Appendix N. Assessing Emissions from Waste-Derived Biogenic Feedstocks

Table of Contents

List of Tables

List of Figures

1. Introduction

This appendix describes various emissions pathways that result in biogenic CO_2 and CH_4 emissions from stationary sources that use waste-derived biogenic feedstocks, and illustrates how the framework could be adapted to derive assessment factors for these biogenic feedstocks. For the purposes of this appendix, the waste-derived biogenic feedstock can be defined as the portion of the biogenic waste material whose management results in point source emissions (i.e., stack emissions). For example, for MSW sent to a combustor, the biogenic feedstock is the entire biogenic fraction of the MSW sent to the combustor. For MSW sent to a landfill, the biogenic feedstock is the collected landfill gas—an amount representing less than the entire biogenic fraction of the landfilled MSW.

As discussed in this appendix, waste-derived biogenic feedstocks include the following:

- Landfill gas[1] generated through the decomposition of municipal solid waste (MSW) in a landfill;
- The biogenic fraction of MSW;
- Biogas generated from the decomposition of livestock waste,[2] biogenic MSW, and/or other food waste in an anaerobic digester;
- Livestock waste; and
- Biogas generated through the treatment of waste water, due to the anaerobic decomposition of biological materials.

The following emission pathways that result in biogenic CO_2 emissions from stationary sources using waste-derived biogenic feedstocks are evaluated:

- Combustion of landfill gas, through either a flare or combustion in an electric generating unit (EGU);
- Combustion of MSW;
- Combustion of biogas from an anaerobic digester used to manage livestock waste and/or food waste, through either a flare or combustion in an EGU;
- Combustion of livestock waste; and
- Combustion of biogas from an anaerobic digester used to manage wastewater and associated sludges.

This appendix is organized by the aforementioned emissions pathways. These selected pathways are not meant to represent an exhaustive list of all possible alternate fate pathways. Included in this appendix are illustrative methods for how the framework can be applied to waste-derived biogenic feedstocks used at stationary sources to assess net biogenic carbon-based contributions to the atmosphere using the example pathways described above. These illustrative methods are complemented with illustrations of biogenic assessment factor (*BAF*) values derived through application of the framework to the selected emission pathways.

In the context of stationary sources, greenhouse gas (GHG) emissions from waste-management options can be categorized into direct emissions and indirect emissions.[3] The illustrative framework applications in this appendix address point source biogenic CO_2 and CH_4 emissions from stationary sources using waste-derived feedstocks. Point source emissions of biogenic CO_2 occur as a result of combustion of landfill gas, biogas, MSW, or livestock waste. Combustion typically occurs

---

[1] Landfill gas and biogas consists of approximately 50% methane (CH_4) and 50% CO_2, with small percentages of other gases, such as volatile organic compounds (VOCs).
[2] In this appendix, "livestock waste" refers to eliminated products (e.g., manure, litter, urine) resulting from the digestive process by farm animals (e.g., cattle, sheep, goat, swine, poultry, equine animals, etc.) and associated biogenic materials managed as waste materials (e.g., bedding materials and uneaten animal feed).
[3] Indirect emissions refer to emissions released directly to the atmosphere, rather than through a stack or vent. Indirect emissions include uncollected GHGs (e.g., biogas) that are released to the atmosphere and collected GHGs (e.g., biogas) that are subsequently leaked to the atmosphere.

in a flare or in an EGU. In applications where landfill gas and biogas are combusted, combustion results in the destruction of CH_4 and the emission of CO_2. However, since combustion efficiency is less than 100%, not all CH_4 is destroyed, such that some uncombusted CH_4 is released as a point source emission. CH_4 has a significantly higher global warming potential (GWP) than CO_2.[4] As a result, destruction of CH_4 that would have been released to the atmosphere as an indirect emission in the absence of combustion results in a reduction of CO_2-equivalent (CO_2e) contribution to the atmosphere.

Indirect emissions of CH_4 and CO_2 occur at landfills, wastewater treatment facilities, and in livestock settings including housing, conveyances, uncovered lagoons storing livestock waste and/or food waste, and land application areas. Indirect emissions of CH_4 and CO_2 also have the potential to occur via other waste management techniques, including anaerobic digesters. Note that some waste management strategies may result in both direct and indirect GHG emissions (e.g., landfills, wastewater treatment facilities, and anaerobic digesters). Table N-1 summarizes different GHG emissions pathways related to the management of waste.

Table N-1. Waste Management GHG Emissions Pathways Considered.

Type of Waste	Waste Management Option	Biogenic Feedstock	Direct Emissions[1]	Indirect Emissions
MSW	Landfill	Landfill gas	CH_4 and CO_2 emissions from combustion of collected landfill gas (flare or EGU)	CH_4 and CO_2 emissions at the landfill cap, leaks in landfill gas header piping and wells, leachate collection sumps, and cracks or penetrations in the landfill surface or side slopes
Food waste	Aerobic digestion (composting)	Food waste	N/A	CO_2 emissions (oxidation from decomposition)[2]
MSW	MSW combustor	MSW	CO_2 emissions from combustion, typically in an EGU	CH_4 and CO_2 emissions from pretreatment handling practices

[4] Methane is a potent GHG, with a 100-year global warming potential (GWP) of 21 (IPCC, 1996). It should be noted that in the IPCC Fourth Assessment Report, the 100-year GWP of CH_4 was revised to 25 (IPCC, 2007). To comply with international reporting standards under the UNFCCC, official emission estimates reported by the United States use the IPCC Second Assessment Report GWP values (IPCC 1996). The United States will transition to using the revised GWPs beginning in 2015. In this framework, the GWP of 25 is used for the central examples within each section. The GWPs of 21 and 28 are used in the sensitivity analyses for each section.

Type of Waste	Waste Management Option	Biogenic Feedstock	Direct Emissions[1]	Indirect Emissions
Livestock waste	Housing, conveyances, storage in an open lagoon, pond, pit, or pile[3]	Biogas	N/A	CH_4 and CO_2 emissions from uncovered lagoon, pond, or pit
Livestock waste and/or food waste	Anaerobic digester	Biogas	CO_2 emissions from combustion of collected biogas (flare or EGU)	Potential for indirect CH_4 emissions from digester if not all CH_4 produced is captured; CH_4 emissions from digester effluent
Livestock waste	Aerobic digestion treated waste (e.g., handled as a solid or sprayed on a field)	Manure and litter	N/A	CO_2 emissions (oxidation from decomposition)
Livestock waste	Livestock waste combustor	Manure and litter	CO_2 emissions from combustion, often in an EGU; CH_4 emissions from incomplete combustion	CH_4 and CO_2 emissions from pretreatment handling practices
Wastewater	Aerobic wastewater treatment process	Wastewater	N/A	CO_2 and CH_4 emissions from uncovered treatment ponds (CH_4 emissions from instances where partial anaerobic conditions are present)
Wastewater	Anaerobic wastewater treatment process	Biogas	CO_2 emissions from combustion of collected biogas (flare or EGU)	Potential for indirect CH_4 emissions from digester if not all CH_4 produced is captured; CH_4 emissions from digester effluent

[1] Point source emissions consist primarily of combustion emissions (i.e., CO_2) and secondarily of uncombusted CH_4 emissions via incomplete destruction of biogas during combustion (EPA, 2008b).
[2] If compost piles become anaerobic, CH_4 and N_2O may also be generated and emitted.
[3]The term conveyances refers to indirect emissions from the piping when transferring waste to and from units. The term pile refers to poultry litter storage piles.

There are critical differences between the waste-derived biogenic feedstocks addressed in this appendix and the other forest- and agricultural-derived biogenic feedstocks addressed by the framework. The biologically based material in waste-derived feedstocks was removed from the land base for economic and production purposes outside of generating materials for the waste stream (e.g., for manufacture of consumer and industrial products, such as newspaper, food, and construction materials). Materials in the waste stream represents material that has been discarded, where final disposition of the material must be managed in some fashion (EPA, 2011b). As a result, if waste-derived feedstocks had not been processed or used by a stationary source, the material would have been managed through an alternative strategy with an alternative emissions pathway. Whatever the waste management strategy, it would result in biogenic CO_2 emissions and likely some amount of CO_2e GHG emissions (e.g., CH_4 emissions as a result of anaerobic decomposition). Evaluating the carbon cycle effects of waste management at a stationary source involves a comparison of the biogenic CO_2 and CH_4 emissions at the stationary source against an alternative emissions pathway that would have resulted under an alternate management strategy.

Evaluating these alternate waste management GHG emissions pathways does not require an analysis of the carbon cycle effects that transpired during the growth and harvest of the primary biogenic materials on the landscape. As a result, many of the biogenic attributes related to the carbon cycle effects of the growth, harvest, and use of other biogenic feedstocks are not relevant for waste-derived biogenic feedstocks. In many cases, as demonstrated in this appendix, a number of the terms in the assessment factor equation drop out when evaluating emission pathways related to waste-derived biogenic feedstocks.

1.1. A Simplified Biogenic Assessment Factor Equation for Waste-Derived Biogenic Feedstocks

The *BAF* equation presented in the framework for the non-waste-derived feedstocks (i.e., forestry-derived, agriculture-derived) can be simplified for application to waste-derived biogenic feedstocks. This section provides the simplified general assessment factor equation which is then modified to calculate illustrative *BAF* values for waste-derived feedstocks under different waste management strategies, shown in later sections.

In the assessment factor equation presented in the main body of the framework, the Avoided Emissions (*AVOIDEMIT*) term accounts for the avoidance of estimated biogenic emissions that could have occurred on the feedstock landscape without biogenic feedstock removal (e.g., avoided decomposition or burning), or per an alternative management strategy. The *AVOIDEMIT* term can be adjusted by the emission pathways specific to the type of waste-derived feedstock and waste management strategy. For example, for certain biogas waste feedstocks, *AVOIDEMIT* can be adjusted by the biogas collection efficiency, biogas combustion efficiency, or other factors affecting emission pathways. As a result, some of the terms in the equation as presented in Equation 2 in the main document of the framework are not relevant to the waste-derived feedstocks discussed in this appendix as illustrated below:

$$\boldsymbol{BAF} = \frac{\boldsymbol{NBE}}{\boldsymbol{PGE}} = \frac{(\boldsymbol{PGE})(\boldsymbol{GROW} + \boldsymbol{AVOIDEMIT} + \boldsymbol{SITETNC} + \boldsymbol{LEAK})(\boldsymbol{L})(\boldsymbol{P})}{\boldsymbol{PGE}}$$

The *BAF* is then simplified to (Equation 3 in the main document):

$$\boldsymbol{BAF} = (\boldsymbol{GROW} + \boldsymbol{AVOIDEMIT} + \boldsymbol{SITETNC} + \boldsymbol{LEAK})(\boldsymbol{L})(\boldsymbol{P})$$

When only the waste-derived biogenic feedstocks are considered, the following terms can be dropped: Net Growth on the Production Landscape (*GROW*), Total Net Change in Production Site Non-feedstock Carbon Pools (*SITETNC*), Leakage Associated with Feedstock Production (*LEAK*), the Feedstock Carbon Losses during Storage, Transport and Processing (L), and the Feedstock Carbon Embodied in Products (P).

As a result, the full assessment framework equation as applied to biogenic CO_2 emissions from waste-derived feedstocks can be simplified to Equation N.1.

$$\boldsymbol{BAF = AVOIDEMIT} \qquad \textbf{(EQ. N.1)}$$

AVOIDEMIT represents the avoided biogenic emissions that could have occurred per an alternative management strategy instead of the waste-derived feedstock's use in bioenergy production, relative to biogenic feedstock consumption. As discussed in the main document, negative, positive and zero *BAF*s (which is the same as *AVOIDEMIT* in this appendix), have different implications. A positive value implies that use of the feedstock for bioenergy production contributes more emissions to the atmosphere than would have occurred under the alternative management strategy. A zero value implies that both practices are equivalent in terms of how much emissions they contribute to the atmosphere. A negative value implies that using the feedstock for bioenergy production contributes less emissions to the atmosphere than the alternative management practice. In practice, as applied here, the *AVOIDEMIT* term is a proportion expressed as tCO_2e avoided (i.e., the emissions reduced, in CO_2e, resulting from an alternate waste management strategy to the combustion method) per tCO_2e emitted using the combustion method (i.e., the emissions, in CO_2e, resulting from the combustion waste management strategy). The *AVOIDEMIT* term is applied because the waste management strategy (e.g., collection and combustion of landfill gas) typically results in avoided CO_2e emissions that would have occurred in the absence of that management strategy (e.g., had the landfill gas not been collected and combusted, it may have been released as an indirect emission).[5] The *AVOIDEMIT* term, as applied to the waste-derived biogenic feedstocks described in this appendix, can be conceptually expressed as Equation N.2:

$$\boldsymbol{AVOIDEMIT = 1 - \frac{CO_2e\ emissions\ from\ treatment\ alternative\ to\ combustion}{CO_2e\ emissions\ from\ combustion\ treatment}} \qquad \textbf{(EQ.N.2)}$$

The *AVOIDEMIT* term is calculated for the specific waste-derived feedstock being managed relative to a specific, alternative practice. The following sections of this appendix go into detailed discussion about illustrative methodologies for the calculation of a *BAF* for waste-derived biogenic feedstocks.

Table N-2 presents a summary of illustrative *BAF* values calculated from example inputs using the methodology presented in subsequent sections of this appendix for the waste-derived biogenic feedstocks. These illustrative *BAF* values are dependent on the assumptions applied to the actual waste feedstock and to the alternate fate of the waste feedstock.

---

[5] This treatment is conceptually comparable to how the *AVOIDEMIT* term is applied to biogenic feedstocks that are harvested from the landscape.

Table N-2. Illustrative Example *BAF* Values Associated with the Treatment Methods of the Waste Feedstocks Discussed in this Appendix.

Waste Treatment Option	Biogenic Feedstock	Actual Treatment Fate	Alternate Treatment Fate	Illustrative *BAF*	Section Number
MSW, landfill	Landfill gas	Treatment with flares (higher DE)	No gas treatment	−1.48	2.2.1
	Landfill gas	Treatment with an EGU (lower DE)	No gas treatment	−1.38	2.2.2
	Landfill gas	Treatment with an EGU installed partway through the year	No gas treatment	−0.64	2.2.3
MSW, combustion	Biogenic fraction of MSW	Incineration	Landfill gas treatment with flaring or EGU	−0.02	3.2.1
			Landfill with no gas treatment	−1.52	3.2.2
Livestock waste, anaerobic digester	Manure, litter, and biogas	Treatment with flares, when anaerobic digester measurement data are available	Uncovered anaerobic lagoon	-2.56	4.2.1
		Treatment with flares, prior to the installation of an anaerobic digester	Uncovered anaerobic lagoon	−1.95	4.2.2
Livestock waste, combustion	Manure, litter, and biogas	Incineration	1-year litter storage prior to field spreading	0.06	5.2.1
			Uncovered anaerobic lagoon	−2.67	5.2.2
Wastewater and wastewater sludge, anaerobic digester	Biogas	Treatment with flares	Lagoon (with aerobic and anaerobic zones)	−0.88	6.2

DE = destruction efficiency

Note: Assumptions and scenario details for each waste treatment option and the associated *BAF* calculations are explained in the text. The parameterization of variables used in the calculations presented here are illustrative only; parameter values used in these calculations may not apply to all applications of the framework vis-à-vis the use of waste-derived biogenic feedstocks used at stationary sources.

1.2. Biogenic Municipal Solid Waste Management

Biogenic MSW refers to the biogenic (organic) fraction of MSW. In 2012, approximately 250.9 million tons of MSW were generated in the United States (EPA, 2014a). Biogenic materials were the largest component of MSW before recycling (see Table N-3). Of the total MSW generated, 135 million tons (53.8%) went to landfills, 86.6 million tons (34.5%) were recovered (e.g., recycled or composted), and 29.3 million tons (11.7%) were combusted with energy recovery (this includes biogenic as well as fossil fuel-based materials, such as plastics). The proportions of waste recycled, composted, incinerated, or landfilled differ regionally due to multiple factors, including local economics, regulatory differences at the state and local levels, public perceptions, and infrastructure requirements (Bogner et al., 2007; EPA, 2010c). However, there is a lack of literature describing the degree to which composition of MSW can vary from region to region. Therefore, for the purposes of the framework, we will use a national average composition based on EPA data through 2012 (EPA, 2014a).

Although composition of MSW may vary from region to region, this mainly contributes to potential generation amount of CO_2 and CH_4 in a given landfill, whereas the goal of the framework methodology for waste-derived feedstocks is ultimately concerned with how the CO_2 and CH_4 from MSW is treated used in one activity versus another. From this perspective, CO_2 and CH_4 from MSW can be treated similarly across the U.S.

Table N-3. Percent of MSW Generated and Recovered by MSW Class in 2012 (EPA, 2014a).

MSW Class	Biogenic?	Percent Generated	Percent Recovered (as percent of generation)
Paper and paperboard	Yes	27.4	64.6
Yard trimmings	Yes	13.5	57.7
Food scraps	Yes	14.5	4.8
Plastics	No	12.7	8.8
Metals	No	8.9	34.0
Rubber and leather	Partial	3.0	17.9
Textiles	Partial	5.7	15.7
Wood	Yes	6.3	15.2
Glass	No	4.6	27.7
Miscellaneous	Uncertain	1.6	negligible

In the United States, MSW typically has one of four fates (Bogner et al., 2007):

- Landfilling;
- Combustion;
- Processing in an anaerobic digester; or
- Composting.

Sections 2 and 3 of this appendix discuss in detail the GHG emissions pathways for MSW landfills and MSW combustion, respectively. Food waste can be treated through anaerobic digestion systems and is relatively common at wastewater treatment plants. The excess capacity of the digestion system can be supplemented from food waste (e.g., EMBUD plant). Waste treatment through anaerobic digestion is discussed for both livestock waste management and wastewater treatment. Composting is not a stationary source activity, and is therefore not discussed in this appendix.

2. Biogenic MSW Disposal in MSW Landfills and Associated GHG Emissions Pathways

GHG emissions pathways at MSW landfills result in CH_4 and CO_2 emissions. In general, landfill-related CH_4 and CO_2 emissions are of biogenic origin and primarily result from the decomposition, under anaerobic or aerobic conditions, of organic matter such as food, yard wastes, and paper. The decomposition of organic matter in a landfill occurs through a series of microbial reactions, primarily under anaerobic conditions (Bogner, 1992). Methane and CO_2 are produced through the action of methanogenic bacteria as they consume the organic matter and convert it into stabilized organic materials and biogas. By volume, the composition of landfill gas ranges from 45% to 55% CH_4 and CO_2, but is generally assumed to be half CH_4 and half CO_2 (EPA, 2010a). Landfill gas also contains small amounts of nitrogen, oxygen, and hydrogen; less than 1% non-methane organic compounds (NMOCs); and trace amounts of inorganic compounds (EPA, 2014b). Landfill gas will continue to generate for many years, even decades, after an initial mass of waste is placed in a landfill due to the slow degradation process and compaction of the waste.

