 1988). Landfills in effect store some of carbon from the cellulose and hemicellulose and all of the carbon from the lignin that is buried initially. The amount of storage will vary with environmental conditions in the landfill; pH and moisture content have been identified as the two most important variables controlling decomposition (Barlaz et al, 1990). These variables and their effects on each material type's emission factor are discussed further below.

6.2.2 Estimating Emissions from Landfills

As discussed in section 6.2.1, when biodegradable materials such as wood products, food wastes and yard trimmings are placed into a landfill, a fraction of the carbon within these materials degrades into CH₄ emissions. The quantity and timing of CH₄ emissions released from the landfill depends upon three factors: (1) how much of the original material decays into CH₄, (2) how readily the material decays under different landfill moisture conditions, and (3) landfill gas collection practices. This section describes how these three factors are addressed in WARM.

6.2.2.1 Methane Generation and Landfill Carbon Storage

The first step is to determine the amount of carbon contained in degradable materials that is emitted from the landfill as CH₄, and the amount that remains in long-term storage within the landfill. Although a large body of research exists on CH₄ generation from mixed solid wastes, only a few investigators—most notably Dr. Morton Barlaz and colleagues at North Carolina State University—have measured the behavior of specific waste wood, paper, food waste and yard trimming components. The results of their experiments yield data on the inputs—specifically the initial carbon contents, CH₄ generation and carbon stored—that are required for calculating material-specific emission factors for WARM.

Barlaz (1998) developed a series of laboratory experiments designed to measure biodegradation of these materials in a simulated landfill environment, in conditions designed to promote decomposition (i.e., by providing ample moisture and nutrients). Each waste component (e.g., grass, branches, leaves, paper) was dried; analyzed for cellulose, hemicellulose and lignin content; weighed; placed in two-liter plastic containers (i.e., reactors); and allowed to decompose anaerobically under moist conditions (Eleazer et al., 1997). At the end of the experiment, the contents of the reactors were dried, weighed and analyzed for cellulose, hemicellulose, lignin and (in the case of food waste only) protein content. The carbon in these residual components is assumed to represent carbon that would remain undegraded over the long term in landfills: that is, it would be stored.

Based on these components, Dr. Barlaz estimated the initial biogenic carbon content of each waste material as a percent of dry matter. For some materials, the carbon content estimates have been updated to reflect more recent studies or to better reflect changes in material composition in recent years. Exhibit 6-3 shows the initial carbon contents of the wastes analyzed by Barlaz (1998) and Wang et al. (2011).

Exhibit 6-3: Initial Biogenic Carbon Content of Materials Tested in Barlaz (1998) and Wang et al. (2011)

| Material | Initial Biogenic Carbon Content, % of Dry Matter | Source |
|----------------------------|--|----------------------------|
| Corrugated Containers | 47% | Barlaz (1998) |
| Newspaper | 49% | Barlaz (1998) |
| Office Paper | 32% | Barlaz (1998) ^a |
| Coated Paper | 34% | Barlaz (1998) |
| Food Waste | 50% | Barlaz (1998) |
| Grass | 45% | Barlaz (1998) |
| Leaves | 46% | Barlaz (1998) |
| Branches | 49% | Barlaz (1998) |
| Mixed MSW | 42% | Barlaz (1998) |
| Gypsum Board | 5% | Barlaz (1998) |
| Dimensional Lumber | 49% | Wang et al. (2011) |
| Medium-density Fiberboard | 44% | Wang et al. (2011) |
| Wood Flooring ^b | 46% | Wang et al. (2011) |

^a Based on 2014 discussions with Dr. Morton Barlaz, the carbon content of office paper has been updated to account for an average calcium carbonate (CaCO₃) content of 20 percent in office paper in recent years.

^b Based on an average of carbon content values for red oak and plywood in Wang et al. (2011).

The principal stocks and flows in the landfill carbon balance are:

- Initial carbon content (Initial C);
- Carbon output as CH₄ (CH₄^C);
- Carbon output as CO₂ (CO₂^C); and
- Residual carbon (i.e., landfill carbon storage, LF^C).

The initial carbon content, along with the other results from the Barlaz (1998), Wang et al. (2013), Wang et al. (2011), and Levis et al. (2013) experiments are used to estimate each material type's emission factor in WARM. The Barlaz (1998), Wang et al. (2013), Wang et al. (2011), and Levis et al. (2013) experiments did not capture CO₂ emissions in the carbon balance; however, in a simple system where the only carbon fates are CH₄, CO₂ and carbon storage, the carbon balance can be described as

$$\text{CH}_4^{\text{C}} + \text{CO}_2^{\text{C}} + \text{LF}^{\text{C}} = \text{Initial C}$$

If the only decomposition is anaerobic, then CH₄^C = CO₂^C.³² Thus, the carbon balance can be expressed as

$$= \text{Initial C} \times 2 \times \text{CH}_4^{\text{C}} + \text{LF}^{\text{C}} = \text{Initial C}$$

Exhibit 6-4 shows the measured experimental values, in terms of the percentage of initial carbon for each of the materials analyzed, the implied landfill gas yield, and the sum of outputs as a

³² The emissions ratio of CH₄ to CO₂ is 1:1 for carbohydrates (e.g., cellulose, hemicellulose). For proteins, the ratio is 1.65 CH₄ per 1.55 CO₂; for protein, it is C_{3.2}H₅ON_{0.86} (Barlaz et al., 1989). Given the predominance of carbohydrates, for all practical purposes, the overall ratio is 1:1.

percentage of initial carbon (Barlaz, 1998; Wang et al., 2013; Wang et al., 2011; Levis et al., 2013). As the sum of the outputs shows, the balance between carbon outputs and carbon inputs generally was not perfect. This imbalance is attributable to measurement uncertainty in the analytic techniques.

Exhibit 6-4: Experimental Values for CH₄ Yield and Carbon Storage^a

| (a) Material | (b) Measured CH ₄ Yield as a % of Initial Carbon | (c) Implied Yield of Landfill Gas (CH ₄ +CO ₂) as a Proportion of Initial Carbon (c = 2 × b) | (d) Measured Proportion of Initial Carbon Stored | (e) Output as % of Initial Carbon (e = c + d) |
|---------------------------|--|---|--|--|
| Corrugated Containers | 17% | 35% | 55% | 90% |
| Newspaper | 8% | 16% | 85% | 100% |
| Office Paper | 29% | 58% | 12% | 70% |
| Coated Paper | 13% | 26% | 79% | 100% |
| Food Waste | 32% | 63% | 16% | 79% |
| Grass | 23% | 46% | 53% | 99% |
| Leaves | 8% | 15% | 85% | 100% |
| Branches | 12% | 23% | 77% | 100% |
| Mixed MSW | 16% | 32% | 19% | 50% |
| Gypsum Board | 0% | 0% | 55% | 55% |
| Dimensional Lumber | 1% | 3% | 88% | 91% |
| Medium-density Fiberboard | 1% | 1% | 84% | 85% |
| Wood Flooring | 2% | 5% | 99% | 100% |

^aThe CH₄, CO₂, and carbon stored from these experiments represents only the biogenic carbon in each material type.

To calculate the WARM emission factors, adjustments were made to the measured values so that exactly 100 percent of the initial carbon would be accounted for. After consultation with Dr. Barlaz, the following approach was adopted to account for exactly 100 percent of the initial carbon:

- For most materials where the total carbon output is less than the total carbon input (e.g., corrugated containers, office paper, food waste, grass, leaves), the “missing” carbon was assumed to be emitted as equal quantities of CH₄^C and CO₂^C. In these cases (corrugated containers, office paper, food waste, grass, leaves), the CH₄^C was increased with respect to the measured values as follows:

$$\frac{\text{Initial C-LF}^{\text{C}}}{2} = \text{CH}_4^{\text{C}}$$

This calculation assumes that CO₂^C = CH₄^C. In essence, the adjustment approach was to increase landfill gas production, as suggested by Dr. Barlaz.

- For coated paper, newspaper, and wood flooring, where carbon outputs were greater than initial carbon, the measurements of initial carbon content and CH₄ mass were assumed to be accurate. Here, the adjustment approach was to decrease carbon storage. Thus, landfill carbon storage was calculated as the residual of initial carbon content minus (2 × CH₄^C).

The resulting adjusted CH₄ yields and carbon storage are presented in Exhibit 6-5.

- For branches, dimensional lumber, medium-density fiberboard, and mixed MSW, the measured CH₄ yield as a percentage of initial carbon was considered to be the most realistic estimate for methane yield, based on consultation with Dr. Barlaz. Therefore, no adjustment was made for these materials.

- For gypsum board, the sulfate in wallboard is estimated to reduce methane generation, as bacteria use sulfate preferentially to the pathway that results in methane, as suggested by Dr. Barlaz. As such, methane yield from gypsum board is likely to be negligible and is therefore adjusted to 0% in WARM.

Exhibit 6-5: Adjusted CH₄ Yield and Carbon Storage by Material Type

| Material | Adjusted Yield of CH ₄ as Proportion of Initial Carbon | Adjusted Carbon Storage as Proportion of Initial Carbon |
|--|---|---|
| Corrugated Containers ^a | 22% | 55% |
| Newspaper ^b | 8% | 84% |
| Office Paper ^a | 44% | 12% |
| Coated Paper ^b | 13% | 74% |
| Food Waste ^a | 42% | 16% |
| Grass ^a | 23% | 53% |
| Leaves ^a | 8% | 85% |
| Branches ^c | 12% | 77% |
| Mixed MSW ^c | 16% | 19% |
| Gypsum Board ^d | 0% | 55% |
| Dimensional Lumber ^c | 1% | 88% |
| Medium-density Fiberboard ^c | 1% | 84% |
| Wood Flooring ^b | 2% | 95% |

^a CH₄ yield is adjusted to account for measurement uncertainty in the analytic techniques to measure these quantities. For corrugated containers, office paper, food waste, grass, leaves, the yield of CH₄ was increased such that the proportion of initial carbon emitted as landfill gas (i.e., 2 × CH₄) plus the proportion that remains stored in the landfill is equal to 100% of the initial carbon.

^b For coated paper, newspaper, and wood flooring, the proportion of initial carbon that is stored in the landfill is decreased such that the proportion of initial carbon emitted as landfill gas (i.e., 2 × CH₄) plus the proportion that remains stored in the landfill is equal to 100% of the initial carbon.

^c For branches, dimensional lumber, medium-density fiberboard, and mixed MSW, the measured CH₄ yield as a percentage of initial carbon and measured proportion of initial carbon stored shown in columns b and d, respectively of Exhibit 6-4 was considered to be the most realistic estimate for methane yield. Therefore, these values were not adjusted.

^d For gypsum board, the sulfate in wallboard is estimated to reduce methane generation; thus, the methane yield from gypsum board is likely to be negligible and is therefore adjusted to 0%.

Dr. Barlaz's experiment did not test all of the biodegradable material types in WARM. EPA identified proxies for the remaining material types for which there were no experimental data. Magazines and third-class mail placed in a landfill were assumed to contain a mix of coated paper and office paper and were therefore assumed to behave like an average of those two materials. Similarly, phone books and textbooks were assumed to behave in the same way as newspaper and office paper, respectively. Results from two studies by Wang et al. were used for dimensional lumber, medium-density fiberboard, and wood flooring (Wang et al., 2013; Wang et al., 2011). For wood flooring, the ratio of dry-to-wet weight was adjusted to more accurately represent the moisture content of wood lumber (Staley and Barlaz, 2009). Drywall was assumed to have characteristics similar to gypsum board. Exhibit 6-6 shows the landfill CH₄ emission factors and the final carbon storage factors for all applicable material types.

Exhibit 6-6: CH₄ Yield for Solid Waste Components

| Material | Initial Biogenic Carbon Content | Adjusted Yield of CH ₄ as Proportion Of Initial Carbon | Final (Adjusted) CH ₄ Generation, MTCO ₂ E/Dry Metric Ton ^a | Final (Adjusted) CH ₄ Generation (MTCO ₂ E /Wet Short Ton) ^b |
|----------------------------|---------------------------------|---|--|---|
| Corrugated Containers | 47% | 22% | 3.48 | 2.62 |
| Magazines/Third-Class Mail | 36% | 12% | 1.43 | 1.19 |
| Newspaper | 49% | 8% | 1.33 | 1.05 |
| Office Paper | 32% | 44% | 4.71 | 3.89 |
| Phonebooks | 49% | 8% | 1.33 | 1.05 |
| Textbooks | 32% | 44% | 4.71 | 3.89 |
| Dimensional Lumber | 49% | 1% | 0.24 | 0.17 |
| Medium-Density Fiberboard | 44% | 1% | 0.08 | 0.06 |
| Food Waste | 49% | 40% | 6.63 | 1.62 |
| Yard Trimmings | | | | |
| Grass | 45% | 23% | 3.48 | 0.57 |
| Leaves | 46% | 8% | 1.17 | 0.65 |
| Branches | 49% | 12% | 1.90 | 1.45 |
| Mixed MSW | 42% | 16% | 2.23 | 1.62 |
| Drywall | 5% | 0% | 0 | 0 |
| Wood Flooring | 43% | 2% | 0.27 | 0.18 |

^a Final adjusted CH₄ generation per dry metric ton is the product of the initial carbon content and the final percent carbon emitted as CH₄ multiplied by the molecular ratio of carbon to CH₄ (12/16).

^b CH₄ generation is converted from per dry metric ton to per wet short ton by multiplying the CH₄ generation on a dry metric ton basis by (1 – the material's moisture content) and by converting from metric tons to short tons of material.

6.2.2.2 Component-Specific Decay Rates

The second factor in estimating material-specific landfill emissions is the rate at which a material decays under anaerobic conditions in the landfill. The decay rate is an important factor that influences the landfill collection efficiency described further in the next section. Although the final adjusted CH₄ yield shown in Exhibit 6 will eventually occur no matter what the decay rate, the rate at which the material decays influences how much of the CH₄ yield will eventually be captured for landfills with collection systems.

Recent studies by De la Cruz and Barlaz (2010) found that different materials degrade at different rates relative to bulk MSW rates of decay. For example, one short ton of a relatively inert wood material—such as lumber—will degrade slowly and produce a smaller amount of methane than food waste, which readily decays over a much shorter timeframe. Materials will also degrade faster under wetter landfill conditions. Consequently, the rate at which CH₄ emissions are generated from decaying material in a landfill depends upon: (1) the type of material placed in the landfill, and (2) the moisture conditions of the landfill.

De la Cruz and Barlaz (2010) measured component-specific decay rates in laboratory experiments that were then scaled to field-level, component-specific decay rates based on mixed MSW field-scale decay rates published in EPA (1998) guidance.