There are two general pathways for CH_4 and CO_2 emissions from landfills—indirect emissions and direct emissions (i.e., point source combustion emissions). These two emissions pathways are affected by the presence of an active gas collection and control system (i.e., flare or EGU). The remainder of this section first discusses the emission pathways as they relate to controlled and uncontrolled landfills, and then goes into further detail about key parameters affecting the amount and type of emissions from these pathways.

- <u>*Uncontrolled Landfills*</u>—An "uncontrolled" landfill refers to a landfill that has no active system, such as a gas collection and control system, in place to minimize indirect landfill gas emissions to the atmosphere. Though the landfill biogas is not collected from uncontrolled landfills, the biogas may be managed through the use of a topsoil cover to passively treat the uncollected biogas via CH_4 oxidation. Indirect emissions are the primary emissions pathway from uncontrolled landfills (see Figure N-1).
    - *Direct emissions*: None.
    - *Indirect emissions:* The primary GHG emissions pathway at uncontrolled landfills is indirect emissions of CH_4 and CO_2 through the landfill soil cover. A fraction of the CH_4 in the biogas (ranging from 10% to 35% (IPCC, 2006; EPA, 2013c; SWICS, 2009) will be oxidized by bacteria in the cover soil as the gas migrates vertically through the landfill cover soils.
- <u>*Controlled Landfills*</u>—A "controlled" landfill refers to a landfill that has an active landfill gas collection and control system in place. The collection system consists of network of pipes and collection wells strategically placed throughout the disposal areas to collect and transport the biogas to a central control system. A control system typically involves a combustion device such as a flare, turbine, or boiler for combustion of the collected landfill gas. Controlled landfills also include a topsoil cover to passively treat the remaining landfill gas that is not collected via CH_4 oxidation. In the United States, there are approximately 594 operational landfill gas-to-energy projects, at which landfill gas is used as fuel for generation of electricity or process heat in industrial applications (EPA, 2013a).

Approximately 25% of the roughly 2,400 currently operating or recently closed MSW landfills in the United States include landfill gas collection and control systems (flaring or energy generation) (EPA, 2013a). An estimated 540 additional, existing domestic MSW landfills have the potential to capture landfill gas for energy use (EPA, 2013a). The primary GHG emissions pathway at controlled landfills is direct emissions of CO_2 (see Figure N-2).

- *Direct emissions:* The primary GHG emissions pathway at controlled landfills is point source emissions of CO_2. The CH_4 in the landfill gas that is collected and combusted will be converted to CO_2; the CO_2 in the collected landfill gas will be directly emitted as CO_2; and the CH_4 in the collected landfill gas that is not combusted will be directly emitted as CH_4.
- *Indirect emissions:* Both CH_4 and CO_2 will be emitted through the landfill soil cover. A fraction of the CH_4 in the biogas (ranging from 10% to 35% (IPCC, 2006; EPA, 2013c; SWICS, 2009) will be oxidized by bacteria in the cover soil as the gas migrates vertically through the landfill cover soils.

When organic materials are landfilled, a portion of the carbon in the materials will not readily degrade due to several factors, including environmental conditions (e.g., moisture, pH, temperature), and the creation of anaerobic environments through waste disposal and compaction. When the environment in which wastes are placed becomes anaerobic, the organisms that normally break down the waste cannot survive to decompose a portion of the organic materials, thus this portion will remain in the landfill. This process is referred to as carbon storage because this carbon is permanently removed from the global carbon cycle.

Cellulose and hemicellulose are the major biodegradable components of MSW (Barlaz, 1998; Barlaz, 2006). Additionally, lignin will not degrade at all when placed in a modern landfill (Barlaz, 1998). On a dry weight basis, MSW contains between 30% and 50% cellulose, 7% to 12% hemicellulose, and 15% to 28% lignin (Hilger and Barlaz, 2001). The amount of cellulose and hemicellulose in the organic materials that will degrade depends on the type of material. Laboratory bench scale research has been conducted to quantify carbon storage factors for several materials of the MSW stream (Barlaz, 1998; ICF, 2008), including yard waste, food, and various paper products. These carbon storage factors represent the mass of carbon stored in a landfill per initial mass of the component and range from 0.05 to 0.47 kg of carbon sequestered per dry kg of waste component (Barlaz, 1998; ICF, 2008). The 2006 IPCC Guidelines (IPCC, 2006a) recommends a default factor of 0.5 for the fraction of degradable organic carbon that is anaerobically decomposed in the landfill, suggesting that 50% of the biogenic carbon placed in a landfill becomes stored carbon.

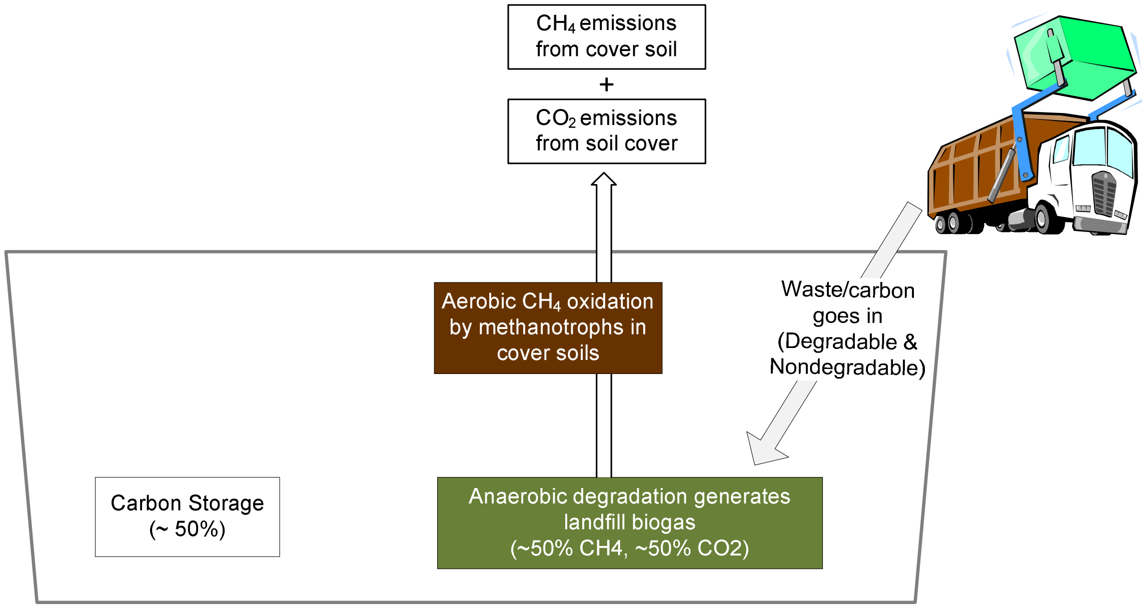

Figure N-1. Carbon Balance for an Uncontrolled Landfill.

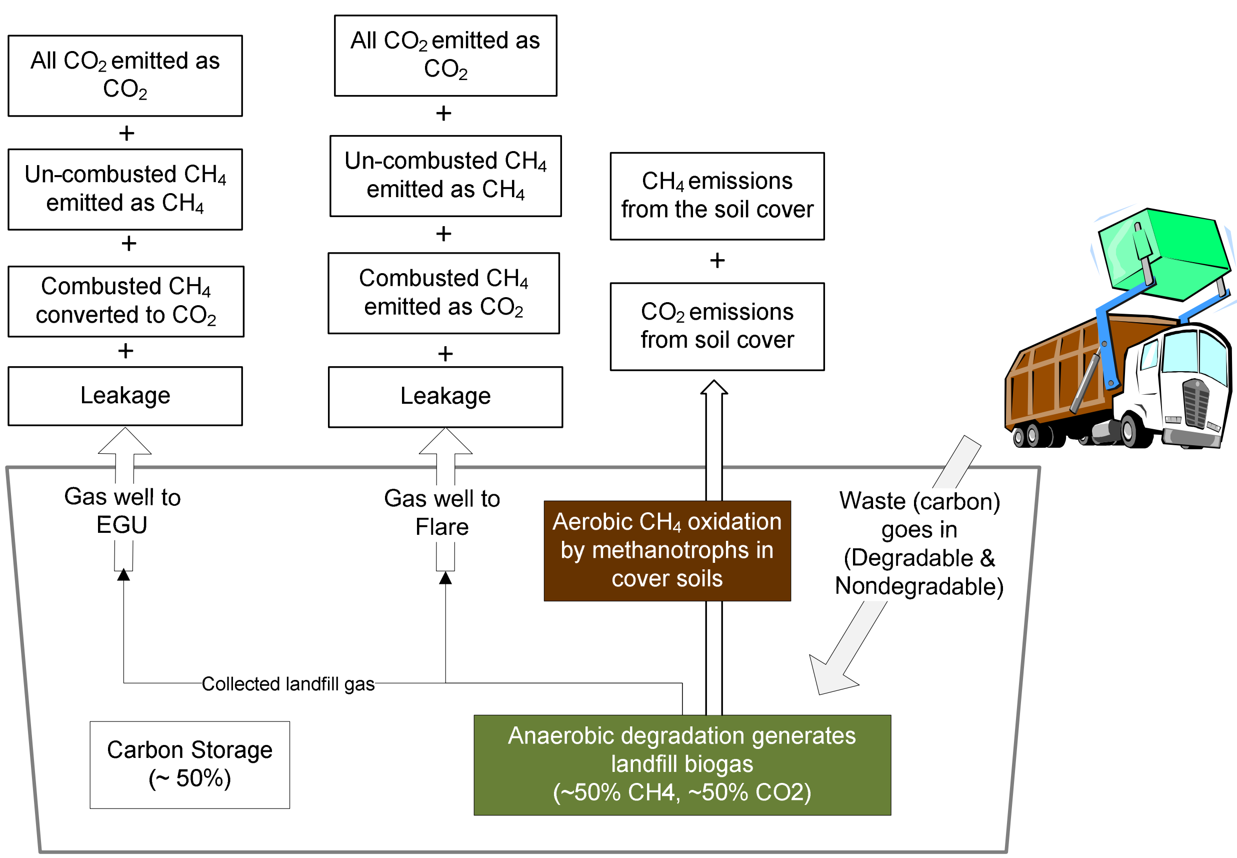

Figure N-2. Carbon Balance for a Controlled Landfill.

2.1. Indirect Emissions from MSW Landfills

The first pathway for GHG emissions from landfills assessed in this framework is indirect emissions (CH_4 and CO_2) released directly from the landfill cover to the atmosphere. The amount and rate of total CH_4 generation in landfills, as well as the amount of indirect emissions of CH_4 and CO_2, depends upon the quantity and composition of the landfilled material, as well as the landfill design and surrounding environmental conditions. If not collected and combusted, a portion of the CH_4 generated in a landfill oxidizes to CO_2 as it travels through the top layer of the landfill cover; the remaining unoxidized portion of the landfill gas is emitted through the landfill cover. This process results in indirect emissions of both CH_4 and CO_2 through the landfill cover.

Methane oxidation efficiency is directly affected by the thickness, physical properties, moisture content, and temperature of landfill cover soils. The rate of CH_4 oxidation in landfill cover soils is linear to a point, after which the methanotrophs in the cover soils reach an upper limit in their ability to oxidize the CH_4 and the remaining CH_4 passes through the cover soil without being oxidized (Chanton et al., 2011b). Methane oxidation efficiency can vary substantially between and within landfills. Cover soil properties (i.e., temperature and soil moisture) van vary as a function of climate, such that the efficiency of CH_4 oxidation may vary regionally and seasonally (Spokas and Bogner, 2011). In hot, arid climates, CH_4 oxidation in landfill cover soils can be limited, resulting in higher indirect CH_4 emissions than in cooler, wetter climates. In hot, arid climates soil moisture is limited for much of the year, thus reducing CH_4 oxidation rates, and seasonally high soil temperatures prevent methanotrophic activity (Chanton et al., 2011a, Spokas and Bogner, 2011).

The IPCC (2006a) and EPA (2009a) default value for the CH_4 oxidation fraction in cover soils of modern, managed landfills such as those found in the United States is 10% of generated CH_4. EPA considers 10% to be a conservative (lower end) default oxidation fraction. Some studies point to an average CH_4 oxidation rate of approximately 40% (ranging from negligible to 100%) of the total CH_4 arriving at the base of the landfill cover soils (Bogner et al., 2007; Chanton et al., 2009; Chanton et al., 2011a; Spokas and Bogner, 2011). Because field and laboratory studies have shown large variations in oxidation rates, particularly for landfills with active gas collection and control systems, EPA expanded the default oxidation fraction value to include those based on the calculated CH_4 flux[6] rate in grams per square meter per day ($g/m^2/day$) to the bottom of a landfill's cover soil prior to any oxidation (EPA, 2013c, 40 CFR § 98).

- For high rates of CH_4 flux (greater than 70 $g/m^2/day$) the default oxidation fraction is 10%;
- For moderate rates of CH_4 flux (10 to 70 $g/m^2/day$) the default oxidation fraction is 25%;
- For low rates of CH_4 flux (less than 10 $g/m^2/day$) the default oxidation fraction is 35%

[6] The methane flux rate is referred to as the continuous flow of methane from an area within a landfill where methane is produced to the atmosphere over a specified period of time.

2.2. Direct Emissions from MSW Landfills

The second pathway for GHG emissions from landfills is direct, point source emissions of CO_2 and, depending on the destruction efficiency (DE) of the combustion device, CH_4 emissions from landfill gas collection and combustion through flaring or use as a fuel in an EGU (often referred to as landfill gas-to-energy projects).[7]

Landfill gas collection systems vary in landfill gas collection efficiency (CE). Recovery ranges from 35% to 90% of the gas generated in a particular landfill cell, depending on the placement of the piping network and collection wells (Spokas et al., 2006; EPA, 2012a). The default collection efficiency recommended by EPA is 75% (the average from a range of 50% to 95%), meaning that 75% of the landfill gas generated is collected and routed to a control device (EPA, 2008a; EPA, 2010b; EPA, 2013c). However, actual collection efficiencies may vary substantially, and due to the cost of determining the amount of landfill gas generated in a landfill, are not cost-effective and therefore difficult to quantify. Very few published studies documenting measured CEs exist, and of those, the results are highly variable and appear to be correlated with the type of landfill cover system. For example, Spokas et al. (2006) conducted field studies of the methane mass balance at three landfills in France and quantified collection efficiencies ranging from 54% to 100%, depending on cover type and presence of a gas collection system.

Collected landfill gas may be combusted using a flare, as a fuel for an EGU, or directly in boilers and other applications. Landfill gas may be purified to create compressed natural gas or liquefied natural gas, or for injection into natural gas pipelines. Of the total estimated CH_4 generated at MSW and industrial landfills in 2012, 30.3% was flared, 34.5% was used to generate electricity, and 3.5% was oxidized at the landfill cap (EPA, 2014b).

The combustion process destroys, or oxidizes, the CH_4 in the landfill gas to CO_2, resulting in CO_2 emissions.[8] A portion of the collected gas will not be combusted due to inefficiencies in the combustion device, thus this fraction of CH_4 will be emitted to the atmosphere as CH_4. Destruction efficiencies for CH_4 in landfill gas range from 90% to 99.9% (IPCC, 2006; SWICS, 2009; New Zealand Ministry for the Environment, 2010; EPA, 2013c). Additionally, the CO_2 in the collected gas will not be combusted and will be directly emitted as CO_2.

MSW landfills with a design capacity of 2.5 million megagrams (Mg) and 2.5 million cubic meters of waste are required to calculate their annual emissions of non-methane organic compounds (NMOC). Landfills that emit 50 Mg or more of NMOC per year are required by EPA regulations to install a landfill gas capture and control system in order to control NMOC emissions (EPA, 1996). To

[7] Typically, both GHG emissions pathways will be present at a landfill, as landfills with landfill gas collection and destruction systems generally do not capture all CH_4 generated in the landfill. Uncaptured CH_4 will either be oxidized via methanotrophic activity in the cover soils, or will be released directly to the atmosphere as indirect emissions.

[8] Note that as the combustion process is never complete, some CH_4 in landfill gas is not destroyed and therefore stack gas emissions contain a small percentage of CH_4.

comply with EPA regulations, landfill operators must, at a minimum, collect and combust their biogas. A co-benefit of NMOC emissions control is the destruction of CH_4 present in the landfill gas.

Both uncontrolled and controlled landfills include liners and leachate collection systems to prevent pollutants from migrating beyond the landfill, which can result in ground and/or surface water pollution.[9] Both uncontrolled and controlled landfills also store carbon. A portion of the carbon of the landfilled biomass materials will not decompose due to the anaerobic environment created through modern landfilling. The carbon that does not decompose is therefore removed from the global carbon cycle and stored in the landfill. The fraction of the amount of carbon stored in a landfill is typically assumed to be approximately 50%.

Once a landfill has reached its design capacity, it is closed.[10] A final cover is installed and the site owner is required to monitor and maintain a closed landfill throughout a post-closure monitoring period (EPA, 1996). Post-closure monitoring includes leachate collection and treatment, groundwater monitoring, inspection of the final cover and maintenance as required, and monitoring to ensure that CH_4 is not migrating off-site. Collection and combustion of landfill gas may continue throughout this period. EPA regulations (40 CFR § 258.61) specify a 30-year post-closure monitoring period unless this period is extended by a regulatory agency on a site-specific basis (EPA, 1996).

2.3. Method for Calculating an Illustrative *BAF* Value for Biogenic Emissions from MSW Landfilling

The assessment factor equation can be applied to direct biogenic emissions resulting from the collection and combustion of landfill gas. The biogenic feedstock from an MSW landfill is the biogas generated from MSW decomposition and the biogas collected from the landfill. This section provides a method for calculating an illustrative *BAF* value to be applied to direct biogenic emissions from MSW landfills. The *BAF* methodology for MSW landfilling neither includes benefits from off-setting fossil fuels through landfill gas-to-energy projects, nor any carbon storage.

In Equation N.2, the *AVOIDEMIT* term is used to represent the net GHG emissions reductions achieved through capture and combustion of landfill gas, compared to an alternate, Reference case emissions pathway of indirect CH_4 and CO_2 emissions through the landfill cover (had the landfill gas not been collected and combusted). In other words, biogenic emissions from a controlled landfill are being compared to the biogenic emissions from an uncontrolled landfill.

In practice, as applied here, the *AVOIDEMIT* term is expressed as 1 minus the ratio of metric tons of CO_2e (tCO_2e) avoided (i.e., the point and indirect emissions, in CO_2e, of the collected biogas had that biogas not been collected and combusted, after accounting for indirect emissions of CO_2 and CH_4, and the CH_4 oxidation that would have occurred in the landfill cover soil) per tCO_2e removed via

[9] Synthetic liners and compacted clay soil typically line the sides and bottom of a landfill to protect groundwater and the underlying soil from leachate releases. Leachate collection and removal systems sit on top of the liners to remove leachate from the landfill for collection and disposal.