To scale the laboratory-scale, component-specific decay rate measurements to field-scale values, De la Cruz and Barlaz (2010) assumed that the weighted average decay rate for a waste mixture of the same composition as MSW would be equal to the bulk MSW decay rate. They also related a lab-scale decay rate for mixed MSW to the field-scale decay rate using a scaling factor. Using these two relationships, the authors were able to estimate field-scale decay rates for different materials based on the laboratory data. The following equations were used to estimate the component-specific decay rates:

Equation 1

$$f \times \sum_{i=1}^n k_{lab,i} \times (wt. fraction)_i = decay\ rate$$

Equation 2

$$k_{field,i} = f \times k_{lab,i}$$

where,

- f = a correction factor to force the left side of the equation to equal the overall MSW decay rate
- $k_{lab,i}$ = the component-specific decay rate calculated from lab experiments
- $k_{field,i}$ = the component-specific decay rate determined for the field
- i = the i^{th} waste component

Based on the results from De la Cruz and Barlaz (2010), the Excel version of WARM allows users to select different component-specific decay rates based on different assumed moisture contents of the landfill to estimate the rate at which CH₄ is emitted for each material type (or “component”). The five MSW decay rates used are:

1. $k = 0.02/\text{year}$ (“Dry”), corresponding to landfills receiving fewer than 20 inches of annual precipitation: based values reported in EPA (2010)
2. $k = 0.04/\text{year}$ (“Moderate”), corresponding to landfills receiving between 20 and 40 inches of annual precipitation: based values reported in EPA (2010)
3. $k = 0.06/\text{year}$ (“Wet”), corresponding to landfills receiving greater than 40 inches of annual precipitation: based values reported in EPA (2010)
4. $k = 0.12/\text{year}$ (“Bioreactor”), corresponding to landfills operating as bioreactors where water is added until the moisture content reaches 40 percent moisture on a wet-weight basis: based on expert judgment using values reported in Barlaz et al. (2010) and Tolaymat et al. (2010)
5. $k = 0.052/\text{year}$ (“National Average”), corresponding to a weighted average based on the share of waste received at each landfill type: based on expert judgment using values reported in EPA (2010)

The final waste component-specific decay rates as a function of landfill moisture conditions are provided in Exhibit 6-7.

Exhibit 6-7: Component-Specific Decay Rates (yr⁻¹) by Landfill Moisture Scenario

| Material | Landfill Moisture Conditions | | | | |
|----------------------------|------------------------------|----------|------|------------|------------------|
| | Dry | Moderate | Wet | Bioreactor | National Average |
| Corrugated Containers | 0.01 | 0.02 | 0.03 | 0.06 | 0.03 |
| Magazines/Third-Class Mail | 0.06 | 0.12 | 0.18 | 0.37 | 0.16 |
| Newspaper | 0.02 | 0.03 | 0.05 | 0.10 | 0.04 |
| Office Paper | 0.01 | 0.03 | 0.04 | 0.09 | 0.04 |
| Phone Books | 0.02 | 0.03 | 0.05 | 0.10 | 0.04 |
| Textbooks | 0.01 | 0.03 | 0.04 | 0.09 | 0.04 |
| Dimensional Lumber | 0.04 | 0.08 | 0.12 | 0.25 | 0.11 |
| Medium-Density Fiberboard | 0.03 | 0.06 | 0.10 | 0.19 | 0.08 |
| Food Waste | 0.07 | 0.14 | 0.22 | 0.43 | 0.19 |
| Yard Trimmings | 0.10 | 0.20 | 0.29 | 0.59 | 0.26 |
| Grass | 0.15 | 0.30 | 0.45 | 0.89 | 0.39 |

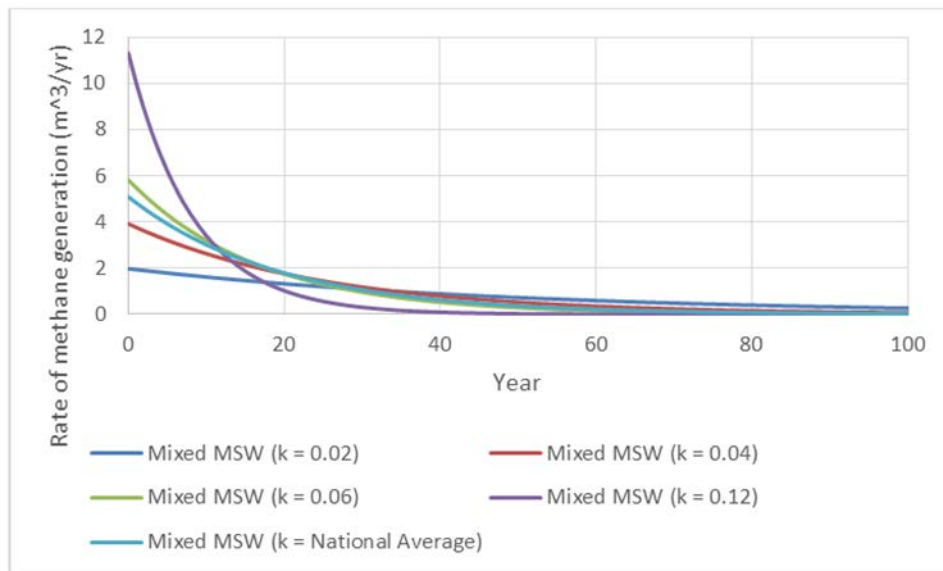
| Material | Landfill Moisture Conditions | | | | National Average |
|----------------------------|------------------------------|----------|------|------------|------------------|
| | Dry | Moderate | Wet | Bioreactor | |
| Leaves | 0.09 | 0.17 | 0.26 | 0.51 | 0.22 |
| Branches | 0.01 | 0.02 | 0.02 | 0.05 | 0.02 |
| Mixed MSW | 0.02 | 0.04 | 0.06 | 0.12 | 0.05 |
| Drywall ^a | – | – | – | – | – |
| Wood Flooring ^a | – | – | – | – | – |

– = Zero Emissions.

^aDecay rates were not estimated since WARM assumes that the construction and demolition landfills where these materials are disposed of do not collect landfill gas.

The profile of methane emissions as materials decay in landfills over time is commonly approximated using a first-order decay methodology summarized in De la Cruz and Barlaz (2010). The CH₄ generation potential of landfilled waste decreases gradually throughout time and can be estimated using first order decomposition mathematics. The profile of methane emissions from landfills over time for mixed MSW is shown in Exhibit 6-8 as a graphic representation of the methane emissions approximated using a first-order decay equation. As Exhibit 6-8 shows, materials will degrade faster under wetter conditions in landfills (i.e., landfills whose conditions imply higher decay rates for materials).

Exhibit 6-8. Rate of Methane Generation for Mixed MSW as a Function of Decay Rate



Although in each landfill moisture scenario, the total final CH₄ yield for solid waste components (Exhibit 6-6) will eventually be emitted over time, the rate at which methane is emitted greatly depends on the decay rate. Finally, since different materials have very different methane emission profiles in landfills, the effectiveness and timing of the installation of landfill gas collection systems can greatly influence methane emissions, as discussed in the next section.

6.2.2.3 Landfill Gas Collection

WARM estimates the amount of methane that is collected by landfill gas collection equipment. In practice, the landfill gas collection system efficiency does not remain constant over the duration of gas production. Rather, the gas collection system at any particular landfill is typically expanded over time. Usually, only a small percentage (or none) of the gas produced soon after waste burial is collected, while almost all of the gas produced is collected once a final cover is installed. To provide a better estimate of gas collection system efficiency, EPA uses a Monte Carlo analysis to estimate the fraction of produced gas that is vented directly, flared and utilized for energy recovery while considering annual waste disposal and landfill operating life (Levis and Barlaz 2014).³³

The gas collection efficiencies that WARM uses are evaluated from the perspective of a short ton of a specific material placed in the landfill at year zero. The efficiencies are calculated based on one of five moisture conditions (dry, moderate, wet, bioreactor, and national average conditions, described in section 6.2.2.2) and one of four landfill gas collection practices over a 100-year time period, which is approximately the amount of time required for 95 percent of the potential landfill gas to be produced under the “Dry” (k = 0.02/yr) landfill scenario. The final average efficiency is equal to the total CH₄ collected over 100 years divided by the total CH₄ produced over 100 years.

The combination of four different landfill gas collection scenarios and five different landfill moisture conditions means there are 20 possible landfill gas collection efficiencies possible for each material in WARM. The landfill collection efficiency scenarios are described below and the assumptions for each are shown in Exhibit 6-9:

1. Typical collection – phased-in collection with an improved cover; judged to represent the average U.S. landfill, although every landfill is unique and a typical landfill is an approximation of reality.
2. Worst-case collection – the minimum collection requirements under EPA’s New Source Performance Standards.
3. Aggressive collection – landfills where the operator is aggressive in gas collection relative to a typical landfill; bioreactor landfills are assumed to collect gas aggressively.
4. California regulatory scenario³⁴ – equivalent to landfill management practices based on California regulatory requirements.

Exhibit 6-9: WARM Gas Collection Scenario Assumptions and Efficiencies Compared to EPA AP-42 (1998) with Landfill Gas Recovery for Energy

| Scenario | Gas Collection Scenario Description | Gas Collection Scenario | Landfill Gas Collection Efficiency (%) for Mixed MSW ^a | | | | |
|----------|--|-------------------------|---|------|------|------|------------------|
| | | | MSW Decay Rate (yr ⁻¹) | | | | |
| | | | 0.02 | 0.04 | 0.06 | 0.12 | National Average |
| AP-42 | EPA default gas collection assumption (EPA 1998 AP-42) (not modeled in WARM) | All years: 75% | 75.0 | 75.0 | 75.0 | 75.0 | 75.0 |

³³ This improved analysis of landfill gas collection was incorporated in June 2014 into WARM Version 13.

³⁴ This additional landfill gas collection scenario was incorporated in June 2014 into WARM Version 13 to allow WARM users to estimate and view landfill management results based on California regulatory requirements.

| Scenario | Gas Collection Scenario Description | Gas Collection Scenario | Landfill Gas Collection Efficiency (%) for Mixed MSW ^a | | | | |
|----------|---|---|---|------|------|------|------------------|
| | | | MSW Decay Rate (yr ⁻¹) | | | | National Average |
| | | | 0.02 | 0.04 | 0.06 | 0.12 | |
| 1 | "Typical collection", judged to represent the average U.S. landfill | Years 0–1: 0% Years 2-4: 50% Years 5–14: 75% Years 15 to 1 year before final cover: 82.5% Final cover: 90% | 68.2 | 65.0 | 64.1 | 60.6 | 64.8 |
| 2 | "Worst-case collection" under EPA New Source Performance Standards (NSPS) | Years 0-4: 0% Years 5-9: 50% Years 10–14: 75% Years 15 to 1 year before final cover: 82.5% Final cover: 90% | 66.2 | 61.3 | 59.2 | 50.6 | 60.3 |
| 3 | "Aggressive gas collection," typical bioreactor operation | Year 0: 0% Years 0.5-2: 50% Years 3–14: 75% Years 15 to 1 year before final cover: 82.5% Final Cover: 90% | 68.6 | 65.8 | 66.3 | 63.9 | 66.4 |
| 4 | "California regulatory scenario", landfill management based on California regulatory requirements | Year 0: 0% Year 1: 50% Years 2-7: 80% Years 8 to 1 year before final cover: 85% Final cover: 90% | 83.6 | 79.5 | 77.4 | 72.9 | 78.8 |

^a The values in this table are for landfills that recover gas for energy. In reality, a small share of gas recovered is eventually flared. The values provided in this table include both the gas recovered for energy and the small portion recovered for flaring.

The landfill gas collection efficiencies by material type for each of the four landfill collection efficiency scenarios and each of the five moisture conditions are provided in Exhibit 6-10. In addition to the gas collected, EPA also takes into account the percentage of gas that is flared, oxidized and emitted for landfills that recover gas for energy, as described in Levis and Barlaz (2014). Some of the uncollected methane is oxidized to CO₂ as it passes through the landfill cover; Levis and Barlaz (2014) adapted EPA recommendations for methane oxidation (71 FR 230, 2013) to develop the following oxidation rates at various stages of landfill gas collection:

- Without gas collection or final cover: 10 percent
- With gas collection before final cover: 20 percent
- After final cover installation: 35 percent

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 percent to 35 percent (71 FR 230, 2013). 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 listed above. Landfills with a final cover and a gas collection system in place will have a relatively low flux through the cover, which justifies the upper end of the range (35 percent) given by EPA. Similarly, landfills without a gas collection system in place will have a relatively high flux, suggesting that an oxidation rate of 10 percent is most appropriate. Landfills with a gas collection system in place but prior to final cover placement were assigned an oxidation rate of 20 percent. Based on preliminary calculations for a variety of landfill geometries and waste densities, Levis and Barlaz (2014) determined that the methane flux would justify an oxidation rate of 25 percent most but not all of the time. As such,

an oxidation rate of 20 percent was adopted in WARM for landfills with gas collection before final cover (Levis and Barlaz, 2014).

For landfill gas that is not collected for energy use, EPA takes into account the percentage of landfill CH₄ that is flared (when recovery for flaring is assumed), oxidized near the surface of the landfill, and emitted. Based on analysis by Levis and Barlaz, EPA estimated the percentage of the landfill CH₄ generated that are either flared, chemically oxidized or converted by bacteria to CO₂, and emitted for each material type for each of the four landfill collection efficiency scenarios and each of the five moisture conditions (Levis and Barlaz, 2014).

Exhibit 6-10: Waste Component-Specific Collection Efficiencies by Landfill Moisture Condition with Landfill Gas Recovery for Energy

| Material | Typical Landfill Scenario | | | | | Worst-Case Landfill Scenario | | | | | Aggressive Collection Landfill Scenario | | | | | California Regulations Collection Scenario | | | | |
|--------------------------------|---------------------------|----------|-----|-------------|---------------|------------------------------|----------|-----|-------------|---------------|---|----------|-----|-------------|---------------|--|----------|-----|-------------|---------------|
| | Dry | Moderate | Wet | Bio-reactor | National Avg. | Dry | Moderate | Wet | Bio-reactor | National Avg. | Dry | Moderate | Wet | Bio-reactor | National Avg. | Dry | Moderate | Wet | Bio-reactor | National Avg. |
| Corrugated Containers | 61% | 55% | 54% | 55% | 56% | 60% | 54% | 53% | 50% | 54% | 61% | 56% | 56% | 58% | 57% | 66% | 59% | 60% | 62% | 61% |
| Magazines/ Third-Class Mail | 59% | 55% | 52% | 45% | 54% | 55% | 46% | 40% | 26% | 43% | 61% | 58% | 57% | 51% | 57% | 67% | 63% | 61% | 54% | 62% |
| Newspaper | 62% | 59% | 59% | 57% | 59% | 61% | 56% | 55% | 49% | 56% | 62% | 59% | 61% | 60% | 61% | 67% | 64% | 65% | 65% | 65% |
| Office Paper | 62% | 58% | 58% | 57% | 59% | 61% | 56% | 55% | 50% | 56% | 62% | 59% | 60% | 60% | 60% | 67% | 63% | 64% | 65% | 64% |
| Phone Books | 62% | 59% | 59% | 57% | 59% | 61% | 56% | 55% | 49% | 56% | 62% | 59% | 61% | 60% | 61% | 67% | 64% | 65% | 65% | 65% |
| Textbooks | 62% | 58% | 58% | 57% | 59% | 61% | 56% | 55% | 50% | 56% | 62% | 59% | 60% | 60% | 60% | 67% | 63% | 64% | 65% | 64% |
| Dimensional Lumber | 62% | 59% | 57% | 50% | 58% | 59% | 52% | 48% | 35% | 50% | 63% | 61% | 60% | 55% | 60% | 68% | 66% | 65% | 60% | 65% |
| Medium-Density Fiberboard | 62% | 60% | 59% | 53% | 59% | 60% | 55% | 51% | 40% | 53% | 63% | 62% | 62% | 58% | 62% | 68% | 66% | 67% | 62% | 67% |
| Food Waste | 58% | 53% | 50% | 42% | 52% | 53% | 43% | 36% | 22% | 40% | 59% | 56% | 55% | 49% | 55% | 65% | 61% | 59% | 51% | 60% |
| Food Waste (meat only) | 58% | 53% | 50% | 42% | 52% | 53% | 43% | 36% | 22% | 40% | 59% | 56% | 55% | 49% | 55% | 65% | 61% | 59% | 51% | 60% |
| Food Waste (non-meat) | 58% | 53% | 50% | 42% | 52% | 53% | 43% | 36% | 22% | 40% | 59% | 56% | 55% | 49% | 55% | 65% | 61% | 59% | 51% | 60% |
| Beef | 58% | 53% | 50% | 42% | 52% | 53% | 43% | 36% | 22% | 40% | 59% | 56% | 55% | 49% | 55% | 65% | 61% | 59% | 51% | 60% |
| Poultry | 58% | 53% | 50% | 42% | 52% | 53% | 43% | 36% | 22% | 40% | 59% | 56% | 55% | 49% | 55% | 65% | 61% | 59% | 51% | 60% |
| Grains | 58% | 53% | 50% | 42% | 52% | 53% | 43% | 36% | 22% | 40% | 59% | 56% | 55% | 49% | 55% | 65% | 61% | 59% | 51% | 60% |
| Bread | 58% | 53% | 50% | 42% | 52% | 53% | 43% | 36% | 22% | 40% | 59% | 56% | 55% | 49% | 55% | 65% | 61% | 59% | 51% | 60% |
| Fruits and Vegetables | 58% | 53% | 50% | 42% | 52% | 53% | 43% | 36% | 22% | 40% | 59% | 56% | 55% | 49% | 55% | 65% | 61% | 59% | 51% | 60% |
| Dairy Products | 58% | 53% | 50% | 42% | 52% | 53% | 43% | 36% | 22% | 40% | 59% | 56% | 55% | 49% | 55% | 65% | 61% | 59% | 51% | 60% |
| Yard Trimmings | 54% | 47% | 44% | 39% | 47% | 47% | 37% | 31% | 21% | 35% | 55% | 51% | 49% | 44% | 50% | 61% | 55% | 52% | 45% | 54% |
| Grass | 49% | 43% | 39% | 33% | 41% | 39% | 27% | 20% | 9% | 25% | 51% | 47% | 45% | 39% | 46% | 57% | 51% | 48% | 38% | 50% |
| Leaves | 56% | 51% | 47% | 40% | 49% | 50% | 40% | 33% | 19% | 37% | 58% | 54% | 52% | 46% | 53% | 64% | 59% | 57% | 48% | 58% |
| Branches | 61% | 53% | 51% | 52% | 54% | 60% | 52% | 51% | 49% | 53% | 61% | 54% | 53% | 54% | 55% | 65% | 57% | 57% | 58% | 59% |
| Mixed MSW | 62% | 60% | 60% | 57% | 60% | 61% | 56% | 55% | 47% | 56% | 63% | 61% | 62% | 60% | 62% | 67% | 65% | 67% | 65% | 66% |

| Material | Typical Landfill Scenario | | | | | Worst-Case Landfill Scenario | | | | | Aggressive Collection Landfill Scenario | | | | | California Regulations Collection Scenario | | | | |
|----------------------------|---------------------------|----------|-----|-------------|---------------|------------------------------|----------|-----|-------------|---------------|---|----------|-----|-------------|---------------|--|----------|-----|-------------|---------------|
| | Dry | Moderate | Wet | Bio-reactor | National Avg. | Dry | Moderate | Wet | Bio-reactor | National Avg. | Dry | Moderate | Wet | Bio-reactor | National Avg. | Dry | Moderate | Wet | Bio-reactor | National Avg. |
| Gypsum ^a | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Wood Flooring ^a | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |

- = Zero Emissions.

^aWARM assumes that construction and demolition landfills do not collect landfill gas.

6.2.3 Emissions from Transportation to Landfills and Landfill Operation

WARM includes emissions associated with transportation and landfilling the material. Transportation energy emissions occur when fossil fuels are combusted to collect and transport material to the landfill facility and then to operate landfill operational equipment. To calculate the emissions, WARM relies on assumptions from FAL (1994) for the equipment emissions and NREL's US Life Cycle Inventory Database (USLCI) (NREL 2015). The NREL emission factor assumes a diesel, short-haul truck. Exhibit 6-11 provides the transportation emission factor calculation.

Exhibit 6-11: Transportation CO₂ Emissions Assumptions and Calculation

| Equipment | Diesel Fuel (gallons/ 10 ³ lbs of MSW landfilled) | Total Energy (Btu/10 ³ lb of MSW landfilled) | Total Energy (Btu/Short Ton of MSW landfilled) | MTCE (per million Btus) | Total (MTCO ₂ E/Short Ton) |
|---------------------|--|---|---|----------------------------|---|
| Collection Vehicles | 0.13 | 18,736 | 34,473 | – | – |
| Landfill Equipment | 0.70 | 115,400 | 230,800 | – | – |
| Total | 1.60 | 263,700 | 527,400 | 0.005 | 0.02 |

– = Zero Emissions.

6.2.4 Estimating Landfill Carbon Storage

The other anthropogenic fate of carbon in landfills is storage. As described in section 6.2.1, a portion of the carbon in biodegradable materials (i.e., food waste, yard trimmings, paper and wood) that is not completely decomposed by anaerobic bacteria remains stored in the landfill. This carbon storage would not normally occur under natural conditions, so it is counted as an anthropogenic sink (IPCC, 2006; Bogner et al., 2007).

The discussion in section 6.2.2 on initial carbon contents and CH₄ generation includes the measured carbon stored from the Barlaz (1998), Wang et al. (2013), Wang et al. (2011), and Levis et al. (2013) experiments. For the most part, the amount of stored carbon measured as the output during these experiments is considered the final ratio of carbon stored to total initial dry weight of each material type. For newspaper, wood flooring, and coated paper—which is used to estimate landfill characteristics for magazines and third-class mail—the amount of carbon stored is reduced because carbon outputs were *greater than* initial carbon.

To estimate the final carbon storage factor, the proportion of initial carbon stored found in Exhibit 6-5 is multiplied by the initial carbon contents in Exhibit 6-3 to obtain the ratio of carbon storage to dry weight for each material type found in Exhibit 6-12. These estimates are then converted from dry weight to wet weight and from grams to metric tons of CO₂ per wet short ton of material. The last column of Exhibit 6-12 provides the final carbon storage factors for the biodegradable solid waste components modeled in WARM.

Exhibit 6-12: Carbon Storage for Solid Waste Components

| Material | Ratio of Carbon Storage to Dry Weight (gram C/dry gram) | Ratio of Dry Weight to Wet Weight | Ratio of Carbon Storage to Wet Weight (gram C/wet gram) | Amount of Carbon Stored (MTCO ₂ E per Wet Short Ton) |
|----------------------------|---|-----------------------------------|---|---|
| Corrugated Containers | 0.26 | 0.83 | 0.22 | 0.72 |
| Magazines/Third-Class Mail | 0.28 | 0.92 | 0.25 | 0.85 |
| Newspaper | 0.41 | 0.87 | 0.36 | 1.19 |
| Office Paper | 0.04 | 0.91 | 0.04 | 0.12 |
| Phonebooks | 0.41 | 0.87 | 0.36 | 1.19 |
| Textbooks | 0.04 | 0.91 | 0.04 | 0.12 |
| Dimensional Lumber | 0.44 | 0.75 | 0.33 | 1.09 |
| Medium-Density Fiberboard | 0.37 | 0.75 | 0.28 | 0.92 |
| Food Waste | 0.10 | 0.27 | 0.03 | 0.09 |
| Yard Trimmings | 0.31 | 0.45 | 0.16 | 0.54 |
| Grass | 0.24 | 0.18 | 0.04 | 0.14 |
| Leaves | 0.39 | 0.62 | 0.24 | 0.79 |
| Branches | 0.38 | 0.84 | 0.32 | 1.06 |
| Mixed MSW | 0.08 | 0.80 | 0.06 | 0.21 |
| Drywall | 0.03 | 0.94 | 0.02 | 0.08 |
| Wood Flooring | 0.42 | 0.75 | 0.31 | 1.04 |

6.2.5 Electric Utility GHG Emissions Avoided

The CH₄ component of landfill gas that is collected from landfills can be combusted to produce heat and electricity, and recovery of heat and electricity from landfill gas offsets the combustion of other fossil fuel inputs. WARM models the recovery of landfill gas for electricity generation and assumes that this electricity offsets non-baseload electricity generation in the power sector.

WARM applies non-baseload electricity emission rates to calculate the emissions offset from landfill gas energy recovery because the model assumes that incremental increases in landfill energy recovery will affect non-baseload power plants (i.e., power plants that are “demand-following” and adjust to marginal changes in the supply and demand of electricity). EPA calculates non-baseload emission rates as the average emissions rate from power plants that combust fuel and have capacity factors less than 0.8 (EPA, 2015a).

EPA estimates the avoided GHG emissions per MTCO₂E of CH₄ combusted using several physical constants and data from EPA’s Landfill Methane Outreach Program and eGRID (EPA, 2013; EPA, 2015a). The mix of fuels used to produce electricity varies regionally in the United States; consequently, EPA applies a different CO₂-intensity for electricity generation depending upon where the electricity is offset. The Excel version of WARM includes CO₂-intensity emission factors for non-baseload electricity generated in nine different U.S. regions as well as a U.S.-average CO₂-intensity (EPA, 2015a). The formula used to calculate the quantity of electricity generation emissions avoided per MTCO₂E of CH₄ combusted is as follows:

$$\frac{BTU_{CH_4}}{H_{LFGTE}} \times a \times E_{Grid} = R$$

Where:

Btu_{CH₄} = Energy content of CH₄ per MTCO₂E CH₄ combusted; assumed to be 1,012 Btu per cubic foot of CH₄ (EPA, 2013), converted into Btu per MTCO₂E CH₄ assuming 20 grams per cubic foot of CH₄ at standard temperature and pressure and a global warming potential of CH₄ of 21

- H_{LFGTE} = Heat rate of landfill gas to energy conversion; assumed to be 11,700 Btu per kWh generated (EPA, 2013)
- a = Net capacity factor of electricity generation; assumed to be 85 percent (EPA, 2013)
- E_{grid} = Non-baseload CO₂-equivalent GHG emissions intensity of electricity produced at the regional or national electricity grid; values assumed for each region and U.S. average are shown in Exhibit 6-14
- R = Ratio of GHG emissions avoided from electricity generation per MTCO₂E of CH₄ combusted for landfill gas to energy recovery

Exhibit 6-13 shows variables in the GHG emissions offset for the national average fuel mix. The final ratio is the product of columns (a) through (h). Exhibit 6-14 shows the amount of carbon avoided per kilowatt-hour of generated electricity and the final ratio of MTCO₂E avoided of utility carbon per MTCO₂E of CH₄ combusted (column (g) and resulting column (i)).

Exhibit 6-13: Calculation to Estimate Utility GHGs Avoided through Combustion of Landfill CH₄ for Electricity Based on National Average Electricity Grid Mix

| (a) | (b) | (c) | (d) | (e) | (f) | (g) | (h) | (i) |
|--|---|---|-------------------------------|-------------------------------|-----------------------------------|--|---|--|
| Metric Tons CH ₄ /MTCO ₂ E CH ₄ Combusted | Grams CH ₄ /Metric Ton CH ₄ | Cubic Ft. CH ₄ /Gram CH ₄ | Btu/Cubic Ft. CH ₄ | kWh Electricity Generated/Btu | Electricity Generation Efficiency | Kg Utility CO ₂ Avoided/kWh Generated Electricity | Metric Tons Avoided Utility CO ₂ /Kg Utility CO ₂ | Ratio of MTCO ₂ E Avoided Utility CO ₂ per MTCO ₂ E CH ₄ Combusted |
| 0.04 | 1,000,000 | 0.05 | 1,012 | 0.00009 | 0.85 | 0.75 | 0.001 | 0.11 |

Exhibit 6-14: Ratio of MTCO₂E Avoided Utility Carbon per MTCO₂E CH₄ Combusted by Region

| Region | Kg Utility CO ₂ Avoided/kWh Generated Electricity | Ratio of MTCO ₂ E Avoided Utility C per MTCO ₂ E CH ₄ |
|--------------------|--|--|
| Pacific | 0.52 | 0.08 |
| Mountain | 0.78 | 0.12 |
| West-North Central | 1.00 | 0.15 |
| West-South Central | 0.66 | 0.10 |
| East-North Central | 0.90 | 0.13 |
| East-South Central | 0.81 | 0.12 |
| New England | 0.53 | 0.08 |
| Mid Atlantic | 0.69 | 0.10 |
| South Atlantic | 0.79 | 0.12 |
| National Average | 0.75 | 0.11 |

If regional avoided utility emission factors are not employed, WARM calculates U.S.-average avoided utility emission factors based on the percent of CH₄ generated at landfills in the nation with landfill gas recovery and electricity production found in Exhibit 6-1, and assuming U.S.-average, non-baseload electricity GHG emission intensity. Exhibit 6-15 shows this calculation for each material type for the national average fuel mix.