[10] A closed landfill as referred to in this context means a landfill that no longer accepts waste for disposal.

combustion (i.e., the emissions, in CO_2e, of the collected and combusted biogas, after accounting for the CE of the gas collection system and the DE of the biogas destruction device). For the biogas feedstock that is generated and collected from landfills, the *AVOIDEMIT* term can be conceptually expressed by 1 minus a simplified ratio of CO_2e emissions of the treatment fates:

$$\boldsymbol{AVOIDEMIT} = \mathbf{1} - \frac{\mathbf{CO_2e\ emissions\ from\ treatment\ alternative\ to\ combustion}}{\mathbf{CO_2e\ emissions\ from\ combustion\ treatment}} \qquad \textbf{(EQ.N.2)}$$

Note that the same amount of biogas and constituents of the biogas are considered for both the actual and alternate treatment fates.

2.3.1. Boundaries and Assumptions for MSW Landfilling Methodology

The methodology presented in this appendix for treatment of MSW through landfilling does not consider offsets from electricity generation, carbon storage, or losses from the gas collection system. Assumptions regarding the operation of the gas collection system are also made. The rationale for the boundary considered within the scope and major assumptions made are provided as follows:

- Offsets—Landfill gas-to-energy projects reduce fossil fuel usage whereas flaring landfill gas does not. However, because this is not a lifecycle analysis, the effects of reduced fossil fuel usage is not included in the calculations presented here. The EPA's Landfill Gas Energy Benefits Calculator can be used to estimate direct, avoided, and total greenhouse gas reductions, as well as environmental and energy benefits, for the current year of a landfill gas energy project if desired (EPA, 2012b).
- Carbon storage—Carbon storage refers to the fraction of carbon remaining in the biogenic materials after accounting for the carbon exiting the system as landfill gas or that is dissolved in the leachate. The amount of carbon storage will vary with environmental conditions in the landfill, but can be generally thought to be about half of the carbon in each biomass material that remains in a landfill. Carbon storage is not considered in the treatment of waste-derived biogenic feedstocks by MSW landfilling in this framework because the amount of carbon storage in a given landfill will theoretically be equivalent despite the treatment fate of the landfill biogas.
- Losses—Indirect emissions from equipment leaks (e.g., valves, connectors, and open-ended lines) on or associated with a wellhead, or in the delivery infrastructure from the biogas collection system to the biogas destruction device are possible. However, in the context of landfill gas collection and control, losses are expected to be insignificant, especially for instances where the biogas destruction device is co-located at a landfill.
- Operation of the gas collection system—One important assumption to note is that the methodology for MSW landfilling assumes the landfill gas collection system is operating continuously. It is possible to perform the calculations with a gas collection system that is not continuously operated by applying an additional factor to account for the fraction that the recovery system was operating (fRec) to the equations used to calculate the CO_2 and CH_4 emissions from landfills with gas collection and control.

2.3.2. Explanation of MSW Landfilling Methodology

Both the numerator and denominator of the *AVOIDEMIT* equation can be calculated using Equation N.3. This equation considers the following emissions pathways from an MSW landfill with or without gas collection and control the amount of

- Indirect CH_4 emissions from the landfill surface;
- Indirect CO_2 emissions from the landfill surface;
- Direct CH_4 emissions from the CH_4 in the collected landfill gas that is not combusted (as a result of a combustion efficiency less than 100%);
- Direct CH_4 emissions in the collected landfill gas that is combusted and converted to CO_2; and
- Direct CO_2 emissions in the collected biogas that is emitted as CO_2.

$$\boldsymbol{CO_2e\ emissions\ from\ MSW\ landfilling}$$

$$= \boldsymbol{GWP_{CH_4}(CH_4R - CH_4D + CH_4U) + \left(CH_4D \times \frac{44}{16}\right) + CO_2R + CO_2U} \qquad \textbf{(EQ. N.3)}$$

Where:

CO_2e emissions	= metric tons CO_2e emissions from MSW landfilling (MT/year).
GWP_{CH_4}	= 100-year GWP of CH_4, 25 (IPCC, 2007).
CH_4R	= the amount of CH_4 recovered and sent to the landfill gas destruction device (Equation N.4).
CH_4D	= amount of CH_4 destroyed via combustion (Equation N.5).
CH_4U	= amount of uncollected CH_4 emitted through landfill cover surface; separate calculations for landfills with gas collection and landfills without gas collection (Equation N.6 or Equation N.7, depending on the presence of a gas collection system).
CO_2R	= the amount of CO_2 recovered, sent to the landfill gas destruction device, and emitted to the atmosphere (Equation N.8).
CO_2U	= amount of uncollected CO_2 emitted through landfill cover surface (Equation N.9 or Equation N.10, depending on the presence of a gas collection system).
44/16	= molecular weight ratio of CO_2 to CH_4.

Equation N.3 can be grouped and explained in three major parts:

- The first part, $GWP_{CH_4}(CH_4R - CH_4D + CH_4U)$, accounts for the amount of CH_4 that is collected, but not combusted (CH_4R – CH_4D) plus the amount of CH_4 in the generated landfill gas that is not collected and emitted as indirect emissions through the landfill cover surface as CH_4. Because the terms in Equation N.3 need to be in units of tCO_2e, these quantities must be adjusted by the 100-year GWP for CH_4.

- The second part, ($CH_4D \times 44/16$), accounts for the quantity of CH_4 that is collected and oxidized to CO_2 during combustion. The amount of CH_4 destroyed needs to be adjusted by the 44/16 conversion factor because the gas is being converted to CO_2.
- The third part, $CO_2R + CO_2D + CO_2U$, accounts for all of the CO_2 emissions (direct and indirect).
  - CO_2R is the amount of CO_2 in the biogas that is collected and sent to the destruction device; this quantity will be directly emitted as CO_2;
  - CO_2D is the amount of CO_2 that is collected, but not passed through the destruction device;
  - CO_2U is the amount of CO_2 in the generated landfill gas that is not collected and emitted as indirect emissions through the landfill cover surface as CO_2. This quantity of CO_2 is not adjusted for oxidation as the gas passes through the cover.

The annual amount of CH_4 that is collected, or recovered, from the landfill gas and sent to the destruction device can be calculated using Equation N.4. The CH_4 concentration in the landfill gas is typically monitored, or may be assumed as a percentage between 45% and 55%.

$$\mathbf{CH_4R = V \times \frac{C_{CH_4}}{100\%} \times 0.0423 \times \frac{520^{\circ}\,R}{T} \times \frac{P}{1\,atm} \times \frac{0.454\,metric\,ton}{1{,}000\,lbs}} \qquad \textbf{(EQ. N.4)}$$

Where:

CH_4R	= amount of CH_4 recovered from the landfill and sent to the landfill gas destruction device (metric tons CH_4/year).
V	= annual volumetric flow rate of biogas to the landfill gas destruction device (cubic feet biogas per year), as determined from daily monitoring.
C_{CH_4}	= average annual CH_4 concentration of biogas (percent, fraction, wet basis).
0.0423	= density of CH_4 pounds per standard cubic foot (at 520ºR or 15.74ºC and 1 atm).
T	= annual average temperature (ºR) at which flow is measured.
P	= annual average pressure (atm) at which flow is measured.
0.454/1000	= conversion factor from pounds to metric tons.

Equation N.5 can be used to calculate the quantity of CH_4 destroyed in a landfill gas destruction device. As mentioned previously, achieving 100% destruction efficiency is not feasible, thus the amount of CH_4 recovered must be adjusted by the destruction, or combustion, efficiency of the landfill gas destruction device. This adjustment accounts for the proportion of collected CH_4 in the biogas that is not destroyed by the destruction device. The collected CH_4 in the landfill gas that is not combusted is a direct source of CH_4 emissions to the atmosphere.

$$CH_4D = CH_4R \times DE \qquad \textbf{(EQ. N.5)}$$

Where:

CH_4D = CH_4 destroyed at a landfill gas destruction device (metric tons CH_4/year).

CH_4R = amount of CH_4 recovered and sent to the landfill gas destruction device (Equation N.4).

DE = CH_4 destruction efficiency from flaring or combustion in an EGU, decimal percent. The DE varies with the type of landfill gas destruction device used; it can be estimated as the lesser of the manufacturer's specified destruction efficiency and 0.99 (EPA, 2013c).

The presence of a landfill gas collection system affects the amount of indirect CH_4 emissions from the landfill. When calculating the amount of indirect CH_4 emitted from a landfill with gas collection, only the uncollected portion of CH_4 in the landfill gas is adjusted for oxidation. Alternatively, for a landfill without gas collection, all of the CH_4 in the generated landfill gas is adjusted for oxidation. Equations N.6 and N.7 can be used to determine the amount of uncollected, or indirect, CH_4 emissions from a landfill with gas collection and a landfill without gas collection, respectively.

Both equations adjust the amount of CH_4 recovered by the term, 1/CE, which represents the portion of generated landfill gas that is not collected by the gas collection system. Equation N.6 subtracts the term CH_4R to account for the quantity of CH_4 that is collected and sent to the destruction device so that only the uncollected portion is adjusted for oxidation. Note that this term is not included in Equation N.7 because all CH_4 generated must be adjusted for oxidation in landfills without gas collection.

$$CH_4U\text{, gas collection} = \left(\left(\frac{1}{CE} \times CH_4R\right) - CH_4R\right) \times (1 - OX) \qquad \textbf{(EQ. N.6)}$$

$$CH_4U\text{, without gas collection} = \left(\frac{1}{CE} \times CH_4R\right) \times (1 - OX) \qquad \textbf{(EQ. N.7)}$$

Where:

CE = collection efficiency of the landfill gas collection system, decimal percent

CH_4R = the amount of CH_4 recovered and sent to the landfill gas device (Equation N.4)

OX = methane oxidation fraction

The amount of CO_2 recovered from the landfill gas that is sent to the destruction device can be calculated using Equation N.8.

$$CO_2R = V \times \left(1 - \frac{C_{CH_4}}{100\%}\right) \times 0.1166 \times \frac{520°R}{T} \times \frac{P}{1\ atm} \times \frac{0.454\ metric\ ton}{1{,}000\ lbs} \qquad \textbf{(EQ. N.8)}$$

Where:

CO_2R = the amount of CO_2 recovered and sent to the landfill gas destruction device (metric tons CO_2/year).

V = annual volumetric flow rate of biogas to the landfill gas destruction device (cubic feet biogas per year), as determined from daily monitoring.

$(1 - C_{CH_4}/100\%)$ = average annual CO_2 concentration of landfill gas, (C = average annual CH_4 concentration of biogas, percent, fraction wet basis).

0.1160 = density of CO_2 pounds per standard cubic foot (at 520ºR or 15.74ºC and 1 unit of average annual pressure [atm]).

T = average annual temperature (ºR) at which flow is measured.

P = atm at which flow is measured.

0.454/1000 = conversion factor from pounds to metric tons.

Calculating indirect CO_2 emissions from the landfill surface is similar to that used to calculate indirect CH_4 emissions from the landfill surface (see Equations N.6 and N.7). Equations N.9 and N.10 present two ways to calculate indirect CO_2 emissions from either a landfill with a gas collection system, or one without.

Both equations are adjusted by the CE in order to consider only the portion of uncollected CO_2 that is emitted as CO_2 through the landfill cover surface and the portion of uncollected CH_4 that is emitted through the landfill cover surface and oxidized to CO_2 by the methanotrophic bacteria. The conversion factor of 44/16 is applied to the portion of CH_4 in the uncollected gas that is oxidized to CO_2.

$$\mathbf{CO_2U, gas\ collection} = \left(\left(\frac{1}{CE} \times CO_2R\right) - CO_2R\right) + OX\left(\left(\frac{1}{CE} \times CH_4R\right) - CH_4R\right) \times \frac{44}{16} \quad \textbf{(EQ. N.9)}$$

$$\mathbf{CO_2U, without\ gas\ collection} = \frac{1}{CE} \times CO_2R + \left(OX \times \frac{1}{CE} \times CH_4R\right) \times \frac{44}{16} \quad \textbf{(EQ. N.10)}$$

Where:

CE = collection efficiency of the landfill gas collection system, decimal percent.

CO_2R = amount of CO_2 recovered and sent to the landfill gas destruction device (Equation N.8).

CH_4R = the amount of CH_4 recovered and sent to the landfill gas destruction device (Equation N.4).

OX = methane oxidation fraction.

44/16 = molecular weight ratio of CO_2 to CH_4.

Several parameters are presented and used in the equations in the remainder of this section. Table N-4 presents the parameters used, typical or default values, ranges presented in the literature, and references.

Table N-4. Summary of Parameters Used When Calculating a *BAF* for MSW Landfilling.

Parameter Description	Symbol	Value Used in Examples	Range	Units	Comments	Reference (for value column)
Oxidation fraction	OX	0.10	0.10 to 0.35	Fraction	0.10 is the default used in many accounting methodologies	IPCC, 2006
Oxidation fraction	OX	0.25	0.10 to 0.35	Fraction	Higher oxidation fractions are observed for landfills with gas collection systems and low CH_4 flux rates	EPA, 2013c; SWICS, 2009
Concentration of CH_4 in the landfill gas or biogas	C_{CH_4}	0.55	0.45 to 0.60	Percent		IPCC, 2006
Collection efficiency	CE	0.75	0.60 to 0.95	Fraction	Higher CEs are associated with closed landfills and well-designed systems with low permeable covers	EPA, 2010b; EPA, 2013c
Destruction efficiency (of a landfill gas flare)	DE	0.99	0.90 to 0.9977	Fraction	0.99 is considered the default DE of CH_4 for a flare	EPA, 2011a; EPA, 2013c
Destruction efficiency (of an EGU)	DE	0.97	0.96 to 0.99	Fraction	DE of CH_4 in a direct use system (e.g., boilers, heaters) varies by technology	EPA, 2011a; EPA, 2013c
Density of CH_4 in landfill gas	–	0.0423	–	lbs/scf	At 520 ºR or 15.74 ºC and 1 atm	EPA, 2011a; EPA, 2013c

Parameter Description	Symbol	Value Used in Examples	Range	Units	Comments	Reference (for value column)
Density of CO_2 in landfill gas	–	0.1160	–	lbs/scf	At 520 ºR or 15.74 ºC and 1 atm	Calculated value[1]

CE = collection efficiency; DE = destruction efficiency; EGU = electricity generating unit; F = fraction of CH_4 in landfill gas; lbs/scf = pounds per standard cubic foot; OX = oxidation fraction; R = Rankine

[1] This value is calculated using a 60 degree Fahrenheit conversion: 44.01 * (2.20462/836.6) = 0.1160, where 44.01 = the molecular weight of CO_2; 2.20462 is a unit conversion factor from kilograms to pounds; and 836.6 scf/kg-mol is the molar volume conversion factor.

2.4. Example *AVOIDEMIT* and *BAF* Calculations for Landfill Biogas

Three example scenarios are presented here for calculating a *BAF* value for landfill gas. In order to derive a *BAF* value for landfill gas, the numerator and denominator of the *AVOIDEMIT* must be calculated specific to the treatment and alternate fate of the collected landfill gas feedstock. Scenarios differ by the treatment of the collected gas (the denominator in the *AVOIDEMIT* term) and the alternate fate of the collected gas (the numerator in the *AVOIDEMIT* term).

2.4.1. Example Calculations for a Controlled Landfill (Flaring) Compared to an Uncontrolled Landfill

In this example, a *BAF* value is calculated for the treatment of collected gas via flares (denominator) and the alternate fate is to not collect or control any gas generated in the landfill (numerator). Equations N.4 through N.10 can be used to determine the inputs into Equation N.3 as shown below.

In this example, the landfill with gas collection recovered approximately 150 million cubic feet of landfill gas in the past year. The landfill gas monitoring system automatically corrects for temperature and pressure, and computed an annual average CH_4 concentration in the gas of 55%.

Step 1: Calculate the Amount of CH_4 and CO_2 Recovered by the Landfill Gas Collection System

The starting point for both treatment fates for treatment through MSW landfilling is the amount of gas recovered. Equations N.4 and N.8 can be used to calculate the amount of CH_4 and CO_2 recovered by the landfill gas collection system:

$$\mathbf{CH_4R = 150{,}000{,}000 \times \frac{55}{100} \times 0.0423 \times \frac{520}{520} \times \frac{1}{1} \times \frac{0.454}{1{,}000} = 1584.35}\ \boldsymbol{MT\ CH_4}$$

$$\mathbf{CO_2R = 150{,}000{,}000 \times \left(1 - \frac{55}{100}\right) \times 0.1160 \times \frac{520}{520} \times \frac{1}{1} \times \frac{0.454}{1{,}000} = 3554.82}\ \boldsymbol{MT\ CO_2}$$

Step 2: Calculate the CO_2e Emissions for MSW Landfilling without Biogas Collection and Control

The numerator calculates the CO_2e emissions profile of the biogas feedstock had the gas not been collected and combusted. Because there is no gas collection or control for the alternate fate, the CH_4R, CH_4D, CO_2R, and CO_2D terms in Equation N.3 can be dropped, leaving only the CH_4U and CO_2U terms. Equations N.7 and N.10 can be used to calculate the amount of indirect CH_4 and CO_2 emitted by a landfill without gas collection and control, assuming a representative CE of 75% and 10% oxidation fraction:

$$\mathbf{CH_4U, without\ gas\ collection} = \left(\frac{1}{0.75} \times 1584.35\right) \times (1 - 0.10) = 1901.22\ MT\ CH_4$$

$$\mathbf{CO_2U, without\ gas\ collection} = \frac{1}{0.75} \times 3554.82 + \left(0.10 \times \frac{1}{0.75} \times 1584.35\right) \times \frac{44}{16} = 5320.69\ MT\ CO_2$$

The net CO_2e emissions profile of the gas feedstock had the gas not been collected and combusted is calculated using Equation N.3:

$$CO_2e\ emissions\ from\ MSW\ landfilling\ without\ gas\ collection$$

$$= 25(0 - 0 + 1901.22) + \left(0 \times \frac{44}{16}\right) + 0 + 5320.69 = 52,851.08\ MT\ CO_2e$$

Step 3: Calculate the CO_2e Emissions with Gas Collection and Control (Flaring)

The denominator calculates the CO_2e emissions profile of the gas feedstock had the gas been collected and combusted using a flare with a destruction efficiency of 99%. Equation N.5 can be used to calculate the CH_4D term in Equation N.3:

$$\mathbf{CH_4D} = 1584.35 \times 0.99 = 1568.50\ \mathrm{MT}\ CH_4$$

Additionally, Equations N.6 and N.9 can be used to calculate the amount of indirect CH_4 and CO_2 emitted by a landfill with gas collection and control, assuming a representative CE of 75% and 10% oxidation fraction:

$$\mathbf{CH_4U, gas\ collection} = \left(\left(\frac{1}{0.75} \times 1584.35\right) - 1584.35\right) \times (1 - 0.10) = 475.30\ MT\ CH_4$$

$$\mathbf{CO_2U, gas\ collection} = \left(\left(\frac{1}{0.75} \times 3554.82\right) - 3554.82\right) + 0.10\left(\left(\frac{1}{0.75} \times 1584.35\right) - 1584.35\right) \times \frac{44}{16} = 1330.17\ MT\ CO_2$$

Equation N.3 can now be used to calculate the CO_2e emissions profile of the feedstock given that the gas was collected and combusted via flaring:

$$CO_2e\ emissions\ from\ MSW\ landfilling\ with\ gas\ collection$$

$$= 25(1584.35 - 1568.30 + 475.30) + \left(1568.50 \times \frac{44}{16}\right) + 3554.82 + 1330.17 = 21,477.06\ MT\ CO_2e$$

Step 4: Calculate the *BAF* Value

Bringing the numerator and the denominator into the *AVOIDEMIT* term and calculating the assessment factor equation (Equation N.1 and Equation N.2) results in:

BAF = AVOIDEMIT = 1 – (52,851.08 / 21,477.06)

$$BAF = -1.46$$

Negative *BAF* values, such as that calculated in Example 1, indicate that combustion of collected landfill gas feedstock by a stationary source results in a net CO_2e emissions reduction relative to releasing the collected landfill gas directly to the atmosphere without gas collection and combustion.