Exhibit 6-15: Overall Avoided Utility CO₂ Emissions per Short Ton of Waste Material (National Average Grid Mix)

| (a) Material | (b) CH ₄ Generation (MTCO ₂ E/ Wet Short Ton) (Exhibit 6-6) | Methane from Landfills With LFG Recovery and Electricity Generation | | | | | (h) Net Avoided CO ₂ Emissions from Energy Recovery (MTCO ₂ E/ Wet Short Ton) (h = f × g) |
|--------------------------------|---|---|--|--|--|--|--|
| | | (c) Percentage of CH ₄ Recovered (Exhibit 6-10) | (d) Utility GHG Emissions Avoided per MTCO ₂ E CH ₄ Combusted (MTCO ₂ E) (Exhibit 6-14) | (e) Percentage of CH ₄ Recovered for Electricity Generation Not Utilized Due to LFG System "Down Time" | (f) Utility GHG Emissions Avoided (MTCO ₂ E/Wet Short Ton) (f = b × (1-c) × d × (1-e)) | (g) Percentage of CH ₄ From Landfills With LFG Recovery and Electricity Generation (Exhibit 6-1) | |
| Corrugated Containers | 2.62 | 56% | -0.11 | 3% | -0.16 | 72% | -0.11 |
| Magazines/ Third-Class Mail | 1.19 | 54% | -0.11 | 3% | -0.07 | 72% | -0.05 |
| Newspaper | 1.05 | 59% | -0.11 | 3% | -0.07 | 72% | -0.05 |
| Office Paper | 3.89 | 59% | -0.11 | 3% | -0.25 | 72% | -0.18 |
| Phonebooks | 1.05 | 59% | -0.11 | 3% | -0.07 | 72% | -0.05 |
| Textbooks | 3.89 | 59% | -0.11 | 3% | -0.25 | 72% | -0.18 |
| Dimensional Lumber | 0.17 | 58% | -0.11 | 3% | -0.01 | 72% | -0.01 |
| Medium-Density Fiberboard | 0.06 | 59% | -0.11 | 3% | 0.00 | 72% | 0.00 |
| Food Waste | 1.62 | 52% | -0.11 | 3% | -0.09 | 72% | -0.06 |
| Yard Trimmings | 0.81 | 47% | -0.11 | 3% | -0.04 | 72% | -0.03 |
| Grass | 0.57 | 41% | -0.11 | 3% | -0.03 | 72% | -0.02 |
| Leaves | 0.65 | 49% | -0.11 | 3% | -0.03 | 72% | -0.02 |
| Branches | 1.45 | 54% | -0.11 | 3% | -0.08 | 72% | -0.06 |
| Mixed MSW | 1.62 | 60% | -0.11 | 3% | -0.10 | 72% | -0.07 |
| Drywall ^a | 0.00 | – | -0.11 | 3% | – | – | – |
| Wood Flooring ^a | 0.18 | – | -0.11 | 3% | – | – | – |

– = Zero Emissions.

^a WARM assumes that construction and demolition landfills do not collect landfill gas.

6.2.6 Net GHG Emissions from Landfilling

CH₄ emissions, transportation CO₂ emissions, carbon storage and avoided utility GHG emissions are then summed to estimate the net GHG emissions from landfilling each material type. Exhibit 6-16 shows the net emission factors for landfilling each material based on typical landfill gas collection practices, average landfill moisture conditions (i.e., for landfills receiving between 20 and 40 inches of precipitation annually), and U.S.-average non-baseload electricity grid mix.

Exhibit 6-16: Net GHG Emissions from Landfilling (MTCO₂E/Short Ton)

| Material | Raw Material Acquisition and Manufacturing (Current Mix of Inputs) | Transportation to Landfill | Landfill CH ₄ | Avoided CO ₂ Emissions from Energy Recovery | Landfill Carbon Sequestration | Net Emissions (Post-Consumer) |
|----------------|--|----------------------------|--------------------------|--|-------------------------------|-------------------------------|
| Aluminum Cans | – | 0.02 | – | – | – | 0.02 |
| Aluminum Ingot | – | 0.02 | – | – | – | 0.02 |
| Steel Cans | – | 0.02 | – | – | – | 0.02 |

| Material | Raw Material Acquisition and Manufacturing (Current Mix of Inputs) | Transportation to Landfill | Landfill CH ₄ | Avoided CO ₂ Emissions from Energy Recovery | Landfill Carbon Sequestration | Net Emissions (Post-Consumer) |
|--------------------------------------|--|----------------------------|--------------------------|--|-------------------------------|-------------------------------|
| Copper Wire | - | 0.02 | - | - | - | 0.02 |
| Glass | - | 0.02 | - | - | - | 0.02 |
| HDPE | - | 0.02 | - | - | - | 0.02 |
| LDPE | - | 0.02 | - | - | - | 0.02 |
| PET | - | 0.02 | - | - | - | 0.02 |
| LLDPE | - | 0.02 | - | - | - | 0.02 |
| PP | - | 0.02 | - | - | - | 0.02 |
| PS | - | 0.02 | - | - | - | 0.02 |
| PVC | - | 0.02 | - | - | - | 0.02 |
| PLA | - | 0.02 | - | - | -1.66 | -1.64 |
| Corrugated Containers | - | 0.02 | 1.05 | -0.11 | -0.72 | 0.23 |
| Magazines/Third-Class Mail | - | 0.02 | 0.48 | -0.05 | -0.85 | 0.39 |
| Newspaper | - | 0.02 | 0.40 | -0.05 | -1.19 | -0.82 |
| Office Paper | - | 0.02 | 1.49 | -0.18 | -0.12 | 1.22 |
| Phonebooks | - | 0.02 | 0.40 | -0.05 | -1.19 | -0.82 |
| Textbooks | - | 0.02 | 1.49 | -0.18 | -0.12 | 1.22 |
| Dimensional Lumber | - | 0.02 | 0.06 | 0.01 | -1.09 | -1.01 |
| Medium-density Fiberboard | - | 0.02 | 0.02 | 0.00 | -0.92 | -0.88 |
| Food Waste | - | 0.02 | 0.67 | -0.06 | -0.09 | 0.54 |
| Food Waste (meat only) | - | 0.02 | 0.67 | -0.06 | -0.09 | 0.54 |
| Food Waste (non-meat) | - | 0.02 | 0.67 | -0.06 | -0.09 | 0.54 |
| Beef | - | 0.02 | 0.67 | -0.06 | -0.09 | 0.54 |
| Poultry | - | 0.02 | 0.67 | -0.06 | -0.09 | 0.54 |
| Grains | - | 0.02 | 0.67 | -0.06 | -0.09 | 0.54 |
| Bread | - | 0.02 | 0.67 | -0.06 | -0.09 | 0.54 |
| Fruits and Vegetables | - | 0.02 | 0.67 | -0.06 | -0.09 | 0.54 |
| Dairy Products | - | 0.02 | 0.67 | -0.06 | -0.09 | 0.54 |
| Yard Trimmings | - | 0.02 | 0.36 | -0.03 | -0.54 | -0.18 |
| Grass | - | 0.02 | 0.27 | -0.02 | -0.14 | 0.13 |
| Leaves | - | 0.02 | 0.28 | -0.02 | -0.79 | -0.52 |
| Branches | - | 0.02 | 0.60 | -0.06 | -1.06 | -0.51 |
| Mixed Paper (general) | - | 0.02 | 0.93 | -0.11 | -0.72 | 0.13 |
| Mixed Paper (primarily residential) | - | 0.02 | 0.90 | -0.10 | -0.76 | 0.07 |
| Mixed Paper (primarily from offices) | - | 0.02 | 0.88 | -0.10 | -0.64 | 0.17 |
| Mixed Metals | - | 0.02 | - | - | - | 0.02 |
| Mixed Plastics | - | 0.02 | - | - | - | 0.02 |
| Mixed Recyclables | - | 0.02 | 0.74 | -0.07 | -0.65 | 0.04 |
| Mixed Organics | - | 0.02 | 0.53 | -0.05 | -0.30 | 0.20 |
| Mixed MSW | - | 0.02 | 0.61 | -0.07 | -0.21 | 0.35 |
| Carpet | - | 0.02 | - | - | - | 0.02 |
| Personal Computers | - | 0.02 | - | - | - | 0.02 |
| Clay Bricks | - | 0.02 | - | - | - | 0.02 |
| Concrete | - | 0.02 | - | - | - | 0.02 |
| Fly Ash | - | 0.02 | - | - | - | 0.02 |
| Tires | - | 0.02 | - | - | - | 0.02 |
| Asphalt Concrete | - | 0.02 | - | - | - | 0.02 |
| Asphalt Shingles | - | 0.02 | - | - | - | 0.02 |

| Material | Raw Material Acquisition and Manufacturing (Current Mix of Inputs) | Transportation to Landfill | Landfill CH ₄ | Avoided CO ₂ Emissions from Energy Recovery | Landfill Carbon Sequestration | Net Emissions (Post-Consumer) |
|----------------------------|--|----------------------------|--------------------------|--|-------------------------------|-------------------------------|
| Drywall | - | 0.02 | - | - | -0.08 | -0.06 |
| Fiberglass Insulation | - | 0.02 | - | - | - | 0.02 |
| Vinyl Flooring | - | 0.02 | - | - | - | 0.02 |
| Wood Flooring ^a | - | 0.02 | 0.16 | 0.00 | -1.04 | -0.86 |

- = Zero Emissions.

^a WARM assumes that construction and demolition landfills do not collect landfill gas

In WARM, emissions from landfills are dependent on the user selection of one of four different landfill scenarios (i.e., “Landfills: National Average,” “Landfills Without LFG Recovery,” “Landfills With LFG Recovery and Flaring,” and “Landfills With LFG Recovery and Electric Generation”) as described in section 1. The net landfilling emission factors for landfilling each material based on the default options in WARM (i.e., typical landfill gas collection practices, average landfill moisture conditions and U.S.-average non-baseload electricity grid mix) are shown in Exhibit 6-17.

Exhibit 6-17: Landfilling Net Emission Factors in WARM Using Default Options (MTCO₂E/Ton)

| Material | Landfills: National Average (Exhibit 6-16) | Landfills without LFG Recovery | Landfills with LFG Recovery and Flaring | Landfills with LFG Recovery and Electricity Generation |
|----------------------------|--|--------------------------------|---|--|
| Aluminum Cans | 0.02 | 0.02 | 0.02 | 0.02 |
| Aluminum Ingot | 0.02 | 0.02 | 0.02 | 0.02 |
| Steel Cans | 0.02 | 0.02 | 0.02 | 0.02 |
| Copper Wire | 0.02 | 0.02 | 0.02 | 0.02 |
| Glass | 0.02 | 0.02 | 0.02 | 0.02 |
| HDPE | 0.02 | 0.02 | 0.02 | 0.02 |
| LDPE | 0.02 | 0.02 | 0.02 | 0.02 |
| PET | 0.02 | 0.02 | 0.02 | 0.02 |
| LLDPE | 0.02 | 0.02 | 0.02 | 0.02 |
| PP | 0.02 | 0.02 | 0.02 | 0.02 |
| PS | 0.02 | 0.02 | 0.02 | 0.02 |
| PVC | 0.02 | 0.02 | 0.02 | 0.02 |
| PLA | -1.64 | -1.64 | -1.64 | -1.64 |
| Corrugated Containers | 0.23 | 1.66 | 0.45 | 0.06 |
| Magazines/Third-Class Mail | -0.39 | 0.25 | -0.37 | -0.46 |
| Newspaper | -0.82 | -0.23 | -0.75 | -0.89 |
| Office Paper | 1.22 | 3.40 | 1.51 | 0.95 |
| Phonebooks | -0.82 | -0.23 | -0.75 | -0.89 |
| Textbooks | 1.22 | 3.40 | 1.51 | 0.95 |
| Dimensional Lumber | -1.01 | -0.92 | -1.01 | -1.02 |
| Medium-density Fiberboard | -0.88 | -0.85 | -0.88 | -0.89 |
| Food Waste | 0.54 | 1.39 | 0.56 | 0.45 |
| Food Waste (meat only) | 0.54 | 1.39 | 0.56 | 0.45 |
| Food Waste (non-meat) | 0.54 | 1.39 | 0.56 | 0.45 |
| Beef | 0.54 | 1.39 | 0.56 | 0.45 |
| Poultry | 0.54 | 1.39 | 0.56 | 0.45 |
| Grains | 0.54 | 1.39 | 0.56 | 0.45 |
| Bread | 0.54 | 1.39 | 0.56 | 0.45 |
| Fruits and Vegetables | 0.54 | 1.39 | 0.56 | 0.45 |

| Material | Landfills: National Average (Exhibit 6-16) | Landfills without LFG Recovery | Landfills with LFG Recovery and Flaring | Landfills with LFG Recovery and Electricity Generation |
|---|---|-----------------------------------|--|--|
| Dairy Products | 0.54 | 1.39 | 0.56 | 0.45 |
| Yard Trimmings | -0.18 | 0.21 | -0.17 | -0.22 |
| Grass | 0.13 | 0.39 | 0.12 | 0.10 |
| Leaves | -0.52 | -0.18 | -0.51 | -0.55 |
| Branches | -0.51 | -0.26 | -0.39 | -0.61 |
| Mixed Paper (general) | 0.13 | 1.44 | 0.30 | -0.03 |
| Mixed Paper (primarily residential) | 0.07 | 1.33 | 0.23 | -0.09 |
| Mixed Paper (primarily from offices) | 0.17 | 1.42 | 0.29 | 0.02 |
| Mixed Metals | 0.02 | 0.02 | 0.02 | 0.02 |
| Mixed Plastics | 0.02 | 0.02 | 0.02 | 0.02 |
| Mixed Recyclables | 0.04 | 1.15 | 0.36 | -0.14 |
| Mixed Organics | 0.20 | 0.83 | 0.22 | 0.14 |
| Mixed MSW | 0.35 | 1.27 | 0.46 | 0.24 |
| Carpet | 0.02 | 0.02 | 0.02 | 0.02 |
| Personal Computers | 0.02 | 0.02 | 0.02 | 0.02 |
| Clay Bricks | 0.02 | 0.02 | 0.02 | 0.02 |
| Concrete | 0.02 | 0.02 | 0.02 | 0.02 |
| Fly Ash | 0.02 | 0.02 | 0.02 | 0.02 |
| Tires | 0.02 | 0.02 | 0.02 | 0.02 |
| Asphalt Concrete | 0.02 | 0.02 | 0.02 | 0.02 |
| Asphalt Shingles | 0.02 | 0.02 | 0.02 | 0.02 |
| Drywall | -0.06 | -0.06 | -0.06 | -0.06 |
| Fiberglass Insulation | 0.02 | 0.02 | 0.02 | 0.02 |
| Vinyl Flooring | 0.02 | 0.02 | 0.02 | 0.02 |
| Wood Flooring | -0.86 | -0.86 | -0.86 | -0.86 |

6.3 LIMITATIONS

The landfilling analysis has several limitations associated with it; these are discussed in the following paragraphs.

- The net GHG emissions from landfilling each material are quite sensitive to the LFG recovery rate. Because of the high global warming potential of CH₄, 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 distribution of waste in place is not a perfect proxy for the distribution of ongoing waste generation destined for landfill.
- Ongoing shifts in the use of landfill cover and liner systems are likely to influence the rate of CH₄ 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 biodegradable wastes. Over the long term, these improvements may result in a decrease in CH₄ generation and an increase in carbon storage. Moreover, Dr. Barlaz believes that the CH₄ yields from his laboratory experiments are likely to be higher than CH₄ yields in a landfill, because the

laboratory experiments were designed to generate the maximum amount of CH₄ possible. If the CH₄ yields from the laboratory experiments were higher than yields in a landfill, the net GHG emissions from landfilling biodegradable materials would be lower than estimated here.

- EPA assumed that once wastes are disposed in a landfill, they are never removed. In other words, it was 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 CO₂ in the combustor.
- The estimate of avoided utility GHG emissions per unit of CH₄ combusted assumes that all landfill gas-to-energy projects produce electricity. In reality, some projects are “direct gas” projects, in which CH₄ is piped directly to the end user for use as fuel. In these cases, the CH₄ typically 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 the analysis.
- For landfilling of yard trimmings (and other organic materials), EPA assumed that all carbon storage in a landfill environment is incremental to the storage that occurs in a non-landfill environment. In other words, it was 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 CO₂, 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 postconsumer GHG emissions are understated.
- The key assumptions that have not already been discussed as limitations are the assumptions used in developing “corrected” CH₄ yields for biodegradable materials in MSW. Because of the high GWP of CH₄, a small difference between estimated and actual CH₄ generation values would have a large effect on the GHG impacts of landfilling and the ranking of landfilling relative to other MSW management options.

6.4 REFERENCES

- 61 FR 49. (1996). Standards of Performance for New Stationary Sources and Guidelines for Controls of Existing Sources, Municipal Solid Waste Landfills. *61 Federal Register* 49 (12 March 1996), pp. 9905-9944.
- 71 FR 230. (2013). Revisions to the Greenhouse Gas Reporting Rule and Final Confidentiality Determinations for New or Substantially Revised Data Elements; Final Rule. *78 Federal Register* 230 (29 November 2013), pp. 71904-71981.
- Barlaz, M.A., Bareither, C.A., Hossain, A., Saquing, J., Mezzari, I., Benson, C.H., Tolaymat, T.M., Yazdani, R. (2010). Performance of North American bioreactor landfills. II: Chemical and biological characteristics. *Journal of Environmental Engineering-ASCE* 2010 (136), 839-853.

- Barlaz, M.A. (2008). Memorandum to Parties Interested in Carbon Sequestration from Municipal Solid Waste: "Corrections to Previously Published Carbon Storage Factors." February 27, 2008.
- Barlaz, M.A. (2005). Letter to Randy Freed, ICF International: "Decomposition of Leaves." June 29, 2005.
- Barlaz, M.A. (1998). Carbon storage during biodegradation of municipal solid waste components in laboratory-scale landfills. *Global Biogeochemical Cycles*, 12 (2), 373–380.
- Barlaz, M. A., Chanton, J. P., & Green, R. B. (2009). Controls on Landfill Gas Collection Efficiency: Instantaneous and Lifetime Performance. *Journal of the Air & Waste Management Association*, 59 (12).
- Barlaz, M. A., Ham, R. K., & Schaefer, D. M. (1990). Methane Production from Municipal Refuse: A Review of Enhancement Techniques and Microbial Dynamics. *Critical Reviews in Environmental Control*, 19 (6), 557.
- Barlaz, M. A., Ham, R. K., & Schaefer, D. M. (1989). Mass Balance Analysis of Decomposed Refuse in Laboratory Scale Lysimeters. *Journal of Environmental Engineering, ASCE*, 115 (6), 1088–1102.
- Bogner, J., Ahmed, M. A., Diaz, C., Faaij, A., Gao, Q., Hashimoto, S., Mareckova, K., Pipatti, R., & Zhang, T. (2007). Chapter 10L: Waste Management. In B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, & L.A. Meyer (Eds.), *Climate Change 2007: Mitigation*. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press.
- Bingemer, H G., & Crutzen, P. J. (1987). The Production of Methane from Solid Wastes. *Journal of Geophysical Research*, 90 (D2), 2181–2187.
- Chan G., Chu, L., & Wong, M. (2002). Effects of leachate recirculation on biogas production from landfill co-disposal of municipal solid waste, sewage sludge and marine sediment. *Environmental Pollution* 118 (3), 393–399.
- Colberg, P.J. (1988). Anaerobic microbial degradation of cellulose lignin, oligolignols, and monoaromatic lignin derivatives. In A. J .B. Zehnder (Ed.), *Biology of anaerobic microorganisms*. New York: Wiley, pp. 333–372.
- Czepiel, P. M., Mosher, B., Crill, P. M., & Harriss, R. C. (1996). Quantifying the effects of oxidation on landfill methane emissions. *Journal of Geophysical Research*, 101, 16721–16729.
- De la Cruz, F. B., & Barlaz, M. A. (2010). Estimation of Waste Component-Specific Landfill Decay Rates Using Laboratory-Scale Decomposition Data. *Environmental Science & Technology*, 44 (12), 4722–4728. doi:10.1021/es100240r.
- Eklund B., Anderson, E., Walker, B., & Burrows, D. (1998). Characterization of landfill gas composition at the Fresh Kills municipal solid-waste landfill. *Environ Sci Technol*, 32, 2233–2237.
- Eleazer, W.E., Odle, W. S. III, Wang, Y. S., & Barlaz, M. A. (1997). "Biodegradability of municipal solid waste components in laboratory-scale landfills." *Env. Sci. Tech*, 31 (3), 911–917.
- EPA. (2015a). *Emissions & Generation Resource Integrated Database (eGRID)*. Available from EPA at <http://www.epa.gov/energy/egrid>.
- EPA. (2015b). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2013*. (EPA 430-R-15-004). Washington, DC: U.S. Government Printing Office. Retrieved from <http://www3.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2015-Main-Text.pdf>

- EPA. (2013). *The Landfill Methane Outreach Program (LMOP) LFGE Benefits Calculator*. Available online at: <http://www.epa.gov/lmop/projects-candidates/lfge-calculator.html>.
- EPA. (2010). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008*. (EPA publication no. EPA 430-R-10-006.) Washington, DC: U.S. Environmental Protection Agency, Office of Atmospheric Programs, April. Retrieved from: <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/archive.html>.
- EPA. (1998). *AP-42 Emission factors for municipal solid waste landfills – Supplement E*. Washington, DC: U.S. Environmental Protection Agency.
- FAL (1994). *The Role of Recycling in Integrated Solid Waste Management to the Year 2000*. Franklin Associates, Ltd. (Stamford, CT: Keep America Beautiful, Inc.), pp. 1-16.
- Freed, J.R., Skog, K., Mintz, C., & Glick, N. (2004). Carbon Storage due to Disposal of Biogenic Materials in U.S. Landfills. *Proceedings of the Third Annual Conference on Carbon Sequestration*. U.S. Department of Energy.
- Hartog, C. L. (2003). The Bluestem Bioreactor. Briefing presented at the Bioreactor Workshop, sponsored by USEPA, February 27–28, 2003, Arlington, VA.
- Hilger, H., & Barlaz, M. (2001). Anaerobic decomposition of refuse in landfills and methane oxidation in landfill cover soils, *Manual of Environmental Microbiology*, 2nd Ed., Washington, DC: Am. Soc. Microbiol., pp. 696–718.
- IPCC. (2006). Chapter 3: Solid Waste Disposal. In *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 5: Waste (Vol. 5)*. Intergovernmental Panel on Climate Change (IPCC). Retrieved from <http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol5.html>.
- Levis, J. and Barlaz, M.A. (2014). Landfill Gas Monte Carlo Model Documentation and Results. June 18, 2014.
- Levis, J. W., Barlaz, M. A., DeCarolis, J. F., Ranjithan, S. R. (2013). What is the optimal way for a suburban U.S. city to sustainably manage future solid waste? Perspectives from a Solid Waste Optimization Life-cycle Framework (SWOLF). *Environ. Sci. Technol.*, submitted.
- Liptay, K., Chanton, J., Czepiel, P., & Mosher, B. (1998). Use of stable isotopes to determine methane oxidation in landfill cover soils. *Journal of Geophysical Research*, 103 (D7), 8243–8250.
- National Renewable Energy Laboratory (2015). "U.S. Life Cycle Inventory Database." Retrieved from <https://www.lcacommons.gov/nrel/search>
- Staley, B. F., & Barlaz, M. A. (2009). Composition of Municipal Solid Waste in the United States and Implications for Carbon Sequestration and Methane Yield. *Journal of Environmental Engineering*, 135 (10), 901–909. doi: 10.1061/(ASCE)EE.1943-7870.0000032
- Tolaymat, T.M., Green, R.B., Hater, G.R., Barlaz, M.A., Black, P., Bronson, D., Powell, J. (2010). Evaluation of landfill gas decay constant for municipal solid waste landfills operated as bioreactors. *Journal of the Air & Waste Management Association*, 2010 (60), 91-97.
- Wang, X., Padgett, J. M., Powell, J. S., Barlaz, M. A. (2013). Decomposition of Forest Products Buried in Landfills. *Waste Management*, 33 (11), 2267-2276.
- Wang, X., Padgett, J.M., De la Cruz, F.B., and Barlaz, M.A. (2011). Wood Biodegradation in Laboratory-Scale Landfills. *Environmental Science & Technology*, 2011 (45), 6864-6871.

Warith, M. A., Zekry, M., & Gawri, N. (1999). Effect of leachate recirculation on municipal solid waste biodegradation." *Water Quality Research Journal of Canada*, 34 (2), pp. 267–280.

7 ENERGY IMPACTS

Other chapters in EPA's Waste Reduction Model (WARM) focus on the effects of materials management decisions on greenhouse gases (GHG). Generally, a large portion of GHG emissions is related to energy use in resource acquisition, manufacturing, transportation, and end-of-life life-cycle stages. Not all GHG emissions are related to energy, however, and the effects of GHG are not directly translatable to energy impacts. One of the benefits of WARM is to help users see results in terms of both GHG (metric tons of carbon dioxide equivalent or carbon equivalent) and energy (millions of Btu). For background, see the [WARM Background and Overview](#) chapter.

The energy effects of materials occur in each life-cycle stage—source reduction, recycling and reuse, manufacturing—and knowledge of those effects can reduce the demand for raw materials and energy. Energy savings can also result from some waste disposal practices, including waste-to-energy combustors and landfill gas-to-energy systems.

To better understand the relationship between materials management and energy use, WARM provides energy factors for five management scenarios (source reduction, recycling, combustion, landfilling, and anaerobic digestion). This chapter discusses how these energy factors affect the relationship between energy savings and GHG benefits.

7.1 METHODOLOGY FOR DEVELOPING ENERGY FACTORS

The WARM methodology described in the other chapters is similar; the methodology in this chapter focuses on all life-cycle components as they appear through the lens of energy consumption or savings, rather than GHG emissions. Components such as forest carbon storage and landfill carbon sequestration are not components in the energy life cycle, and thus we have not included them as energy factors. We base energy factors primarily on the amount of energy required to produce one ton of a given material. The total energy consumed is a result of direct fuel and electricity consumption associated with raw material acquisition and manufacturing, fuel consumption for transportation, and embedded energy. The other WARM chapters on specific materials describe the energy required for processing and transporting virgin and recycled materials. Although the GHG emission factors are a product of the electricity fuel mix and the carbon coefficients of fuels, our methodology in this chapter is based only on energy consumption; therefore, the energy required for the total process to make one ton of a particular material is the sum of energy consumed across all fuel types.

The total energy, or embodied energy, required to manufacture each material comprises two components: (1) process and transportation energy, and (2) embedded energy (i.e., energy content of the raw material). The first component, to process and transport a material, is conceptually straightforward; but the second component, embedded energy, is more complex. Embedded energy is the energy inherently contained in the raw materials used to manufacture a product. For example, the embedded energy of plastics comes from the petroleum needed to make them. Because petroleum has an inherent energy value, the amount of energy that is saved through plastic recycling and source reduction is directly related to the energy that could have been produced if the petroleum had been used as an energy source rather than as a raw material input. Another example is aluminum, which includes an embedded energy component. The aluminum smelting process requires a carbon anode, which is consumed during the electrolytic reduction process; carbon anodes are made from coal, itself an energy source. Additional examples are carpet and personal computers that contain embedded energy in their plastic (carpet, computers) and aluminum (computers only) components. Total energy values also include both nonrenewable and renewable sources. For example, some aspects of the paper life-cycle include renewable fuel sources that have little effect on GHG emissions.

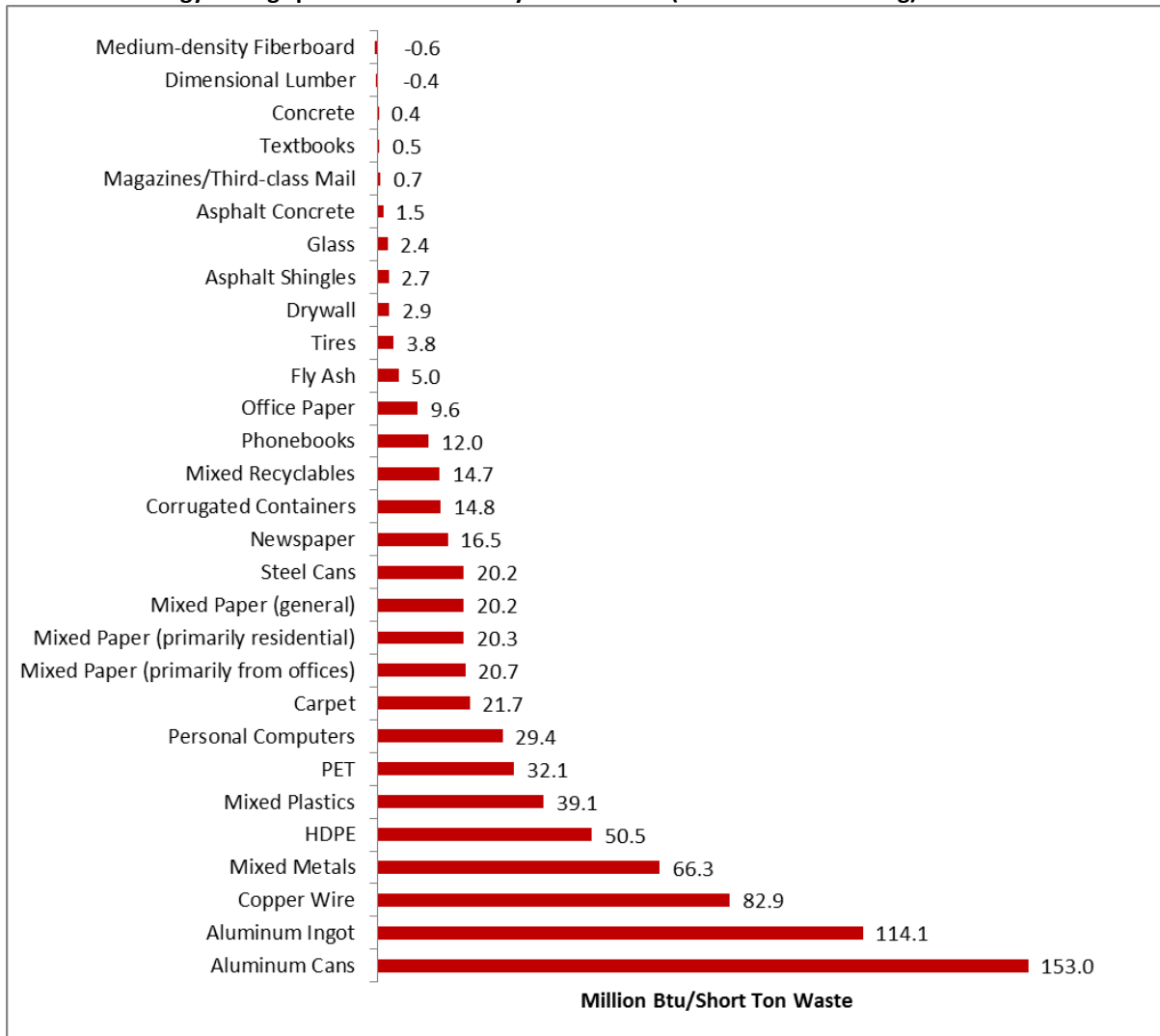
7.2 ENERGY IMPLICATIONS FOR WASTE MANAGEMENT OPTIONS

This chapter discusses the life-cycle energy implications for four management scenarios. As with the GHG emission factors discussed in other chapters, negative values indicate net energy savings.