2.4.2. Example Calculations for a Controlled Landfill (EGU) Compared to an Uncontrolled Landfill

In this example, the same annual volume of landfill gas has been collected as in Section 2.4.1 and a *BAF* value is calculated for the treatment of collected gas via an EGU (denominator). The alternate treatment fate is similar to the numerator calculated in Section 2.4.1, thus the value of the numerator is the same as in Section 2.4.1. The denominator is also similar to that calculated in Section 2.4.1except that the gas DE is 0.97 instead of 0.99 because an EGU typically has a lower DE than a flare. The offsets from electricity generation by the EGU are not included in the framework.

Step 1—Calculate the CO_2e Emissions for MSW Landfilling without Gas Collection and Control

The numerator will be the same as that calculated in Example 1 when the same CE and OX values are used (Equations N.7 and N.10). Similar to Example 1, the net CO_2e emissions profile of the biogas feedstock had the gas not been collected and combusted is calculated using Equation N.3:

$$\boldsymbol{CO_2e\ emissions\ from\ MSW\ landfilling\ without\ gas\ collection}$$

$$= \mathbf{25(0 - 0 + 1901.22) + \left(0 \times \frac{44}{16}\right) + 0 + 5320.69 = 52,851.08}\ \boldsymbol{MT\ CO_2e}$$

Step 2—Calculate the CO_2e Emissions with Gas Collection and Control (EGU)

The denominator calculates the CO_2e emissions profile of the biogas feedstock had the biogas been collected and combusted in an EGU with a DE of 97%. Equation N.5 can be used to calculate the CH_4D term in Equation N.3:

$$\mathbf{CH_4D = 1584.35\ \times 0.97 = 1536.82\ MT}\ \boldsymbol{CH_4}$$

The quantities of indirect CH_4 and CO_2 (Equations N.6 and N.9) will be the same as those presented in Section 2.4.1:

$$\mathbf{CH_4U, gas\ collection} = \mathbf{\left(\left(\frac{1}{0.75} \times\ 1584.35\ \right) - \ 1584.35\ \right) \times\ (1 - 0.10) = 475.31}\ \boldsymbol{MT\ CH_4}$$

$$\mathbf{CO_2U, gas\ collection} = \mathbf{\left(\left(\frac{1}{0.75} \times 3554.82\right) - 3554.82\right) + \ 0.10\left(\left(\frac{1}{0.75} \times 1584.35\right) - 1584.35\right) \times \frac{44}{16} = 1330.17}\ \boldsymbol{MT\ CO_2}$$

Equation N.3 can now be used to calculate the CO_2e emissions profile of the feedstock given that the biogas was collected and combusted via an EGU:

$$CO_2e\ emissions\ from\ MSW\ landfilling\ with\ gas\ collection$$

$$= 25(1584.35 - 1536.82 + 475.30) + \left(1536.82 \times \frac{44}{16}\right) + 3554.82 + 1330.17$$
$$= 22,182.09\ MT\ CO_2e$$

Step 4: Calculate the *BAF* Value

Bringing the numerator and the denominator into the *AVOIDEMIT* term and calculating the assessment factor equation (Equations N.1 and N.2) results in:

BAF = AVOIDEMIT = 1 – (52,851.08 / 22,182.09)

BAF = -1.38

The *BAF* for this example is slightly greater than the *BAF* of −1.46 calculated in Section 2.4.1 as a result of the lower DE of the EGU relative to combustion using a flare.

2.4.3. Example Calculations for a Controlled Landfill (EGU) with a Gas Collection System Installed Mid-Way through the Year Compared to an Uncontrolled Landfill

In this example, the same annual volume of landfill gas has been collected as in Section 2.4.1 and 2.4.2. A *BAF* value is calculated for the treatment of collected gas via a gas collection system and EGU (denominator) that was operationalized midway through the year. The alternate treatment fate is similar to the numerator calculated in Section 2.4.1 and 2.4.2, thus the value of the numerator is the same as in Section 2.4.1 and 2.4.2. The method of calculating the denominator is different from that presented in Section 2.4.1 and 2.4.2in that an extra term has been added to account for the fraction of hours the gas collection system and control device operated during the year (fRec).

Step 1: Calculate the Amount of CH_4 and CO_2 Recovered by the Landfill Gas Collection System

The starting point for both treatment fates, the amount of gas recovered, is the same as Section 2.4.1 and 2.4.2 (Equations N.4 and N.8):

$$\mathrm{CH_4R} = 150,000,000 \times \frac{55}{100} \times 0.0423 \times \frac{520}{520} \times \frac{1}{1} \times \frac{0.454}{1,000} = 1584.35\ MT\ CH_4$$

$$\mathrm{CO_2R} = 150,000,000 \times \left(1 - \frac{55}{100}\right) \times 0.1160 \times \frac{520}{520} \times \frac{1}{1} \times \frac{0.454}{1,000} = 3554.82\ MT\ CO_2$$

Step 2: Calculate the Fraction of Hours the Recovery System Operated During the Year

fRec = actual operating hours of the recovery system/number of hours in the year

In this example, the gas collection system was installed and fully operational on May 1st in a non-leap year. There are 244 days between May 1st and December 31st, or 5856 hours. Therefore, fRec = 5856/8760 = 0.66849.

Step 3: Calculate the CO_2e Emissions for MSW Landfilling without Gas Collection and Control

Equations N.7 and N.10 are slightly modified by dividing the amount of recovered CH_4 and CO_2 by fRec to give Equations N.11 and N.12:

$$\mathbf{CH_4U, without\ gas\ collection} = \left(\frac{1}{CE} \times \frac{CH_4R}{fRec}\right) \times (1 - OX) \qquad \textbf{(EQ. N.21)}$$

$$\mathbf{CH_4U, without\ gas\ collection} = \left(\frac{1}{0.75} \times \frac{1584.35}{0.66849}\right) \times (1 - 0.10) = 2,837.64\ MT\ CH_4$$

$$\mathbf{CO_2U, without\ gas\ collection} = \frac{1}{CE} \times \frac{CO_2R}{fRec} + \left(OX \times \frac{1}{CE} \times \frac{CH_4R}{fRec}\right) \times \frac{44}{16} \qquad \textbf{(EQ. N.12)}$$

$$\mathbf{CO_2U, without\ gas\ collection} = \frac{1}{0.75} \times \frac{3554.82}{0.66849} + \left(0.10 \times \frac{1}{0.75} \times \frac{1584.35}{0.66849}\right) \times \frac{44}{16} = 7,941.32\ MT\ CO_2$$

Similar to Section 2.4.1 and 2.4.2, the net CO_2e emissions profile of the gas feedstock had the gas not been collected and combusted is calculated using Equation N.3:

CO_2e emissions from MSW landfilling without gas collection =

$$25(0 - 0 + 2837.64) + \left(0 \times \frac{44}{16}\right) + 0 + 7941.32 = 78,882.21\ MT\ CO_2e$$

Step 4: Calculate the CO_2e emissions with gas collection and control (EGU)

The denominator calculates the CO_2e emissions profile of the gas feedstock had the biogas been collected and combusted in an EGU with a DE of 97%. Equation N.5 can be used to calculate the CH_4D term in Equation N.3:

$$\mathbf{CH_4D} = 1584.35 \times 0.97 = 1536.82\ \mathrm{MT}\ CH_4$$

The quantities of indirect CH_4 and CO_2 (Equations N.6 and N.9) will be the similar to those presented in Examples 1 and 2, except that fRec must now be factored into Equations N.6 and N.9 to give Equations N.13 and N.14:

$$\mathbf{CH_4U, gas\ collection} = \left(\left(\frac{1}{CE} \times \frac{CH_4R}{fRec}\right) - CH_4R\right) \times (1 - OX) \qquad \textbf{(EQ. N.33)}$$

$$\mathbf{CH_4U, gas\ collection} = \left(\left(\frac{1}{0.75} \times \frac{1584.35}{0.66849}\right) - 1584.35\right) \times (1 - 0.10)$$
$$= 1418.12\ MT\ CH_4$$

$$\mathbf{CO_2U, without\ gas\ collection} = \frac{1}{CE} \times \frac{CO_2R}{fRec} + \left(OX \times \frac{1}{CE} \times \frac{CH_4R}{fRec}\right) \times \frac{44}{16} \qquad \textbf{(EQ. N.44)}$$

$$\mathbf{CO_2U, gas\ collection} = \left(\left(\frac{1}{0.75} \times \frac{3554.82}{0.66849}\right) - 3554.82\right) +$$
$$0.10\left(\left(\frac{1}{0.75} \times \frac{1584.35}{0.6649}\right) - 1584.35\right) \times \frac{44}{16} = 3950.81\ MT\ CO_2$$

Equation N.3 can now be used to calculate the CO_2e emissions profile of the feedstock given that the biogas was collected and combusted via an EGU:

CO_2e emissions from MSW landfilling with gas collection

$$= 25\ (1584.35 - 1536.82 + 1411.72) + (1536.82 \times 44/16) + 3554.82 + 3950.81 = 48{,}213.22 \text{ MT } CO_2e$$

Step 5: Calculate the *BAF* Value

Bringing the numerator and the denominator into the *AVOIDEMIT* term and calculating the assessment factor equation (Equation N.1 and N.2) results in:

$$BAF = AVOIDEMIT = 1 - (78{,}882.21 / 48{,}213.22)$$

$$BAF = -0.64$$

The *BAF* for this example is approximately two and a half times greater than the *BAF* of −1.50 calculated in Section 2.4.2 as a result of the fraction of hours the gas collection and control system were operational during the year.

2.5. Sensitivity Analysis for MSW Landfill Biogas

A simple sensitivity analysis is presented to better understand the relationship between and impact of certain key parameters in the framework for MSW landfilling. Key parameters specific to MSW landfilling include the oxidation fraction (OX), the collection efficiency (CE) of the landfill gas collection system, the destruction efficiency (DE) of the selected combustion device, and the CH_4 GWP used (i.e., 21, 25, or 28). Table N-5 presents the range of *BAF* values after modifying the key parameters and using the inputs from Example 2-1 in Section 2.3 of this appendix. Sources for the parameter values used here can be found in Table N-4 of Section 2.3.2. The actual fate is MSW landfilling with flaring and the alternate fate is MSW landfilling without gas collection and combustion.

Two categories of analyses are presented in Table N-5: the first (1a through 1d) compares the impact of modifying the CE and DE values, while the second (2a through 2d) compares the impact of modifying all 3 key parameters. In the second set of analyses, a value for OX other than the representative value of 0.10 was used in the actual fate (i.e., denominator) calculations. The only difference between the a, b, c, and d analyses is the change in OX factors. For example, when comparing Analyses 1a and 2a, the only difference is that 1a uses an OX of 0.10 for both the actual and alternate fates, while 2a uses different OX values for each fate. Analyses 2a, b, c, and d yield lower *BAF* values than Analyses 1a, b, c, and d. Analysis 2c yields the lowest *BAF* values and Analysis 1b yields the highest *BAF* value. Despite modifying the key parameters, all *BAF* values are negative.

Table N-5. Sensitivity Analysis for MSW Landfilling.

Analysis	Key Parameter and Value			BAF		
	OX	CE	Flare DE	GWP=21	GWP=25	GWP=28
1a	0.10	0.75	0.99	−1.319	−1.461	−1.551
2a	Without GCS = 0.10 With GCS = 0.25	0.75	0.99	−1.504	−1.681	−1.795
1b	0.10	0.75	0.98	−1.285	−1.421	−1.508
2b	Without GCS = 0.10 With GCS = 0.25	0.75	0.98	−1.465	−1.634	−1.743
1c	0.10	0.95	0.99	−2.577	−3.031	−3.352
2c	Without GCS = 0.10 With GCS = 0.25	0.95	0.99	−2.660	−3.143	−3.485
1d	0.10	0.75	0.99	−1.319	−1.461	−1.551
2d	Without GCS = 0.10 With GCS = 0.25	0.75	0.99	−1.719	−1.940	−2.086

Note: References for the key parameters and values are presented in Table N-4 of Section 2.3.2.
Note: Methane is a potent GHG, with a 100-year GWP of 21 (IPCC, 1996). It should be noted that in the IPCC Fourth Assessment Report, the 100-year GWP of CH_4 was revised to 25 (IPCC, 2007). To comply with international reporting standards under the UNFCCC, official emission estimates reported by the United States use the IPCC Second Assessment Report GWP values (IPCC, 1996). The United States will transition to using the revised GWPs beginning in 2015. In this framework, the GWP of 25 for the central examples within each section. The GWPs of 21 and 28 are used in the sensitivity analyses for each section.

3. Disposal of Biogenic MSW through Combustion and Associated GHG Emissions Pathways

As an alternative to disposing of MSW in a landfill, it can be directly combusted in waste-to-energy facilities to generate electricity. In the United States, almost all incineration of MSW occurs at waste-to-energy facilities or industrial facilities where energy is recovered (EPA, 2014b). Based on data from EPA's Greenhouse Gas Reporting Program (GHGRP) and EPA's Emissions and Generation Resource Integrated Database (eGRID), there are roughly 142 MSW combustors in the United States that emit approximately 30 million metric tons of biogenic CO_2e.[11] Incineration oxidizes almost all of the carbon in the MSW to CO_2 (Astrup et al., 2009). Generally less than 0.5% of the carbon remains in the ashes (i.e., it is not emitted to the atmosphere, Astrup et al., 2009).

Although MSW consists mainly of biogenic resources such as food, paper, and wood products, it also includes resources derived from fossil fuels, such as tires[12] and plastics. After the MSW is delivered

[11] Based on GHGRP data for the 2011 reporting year and eGRID data for the 2009 reporting year.
[12] Tires contain a biogenic component in the form of natural rubber. Whole tires (including steel, etc.) from the combined grouping of passenger vehicles and trucks are, on average, composed of 28% natural rubber (Rubber Manufacturers Association, unpublished data 2013). Tire-derived-fuel is used in cement kilns, utility boilers, pulp and paper mills, industrial boilers, and dedicated scrap tire-to-energy facilities (EPA 2009b).

to a stationary source facility, it is incinerated in an EGU either "as is" (mass burn without recovery of recyclables), as refuse-derived fuel (burn after recyclables have been recovered), or combustion with energy recovery of source separated materials in MSW (e.g., wood pallets and tire-derived fuel; EPA, 2009b). Point source stack emissions from combustion of biogenic MSW feedstocks are primarily CO_2. For the purposes of this document, biogenic MSW is the feedstock when disposed of in a combustor.

3.1. Method for Calculating an Illustrative *BAF* Value for Biogenic Emissions Resulting From MSW Combustion

The assessment factor equation can be applied to direct biogenic CO_2 emissions from MSW combustion. This section provides an illustrative method for calculating a *BAF* value that is applied to direct biogenic CO_2 emissions from MSW combustors. Here, the biogenic feedstock is MSW that is collected and incinerated, oxidizing the biogenic waste-feedstock to CO_2 emissions.

Landfilling the biogenic MSW can be considered the alternate fate of the MSW feedstock had it not been incinerated. The emissions profile resulting from this alternate fate represents the numerator of the emissions ratio term in *AVOIDEMIT*. Were the MSW to have been disposed of in a landfill, it would undergo anaerobic decomposition, resulting in biogas that may or may not be collected and destroyed by combustion. However, a portion of the carbon in the biogenic waste-derived feedstock does not decompose in the landfill; instead that carbon is stored in the landfill. Such storage effectively removes the remaining landfilled carbon from the global carbon cycle by transferring that carbon into long-term storage within a landfill (Staley and Barlaz, 2009).[13] The factors affecting degradation can result in the long-term, potentially permanent, carbon storage of approximately 50% of total landfilled organic carbon (Bogner et al., 2007; Manfredi et al., 2009).

In applying the assessment factor equation, net GHG emissions reductions are accounted for in the *AVOIDEMIT* term. In practice, as applied here, the *AVOIDEMIT* term is a ratio expressed as tCO_2e avoided (i.e., the emissions, in CO_2e, of the MSW had it not been combusted) per tCO_2e removed via combustion (i.e., the emissions, in CO_2e, of the combusted MSW). For the MSW feedstock incinerated in an MSW combustor, the *AVOIDEMIT* term can be conceptually expressed by the simplified ratio of:

$$\boldsymbol{AVOIDEMIT = 1 - \frac{(\text{emissions from non-combustion treatment of MSW})}{(\text{emissions from MSW combustion})}} \qquad \textbf{(EQ. N.15)}$$

3.1.1. Calculating the Numerator

In computing *AVOIDEMIT*, the numerator (i.e., emissions from MSW treatment alternative to incineration) can be calculated under the assumption that had the MSW not been incinerated, it

[13] While cellulose, hemicellulose, and lignin (present in paper and wood products) can degrade and be converted to CH_4 in landfills, the anaerobic conditions in landfills prevent their full degradation (Bogner, 1992; Barlaz, 2006; Wang et al., 2011). Furthermore, the presence of lignin can inhibit cellulose and hemicellulose degradation (Micales and Skog, 1997; Barlaz, 2006). Because lignins effectively prevent degradation, between 84% and 100% of the initial carbon in landfilled wood products is sequestered indefinitely (Micales and Skog, 1997; Wang et al., 2011). The extent of decomposition varies between types of wood (Wang et al., 2011).

would have been landfilled. Given this alternate fate, the value of the numerator must account for the fraction of landfilled MSW that decays anaerobically, thereby producing landfill gas that may or may not be collected. If the landfill gas is collected and combusted (e.g., flared), the collection efficiency and destruction efficiency must be accounted for. In accounting for indirect emissions from the landfill cap, the CH_4 oxidation via the landfill cover soils must be accounted for. And finally, the fraction of landfilled MSW that does not decay such that biogenic carbon is stored within the landfill must also be accounted for. The following equation can be used in the numerator of the *AVOIDEMIT* term:

CO_2e emissions avoided by landfilling the MSW (kg CO_2e/metric ton MSW wet weight) =

$$\mathbf{GWP_{CH_4} \times (CH_{4soils} + CH_{4combustion}) + CO_{2soils} + CO_{2combustion}} \quad \textbf{(EQ. N.16)}$$

Where:

GWP_{CH_4} = 100-year GWP of CH_4, 25 (IPCC, 2007)

$$\mathbf{CH_{4soils} = CH_{4generated} \times (1 - CE) \times (1 - OX)} \quad \textbf{(EQ. N.57)}$$

$$\mathbf{CH_{4combustion} = CH_{4generated} \times (CE) \times (1 - DE)} \quad \textbf{(EQ. N.68)}$$

Where:

$$\mathbf{CH_{4generated} = C \times D_{lfg} \times (\%CH_4) \times (16/12)} \quad \textbf{(EQ. N.79)}$$

C = amount of biogenic C in MSW (kg C/metric ton MSW wet weight).