Waste reduction efforts, such as source reduction and recycling, can result in significant energy savings. Source reduction techniques, such as double-sided copying, reducing the weight of products (light-weighting), and reducing generation of food waste are, in most cases, more effective at reducing energy than recycling because source reduction significantly lowers energy consumption associated with raw material extraction and manufacturing processes.

In relating recycling to landfill disposal, the greatest energy savings per ton come from aluminum cans, as shown in Exhibit 7-1. The savings reflect the nature of aluminum production—manufacturing aluminum cans from virgin inputs is very energy intensive, whereas relatively little energy is required to manufacture cans from recycled aluminum. Significant energy savings also result from recycling carpet because the recycled material can be used to produce secondary goods, and thus avoiding the energy-intensive processes required to manufacture those secondary goods.

Exhibit 7-1: Energy Savings per Short Ton of Recycled Material (Relative to Landfilling)



Note: Positive numbers indicate energy savings from recycling; negative numbers indicate that additional energy is required, compared to landfilling. This figure excludes materials in WARM for which recycling is not a viable end-of-life management option.

Some materials, such as dimensional lumber and medium-density fiberboard, actually consume more energy when they are made from recycled inputs. For those materials, the recovery and processing of recycled material is more energy intensive than making the material from virgin inputs. Although those materials may not provide an energy benefit from recycling from the perspective of GHG emissions, recycling them is still beneficial. For more information on this topic, see Section 7.4.

7.3 APPLYING ENERGY FACTORS

Fuels and energy are limited and expensive resources, and it is increasingly important to examine the effects of waste management practices on energy. Organizations can use the energy factors presented in Exhibit 7-6 through **Error! Reference source not found.** to quantify energy savings associated with waste management practices. Organizations can use these comparisons to weigh the benefits of switching from landfilling to another waste management option. For example, researchers used the comparisons to evaluate the benefits of voluntary programs aimed at source reduction and recycling, such as EPA’s WasteWise and Pay-as-You-Throw programs. Additional information about the methodology of deriving and applying these factors is available in the chapters on individual materials.

To apply the WARM energy factors, two scenarios are necessary: (1) a baseline scenario that represents current management practices (e.g., disposing of one ton of steel cans in a landfill), and (2) an alternative scenario that represents the alternative management practice (e.g., recycling a ton of steel cans).³⁵ With these scenarios, it is possible to calculate the amount of energy consumed or avoided in the baseline and alternative management practices and then to calculate the difference between the alternative scenario and the baseline scenario. The result represents the energy consumed or avoided that is attributable to the alternative management scenario.

Exhibit 7-2 illustrates the application of these factors. The baseline management scenario in the example uses disposal in a landfill that has national average conditions. The Btu number represents the amount of energy required to transport and process the ton. The alternate scenario is based on recycling the ton of cans. The difference, shown as a negative number, indicates that recycling one ton of steel cans rather than landfilling them reduces the energy consumed by 20.23 million Btu.

Exhibit 7-2: Comparison of Waste Reduction Scenarios

| | |
|--|---|
| Baseline: landfill 1 ton of steel cans | 1 ton x 0.27 million Btu/ton = 0.27 million Btu |
| Alternate: recycle 1 ton of steel cans | 1 ton x -19.97 million Btu/ton = -19.97 million Btu |
| Energy Impacts: -19.97 million Btu - 0.53 million Btu = - 20.23 million Btu | |

Note: Negative numbers indicate avoided emissions or energy savings.

7.4 RELATING ENERGY SAVINGS TO GHG BENEFITS

Because it can be difficult to conceptualize energy savings in Btu and GHG emissions reductions in metric ton carbon dioxide equivalent (MTCO2E), the common way to express the amount, the results can be converted to common equivalents such as barrels of crude oil or gallons of gasoline, as shown in Exhibit 7-3. These interpreted results produce important nuances, particularly when applied to convert MTCO2E savings to equivalent energy savings. The conversion is complicated for two reasons: (1) GHG reductions reflect both energy and non-energy savings, and (2) the energy savings reflect savings across a range of fossil fuels. Thus, conversions from total GHG reductions to an equivalency for barrels of oil must be done with caution.

³⁵ The energy factors are expressed in terms of million Btu of energy per short ton of material managed. In the case of recycling, EPA defines one ton of material managed as one ton *collected* for recycling.

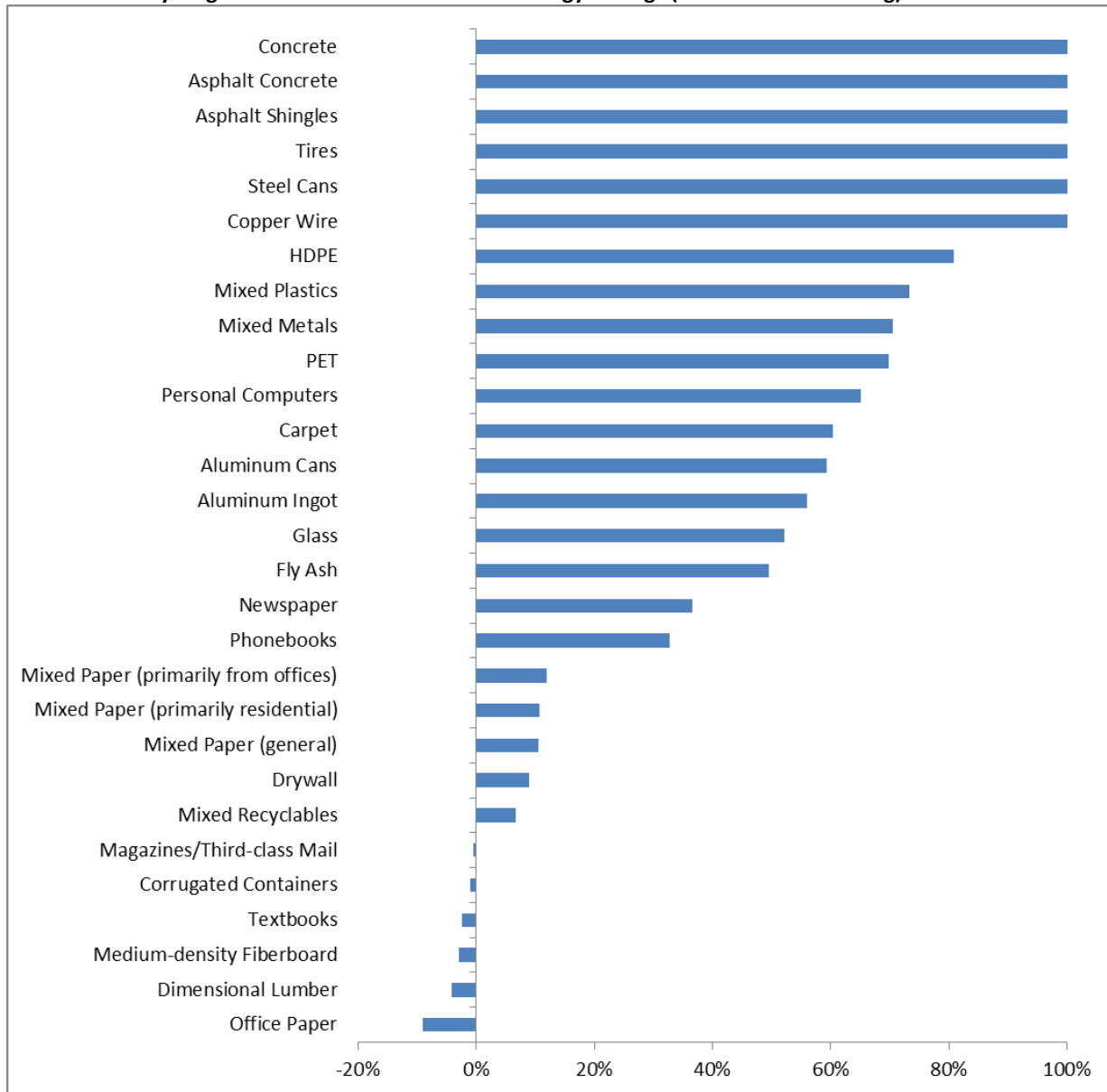
Exhibit 7-3: Common Energy Conversion Factors and Emissions Equivalencies

| Common Energy Conversion Factors | Emissions Equivalencies |
|---|--|
| <p>Fuel:</p> <ul style="list-style-type: none"> • Million Btu per Barrel of Oil: 5.8 • Gallons per Barrel of Oil: 42 • Million Btu per Gallon of Gasoline: 0.124 <p>Cars (average passenger car over one year):</p> <ul style="list-style-type: none"> • Fuel Consumption (gallons of gas): 529 • Fuel Consumption (Million Btu/year): 66 <p>Household (average household per year):</p> <ul style="list-style-type: none"> • Million Btu per day: 0.32 <p>Source: EPA, 2014</p> | <p>Propane Cylinders Used for Home BBQs:</p> <ul style="list-style-type: none"> • CO₂ emissions per cylinder (metric tons): 0.024 <p>Railroad Cars Worth of Coal:</p> <ul style="list-style-type: none"> • CO₂ emissions per Railcar (metric tons): 186.5 <p>Cars (average passenger car over one year):</p> <ul style="list-style-type: none"> • CO₂ Emissions (metric tons): 4.8 <p>Source: EPA, 2014</p> |

Although energy savings are often associated with GHG emissions savings, it is inaccurate to directly convert overall GHG emission benefits into energy savings equivalents. Equivalencies must remain consistent within the energy category or the GHG emission context in which they were created. Exhibit 7-4 illustrates GHG benefits derived from energy savings achieved through recycling relative to landfilling. For example, for asphalt shingles, 100 percent of the GHG savings associated with recycling rather than landfilling are energy-related, whereas for glass, only about half of the GHG savings are energy-related. Because the GHG benefits of glass recycling consist of some energy and some non-energy-related savings, this material type demonstrates the difficulties of converting GHG savings to energy equivalents.³⁶

³⁶ The percentage of emissions savings derived from energy is negative for some paper and wood products because the entire comparative benefit of recycling over landfilling for these materials results from non-energy factors, such as forest carbon storage and landfill carbon sequestration. For more information, see the [Forest Carbon Storage](#) and [Landfilling](#) chapters.

Exhibit 7-4: Recycling GHG Benefits Attributable to Energy Savings (Relative to Landfilling)



Note: Positive numbers indicate GHG benefits attributable to energy savings from recycling; negative numbers indicate that additional energy GHG emissions result from energy required for recycling, compared to landfilling. This figure excludes materials in WARM for which recycling is not a viable end-of-life management option.

Exhibit 7-5 shows how energy savings and GHG savings can differ for a single scenario. The example is for total derived GHG benefits from recycling glass and the conversion of energy savings is to barrels of oil. Using the common equivalency factors, the GHG emission benefits are equivalent to GHG emissions from the combustion of 70 barrels of oil. In contrast, the energy savings associated with recycling glass are equivalent to the energy content of 41 barrels of oil.

Exhibit 7-5: Comparison of Emissions and Energy Benefits from Recycling

| Recycling 100 Short Tons of Glass Compared to Landfilling | |
|--|---|
| GHG Emission Benefits: 30 MTCO ₂ E | Equivalent to the combustion emissions from 70 barrels of oil. |
| Energy Savings: 239 Million Btu | Equivalent to the energy contained in 41 barrels of oil. |

The difference between the benefits and the conversions has important implications. The term “energy savings” covers a diverse mix of fuels (petroleum, electricity, natural gas, coal). In reality, glass manufacturing depends mainly on energy produced from electricity, coal, and natural gas, not from petroleum. The equivalency, stated as “barrels of oil,” is only a simplified and recognizable energy equivalent; little or no petroleum is actually saved.

Exhibit 7-6, Exhibit 7-7, Exhibit 7-8, Exhibit 7-9, Exhibit 7-10, and Exhibit 7-11 show the components of the energy impact factors for source reduction, recycling, combustion, composting, anaerobic digestion, and landfilling, respectively. Exhibit 7-12 shows the net energy impacts of the six materials management options.