D_{lfg} = dissimilation coefficient (fraction of biogenic C that leaves the landfill via decomposition of biogenic waste).

$\%CH_4$ = proportion of gas that is CH_4.

(16/12) = molecular weight ratio of CH_4 to C.

CE = gas collection efficiency.

OX = CH_4 oxidation factor associated with the landfill cover soil.

DE = gas destruction efficiency (i.e., combustion efficiency of flare or EGU).

$$\mathbf{CO_{2soils} = (CO_{2generated} + CH_{4generated} \times 44/16 \times OX) \times (1 - CE)} \quad \textbf{(EQ. N.20)}$$

$$\mathbf{CO_{2combustion} = (CO_{2generated} + CH_{4generated} \times 44/16 \times DE) \times CE} \quad \textbf{(EQ. N.21)}$$

Where:

$$\mathbf{CO_{2generated} = C \times D_{lfg} \times (\%CO_2) \times (44/12)} \quad \textbf{(EQ. N.82)}$$

Where:

C = amount of biogenic C in MSW (kg C/metric ton MSW wet weight).

D_{lfg} = dissimilation coefficient (fraction of biogenic C that leaves the landfill via decomposition of biogenic waste).

$(\%CO_2)$ = proportion of gas that is CO_2.

(44/12) = molecular weight ratio of CO_2 to C.

CE = gas collection efficiency.

OX = CH_4 oxidation factor associated with the landfill cover soil.

DE = gas destruction efficiency (i.e., combustion efficiency of flare or EGU).

3.1.2. Calculating the Denominator

In the derivation of *AVOIDEMIT* (Equation N.15), the denominator (i.e., emissions from MSW combustion) is based on the carbon content of the point source, stack emissions from the MSW combustion device. The value of the denominator is equal to the CO_2e of the combusted MSW, adjusted by the proportion of combusted biogenic carbon in MSW that is converted from C to CO_2. MSW combustion results in near-complete oxidation of C to CO_2; generally less than 0.5% of the initial amount of C remains in solid form (ash) post-combustion. The following equation can be used to calculate the total CO_2e emissions from MSW combustion (the denominator of the *AVOIDEMIT* term):

CO_2e emissions from MSW combustion (kg CO_2e/metric ton MSW wet weight) =

$$C \times 0.995 \times (44/12) \qquad \textbf{(EQ. N.93)}$$

Where:

C = amount of biogenic C in MSW (kg C/metric ton MSW wet weight).

0.995 = proportion of C in MSW that is oxidized through combustion (i.e., combustion efficiency).

(44/12) = molecular weight ratio of CO_2 to C.

After solving for the numerator and the denominator of the *AVOIDEMIT* term, the *BAF* value can be calculated using Equation N.1. See Section 3.2 for an illustrative example calculation of the numerator and denominator in the *AVOIDEMIT* term and its subsequent application in estimating a *BAF* value.

Several parameters are presented and used in the equations in the remainder of this section. Table N-6 presents the parameters used, typical or default values, ranges presented in the literature, and references.

Table N-6. Summary of Parameters Used When Calculating an Illustrative *BAF* for MSW Combustion.

Parameter Description	Symbol	Value	Range	Units	Comments	Reference (for value column)
Oxidation fraction	OX	0.10	0.10 to 0.35	Fraction	0.10 is the default used in many accounting methodologies	IPCC, 2006
Percent of CH_4 or CO_2 in the landfill gas	$\%CH_4$, $\%CO_2$	0.55	0.45 to 0.60	Percent		IPCC, 2006
Collection efficiency	CE	0.75	0.60 to 0.95	Fraction	Higher CEs are associated with closed landfills and well-designed systems with low permeable covers	EPA, 2010b; EPA, 2013c
Destruction efficiency (of a landfill gas flare or EGU)	DE	0.99	0.90 to 0.9977	Fraction	0.99 is considered the default DE of CH_4 for a flare; EGUs may be slightly less	EPA, 2011a; EPA, 2013c
Fraction of biogenic carbon in MSW	C	90	Dependent on the composition of the MSW	Kilograms Carbon per metric ton of MSW, wet weight		Staley and Barlaz, 2009
Dissimila-tion coefficient	Dlfg	0.50	–	Percent	50% of the biogenic carbon in the MSW goes into long-term storage	IPCC, 2006
Combustion efficiency of an MSW combustor	–	0.995	0.98 to 0.9999	Fraction	The proportion of carbon in MSW that is oxidized through combustion	IPCC, 2006; Astrup et al., 2009

3.2. Example *AVOIDEMIT* and *BAF* Calculations for MSW Combustion

Two example scenarios are presented here for calculating a *BAF* value for MSW combustion compared to an alternate of landfilling with gas collection and an alternate of landfilling without gas collection. A hypothetical example is used to calculate *AVOIDEMIT* and the *BAF* for MSW combustion. Actual *AVOIDEMIT* and the *BAF* values will vary depending on the specific circumstances of MSW combustion and its alternate fate.

3.2.1. Example Calculations for MSW Combustion Compared to a Landfill with Gas Collection (EGU)

Equation N.16 can be used to calculate the numerator of the *AVOIDEMIT* term, but Equations N.17 through N.22 must be calculated first in order to solve for Equation N.16. To solve for the numerator, emissions from non-combustion treatment of MSW, it will be assumed that had the MSW not been combusted then it would have been landfilled, thereby producing biogas. Some of the biogas would have been collected and combusted, some would have been oxidized via the landfill cover soils, and the remainder would have been an indirect emission. All of these emission pathways are considered here because the feedstock for combustion of biogenic MSW is the biogenic MSW.

For this hypothetical example, the following conditions apply:

- The amount of biogenic carbon in MSW is estimated at 90 kg C/metric ton MSW wet weight (ww) (i.e., C = 90).
- The amount of biogenic carbon leaving the landfill is estimated at 50% (D_{lfg} = 0.5), such that 50% goes into long-term storage.
- On a mass basis, 55% of the carbon becomes CH_4 and 45% of the carbon becomes CO_2.
- The fraction of CH_4 in the landfill gas that is oxidized via cover soils is the default of 0.10 (OX = 0.1).
- Landfill gas collection efficiency is 75% (CE = 0.75).
- Destruction efficiency of the collected landfill gas is 99% (DE = 0.99).

Step 1: Calculate the CH_4 and CO_2 Generated and Emitted by a Landfill with Gas Collection and Combustion in an EGU

To calculate the numerator, Equations N.19 and N.22 must first be solved:

$$\mathbf{CH_{4generated} = 90\ kg\ C\ per\ metric\ ton\ MSW\ ww \times 0.5 \times (55/100) \times (16/12)}$$

$$\mathbf{= 33.0\ kg\ CH_4\ per\ metric\ ton\ MSW\ ww}$$

$$\mathbf{CO_{2generated} = 90\ kg\ C\ per\ metric\ ton\ MSW\ ww \times 0.5 \times (45/100) \times (44/12)}$$

$$\mathbf{= 74.25\ CO_2\ per\ metric\ ton\ MSW\ ww}$$

Using the computed value from Equation N.19, Equation N.17 can be solved:

$$\mathbf{CH_{4soils} = 33.0 \times (1 - 0.75) \times (1 - 0.1)}$$

$$\mathbf{= 7.425\ kg\ CH_4\ per\ metric\ ton\ MSW\ ww}$$

Using the computed value from Equation N.19, Equation N.18 can be solved:

$$\mathbf{CH_{4combustion} = 33.0 \times (0.75) \times (1 - 0.99)}$$

$$\mathbf{= 0.2475\ kg\ CH_4\ per\ metric\ ton\ MSW\ ww}$$

Using the computed values from Equations N.19 and N.22, Equation N.20 can be solved:

$$\mathbf{CO_{2soils} = (74.25 + (33.0 \times 44/16 \times 0.1)) \times (1 - 0.75)}$$

$$\mathbf{= 20.8312\ kg\ CO_2\ per\ metric\ ton\ MSW\ ww}$$

Using the computed values from Equations N.19 and N.22, Equation N.21 can be solved:

$$\mathbf{CO_{2combustion} = (74.25 + (33.0 \times 44/16 \times 0.99)) \times 0.75}$$

$$\mathbf{= 123.0694\ kg\ CO_2\ per\ metric\ ton\ MSW\ ww}$$

Using the computed values from Equations N.17, N.18, N.20, and N.21, the numerator (i.e., Equation N.16) can be solved:

CO_2e emissions avoided by not having landfilled the MSW (kg CO_2e/metric ton MSW ww)

$$\mathbf{= 25 \times (7.425 + 0.2475) + 20.8312 + 123.0694}$$

$$\mathbf{= 335.713\ kg\ CO_2e\ per\ metric\ ton\ MSW\ ww}$$

Step 2: Calculate the CO_2 Emitted Through MSW Combustion

Next, the denominator (total CO_2e emissions from MSW combustion) of the *AVOIDEMIT* term can be solved (kg CO_2e/metric ton MSW wet weight) using Equation N.23:

CO_2e emissions from MSW combustion

$$\mathbf{= 90 \times 0.995 \times (44/12)}$$

$$\mathbf{= 328.350}$$

Step 3: Calculate the *BAF* Value

Next, the *AVOIDEMIT* term can be computed and input into the assessment factor equation (Equations N.1 and N.2):

$$BAF = AVOIDEMIT$$

$$= 1 - (335.711 / 328.350)$$

$$= -0.022$$

It should be noted that this calculation does not take into account any reduction in fossil fuel usage as a result of any heat, power, or both that may have been generated in the MSW incineration process.

3.2.2. Example Calculations for MSW Combustion Compared to a Landfill without Gas Collection

If the alternate fate of the MSW had been landfilled without gas collection or combustion, then CH_{4soils} and CO_{2soils} would increase in value while $CH_{4combustion}$ and $CO_{2combustion}$ would both be 0.

Step 1: Calculate the CH_4 and CO_2 Generated and Emitted by a Landfill without Gas Collection

To calculate the numerator, Equations N.19 and N.22 must first be solved:

$$CH_{4generated} = 90 \text{ kg C per metric ton MSW ww} \times 0.5 \times (55/100) \times (16/12)$$

$$= 33.0 \text{ kg } CH_4 \text{ per metric ton MSW ww}$$

$$CO_{2generated} = 90 \text{ kg C per metric ton MSW ww} \times 0.5 \times (45/100) \times (44/12)$$

$$= 74.25 \ CO_2 \text{ per metric ton MSW ww}$$

Using the computed value from Equation N.19, Equation N.17 can be solved. The collection efficiency is 0 in this equation since there is no gas collection system.

$$CH_{4soils} = 33.0 \times (1 - 0) \times (1 - 0.1)$$

$$= 29.7 \text{ kg } CH_4 \text{ per metric ton MSW ww}$$

Using the computed values from Equations N.19 and N.22, Equation N.20can be solved:

$$CO_{2soils} = (74.25 + (33.0 \times 44/16 \times 0.1)) \times (1 - 0)$$

$$= 83.325 \text{ kg } CO_2 \text{ per metric ton MSW ww}$$

Using the computed values from Equations N.17 and N.20 the numerator (i.e., Equation N.16) can be solved:

CO_2e emissions avoided by not having landfilled the MSW (kg CO_2e/metric ton MSW ww)

$$= 25 \times (29.7 + 0) + 83.325 + 0$$

$$= 825.825 \text{ kg } CO_2e \text{ per metric ton MSW ww}$$

Step 2: Calculate the CO_2e Emitted Through MSW Combustion

Next, the denominator (total CO_2e emissions from MSW combustion) of the *AVOIDEMIT* term can be solved (kg CO_2e/metric ton MSW wet weight) using Equation N.23:

CO_2e emissions from MSW combustion

$$= 90 \times 0.995 \times (44/12)$$

$$= 328.350$$

Step 3: Calculate the *BAF* Value

Next, the *AVOIDEMIT* term can be computed and input into the assessment factor equation (Equations N.1 and N.2):

$$BAF = AVOIDEMIT$$

$$= 1 - (825.825 / 328.350)$$

$$= -1.52$$

It should be noted that this calculation does not take into account any reduction in fossil fuel usage as a result of any heat, power, or both that may have been generated in the MSW incineration process.

3.3. Sensitivity Analysis for MSW Combustion

A simple sensitivity analysis on the key parameters in the MSW combustion methodology is presented in Table N-7 for the actual fate of MSW combustion and the alternate fate of landfilling with gas collection and flaring. Key parameters impacting the *BAF* include the destruction and collection efficiencies (DE and CE, respectively) and the GWP for CH_4 (21, 25, and 28). In each of the six analyses, the DE of the landfill gas was adjusted between 97% and 99%, and the CE was adjusted 60% to 95%, representing a range of low to high performing landfill gas collection system efficiencies. Sources for the parameter values used here can be found in Table N-6 of Section 3.1.2. The inputs used in the analyses are equivalent to those shown in the example calculations in Section 3.2 of this appendix. Note that the carbon content of the MSW does not impact the calculated *BAF* values because it is a factor in both treatment fates and essentially cancels out.

The *BAF* values are most negative compared to the other analyses, when MSW combustion is compared to a landfill with a 75% CE and 97% DE, indicating that MSW combustion results in a greater reduction of CO_2e emissions (see Analysis 4, regardless of the GWP value). Alternatively, the most positive *BAF* value is generated when MSW combustion is compared to a highly efficient landfill gas collection and combustion system (i.e., Analysis 6).

Analyses 7 through 12 highlight the areas where the *BAF* value changes from negative to positive as a result of the CE for each GWP value when the DE is held constant at 99%. The *BAF* values were all negative when a DE of 97% was held constant despite the changes in CE and GWP.

Table N-7. Sensitivity Analysis for MSW Combustion.

Analysis	Key Parameter and Value		*BAF*		
	CE	DE	GWP=21	GWP=25	GWP=28
1	0.60	0.99	−0.174	−0.321	−0.431
2	0.60	0.97	−0.196	−0.348	−0.462
3	0.75	0.99	−0.141	−0.022	−0.386
4	0.75	0.97	−0.241	−0.395	−0.510
5	0.95	0.99	0.398	0.376	0.359
6	0.95	0.97	−0.302	−0.458	−0.575
7a	0.70	0.99	−0.011		
8 a	0.71	0.99	0.006		
9b	0.76	0.99		−0.003	
10 b	0.77	0.99		0.017	
11c	0.79	0.99			−0.002
12 c	0.80	0.99			0.020

[a] The point at which the *BAF* changes from negative to positive with a GWP of 21.
[b] The point at which the *BAF* changes from negative to positive with a GWP of 25.
[c] The point at which the *BAF* changes from negative to positive with a GWP of 28.
Note: References for the key parameters and values are presented in Table N-6 of Section 3.1.2.

4. Livestock Waste Management through Anaerobic Processes and Associated GHG Emissions Pathways

Livestock waste management can produce CH_4, CO_2, and N_2O emissions. In 2012, livestock waste management emissions in the United States were estimated at 52.9 Tg CO_2e for CH_4;[14] and 18.0 Tg CO_2e for N_2O (EPA, 2014b). Waste from dairy cattle and swine had the highest CH_4 emissions; waste from beef and dairy cattle had the highest N_2O emissions (EPA, 2014b).

Methane is produced under anaerobic conditions in livestock waste storage and treatment systems, such as liquids or slurries in lagoons, ponds, tanks, pits, or piles. In the United States, the majority of livestock waste is handled as a solid (e.g., in stacks or drylots) or deposited on pasture, range, or paddock lands, where it tends to decompose aerobically and produce little or no CH_4 (EPA, 2014b). Carbon dioxide is also produced under anaerobic conditions and generated when CH_4 in the biogas is combusted.

Both direct and indirect N_2O emissions are emitted during livestock waste management. Direct N_2O emissions from livestock waste are produced as part of the nitrogen cycle through the nitrification and denitrification of the organic nitrogen in livestock dung and urine. The production of direct N_2O emissions from livestock waste depends on the composition of the manure and urine, the type of

[14] This accounts for CH_4 reductions due to capture and destruction of CH_4 at facilities using anaerobic digesters.

bacteria involved in the process, and the amount of oxygen and liquid in the waste management system.

- For direct N_2O emissions to occur, the manure must first be handled aerobically where ammonia (NH_3) or organic N is converted, via nitrification, to nitrates and nitrites, and then handled anaerobically where the nitrates and nitrites are reduced to dinitrogen gas (N_2), with intermediate production of N_2O and nitric oxide (NO), via denitrification (EPA, 2014b). These emissions are most likely to occur in dry manure handling systems that have aerobic conditions, but that also contain pockets of anaerobic conditions due to saturation. A very small portion of the total N excreted is expected to convert to N_2O in the waste management system.
- Indirect N_2O emissions are produced when nitrogen is lost from the system through volatilization (as NH_3 or NO_x) or through runoff and leaching of nitrogen during waste treatment, storage and transportation (EPA, 2014b). The vast majority of volatilization losses from these operations are NH_3 (EPA, 2014b).

The framework does not consider N_2O emissions; therefore the methodology presented in the remainder of this section does not consider N_2O emissions.

With the rise of concentrated animal feeding operations (CAFOs), the traditional use of livestock waste as a soil amendment (where it decomposes aerobically) is not practical (Santoianni et al., 2008).[15] As a result, the use of liquid-based management systems (e.g., uncovered lagoons, pits, anaerobic digesters) that promote anaerobic conditions is increasing in popularity (EPA, 2014b). There are two general pathways for GHG emissions from anaerobic management of livestock waste:[16]

- *Uncontrolled anaerobic storage and treatment*, typically in an uncovered pit or lagoon; and
- *Anaerobic digestion*, with capture and destruction of the generated biogas.

Under uncontrolled anaerobic storage and treatment systems, livestock wastes are typically deposited as a liquid slurry in uncovered lagoons, pits, ponds, or open tanks. This storage practice results in significant indirect CH_4 emissions (EPA, 2009b). Volatile solids contained in livestock waste degrade under anaerobic conditions, thus generating CH_4 biogas. If the biogas produced in uncovered lagoons, pits, ponds, or open tanks is not collected, it is released directly to the atmosphere.

Livestock waste management using anaerobic digesters allows the generated biogas to be captured and destroyed. Anaerobic digesters used for livestock waste management range in technology from contained vessels to covered lagoons. Anaerobic digesters are designed and operated for waste stabilization resulting from the microbial reduction of complex organic compounds to CO_2 and CH_4.

---

[15] Aerobic management of manure may include dry lots (including feedlots), high-rise houses for poultry production (poultry without litter), poultry production with litter, deep bedding systems for cattle and swine, manure composting, aerobic treatment units, and field spreading of manure as a soil amendment.
[16] Food waste from industrial and commercial food processing may also be managed through these approaches.

The decomposition process occurs much faster and is more complete in an anaerobic digester than in an uncontrolled anaerobic storage lagoon (Manfredi and Christensen, 2009). As a result, anaerobic digesters have higher rates of CO_2 and CH_4 generation. The increase in waste degradation and stabilization is mainly accomplished by recirculating the collected leachate within the anaerobic digester. This process enhances microbial degradation of complex organic compounds to simple organics and gaseous biogas products (primarily CO_2 and CH_4).

The vast majority of anaerobic digesters used for livestock waste treatment in the United States collect the biogas for energy use, but flaring of the gas is also practiced (EPA, 2012c, 2013b). Combustion of the biogas produced in an anaerobic digester destroys (via oxidation) most of the CH_4 contained in biogas; the primary resulting emission is CO_2.[17] The 192 anaerobic digester systems used for livestock waste management in the United States avoid an estimated 1.3 million metric tons CO_2e, annually compared to other livestock waste management options (EPA, 2013b). Although the use of anaerobic digesters is increasing in the United States, they are still in limited use considering the number of livestock operations, and are found primarily on large-scale livestock operations. By the end of 2011, approximately 2% of U.S. livestock operations used anaerobic digesters in waste management (EPA, 2012c).

Because anaerobic digesters are designed to enhance CH_4 generation, poor design, operation, or maintenance of anaerobic digesters can result in significant indirect CH_4 emissions. For example, CH_4 can leak from a digester cover or can be vented during digester start-ups, shutdowns, and malfunctions (Bogner et al., 2007; EPA, 2008b; Climate Action Reserve, 2013). However, under normal working conditions, GHG emissions from controlled biological treatment in an anaerobic digester are small relative to indirect CH_4 emissions from uncontrolled anaerobic storage and treatment systems (Bogner et al., 2007, and references therein). As a consequence, using anaerobic digester systems with biogas combustion typically results in substantial net GHG emissions reductions compared to conventional livestock waste storage and treatment, particularly for liquid wastes.

4.1. Method for Calculating an Illustrative *BAF* Value Applied to Biogenic Emissions Resulting from Anaerobic Digestion of Livestock and Food Waste

The assessment factor equation can be applied to point source biogenic CO_2 emissions from an anaerobic digester used to store and treat livestock or food waste.[18] This section provides an illustrative method for calculating a *BAF* value that is applied to point source biogenic CO_2 emissions from anaerobic digesters used to manage livestock waste.

---

[17] Because biogas destruction is not 100% efficient, some CH_4 is released without combustion (EPA, 2009b).

[18] In concept, food waste and yard trimmings managed in an anaerobic digester can be treated similarly to livestock waste managed in an anaerobic digester. However, the focus of this section is on livestock waste. With additional data, biogenic emissions from food waste and yard trimmings could be calculated. Data needs include the total volatile content of food waste and yard trimmings (may vary within and across regions), the proportion of carbon in the volatile matter, and the maximum CH_4 producing capacity of food waste and yard trimmings managed in an anaerobic digester.

Here, the biogenic feedstock is biogas that is collected from an anaerobic digester. As described previously, biogas combustion, whether the biogas is flared or used as a fuel to generate energy, oxidizes the CH_4 contained in the biogas to CO_2. The destruction of CH_4 results in a net reduction of GHG emissions relative to a scenario in which biogas produced through the anaerobic storage and treatment of livestock waste is not captured and combusted, but instead is released to the atmosphere as an indirect emission.

Equation N.1, $BAF = AVOIDEMIT$, can be used to calculate a BAF value for anaerobic digestion of livestock waste. The $AVOIDEMIT$ term is used to represent the net CO_2e emissions reductions that are achieved through biogas capture and combustion. The $AVOIDEMIT$ term accounts for net CO_2e emissions reductions relative to the alternative emissions pathway of indirect CH_4 and CO_2 emissions (i.e., as a result of uncontrolled, anaerobic storage and treatment of livestock waste without biogas collection and combustion).

In practice, as applied here, the $AVOIDEMIT$ term is a ratio expressed as tCO_2e avoided (i.e., the emissions, in CO_2e, that would have occurred had the livestock waste been managed in a waste management system other than an anaerobic digester) per tCO_2e emitted via combustion (i.e., the emissions, in CO_2e, of the combusted biogas that was generated in an anaerobic digester, after accounting for both the combustion efficiency of the biogas destruction device and any losses of biogas from the anaerobic digester[19]). For the biogas feedstock collected from anaerobic digesters, the $AVOIDEMIT$ term can be conceptually expressed as:

$$\boldsymbol{AVOIDEMIT} =$$

$$\mathbf{1} - \frac{(\textbf{emissions from livestock waste management system alternative to an anaerobic digester})}{(\textbf{emissions from combustion of biogas generated in an anaerobic digester})} \qquad \textbf{(EQ N.24)}$$

4.1.1. Calculating the Numerator

In computing $AVOIDEMIT$, the numerator (i.e., emissions from a livestock waste management system alternative to an anaerobic digester) can be calculated by assuming that if an anaerobic digester were not used to manage livestock waste, then this waste would have been managed under a different waste management option,[20] such as an uncovered anaerobic lagoon. The CH_4 that would have been generated under this alternative fate can be estimated using methods presented in IPCC (2006b) and EPA (2009b). Equation N.25 can be used to estimate the annual CO_2 and CH_4 emissions

---

[19] Biogas losses can occur from indirect CH_4 emissions from an anaerobic digester could occur as a result of leaks from a digester cover or through venting during digester start-ups, shutdowns, and malfunctions. Biogas leaks may occur prior to delivery of the collected biogas to the combustion unit for CH_4 destruction, leaks may occur as CH_4 emissions from digester effluent, or as a result of remaining undigested volatile solids.

[20] There are multiple livestock waste management scenarios alternative to using an anaerobic digester. Of these alternatives, aerobic treatment would produce the least amount of CH_4 (zero CH_4 production) whereas an uncovered anaerobic lagoon would generate the most (see EPA 2009b, Table A-3). Depending on ambient temperature, CH_4 production in an uncovered anaerobic lagoon ranges from 66% to 80% of the maximum amount of CH_4 that could potentially be produced from the livestock waste. The appropriate alternative livestock waste management scenario should be used when this calculation is made.

resulting from a livestock waste management strategy other than an anaerobic digester (e.g., had the waste been managed using an uncovered anaerobic lagoon).

Total CO_2e emissions from a livestock waste management other than anaerobic digestion =

$$\textbf{(avoided } CO_2 \textbf{ emissions) + (avoided } CH_4 \textbf{ emissions)} \qquad \textbf{(EQ. N.25)}$$

The avoided CO_2 emissions from a livestock waste management alternate to anaerobic digestion is equal to the degradable carbon in the volatile solids of the livestock waste after removing the amount of carbon which becomes CH_4 and then converting the remaining available carbon to CO_2 as done using Equation N.26:

Avoided CO_2 emissions (metric tons CO_2e/year) =

$$[(P_{CO_2} \times 12/44) - (Avoided_{CH_4}/GWP_{CH_4} \times 12/16)] \times (44/12) \qquad \textbf{(EQ. N.26)}$$

Where:

P_{CO_2} = Potential maximum CO_2 emissions if all degradable carbon is converted to CO_2 (metric tons CO_2/year), see Equation N.34.

(12/44) = molecular weight ratio of C to CO_2 (converts potential CO_2 emissions to carbon).

$Avoided_{CH_4}$ = avoided CH_4 emissions, metric tons CO_2e/year (see Equation N.33).

GWP_{CH_4} = 100-year GWP for CH_4, 25 (IPCC, 2007).

(12/16) = molecular weight ratio of C to CH_4 (converts CH_4 emissions to carbon).

(44/12) = molecular weight ratio of CO_2 to C (converts C less that associated with the CH_4 emissions back to CO_2 emissions).

The most accurate data from which to estimate the total amount of carbon that can be degraded is measurement data on the biogas flow rate and methane concentration from an anaerobic digester that is already in use. If an anaerobic digester is not currently used, or if no biogas measurement data are available, then the amount of carbon that can be degraded will need to be estimated from animal population data.

4.1.2. Methodology When Biogas Flow Rate and Methane Concentration Data Are Available

For each anaerobic digester, the annual flow of CH_4 sent to the biogas combustion device can be calculated using Equation N.27:

$$\mathbf{CH_4F = V \times \frac{C}{100\%} \times 0.0423 \times \frac{520^\circ\ R}{T} \times \frac{P}{1\ atm} \times \frac{0.454}{1{,}000}} \qquad \textbf{(EQ. N.107)}$$

Where:

CH_4F = CH_4 flow from the anaerobic digester to the biogas combustion device (metric tons CH_4/year).

V = Annual volumetric flow rate of biogas to the biogas destruction device (actual cubic feet biogas per year), as determined from daily monitoring.[21]

C = Average annual CH_4 concentration of biogas (percent by volume, wet basis).

0.0423 = Density of CH_4 pounds per standard cubic foot (at 520ºR or 15.56ºC and 1 atm).

T = Average annual temperature (ºR) at which flow is measured.[23]

P = Average annual pressure (atm) at which flow is measured.[23]

0.454/1,000 = conversion factor from pounds to metric tons.

To account for the biogas collection efficiency, leaks from the anaerobic digester must be estimated (such leaks are indirect emissions to the atmosphere). Equation N.28 can be used to calculate the CH_4 lost (metric tons per year) from an anaerobic digester:

$$\mathbf{CH_4L = CH_4F \times \frac{(1-CE)}{CE}} \quad \textbf{(EQ. N.28)}$$

Where:

CH_4L = amount of CH_4 lost via leaks from the anaerobic digester, prior to combustion (metric tons CH_4/year).

CH_4F = CH_4 flow from the anaerobic digester to the biogas combustion device (Equation N.27).

CE = collection efficiency[22] of the anaerobic digester.

For each anaerobic digester, the annual flow of CO_2 in biogas that is sent with the CH_4 to the biogas combustion device can be calculated using Equation N.29:

$$\mathbf{CO_2F = V \times \left(1 - \frac{C_{CH_4}}{100\%} - \frac{M}{100\%}\right) \times 0.1160 \times \frac{520°R}{T} \times \frac{P}{1\ atm} \times \frac{0.454\ metric\ ton}{1{,}000\ lbs}} \quad \textbf{(EQ. N.119)}$$

---

[21] If the pressure or temperature fluctuates significantly during the year, it would be more accurate to calculate the annual methane flow as the sum of monthly flow volumes, corrected to standard conditions by the monthly average temperature and pressure.

[22] Biogas collection efficiency is dependent upon the type of anaerobic digester and its cover. Biogas collection efficiency for a covered anaerobic lagoon depends on the cover type: collection efficiency for a bank to bank, impermeable cover is 0.975; collection efficiency for a modular, impermeable cover is 0.70. Biogas collection efficiency is 0.99 for a complete mix, fixed film, or plug flow digester that is an enclosed vessel (EPA 2009b, Table A-4; 40 CFR 98.363, Table JJ-6). Collection efficiency is the amount of biogas flow from the digester to the combustion device divided by the total amount of biogas generated.

Where:

CO_2F = CO_2 flow from the anaerobic digester to the biogas combustion device (metric tons CO_2/year).

V = Annual volumetric flow rate of biogas to the biogas destruction device (cubic feet biogas per year), as determined from daily monitoring.[23]

$(1 - C_{CH_4}/100\%\text{-}M/100\%)$ = Average annual CO_2 concentration of biogas (volume fraction, wet basis), where C = average annual CH_4 concentration of biogas (volume percent, wet basis) and M = moisture content of biogas (volume percent, wet basis).

0.1160 = Density of CO_2 pounds per standard cubic foot (at 520ºR or 15.74ºC and 1 atm).

T = Annual average temperature (ºR) at which flow is measured.[25]

P = Annual average pressure (atm) at which flow is measured.[25]

0.454 /1,000 = conversion factor from pounds to metric tons.

Equation N.30 can be used to calculate the CO_2 lost (metric tons per year) from each anaerobic digester:

$$\mathbf{CO_2L = CO_2F \times \frac{(1-CE)}{CE}} \qquad \textbf{(EQ. N.30)}$$

Where:

CO_2L = amount of CO_2 lost via leaks from the anaerobic digester, prior to combustion (metric tons CO_2/year).

CO_2F = CO_2 flow from the anaerobic digester to the biogas combustion device (Equation N.29).

CE = collection efficiency of the anaerobic digester.

Equation N.31 can be used to calculate the total CH_4 generation from the anaerobic digester.

$$\mathbf{Total\ CH_4\ Generation = CH_4F + CH_4L} \qquad \textbf{(EQ. N.31)}$$

Where:

---

[23]If the pressure or temperature fluctuates significantly during the year, it would be more accurate to calculate the annual CO_2 flow as the sum of monthly flow volumes, corrected to standard conditions by the monthly average temperature and pressure

Total CH_4 Generation = the quantity of methane generated from the anaerobic digester (metric tons CH_4/year).

CH_4F = CH_4 flow from the anaerobic digester to the biogas combustion device in metric tons CH_4/year (Equation N.27).

CH_4L = amount of CH_4 lost via leaks from the anaerobic digester, prior to combustion in metric tons CH_4/year (Equation N.28).

Equation N.32 can be used to calculate the total CO_2 generation from the anaerobic digester.

$$\textbf{Total CO}_\mathbf{2}\textbf{ Generation} = \mathbf{CO_2F + CO_2L} \qquad \textbf{(EQ. N.32)}$$

Where:

Total CO_2 Generation = the quantity of CO_2 generated from the anaerobic digester (metric tons CO_2/year).

CO_2F = CO_2 flow from the anaerobic digester to the biogas combustion device in metric tons CO_2/year (Equation N.29).

CO_2L = amount of CO_2 lost via leaks from the anaerobic digester, prior to combustion in metric tons CO_2/year (Equation N.30).

The CH_4-producing potential of a specific livestock waste management system is represented by a methane conversion factor (MCF). An anaerobic digester is expected to produce methane at near the maximum methane generation potential (i.e., at a MCF of 1). Most manure management systems will not produce the maximum amount of CH_4 possible because the conditions in the systems are not ideal for CH_4 production. The value of this parameter ranges from 0% to 100%, reflecting the capability of a system to produce the maximum achievable CH_4 (the higher the MCF, the greater the potential for CH_4 production). For liquid systems (e.g., uncovered anaerobic lagoons), MCF values are temperature dependent; in order to assign the appropriate MCF for the type of liquid system used, the average ambient temperature at the system's location must be known (see EPA, 2009b, Table A-3).

The avoided CH_4 emissions parameter in Equation N.25 can be estimated using Equation N.33 when CH_4 generation data are available from an anaerobic digester:

$$\textbf{Avoided CH}_\mathbf{4}\textbf{ Emissions} = \textbf{Total CH}_\mathbf{4}\textbf{ Generation} \times \mathbf{MCF_{WMS}} \times \mathbf{GWP}_{\boldsymbol{CH4}} \qquad \textbf{(EQ. N.123)}$$

Where:

Avoided CH_4 Emissions = the quantity of methane emitted, in CO_2 equivalence, from the alternative waste management system (metric tons CO_2e/year).

Total CH_4 Generation = the quantity of methane generated from the anaerobic digester (metric tons CH_4/year).

MCF_{WMS}	= CH_4 conversion factor (proportion represented as a decimal) for the alternative-scenario, waste management system (see EPA, 2009b, Table A-3).
GWP_{CH4}	= 100-year GWP of CH_4, 25 (IPCC, 2007).

The potential CO_2 emissions can be calculated from the total CH_4 and CO_2 generation from the anaerobic digester using Equation N.34 as follows.

$$\textbf{Potential CO}_2\textbf{ Emissions} = (\textbf{Total CH}_4\textbf{ Generation} \times \mathbf{44/16}) + \textbf{Total CO}_2\textbf{ Generation}$$

(EQ. N.134)

Where:

Potential CO_2 emissions	= maximum CO_2 emissions if all degradable carbon is converted to CO_2 (metric tons CO_2/year).
Total CH_4 Generation	= the quantity of methane generated from the anaerobic digester (metric tons CH_4/year).
Total CO_2 Generation	= the quantity of CO_2 generated from the anaerobic digester (metric tons CO_2/year).
44/16	= molecular weight ratio of CO_2 to CH_4 emissions.

Equation N.26 can then be used to calculate the avoided CO_2 emissions and Equation N.25 can be used to calculate the total CO_2e emissions from a livestock waste management other than anaerobic digestion.

4.1.3. Calculating the Denominator

The total amount of CH_4 and CO_2 emissions from an anaerobic digester, as represented in the denominator of the *AVOIDEMIT* term, is a calculation of the amount of CH_4 sent to the biogas destruction device, minus the amount of CH_4 destroyed during combustion, plus the amount of CH_4 leaked to the atmosphere (the latter accounts for CH_4 collection efficiency). To convert that calculation to CO_2e, it is multiplied by the GWP of CH_4. To account for the CO_2 emitted as a result of CH_4 combustion, the amount of CH_4 destroyed during combustion is added. To this is added the amount of CO_2 in the biogas that flows to the biogas combustion device where it is then emitted to the atmosphere. The following Equation (N.35) can be used to calculate the total amount of CO_2e emissions from an anaerobic digester:

$$\mathbf{CO_2e\ Emissions_{AD}} = \boldsymbol{GWP_{CH_4}}(\mathbf{CH_4F} - \mathbf{CH_4D} + \mathbf{CH_4L}) + \mathbf{CH_4D} \times \mathbf{44/16} + \mathbf{CO_2F} + \mathbf{CO_2L}$$

(EQ. N.145)

Where:

CO_2e $Emissions_{AD}$	= CO_2e emissions from anaerobic digestion (metric tons/year).

GWP_{CH_4} = 100-year GWP of CH_4, 25 (IPCC, 2007).

CH_4F = CH_4 flow to the biogas combustion device (Equation N.27).

CH_4D = amount of CH_4 destroyed via combustion (Equation N.36).

CH_4L = amount of CH_4 lost via leaks prior to combustion (Equation N.28).

CO_2F = CO_2 flow to the biogas combustion device (Equation N.29).

CO_2L = amount of CO_2 lost via leaks prior to combustion (Equation N.30).

44/16 = molecular weight ratio of CO_2 to CH_4.

Equations for most of these terms have already been presented. Equation N.36 can be used to calculate the metric tons of CH_4 destroyed (per year) in a biogas destruction device:

$$\mathbf{CH_4D = CH_4F \times DE} \qquad \textbf{(EQ. N.156)}$$

Where:

CH_4D = CH_4 destroyed at a biogas combustion device (metric tons CH_4/year).

CH_4F = CH_4 flow from the anaerobic digester to the biogas combustion device (Equation N.27).

DE = CH_4 destruction efficiency from flaring or combustion in an EGU. DE varies with the type of biogas destruction device used; it can be estimated as the lesser of the manufacturer's specified destruction efficiency and 0.99 (EPA, 2013c).