Exhibit 7-6: Energy Impacts for Source Reduction (Million Btu/Ton of Material Source Reduced)

| (a) Material | (b) Raw Materials Acquisition and Manufacturing Process Energy | | (c) Raw Materials Acquisition and Manufacturing Transport Energy | | (d) Net Energy (d = b + c) | |
|--------------------------------------|---|------------------------------|---|------------------------------|---|------------------------------|
| | Displace Current Mix of Virgin and Recycled Inputs | Displace Virgin Inputs | Displace Current Mix of Virgin and Recycled Inputs | Displace Virgin Inputs | Displace Current Mix of Virgin and Recycled Inputs | Displace Virgin Inputs |
| Aluminum Cans | -88.74 | -199.30 | -0.95 | -1.27 | -89.69 | -200.57 |
| Aluminum Ingot | -126.03 | -126.03 | -0.92 | -0.92 | -126.95 | -126.95 |
| Steel Cans | -25.11 | -31.58 | -4.78 | -4.96 | -29.88 | -36.54 |
| Copper Wire | -121.45 | -122.52 | -0.91 | -0.82 | -122.36 | -123.35 |
| Glass | -5.99 | -6.49 | -0.91 | -0.97 | -6.90 | -7.46 |
| HDPE | -57.98 | -63.80 | -3.24 | -3.28 | -61.21 | -67.08 |
| LDPE | -67.69 | -67.69 | -3.33 | -3.33 | -71.02 | -71.02 |
| PET | -48.67 | -49.79 | -1.59 | -1.54 | -50.26 | -51.33 |
| LLDPE | -63.06 | -63.06 | -3.31 | -3.31 | -66.37 | -66.37 |
| PP | -63.69 | -63.69 | -2.90 | -2.90 | -66.59 | -66.59 |
| PS | -72.09 | -72.09 | -2.90 | -2.90 | -74.99 | -74.99 |
| PVC | -46.34 | -46.34 | -2.00 | -2.00 | -48.34 | -48.34 |
| PLA | -29.99 | -29.99 | -0.71 | -0.71 | -30.69 | -30.69 |
| Corrugated Containers | -20.45 | -25.13 | -1.87 | -2.05 | -22.32 | -27.18 |
| Magazines/Third-class Mail | -32.95 | -32.99 | -0.28 | -0.28 | -33.23 | -33.27 |
| Newspaper | -35.80 | -39.92 | -0.67 | -0.78 | -36.46 | -40.70 |
| Office Paper | -36.32 | -37.01 | -0.28 | -0.28 | -36.60 | -37.29 |
| Phonebooks | -39.61 | -39.61 | -0.59 | -0.59 | -40.20 | -40.20 |
| Textbooks | -35.01 | -35.07 | -0.59 | -0.59 | -35.60 | -35.66 |
| Dimensional Lumber | -2.53 | -2.53 | -1.15 | -1.15 | -3.67 | -3.67 |
| Medium-density Fiberboard | -10.18 | -10.18 | -1.74 | -1.74 | -11.92 | -11.92 |
| Food Waste | -12.81 | -12.81 | -1.75 | -1.75 | -14.56 | -14.56 |
| Food Waste (meat only) | -40.86 | -40.86 | -2.74 | -2.74 | -43.60 | -43.60 |
| Food Waste (non-meat) | -5.71 | -5.71 | -1.50 | -1.50 | -7.20 | -7.20 |
| Beef | -62.25 | -62.25 | -1.63 | -1.63 | -63.88 | -63.88 |
| Poultry | -22.80 | -22.80 | -3.68 | -3.68 | -26.48 | -26.48 |
| Grains | -5.35 | -5.35 | -0.29 | -0.29 | -5.64 | -5.64 |
| Bread | -6.34 | -6.34 | -0.18 | -0.18 | -6.52 | -6.52 |
| Fruits and Vegetables | -2.95 | -2.95 | -2.12 | -2.12 | -5.07 | -5.07 |
| Dairy Products | -13.61 | -13.61 | -0.65 | -0.65 | -14.27 | -14.27 |
| Yard Trimmings | NA | NA | NA | NA | NA | NA |
| Grass | NA | NA | NA | NA | NA | NA |
| Leaves | NA | NA | NA | NA | NA | NA |
| Branches | NA | NA | NA | NA | NA | NA |
| Mixed Paper | | | | | | |
| Mixed Paper (general) | -28.31 | -31.68 | -1.14 | -1.25 | -29.44 | -32.93 |
| Mixed Paper (primarily residential) | -27.45 | -30.98 | -1.21 | -1.33 | -28.66 | -32.31 |
| Mixed Paper (primarily from offices) | -34.20 | -35.58 | -0.44 | -0.47 | -34.64 | -36.05 |
| Mixed Metals | -47.16 | -84.66 | -3.45 | -3.68 | -50.61 | -93.38 |
| Mixed Plastics | -52.20 | -26.78 | -2.21 | -2.20 | -54.42 | -57.31 |
| Mixed Recyclables | NA | NA | NA | NA | NA | NA |
| Mixed Organics | NA | NA | NA | NA | NA | NA |
| Mixed MSW | NA | NA | NA | NA | NA | NA |
| Carpet | -89.70 | -89.70 | -1.36 | -1.36 | -91.06 | -91.06 |
| Personal Computers | -951.71 | -951.71 | -5.03 | -5.03 | -956.74 | -956.74 |

| (a) Material | (b) Raw Materials Acquisition and Manufacturing Process Energy | | (c) Raw Materials Acquisition and Manufacturing Transport Energy | | (d) Net Energy (d = b + c) | |
|-----------------------|---|---------------------------|---|------------------------------|---|------------------------------|
| | Displace Current Mix of Virgin and Recycled Inputs | Displace Virgin Inputs | Displace Current Mix of Virgin and Recycled Inputs | Displace Virgin Inputs | Displace Current Mix of Virgin and Recycled Inputs | Displace Virgin Inputs |
| Clay Bricks | -5.10 | -5.10 | -0.03 | -0.03 | -5.13 | -5.13 |
| Concrete | NA | NA | NA | NA | NA | NA |
| Fly Ash | NA | NA | NA | NA | NA | NA |
| Tires | -71.14 | -73.79 | -0.57 | -0.54 | -71.71 | -74.33 |
| Asphalt Concrete | -0.94 | -0.94 | -0.73 | -0.73 | -1.68 | -1.68 |
| Asphalt Shingles | -2.17 | -2.17 | -0.93 | -0.96 | -3.13 | -3.13 |
| Drywall | -3.08 | -3.08 | -0.48 | -0.48 | -3.56 | -3.56 |
| Fiberglass Insulation | -3.96 | -4.74 | -0.77 | -0.83 | -4.73 | -5.56 |
| Vinyl Flooring | -9.47 | -9.47 | -1.26 | -1.26 | -10.73 | -10.73 |
| Wood Flooring | -13.05 | -13.05 | -1.40 | -1.40 | -14.45 | -14.45 |

Note: Negative numbers = Energy savings. NA = Not applicable.

Exhibit 7-7: Energy Impacts for Recycling (Million Btu/Ton of Material Recycled)

| Material | Recycled Input Credit Process Energy | Recycled Input Credit Transportation Energy | Net Energy (Post-Consumer) |
|--------------------------------------|---|--|-------------------------------|
| Aluminum Cans | -152.32 | -0.44 | -152.76 |
| Aluminum Ingot | -113.53 | -0.32 | -113.85 |
| Steel Cans | -19.40 | -0.56 | -19.97 |
| Copper Wire | -81.64 | -0.95 | -82.59 |
| Glass | -1.91 | -0.21 | -2.13 |
| HDPE | -49.83 | -0.37 | -50.20 |
| LDPE | NA | NA | NA |
| PET | -33.30 | 1.42 | -31.87 |
| LLDPE | NA | NA | NA |
| PP | NA | NA | NA |
| PS | NA | NA | NA |
| PVC | NA | NA | NA |
| PLA | NA | NA | NA |
| Corrugated Containers | -14.35 | -0.73 | -15.07 |
| Magazines/Third-class Mail | -0.69 | 0.00 | -0.69 |
| Newspaper | -16.07 | -0.42 | -16.49 |
| Office Paper | -10.08 | 0.00 | -10.08 |
| Phonebooks | -11.93 | 0.00 | -11.93 |
| Textbooks | -1.03 | 0.00 | -1.03 |
| Dimensional Lumber | 0.52 | 0.07 | 0.59 |
| Medium-density Fiberboard | 0.65 | 0.21 | 0.86 |
| Food Waste | NA | NA | NA |
| Food Waste (meat only) | NA | NA | NA |
| Food Waste (non-meat) | NA | NA | NA |
| Beef | NA | NA | NA |
| Poultry | NA | NA | NA |
| Grains | NA | NA | NA |
| Bread | NA | NA | NA |
| Fruits and Vegetables | NA | NA | NA |
| Dairy Products | NA | NA | NA |
| Yard Trimmings | NA | NA | NA |
| Grass | NA | NA | NA |
| Leaves | NA | NA | NA |
| Branches | NA | NA | NA |
| Mixed Paper (general) | -19.02 | -1.43 | -20.45 |
| Mixed Paper (primarily residential) | -19.02 | -1.43 | -20.45 |
| Mixed Paper (primarily from offices) | -19.39 | -1.46 | -20.85 |
| Mixed Metals | -65.47 | -0.52 | -65.99 |
| Mixed Plastics | -39.58 | 0.74 | -38.84 |
| Mixed Recyclables | -14.38 | -0.45 | -14.82 |
| Mixed Organics | NA | NA | NA |
| Mixed MSW | NA | NA | NA |
| Carpet | -21.84 | 0.36 | -21.47 |
| Personal Computers | -29.52 | -0.51 | -30.03 |
| Clay Bricks | NA | NA | NA |
| Concrete | -0.01 | -0.09 | -0.11 |
| Fly Ash | -4.77 | 0.00 | -4.77 |
| Tires | -4.95 | 1.39 | -3.56 |
| Asphalt Concrete | -0.53 | -0.69 | -1.22 |
| Asphalt Shingles | -1.98 | -0.45 | -2.43 |
| Drywall | -2.13 | -0.49 | -2.62 |
| Fiberglass Insulation | NA | NA | NA |
| Vinyl Flooring | NA | NA | NA |

| Material | Recycled Input Credit Process Energy | Recycled Input Credit Transportation Energy | Net Energy (Post-Consumer) |
|-----------------|---|--|---------------------------------------|
| Wood Flooring | NA | NA | NA |

Note: Negative energy impacts = Energy savings. NA = Not applicable.

Exhibit 7-8: Energy Impacts for Combustion (Million Btu/Ton of Material Combusted)

| Material | Electric Utility Fuel Consumption | Energy Impacts due to Steel Recovery | Transportation to Combustion Facility | Net Energy (Post-Consumer) |
|--------------------------------------|-----------------------------------|--------------------------------------|---------------------------------------|----------------------------|
| Aluminum Cans | 0.33 | NA | 0.27 | 0.60 |
| Aluminum Ingot | 0.33 | NA | 0.27 | 0.60 |
| Steel Cans | 0.21 | -17.61 | 0.27 | -17.14 |
| Copper Wire | 0.27 | NA | 0.27 | 0.54 |
| Glass | 0.23 | NA | 0.27 | 0.50 |
| HDPE | -20.00 | NA | 0.27 | -19.34 |
| LDPE | -19.89 | NA | 0.27 | -19.24 |
| PET | -10.61 | NA | 0.27 | -10.13 |
| LLDPE | -19.57 | NA | 0.27 | -19.30 |
| PP | -19.57 | NA | 0.27 | -19.31 |
| PS | -17.66 | NA | 0.27 | -17.40 |
| PVC | -7.73 | NA | 0.27 | -7.46 |
| PLA | -8.21 | NA | 0.27 | -7.94 |
| Corrugated Containers | -6.91 | NA | 0.27 | -6.64 |
| Magazines/Third-class Mail | -5.16 | NA | 0.27 | -4.89 |
| Newspaper | -7.80 | NA | 0.27 | -7.53 |
| Office Paper | -6.67 | NA | 0.27 | -6.40 |
| Phonebooks | -7.80 | NA | 0.27 | -7.53 |
| Textbooks | -6.67 | NA | 0.27 | -6.40 |
| Dimensional Lumber | -8.14 | NA | 0.27 | -7.88 |
| Medium-density Fiberboard | -8.14 | NA | 0.27 | -7.88 |
| Food Waste | -2.33 | NA | 0.27 | -2.06 |
| Food Waste (meat only) | -2.33 | NA | 0.27 | -2.06 |
| Food Waste (non-meat) | -2.33 | NA | 0.27 | -2.06 |
| Beef | -2.33 | NA | 0.27 | -2.06 |
| Poultry | -2.33 | NA | 0.27 | -2.06 |
| Grains | -2.33 | NA | 0.27 | -2.06 |
| Bread | -2.33 | NA | 0.27 | -2.06 |
| Fruits and Vegetables | -2.33 | NA | 0.27 | -2.06 |
| Dairy Products | -2.33 | NA | 0.27 | -2.06 |
| Yard Trimmings | -2.75 | NA | 0.27 | -2.48 |
| Grass | -2.75 | NA | 0.27 | -2.48 |
| Leaves | -2.75 | NA | 0.27 | -2.48 |
| Branches | -2.75 | NA | 0.27 | -2.48 |
| Mixed Paper (general) | -6.94 | NA | 0.27 | -6.67 |
| Mixed Paper (primarily residential) | -6.91 | NA | 0.27 | -6.64 |
| Mixed Paper (primarily from offices) | -6.38 | NA | 0.27 | -6.11 |
| Mixed Metals | 0.25 | -11.51 | 0.27 | -10.99 |
| Mixed Plastics | -13.90 | NA | 0.27 | -13.63 |
| Mixed Recyclables | -6.38 | -0.47 | 0.27 | -6.58 |
| Mixed Organics | -2.53 | NA | 0.27 | -2.26 |
| Mixed MSW | -4.91 | NA | 0.27 | -4.64 |
| Carpet | -7.46 | NA | 0.27 | -7.19 |
| Personal Computers | -1.50 | -5.04 | 0.27 | -6.27 |
| Clay Bricks | NA | NA | NA | NA |
| Concrete | NA | NA | NA | NA |
| Fly Ash | NA | NA | NA | NA |
| Tires | -27.78 | -1.01 | 0.27 | -28.52 |
| Asphalt Concrete | NA | NA | NA | NA |
| Asphalt Shingles | -8.80 | NA | 0.27 | -8.53 |
| Drywall | NA | NA | NA | NA |
| Fiberglass Insulation | NA | NA | NA | NA |
| Vinyl Flooring | -7.73 | NA | 0.27 | -7.46 |

| Material | Electric Utility Fuel Consumption | Energy Impacts due to Steel Recovery | Transportation to Combustion Facility | Net Energy (Post-Consumer) |
|-----------------|--|---|--|-----------------------------------|
| Wood Flooring | -10.66 | NA | 0.27 | -10.39 |

Note: Negative energy impacts = Energy savings. NA = Not applicable.

Exhibit 7-9: Energy Impacts for Composting (Million Btu/Ton of Material Composted)

| Material | Transportation Energy (Post-Consumer) |
|--------------------------------------|--|
| Aluminum Cans | NA |
| Aluminum Ingot | NA |
| Steel Cans | NA |
| Copper Wire | NA |
| Glass | NA |
| HDPE | NA |
| LDPE | NA |
| PET | NA |
| LLDPE | NA |
| PP | NA |
| PS | NA |
| PVC | NA |
| PLA | 0.58 |
| Corrugated Containers | NA |
| Magazines/Third-class Mail | NA |
| Newspaper | NA |
| Office Paper | NA |
| Phonebooks | NA |
| Textbooks | NA |
| Dimensional Lumber | NA |
| Medium-density Fiberboard | NA |
| Food Waste | 0.58 |
| Food Waste (meat only) | 0.58 |
| Food Waste (non-meat) | 0.58 |
| Beef | 0.58 |
| Poultry | 0.58 |
| Grains | 0.58 |
| Bread | 0.58 |
| Fruits and Vegetables | 0.58 |
| Dairy Products | 0.58 |
| Yard Trimmings | 0.58 |
| Grass | 0.58 |
| Leaves | 0.58 |
| Branches | 0.58 |
| Mixed Paper (general) | NA |
| Mixed Paper (primarily residential) | NA |
| Mixed Paper (primarily from offices) | NA |
| Mixed Metals | NA |
| Mixed Plastics | NA |
| Mixed Recyclables | NA |
| Mixed Organics | 0.58 |
| Mixed MSW | NA |
| Carpet | NA |
| Personal Computers | NA |
| Clay Bricks | NA |
| Concrete | NA |
| Fly Ash | NA |
| Tires | NA |
| Asphalt Concrete | NA |
| Asphalt Shingles | NA |
| Drywall | NA |
| Fiberglass Insulation | NA |
| Vinyl Flooring | NA |

| Material | Transportation Energy (Post-Consumer) |
|-----------------|--|
| Wood Flooring | NA |

Note: Negative energy impacts = Energy savings. NA = Not applicable.