Section 4.2.1 provides an illustrative example calculation of the *AVOIDEMIT* term and its subsequent application in estimating a *BAF* for the management of livestock waste in an anaerobic digester when biogas measurement data are available.

Several parameters are presented and used in the equations in the remainder of this section. Table N-8 presents the parameters used, default values, ranges presented in the literature, and references.

Table N-8. Summary of Parameters Used When Calculating an Illustrative *BAF* for Livestock Waste Management through Anaerobic Digestion.

Parameter Description	Symbol	Value	Range	Units	Comments	Reference (for value column)
Concentration of CH_4 in the biogas	C_{CH_4}	0.55	0.40 to 0.60	Fraction		EPA, 2013c
Density of CH_4	–	0.662	–	kg CH_4/m^3	At 532°R, or 22.22°C, and 1 atm	EPA, 2009b

Parameter Description	Symbol	Value	Range	Units	Comments	Reference (for value column)
Density of CO_2	–	0.1160	–	Pounds per standard cubic foot	At 520ºR or 15.74ºC and 1 atm	Calculated value[3]
Methane conversion factor for the specific waste management strategy	MCF_{WMS}	0.66	Depends on the type of system and temperature	Percent	Value presented is for an uncovered anaerobic lagoon in a cool climate below 10°C	EPA, 2009b, Table A-3
Typical animal mass, by animal type	TAM_{AT}	604	Numerous	kg/head	Determined using either default values or farm-specific data	EPA, 2009b, Table A-2; IPCC, 2006, Table 10A4-10A9
Volatile solids excretion rate by animal type	VS_{AT}	9.34	Depends on the type of animal group	kg VS/day/kg animal mass	Value presented is used in the example calculations in Section 4.0.[1]	EPA, 2009b, Table A-2; EPA, 2013c, Tables JJ-2 and JJ-3
Maximum CH_4-producing capacity for each animal type	B_0	0.24	0.17 to 0.78	m^3 CH_4 /kg volatile solids	Value presented is for dairy cows	EPA, 2009b, Table A-2
Destruction efficiency	DE	0.99	0.90 to 0.9977	Fraction	0.99 is considered a default	EPA, 2011a; EPA, 2013c
Collection efficiency	CE	0.99	0.70 to 0.99	Decimal percent	0.99 is for an enclosed vessel, plug flow digester	EPA, 2009b, Table A-4
Fraction of volatile solids in livestock waste	VolatileCarbon_AT	0.2979	0.20 to 0.40	kg volatile solids in total dried solids/kg of total dried solids, dry basis	Value is determined from waste volatile solids analysis[2]	Sweeten et al., 2002

[1] VS_{AT} can be determined using either default values or farm-specific data.

[2] If only fuels proximate analysis is available, estimate the volatile solids as the sum of the volatile matter and fixed carbon from the fuels proximate analysis (see Figure N-3).
[3] This value is calculated using a 60 degree Fahrenheit conversion: 44.01 * (2.20462/836.6) = 0.1160, where 44.01 = the molecular weight of CO_2; 2.20462 is a unit conversion factor from kilograms to pounds; and 836.6 scf/kg-mol is the molar volume conversion factor.

4.1.4. Methodology When Biogas Flow Rate and Methane Concentration Data Are Not Available

When biogas measurement data are not available, the CH_4 and CO_2 emissions must be estimated based on animal type and population data. Potential CO_2 emissions can be solved using the following equation:

Potential CO_2 emissions =

$$\Sigma_{\text{animal type}} (TVS_{AT} \times VolatileCarbon_{AT} \times (44/12) \times 365 \times 1/1000) \quad \textbf{(EQ. N.167)}$$

Where:

$\Sigma_{\text{animal type}}$	= If the alternate waste management system accepts waste from more than one animal type then this calculation must be computed for each animal type and then summed across animal types.
TVS_{AT}	= Total volatile solids excreted by animal type (kg/day); see Equation N.38 to calculate TVS_{AT}.
$VolatileCarbon_{AT}$	= Fraction of degradable carbon in the volatile solids of the livestock waste (see Equation N.39).
(44/12)	= molecular weight ratio of CO_2 to C.
365	= number of days per year (i.e., 365 days/year).
1/1,000	= conversion factor from kg to metric tons.

Total volatile solids excreted by animal type (TVS_{AT}) may be calculated using Equation N.38 and by referring to tables external to this appendix (Table A-2, EPA, 2009b and Tables JJ-2 and JJ-3, 40 CFR 98.363):

$$TVS_{AT} = (Population_{AT} \times TAM_{AT} \times VS_{AT}/1000) \quad \textbf{(EQ. N.178)}$$

Where:

TVS_{AT}	= Total volatile solids excreted per animal type (kg/day).
$Population_{AT}$	= Average annual animal population (head), by animal type.[24]

[24] For static populations (e.g., dairy cows, breeding swine), average annual animal populations are estimated using

TAM_{AT} = Typical animal mass, by animal type; determined using either default values (see EPA, 2009b, Table A-2) or farm specific data (kg/head).

VS_{AT} = Volatile solids excretion rate by animal type, using either default values (see 40 CFR 98.363, Tables JJ-2 and JJ-3) or farm specific data (kg VS/day/kg animal mass).

The fraction of degradable carbon in the volatile solids of the livestock waste ($VolatileCarbon_{AT}$) can be estimated using results from proximate and ultimate analyses[25] of the livestock waste specific to the waste of animal type being managed (Equation N.39). Data needed to estimate this parameter can be directly measured or, more simply, can be taken from the body of published scientific literature.[26] However, it is important to understand the differences between the volatile solids measurement methods and the proximate fuel analysis methods. Figure N-3 compares the methods and nomenclature typically used for these different analytical methods.

---

annual animal inventory or equivalent. For growing populations (e.g., meat animals such as beef and veal cattle), average annual animal populations are estimated using the average number of days each animal is kept at the facility and the number of animals produced annually (e.g., growing population = days onsite × (number of animals produced annually / 365)).

[25] Characteristics of a biogenic fuel can be described using proximate and ultimate analyses based on a sample's complete combustion to CO_2 and liquid water. The proximate analysis gives moisture content, volatile content, carbon remaining (fixed carbon), and mineral ash. The ultimate analysis gives the sample's elemental composition as proportions of carbon, hydrogen, oxygen, nitrogen, and sulfur. Standardized test methods have been developed, for example, see Table 3 in Demirbas (2004).

[26] For example, ASAE Standard D384.2 (2005) is useful for estimating general characteristics of livestock and poultry manure. Li et al. (2008) and Henihan et al. (2003) present specific results of proximate and ultimate analyses of chicken litter characteristics; Sweeten et al. (2002 and 2003) present similar specific results but of cattle manure. It should be noted that Sweeten et al. (2002 and 2003) pertain to the composition of Texas feedlot beef cattle manure, values may not be suitable for calculating *BAF* values across all cattle types, regions, etc.

Diagram of Waste Analysis Methods and Nomenclature

Waste Analysis Method	Total Solids		
	Moisture Content	Dried Solids	
		Volatile Solids	Residue
	Dry sample at 105°C to constant weight: "moisture content" is mass lost during this process, commonly expressed as ratio to mass of total solids	Burn in furnace with air at 500 to 550°C to constant weight: "volatile solids" = mass lost during this process, may be expressed as ratio to mass of total solids ("%VS wet basis") or dried solids ("%VS dry basis")	Mass left after burning in furnace, may be expressed as ratio to mass of total solids (wet basis) or dried solids (dry basis)

Proximate Fuel Analysis Method	Total Solids			
	Moisture Content	Dried Solids		
		Volatile Matter	Fixed Carbon	Residue
	Dry sample at 105°C to constant weight: "moisture content" is mass lost during this process, commonly expressed as ratio to mass of total solids	Heat at 900°C in nitrogen for 20 minutes: "volatile matter" = mass lost during this process, commonly expressed as ratio to mass of dried solids	Burn in furnace at 600°C for about 1 hour: "fixed carbons" = mass lost during this process, commonly expressed as ratio to mass of dried solids	Mass left after burning in furnace, commonly expressed as ratio to mass of dried solids

Figure N-3. Comparison of Waste and Proximate Fuel Analyses (Adapted from ASTM, 2013).

The $\text{VolatileCarbon}_{AT}$ term represents the amount of carbon in the livestock waste solids that degrades during livestock waste management. Assuming there is negligible carbon remaining in the residue and that the fixed carbon is not readily biodegradable, $\text{VolatileCarbon}_{AT}$ term can be estimated as follows:

$$\textbf{VolatileCarbon}_{\textbf{AT}} = \frac{\textbf{Carbon}-\textbf{Fixed Carbon}}{\textbf{Volatile Solids}} = \frac{\textbf{Carbon}-\textbf{Fixed Carbon}}{\textbf{Volatile Matter + Fixed Carbon}} \qquad \textbf{(EQ. N.189)}$$

Where:

$\text{VolatileCarbon}_{AT}$ = fraction of the degradable carbon in the volatile solids of the livestock waste (kg degradable carbon in volatile solids/kg of volatile solids, dry basis).[27]

Carbon = fraction of carbon in livestock waste (kg carbon in total dried solids/kg of total dried solids), dry basis (from ultimate analysis).

Fixed Carbon = fraction of dry solids in livestock waste that does not volatilize when heated to 900 °C in nitrogen (kg fixed carbon in total dried solids/kg of total dried solids) but is lost when heated in air at 600 °C, dry basis (from fuels proximate analysis; see Figure N-3).

[27] If the mass of fixed carbon is not 100% carbon then the amount of carbon in the volatile matter may be underestimated, thus giving a low-biased estimate of the $\text{VolatileCarbon}_{AT}$ term (though the bias is likely small).

Volatile Solids = fraction of volatile solids in livestock waste (kg volatile solids in total dried solids/kg of total dried solids), dry basis (from waste volatile solids analysis). If only fuels proximate analysis is available, estimate the volatile solids as the sum of the volatile matter and fixed carbon from the fuels proximate analysis (see Figure N-3).

Volatile Matter = fraction of dry solids that does is lost when heated to 900 °C in nitrogen (kg volatile matter/kg of total dried solids), dry basis.

The avoided CH_4 emissions parameter in Equation N.25 can be populated using Equation N.40, which estimates the annual avoided CH_4 emissions generated from a manure management strategy alternate to anaerobic digestion:

Avoided CH_4 emissions (metric tons CO_2e/year) =

$$\mathbf{\Sigma_{animal\ type}\left(TVS_{AT} \times VS_{WMS} \times Days \times B_0 \times MCF_{WMS} \times 0.662 \times 1/1000 \times GWP_{CH_4}\right)} \quad \textbf{(EQ. N.40)}$$

Where:

$\Sigma_{\text{animal type}}$ = If the alternate waste management system accepts waste from more than one animal type then this calculation must be computed for each animal type and then summed across animal types.

TVS_{AT} = Total volatile solids excreted by animal type (kg/day); the TVS_{AT} equation is presented above (Equation N.38).

VS_{WMS} = Proportion of total manure for each animal type that is managed in each waste management system (assumed to be equivalent to the amount of volatile solids in each waste management system).

Days = Number of days per year (i.e., 365 days/year).

B_0 = Maximum CH_4-producing capacity for each animal type (m^3 CH_4/kg volatile solids; see EPA, 2009b, Table A-2).

MCF_{WMS} = CH_4 conversion factor (proportion represented as a decimal) for the alternative-scenario, waste management system (see EPA, 2009b, Table A-3).

0.662 = density of CH_4, kg CH_4/m^3 (at 532°R, or 22.22°C, and 1 atm).

1/1000 = conversion factor from kg to metric tons.

GWP_{CH_4} = 100-year GWP of CH_4, 25 (IPCC, 2007).

The maximum amount of CH_4 that could potentially be produced from livestock waste managed under ideal conditions is calculated by multiplying the total volatile solids by the maximum CH_4-producing capacity of the livestock waste (B_0). The B_0 values vary by animal type and diet (see EPA, 2009b, Table A-2). Most manure management systems will not produce the maximum amount of CH_4 possible because the conditions in the systems are not ideal for CH_4 production. The CH_4-producing potential of a specific livestock waste management system is represented by a methane conversion factor (MCF). The value of this parameter ranges from 0% to 100% and reflects the capability of a system to produce the maximum achievable CH_4 (the higher the MCF, the greater the potential for CH_4 production). For liquid systems (e.g., uncovered anaerobic lagoons), MCF values are temperature dependent: in order to assign the appropriate MCF for the type of liquid system used, the average ambient temperature at the system's location must be known (see EPA, 2009b, Table A-3).

Summing the avoided CO_2 emissions and the avoided CH_4 emissions (Equation N.25, metric tons CO_2e/year) is the final computation in estimating the numerator in the *AVOIDEMIT* term for a livestock waste management strategy alternative to an anaerobic digester.

As before, the denominator of the *AVOIDEMIT* emission ratio term (i.e., the emissions from combustion of biogas generated in an anaerobic digester) is based on the flow, loss, and destruction terms presented previously (see Equation N.35). However, in the lack of direct biogas measurement data, these terms must be estimated based on the animal population equations just presented.

As noted previously, the maximum amount of CH_4 that could potentially be produced from livestock waste managed under ideal conditions is calculated by multiplying the total volatile solids by the maximum CH_4-producing capacity of the livestock waste (B_0). Thus, total CH_4 generation can be estimated using Equation N.41, which is similar to Equation N.40 except that MCF_{WMS} is assumed to equal 1 and the CH_4 emissions are not converted to CO_2 equivalence.

Total CH_4 generation (tons CH_4/yr) =

$$\boldsymbol{\Sigma_{\text{animal type}} (TVS_{AT} \times VS_{WMS} \times Days \times B_0 \times 0.662 \times 1/1000)} \qquad \textbf{(EQ. N.41)}$$

Where:

$\Sigma_{\text{animal type}}$ = If the alternate waste management system accepts waste from more than one animal type then this calculation must be computed for each animal type and then summed across animal types.

TVS_{AT} = Total volatile solids excreted by animal type (kg/day); the TVS_{AT} equation is presented above (Equation N.38).

VS_{WMS} = Proportion of total manure for each animal type that is managed in each waste management system (assumed to be equivalent to the amount of volatile solids in each waste management system).

Days = Number of days per year (i.e., 365 days/year).

B_0 = Maximum CH_4-producing capacity for each animal type (m^3 CH_4/kg volatile solids; see EPA, 2009b, Table A-2).

0.662 = density of CH_4, kg CH_4/m^3 (at 532°R, or 22.22°C, and 1 atm).

1/1000 = conversion factor from kg to metric tons.

CH_4 sent to the biogas destruction device can be calculated based on the collection efficiency of the anaerobic digester using Equation N.42:

$$\mathbf{CH_4F = Total\ CH_4\ Generation \times CE} \qquad \textbf{(EQ. N.42)}$$

Where:

CH_4F	= CH_4 flow from the anaerobic digester to the biogas combustion device (tons CH_4/yr).
Total CH_4 generation	= total quantity of CH_4 generated in the anaerobic digester (tons CH_4/yr; see Equation N.41).
CE	= collection efficiency[28] of the anaerobic digester.

The CH_4 that is not collected and sent to the biogas destruction device can be calculated by rearranging Equation N.28:

$$\mathbf{CH_4L = Total\ CH_4\ Generation - CH_4F} \qquad \textbf{(EQ. N.193)}$$

Where:

CH_4L	= amount of CH_4 lost via leaks from the anaerobic digester, prior to combustion (metric tons CH_4/year).
Total CH_4 generation	= total quantity of CH_4 generated in the anaerobic digester (tons CH_4/yr; see Equation N.31)
CH_4F	= CH_4 flow from the anaerobic digester to the biogas combustion device (Equation N.42).

Given the potential CO_2 emissions from Equation 37 and re-arranging Equation N.34 yields the following equation for estimating the total CO_2 generation from the anaerobic digester.

$$\mathbf{Total\ CO_2\ Generation = Potential\ CO_2\ Emissions - (Total\ CH_4\ Generation \times 44/16)} \qquad \textbf{(EQ. N.204)}$$

Where:

[28] Biogas collection efficiency is dependent upon the type of anaerobic digester and its cover. Biogas collection efficiency for a covered anaerobic lagoon depends on the cover type: collection efficiency for a bank to bank, impermeable cover is 0.975; collection efficiency for a modular, impermeable cover is 0.70. Biogas collection efficiency is 0.99 for a complete mix, fixed film, or plug flow digester that is an enclosed vessel (EPA 2009b, Table A-4; 40 CFR 98.363, Table JJ-6). Collection efficiency is the amount of biogas flow from the digester to the combustion device divided by the total amount of biogas generated.

Total CO_2 Generation = the quantity of CO_2 generated from the anaerobic digester (metric tons CO_2/year).

Potential CO_2 emissions = maximum CO_2 emissions if all degradable carbon is converted to CO_2 (metric tons CO_2/year from equation N.34).

Total CH_4 Generation = the quantity of methane generated from the anaerobic digester (metric tons CH_4/year; Equation N.41).

44/16 = molecular weight ratio of CO_2 to CH_4 emissions.

Similar to the CH_4 flow and loss terms, the CO_2 flow and loss terms can be calculated based on the collection efficiency of the anaerobic digester as follows:

$$\mathbf{CO_2F = \text{Total } CO_2 \text{ Generation} \times CE} \qquad \textbf{(EQ. N.215)}$$

$$\mathbf{CO_2L = \text{Total } CO_2 \text{ Generation} - CO_2F} \qquad \textbf{(EQ. N.226)}$$

Where:

CO_2F = CO_2 flow from the anaerobic digester to the biogas combustion device (tons CO_2/yr).

Total CO_2 generation = total quantity of CO_2 generated in the anaerobic digester (metric tons CO_2 /year; see Equation N.44).

CE = collection efficiency[29] of the anaerobic digester.

CO_2L = amount of CO_2 lost via leaks from the anaerobic digester, prior to combustion (metric tons CO_2/year).

Equation N.36, presented previously, can be used to calculate the metric tons of CH_4 destroyed (per year) in a biogas destruction device. All of the parameters needed to determine the CO_2e emissions from the anaerobic digester using Equation N.35 are then available.

Section 4.2.2 provides an illustrative example calculation of the *AVOIDEMIT* term and its subsequent application in estimating a *BAF* for the management of livestock waste in an anaerobic digester prior to the availability of biogas measurement data

---

[29] Biogas collection efficiency is dependent upon the type of anaerobic digester and its cover. Biogas collection efficiency for a covered anaerobic lagoon depends on the cover type: collection efficiency for a bank to bank, impermeable cover is 0.975; collection efficiency for a modular, impermeable cover is 0.70. Biogas collection efficiency is 0.99 for a complete mix, fixed film, or plug flow digester that is an enclosed vessel (EPA 2009b, Table A-4; 40 CFR 98.363, Table JJ-6). Collection efficiency is the amount of biogas flow from the digester to the combustion device divided by the total amount of biogas generated.