Exhibit 7-10: Energy Impacts for Anaerobic Digestion (Million Btu/Ton of Material Digested)

| Material | Process Energy | Transportation Energy to Digester | Avoided Utility Energy | Net Energy (Post-Consumer) |
|--------------------------------------|----------------|-----------------------------------|------------------------|----------------------------|
| Aluminum Cans | NA | NA | NA | NA |
| Aluminum Ingot | NA | NA | NA | NA |
| Steel Cans | NA | NA | NA | NA |
| Copper Wire | NA | NA | NA | NA |
| Glass | NA | NA | NA | NA |
| HDPE | NA | NA | NA | NA |
| LDPE | NA | NA | NA | NA |
| PET | NA | NA | NA | NA |
| LLDPE | NA | NA | NA | NA |
| PP | NA | NA | NA | NA |
| PS | NA | NA | NA | NA |
| PVC | NA | NA | NA | NA |
| PLA | NA | NA | NA | NA |
| Corrugated Containers | NA | NA | NA | NA |
| Magazines/Third-class Mail | NA | NA | NA | NA |
| Newspaper | NA | NA | NA | NA |
| Office Paper | NA | NA | NA | NA |
| Phonebooks | NA | NA | NA | NA |
| Textbooks | NA | NA | NA | NA |
| Dimensional Lumber | NA | NA | NA | NA |
| Medium-density Fiberboard | NA | NA | NA | NA |
| Food Waste | 0.26 | 0.04 | -1.83 | -1.52 |
| Food Waste (meat only) | 0.26 | 0.04 | -1.83 | -1.52 |
| Food Waste (non-meat) | 0.26 | 0.04 | -1.83 | -1.52 |
| Beef | 0.26 | 0.04 | -1.83 | -1.52 |
| Poultry | 0.26 | 0.04 | -1.83 | -1.52 |
| Grains | 0.26 | 0.04 | -1.83 | -1.52 |
| Bread | 0.26 | 0.04 | -1.83 | -1.52 |
| Fruits and Vegetables | 0.26 | 0.04 | -1.83 | -1.52 |
| Dairy Products | 0.26 | 0.04 | -1.83 | -1.52 |
| Yard Trimmings | 0.29 | 0.04 | -0.52 | -0.19 |
| Grass | 0.26 | 0.04 | -0.50 | -0.20 |
| Leaves | 0.31 | 0.04 | -0.29 | 0.06 |
| Branches | 0.32 | 0.04 | -0.78 | -0.41 |
| Mixed Paper (general) | NA | NA | NA | NA |
| Mixed Paper (primarily residential) | NA | NA | NA | NA |
| Mixed Paper (primarily from offices) | NA | NA | NA | NA |
| Mixed Metals | NA | NA | NA | NA |
| Mixed Plastics | NA | NA | NA | NA |
| Mixed Recyclables | NA | NA | NA | NA |
| Mixed Organics | 0.27 | 0.04 | -1.20 | -0.88 |
| Mixed MSW | NA | NA | NA | NA |
| Carpet | NA | NA | NA | NA |
| Personal Computers | NA | NA | NA | NA |
| Clay Bricks | NA | NA | NA | NA |
| Concrete | NA | NA | NA | NA |
| Fly Ash | NA | NA | NA | NA |
| Tires | NA | NA | NA | NA |
| Asphalt Concrete | NA | NA | NA | NA |
| Asphalt Shingles | NA | NA | NA | NA |
| Drywall | NA | NA | NA | NA |
| Fiberglass Insulation | NA | NA | NA | NA |
| Vinyl Flooring | NA | NA | NA | NA |

| Material | Process Energy | Transportation Energy to Digester | Avoided Utility Energy | Net Energy (Post-Consumer) |
|-----------------|-----------------------|--|-----------------------------------|---------------------------------------|
| Wood Flooring | NA | NA | NA | NA |

Note: Negative energy impacts = Energy savings. NA = Not applicable.

Assumes dry digestion with digestate curing and national average utility grid mix.

Exhibit 7-11: Energy Impacts for Landfilling (Million Btu/Ton of Material Landfilled)

| Material | Transportation to Landfill | Electric Utility Fuel Consumption | Net Energy (Post-Consumer) |
|--------------------------------------|-----------------------------------|--|-----------------------------------|
| Aluminum Cans | 0.27 | NA | 0.27 |
| Aluminum Ingot | 0.27 | NA | 0.27 |
| Steel Cans | 0.27 | NA | 0.27 |
| Copper Wire | 0.27 | NA | 0.27 |
| Glass | 0.27 | NA | 0.27 |
| HDPE | 0.27 | NA | 0.27 |
| LDPE | 0.27 | NA | 0.27 |
| PET | 0.27 | NA | 0.27 |
| LLDPE | 0.27 | NA | 0.27 |
| PP | 0.27 | NA | 0.27 |
| PS | 0.27 | NA | 0.27 |
| PVC | 0.27 | NA | 0.27 |
| PLA | 0.27 | NA | 0.27 |
| Corrugated Containers | 0.27 | -0.51 | -0.25 |
| Magazines/Third-class Mail | 0.27 | -0.22 | 0.04 |
| Newspaper | 0.27 | -0.22 | 0.05 |
| Office Paper | 0.27 | -0.79 | -0.53 |
| Phonebooks | 0.27 | -0.22 | 0.05 |
| Textbooks | 0.27 | -0.79 | -0.53 |
| Dimensional Lumber | 0.27 | -0.03 | 0.23 |
| Medium-density Fiberboard | 0.27 | -0.01 | 0.26 |
| Food Waste | 0.27 | -0.29 | -0.02 |
| Food Waste (meat only) | 0.27 | -0.29 | -0.02 |
| Food Waste (non-meat) | 0.27 | -0.29 | -0.02 |
| Beef | 0.27 | -0.29 | -0.02 |
| Poultry | 0.27 | -0.29 | -0.02 |
| Grains | 0.27 | -0.29 | -0.02 |
| Bread | 0.27 | -0.29 | -0.02 |
| Fruits and Vegetables | 0.27 | -0.29 | -0.02 |
| Dairy Products | 0.27 | -0.29 | -0.02 |
| Yard Trimmings | 0.27 | -0.13 | 0.14 |
| Grass | 0.27 | -0.08 | 0.19 |
| Leaves | 0.27 | -0.11 | 0.16 |
| Branches | 0.27 | -0.27 | -0.00 |
| Mixed Paper (general) | 0.27 | -0.48 | -0.21 |
| Mixed Paper (primarily residential) | 0.27 | -0.46 | -0.19 |
| Mixed Paper (primarily from offices) | 0.27 | -0.45 | -0.18 |
| Mixed Metals | 0.27 | NA | 0.27 |
| Mixed Plastics | 0.27 | NA | 0.27 |
| Mixed Recyclables | 0.27 | -0.34 | -0.07 |
| Mixed Organics | 0.27 | -0.21 | 0.06 |
| Mixed MSW | 0.27 | -0.34 | -0.07 |
| Carpet | 0.27 | NA | 0.27 |
| Personal Computers | 0.27 | NA | 0.27 |
| Clay Bricks | 0.27 | NA | 0.27 |
| Concrete | 0.27 | NA | 0.27 |
| Fly Ash | 0.27 | NA | 0.27 |
| Tires | 0.27 | NA | 0.27 |
| Asphalt Concrete | 0.27 | NA | 0.27 |
| Asphalt Shingles | 0.27 | NA | 0.27 |
| Drywall | 0.27 | NA | 0.27 |
| Fiberglass Insulation | 0.27 | NA | 0.27 |
| Vinyl Flooring | 0.27 | NA | 0.27 |

| Material | Transportation to Landfill | Electric Utility Fuel Consumption | Net Energy (Post-Consumer) |
|-----------------|-----------------------------------|--|-----------------------------------|
| Wood Flooring | 0.27 | NA | 0.27 |

Note: Negative energy impacts = Energy savings. NA = Not applicable.

Exhibit 7-12: Net Energy Impacts from Source Reduction and MSW Management Options (Million Btu/Ton)

| Material | Source Reduction for Current Mix of Inputs | Recycling | Combustion | Composting | Anaerobic Digestion | Landfilling |
|--------------------------------------|--|-----------|------------|------------|---------------------|-------------|
| Aluminum Cans | -89.69 | -152.76 | 0.60 | NA | NA | 0.27 |
| Aluminum Ingot | -126.95 | -113.85 | 0.60 | NA | NA | 0.27 |
| Steel Cans | -29.88 | -19.97 | -17.14 | NA | NA | 0.27 |
| Copper Wire | -122.36 | -82.59 | 0.54 | NA | NA | 0.27 |
| Glass | -6.90 | -2.13 | 0.50 | NA | NA | 0.27 |
| HDPE | -61.21 | -50.20 | -19.34 | NA | NA | 0.27 |
| LDPE | -71.02 | NA | -19.24 | NA | NA | 0.27 |
| PET | -50.26 | -31.87 | -10.13 | NA | NA | 0.27 |
| LLDPE | -66.37 | NA | -19.30 | NA | NA | 0.27 |
| PP | -66.59 | NA | -19.31 | NA | NA | 0.27 |
| PS | -74.99 | NA | -17.40 | NA | NA | 0.27 |
| PVC | -48.34 | NA | -7.46 | NA | NA | 0.27 |
| PLA | -30.69 | NA | -7.94 | 0.58 | NA | 0.27 |
| Corrugated Containers | -22.32 | -15.07 | -6.64 | NA | NA | -0.25 |
| Magazines/Third-class Mail | -33.23 | -0.69 | -4.89 | NA | NA | 0.04 |
| Newspaper | -36.46 | -16.49 | -7.53 | NA | NA | 0.05 |
| Office Paper | -36.60 | -10.08 | -6.40 | NA | NA | -0.53 |
| Phonebooks | -40.20 | -11.93 | -7.53 | NA | NA | 0.05 |
| Textbooks | -35.60 | -1.03 | -6.40 | NA | NA | -0.53 |
| Dimensional Lumber | -3.67 | 0.59 | -7.88 | NA | NA | 0.23 |
| Medium-density Fiberboard | -11.92 | 0.86 | -7.88 | NA | NA | 0.26 |
| Food Waste | -14.56 | NA | -2.06 | 0.58 | -1.52 | -0.02 |
| Food Waste (meat only) | -43.60 | NA | -2.06 | 0.58 | -1.52 | -0.02 |
| Food Waste (non-meat) | -7.20 | NA | -2.06 | 0.58 | -1.52 | -0.02 |
| Beef | -63.88 | NA | -2.06 | 0.58 | -1.52 | -0.02 |
| Poultry | -26.48 | NA | -2.06 | 0.58 | -1.52 | -0.02 |
| Grains | -5.64 | NA | -2.06 | 0.58 | -1.52 | -0.02 |
| Bread | -6.52 | NA | -2.06 | 0.58 | -1.52 | -0.02 |
| Fruits and Vegetables | -5.07 | NA | -2.06 | 0.58 | -1.52 | -0.02 |
| Dairy Products | -14.27 | NA | -2.06 | 0.58 | -1.52 | -0.02 |
| Yard Trimmings | NA | NA | -2.48 | 0.58 | -0.19 | 0.14 |
| Grass | NA | NA | -2.48 | 0.58 | -0.20 | 0.19 |
| Leaves | NA | NA | -2.48 | 0.58 | 0.06 | 0.16 |
| Branches | NA | NA | -2.48 | 0.58 | -0.41 | -0.00 |
| Mixed Paper (general) | -29.44 | -20.45 | -6.67 | NA | NA | -0.21 |
| Mixed Paper (primarily residential) | -28.66 | -20.45 | -6.64 | NA | NA | -0.19 |
| Mixed Paper (primarily from offices) | -34.64 | -20.85 | -6.11 | NA | NA | -0.18 |
| Mixed Metals | -50.61 | -65.99 | -10.99 | NA | NA | 0.27 |
| Mixed Plastics | -54.42 | -38.84 | -13.63 | NA | NA | 0.27 |
| Mixed Recyclables | NA | -14.82 | -6.58 | NA | NA | -0.07 |
| Mixed Organics | NA | NA | -2.26 | 0.58 | -0.88 | 0.06 |
| Mixed MSW | NA | NA | -4.64 | NA | NA | -0.07 |
| Carpet | -91.06 | -21.47 | -7.19 | NA | NA | 0.27 |
| Personal Computers | -956.74 | -30.03 | -6.27 | NA | NA | 0.27 |
| Clay Bricks | -5.13 | NA | NA | NA | NA | 0.27 |
| Concrete | NA | -0.11 | NA | NA | NA | 0.27 |
| Fly Ash | NA | -4.77 | NA | NA | NA | 0.27 |
| Tires | -71.71 | -3.56 | -28.52 | NA | NA | 0.27 |
| Asphalt Concrete | -1.68 | -1.22 | NA | NA | NA | 0.27 |
| Asphalt Shingles | -3.13 | -2.43 | -8.53 | NA | NA | 0.27 |
| Drywall | -3.56 | -2.62 | NA | NA | NA | 0.27 |

| Material | Source Reduction for Current Mix of Inputs | Recycling | Combustion | Composting | Anaerobic Digestion | Landfilling |
|-----------------------|---|------------------|-------------------|-------------------|----------------------------|--------------------|
| Fiberglass Insulation | -4.73 | NA | NA | NA | NA | 0.27 |
| Vinyl Flooring | -10.73 | NA | -7.46 | NA | NA | 0.27 |
| Wood Flooring | -14.45 | NA | -10.39 | NA | NA | 0.27 |

Note: Negative energy impacts = Energy savings. NA = Not applicable.

- = Zero impact.

7.5 REFERENCES

- EPA. (2014). Greenhouse Gas Equivalencies Calculator. U.S. Environmental Protection Agency, Washington, DC.
- FAL. (2002). Franklin Associates, "Energy and Greenhouse Gas Factors for Personal Computers." August 7, 2002.
- EPA. (2006). *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks*. U.S. Environmental Protection Agency (EPA).