4.2. Illustrative *AVOIDEMIT* and *BAF* Calculations for Livestock Waste Management

4.2.1. Illustrative Calculations when Anaerobic Digester Measurement Data Are Available

When anaerobic digester flow and concentration data are available, these data provide a more accurate estimate of the degradable carbon quantities in the livestock wasted. Therefore, the potential CH_4 and CO_2 emissions from the alternate treatment pathway should be estimated from these measurement data rather than from animal population data. Again, this example is for a dairy farm in a cool climate (average ambient temperature below 10°C) and is comparing the alternate treatment of the livestock waste in an uncovered anaerobic lagoon to an anaerobic digester.

In this hypothetical example, the daily average volumetric biogas flow rate from the anaerobic digester is 54,500 ft^3 per day and the annual volumetric flow volume is 19,892,500 (e.g., 54,500 ft^3/day × 365 days/year). In this hypothetical example, the average annual CH_4 concentration of biogas was measured to be 52.1% (wet basis). Based on daily monitoring, the annual average temperature of the biogas from the anaerobic digester was 77ºF (537ºR) at 1.005 atm, both of which were measured where the flow is measured.

Step 1: Calculate the CH_4 Emissions from the Anaerobic Digester

The amount (metric tons/year) of CH_4 sent from the anaerobic digester to the biogas combustion device, CH_4F, is calculated as (Equation N.42):

$$\mathbf{CH_4F = V \times \frac{C_{CH4}}{100} \times 0.0423 \times \frac{520}{T} \times \frac{P}{1\ atm} \times \frac{0.454}{1,000}}$$

$$\mathbf{CH_4F = 19,892,500 \times 0.521 \times 0.0423 \times (520/537) \times (1.005/1) \times (0.454/1000)}$$

$$\mathbf{= 193.6950\ metric\ tons\ CH_4/year.}$$

The next term to solve in calculating the denominator of the *AVOIDEMIT* term is CH_4D, the amount of CH_4 destroyed at a biogas combustion device (metric tons CH_4/year). This can be calculated using Equation N.36:

$$\mathbf{CH_4D = CH_4F \times DE}$$

The CH_4 DE is estimated as the lesser of the manufacturer's specified DE and 0.99 (EPA, 2013c). A DE value of 0.99 will be used for this example. Thus, the CH_4 destroyed at biogas combustion device can be estimated as:

$$\mathbf{CH_4D = 193.6950 \times 0.99}$$

$$\mathbf{= 191.7581\ MT\ CH_4/year.}$$

The next term in the denominator of the *AVOIDEMIT* term, CH_4L, accounts for the CE. To calculate CH_4 leakage (metric tons CH_4/year) from an anaerobic digester, Equation N.28 can be used:

$$\mathbf{CH_4L = \ CH_4F \times \frac{(1-CE)}{CE}}$$

The previously computed value for CH_4F can be used in this example. The CE is dependent upon the type of anaerobic digester and its cover (for default values, see EPA, 2009b, Table A-4; 40 CFR 98.363, Table JJ-6). This hypothetical example is for an enclosed vessel, mixed plug flow digester where the CE is 0.99, such that:

CH_4L = 193.6950 × (1 – 0.99) / 0.99

= 1.9565 metric tons CH_4/year.

Step 2: Calculate the CO_2 Emissions from the Anaerobic Digester

The next parameter to solve for in the denominator of the *AVOIDEMIT* term is CO_2F, the annual flow of CO_2 in biogas sent (mixed with CH_4) to the biogas combustion device. This can be calculated using Equation N.29:

$$\mathbf{CO_2F = V \times \left[1 - \left(\frac{C_{CH_4}}{100\%}\right) - \left(\frac{M}{100\%}\right)\right] \times 0.1160 \times \frac{520}{T} \times \frac{P}{1\ atm} \times \frac{0.454}{1,000}}$$

The values for V, C, T, and P are the same when solving for CO_2F (Equation N.29) as for when solving for CH_4F (Equation N.27). The only change is in the density of the gas, from CH_4 (0.0423 lbs/ft^3) to that of CO_2 (0.1160 lbs/ft^3) and that Equation N.29 incorporates the fraction of biogas that is not CH_4 or water vapor (i.e., 1 – C_{CH_4}/100%-M/100%). As most anaerobic digesters operate at temperature above 30°C (above 86°F), it can be assumed the cooled biogas (at the flow measurement point) is saturated with water (relative humidity of 100%). Using a psychometric chart, 77°F air holds approximately 20 grams water per kg dry air. Using the molecular weight of 18 g/mol for water and 29 g/mol for air, the moisture content of the biogas is estimated to be 3.1% (i.e., (20/18)/[(1000/29)+(20/18)]). Using Equation N.29, CO_2F can be estimated as:

CO_2F = 19,892,500 × (1 – 0.521-0.031) × 0.1160 × 520/537 × 1.005 × 0.454/1,000

= 459.1102 MT CO_2/year

The final parameter to solve for in the denominator of the *AVOIDEMIT* term is CO_2L, the annual flow of CO_2 in biogas lost from the digester. This can be calculated using Equation N.30, using the value of CO_2F just calculated and the gas collection efficiency (0.99; same as used to determine CH_4L), as follows:

$$\mathbf{CO_2L = \ CO_2F \times \frac{(1-CE)}{CE}}$$

CO_2 = 459.1102 × (1 – 0.99) / 0.99

= 4.6375 MT CO_2/year.

Step 3: Calculate the CO_2e Emissions from the Anaerobic Digester (Denominator)

With estimated values for each of the terms in the denominator of the *AVOIDEMIT* term, the denominator can be solved using Equation N.35:

$$\mathbf{CO_2e\ Emissions_{AD} = 25(CH_4F - CH_4D + CH_4L) + CH_4D \times 44/16 + CO_2F + CO_2L}$$

CO_2e emissions from the anaerobic digester (metric tons /year)

= 25 × (193.6950 – 191.7581 + 1.9565) + 191.7581 × 44/16 + 459.1102+4.6375

= 1,088.4175 metric tons CO_2e /year

Step 4: Calculate the CO_2e Emissions from the Alternate Fate (Numerator)

Now that the terms for the denominator are determined, these values can be used to estimate the total CH_4 and CO_2 generation from the alternate treatment fate (uncovered lagoon) using Equations N.31 and N.32.

Total CH_4 generation (MT CH_4/year) = CH_4F + CH_4L

Total CH_4 generation = 193.6950 + 1.9565

= 195.6515

Total CO_2 generation = CO_2F + CO_2L

Total CO_2 generation = 459.1102 + 4.6375

= 463.7477

For an anaerobic digester, the CH_4 conversion factor, MCF, is assumed to be 1; for the alternative-scenario's waste management system, the CH_4 conversion factor is projected to be 0.66 (see EPA, 2009b, Table A-3; for uncovered anaerobic lagoon in a cool climate below 10°C,[30] MCF_{WMS} = 0.66). Applying Equation N.33, the avoided CH_4 emissions:

Avoided CH_4 emissions (metric tons/year) = Total CH_4 generation × MCF_{WMS} × GWP_{CH4}

= 195.6515 × 0.66 × 25

= 3,228.2498 MT CO_2e per year.

The potential CO_2 emissions are calculated from the total CH_4 and CO_2 generation from the anaerobic digester as:

Potential CO_2 emissions = (Total CH_4 generation × 44/16) + Total CO_2 generation

---

[30] Table A-3 in EPA 2009b assigns CH_4 conversion factors based on ambient temperature, thus accounting for the influence of climate on CH_4 production.

Potential CO_2 emissions = (195.6515 × 44/16) +463.7477

= 1,001.7893 MT CO_2 per year

With estimates of both the potential CO_2 emissions and the avoided CH_4 emissions, the avoided CO_2 emissions resulting from a dairy manure management strategy other than an anaerobic digester can be calculated using Equation N.26 as follows.

Avoided CO_2 emissions = ((Potential CO_2 emissions × 12/44) – (Avoided CH_4 emissions/25 × 12/16)) × (44/12)

= ((1,001.7893 × 12/44) – (3,228.2498/25 × 12/16)) × (44/12)

= 646.6818 MT CO_2 per year

Summing the estimated, avoided CH_4 and CO_2 emissions (both in metric tons CO_2e per year), that result from a dairy manure management strategy other than an anaerobic digester, the total avoided CO_2e emissions can be estimated in units of metric tons CO_2e per year, thus solving the numerator of the *AVOIDEMIT* term (Equation N.24):

Total avoided CO_2e emissions

= (avoided CO_2 emissions) + (avoided CH_4 emissions)

= 646.6818 + 3,228.2498

= 3,874.9317 MT CO_2e per year

Step 5: Calculate the *BAF* Value

With both the numerator and denominator of the *AVOIDEMIT* term having been computed, a *BAF* value can be estimated using Equations N.1 and N.2:

$$BAF = AVOIDEMIT$$

$$BAF = 1 - \frac{3{,}874.9317}{1{,}088.4175}$$

$$BAF = -2.56$$

A negative *BAF* value calculated for this hypothetical scenario indicates that a biogas feedstock produced in an anaerobic digester from the treatment of dairy manure and flared by a stationary source results in net CO_2e emissions reductions.

4.2.2. Example Calculations for Livestock Waste Management Prior to Installation of an Anaerobic Digester (When Measurement Data are Not Available)

Prior to the installation of an anaerobic digester, the only information available to determine the carbon content of the livestock waste and to project the methane generation potential of the anaerobic digester are the equations presented correlating the potential CO_2 emissions and the avoided methane emissions to animal type and population. This example illustrates how to determine the assessment factor based only on the animal population data.

Step 1: Calculate the CO_2e Emissions from the Alternate Fate (Numerator)

To calculate the numerator of the *AVOIDEMIT* term, the total volatile solids in the managed livestock waste must be estimated in order to calculate the avoided CO_2 and CH_4 emissions. Parameters in equation N.25 can be estimated using a hypothetical example of a dairy farm in a cool climate (average ambient temperature below 10°C) consisting of 500 dairy cows with a typical animal mass of 604 kg, and a volatile solids excretion rate of 9.34 kgVS/day/1,000 kg animal mass (see 40 CFR 98.363, Tables JJ-2 and JJ-3). Equation N.38 may be used to calculate total volatile solids excreted per animal type:

$$\mathbf{TVS_{AT} = (Population_{AT} \times TAM_{AT} \times VS_{AT}/1{,}000)}$$

$$\mathbf{= 500 \times 604 \times 9.34 \;/\; 1{,}000}$$

$$\mathbf{= 2{,}820.68 \text{ kg/day}}$$

With TVS_{AT} estimated, the avoided CH_4 emissions resulting from a dairy manure management strategy other than an anaerobic digester can be calculated. In this hypothetical example, the alternative fate evaluated is management of the manure using an uncovered anaerobic lagoon. When calculating the avoided CH_4 emissions associated with the alternative fate of this scenario's dairy manure, several parameters are needed, including the maximum CH_4-producing capacity for dairy cattle (see EPA, 2009b, Table A-2, for the appropriate default value; for dairy cows, B_0 = 0.24 m^3 CH_4/kg); and a CH_4 conversion factor for the alternative-scenario's waste management system (see EPA, 2009b, Table A-3; for uncovered anaerobic lagoon in a cool climate below 10°C,[31] MCF_{WMS} = 0.66). Equation N.40 can be used to calculate the avoided CH_4 emissions:

Avoided CH_4 emissions (metric tons/year)

$$\mathbf{= (TVS_{AT} \times VS_{WMS} \times Days \times B_0 \times MCF_{WMS} \times 0.662 \times 1 \;/1{,}000 \times 25)}$$

$$\mathbf{= (2{,}820.68 \text{ kg/day} \times 1 \times 365 \text{ days/year} \times 0.24 \text{ m}^3\ CH_4\text{/kg} \times 0.66 \times 0.662 \text{ kg } CH_4\text{/m}^3 \times 1 \text{ metric ton/1,000 kg} \times 25)}$$

$$\mathbf{= 2{,}698.9812 \text{ metric tons } CO_2e \text{ per year}}$$

In order to estimate avoided CO_2 emissions from a dairy manure management strategy other than an anaerobic digester, the proportion of the carbon in the volatile matter of the dairy manure ($VolatileCarbon_{AT}$) must be calculated. In the $VolatileCarbon_{AT}$ term, the fixed carbon is removed from the total carbon in the dairy manure because the fixed carbon is assumed not to degrade. Data

---

[31] Table A-3 in EPA 2009b assigns CH_4 conversion factors based on ambient temperature, thus accounting for the influence of climate on CH_4 production.

results from proximate and ultimate analyses of cattle manure (Sweeten et al., 2002)[32] were used to populate parameter values in Equation N.39:

$$\textbf{VolatileCarbon}_{\textbf{AT}} = \frac{\textbf{Carbon–Fixed Carbon}}{\textbf{Volatile Solids}} = \frac{\textbf{Carbon–Fixed Carbon}}{\textbf{Volatile Matter + Fixed Carbon}}$$

$$= \frac{\mathbf{0.2959 - 0.1127}}{\mathbf{0.5022 + 0.117}}$$

$$\mathbf{= 0.2979}$$

With TVS_{AT} and $VolatileCarbon_{AT}$ estimated, the potential maximum CO_2 emissions (Equation N.25) resulting from a dairy manure management strategy other than an anaerobic digester can then be estimated. In this scenario, the alternate fate is manure management using an open anaerobic lagoon. Because there is only one animal type (dairy cows), Equation N.37 only needs to be calculated once, as follows:

Potential CO_2 emissions = (TVS_{AT} × $VolatileCarbon_{AT}$ × (44/12) × 365 × 1 /1000)

= 2,820.68 × 0.2979 × (44/12) × 365 × 1 /1,000

= 1,124.5755 MT CO_2 per year

With estimates of both the potential CO_2 emissions and the avoided CH_4 emissions, the avoided CO_2 emissions resulting from a dairy manure management strategy other than an anaerobic digester can be calculated. For this calculation the total potential CO_2 emissions from the decomposition of TVS_{AT} must first be converted to carbon. From this the CH_4 emissions, converted to carbon must be subtracted. The result is then converted back to CO_2 (see Equation N.26).

Avoided CO_2 emissions = ((Potential CO_2 emissions × 12/44) – (Avoided CH_4 emissions/25 × 12/16)) × (44/12)

= ((1,124.575 × 12/44) – (2,698.9812/25 × 12/16)) × (44/12)

= 827.6877 MT CO_2 per year

Summing the estimated, avoided CH_4 and CO_2 emissions (both in metric tons CO_2e per year), that result from a dairy manure management strategy other than an anaerobic digester, the total avoided CO_2e emissions can be estimated in units of metric tons CO_2e per year, thus solving the numerator of the *AVOIDEMIT* term (Equation N.25):

Total avoided CO_2e emissions

= (avoided CO_2 emissions) + (avoided CH_4 emissions)

---

[32] Data specific to Wisconsin dairy cattle would be preferred but in the absence of these data, data from Sweeten et al. (2002) were applied.

= 827.6877 + 2,698.9812

= 3,526.6689 MT CO_2e per year

Step 2: Calculate the CO_2e Emissions from the Actual Fate (Denominator)

In order to calculate the emissions from the anaerobic digester (i.e., denominator of the *AVOIDEMIT* term), these same equations can be used to calculate the projected emissions from the total CH_4 and CO_2 generation.

The total CH_4 generation for the anaerobic digester is calculated using Equation N.41.

Total CH_4 generation (metric tons CH_4/year)

= (TVS_{AT} × VS_{WMS} × Days × B_0 × 0.662 kg CH_4/m^3 × 1 metric ton/1,000 kg)

= (2,820.68 kg/day × 1 × 365 days/year × 0.24 m^3 CH_4/kg × 0.662 kg CH_4/m^3 × 1 metric ton/1,000 kg)

= 163.5746 MT CH_4/year.

The potential CO_2 emissions have already been calculated (1,124.5755 metric tons CO_2/year). However, the methane produced will lower the CO_2 emissions from the anaerobic digester. The total CO_2 generation is calculated by subtracting the carbon associated the CH_4 generation from the potential CO_2 emissions using Equation N.44 as follows:

Total CO_2 generation (metric tons CO_2/year)

= ((Potential CO_2 emissions) – (Total CH_4 generation × 44/16))

= ((1,124.5755 × 12/44) – (163.5746 × 12/16)) × (44/12)

= 674.7453 MT CO_2 per year

The actual flow and loss terms can be computed from the capture efficiency of the anaerobic digester using Equations N.42, N.43, N.45, and N.46. The collection efficiency is dependent upon the type of anaerobic digester and its cover (for default values, see EPA, 2009b, Table A-4; 40 CFR 98.363, Table JJ-6). This hypothetical example is for an enclosed vessel, mixed plug flow digester where the collection efficiency is 0.99, such that:

CH_4_F	**= Total CH_4 generation × CE**	**= 163.5746×0.99**	**= 161.9389**
CH_4_L	**= Total CH_4 generation − CH_4_F**	**= 163.5746 − 161.9389**	**= 1.6357**
CO_2F	**= Total CO_2 generation × CE**	**= 674.7453×0.99**	**= 667.9978**
CO_2L	**= Total CO_2 generation − CO_2F**	**= 674.7453 − 667.9978**	**= 6.7475**

The next term to solve in calculating the denominator of the *AVOIDEMIT* term is CH_4D, the amount of CH_4 destroyed at a biogas combustion device (MT CH_4/year). This can be calculated using Equation N.36:

$$\mathbf{CH_4D = CH_4F \times DE}$$

CH_4F was previously solved. The CH_4 DE is estimated as the lesser of the manufacturer's specified destruction efficiency and 0.99 (EPA, 2013c). A DE value of 0.99 will be used for this example. Thus, the CH_4 destroyed at biogas combustion device can be estimated as:

$$\mathbf{CH_4D = 161.9389 \times 0.99}$$

$$\mathbf{= 160.3195\ MT\ CH_4/year.}$$

With estimated values for each of the terms in the denominator of the *AVOIDEMIT* term, the denominator can be solved using Equation N.35:

$$\mathbf{CO_2e\ Emissions_{AD} = 25(CH_4F - CH_4D + CH_4L) + CH_4D \times 44/16 + CO_2F + CO_2L}$$

CO_2e emissions from the anaerobic digester (MT /year)

$$\mathbf{= 25 \times (161.9389 - 160.3195 + 1.6357) + 160.3195 \times 44/16 + 667.9978 + 6.7475}$$

$$\mathbf{= 1{,}197.0014\ MT\ CO_2e\ /year}$$

Step 3: Calculate the *BAF* Value

With both the numerator and denominator of the *AVOIDEMIT* term having been computed, a *BAF* value can be estimated using Equations N.1 and N.2:

$$\boldsymbol{BAF = AVOIDEMIT}$$

$$\boldsymbol{BAF} = \mathbf{1 - \frac{3{,}526.6689}{1{,}197.0014}}$$

$$\boldsymbol{BAF} = \mathbf{-1.95}$$

A negative *BAF* value calculated for this hypothetical scenario indicates that a biogas feedstock produced in an anaerobic digester from the treatment of dairy manure and flared by a stationary source results in net CO_2e emissions reductions.

4.3. Sensitivity Analysis for Anaerobic Digestion of Livestock and Food Waste

For the livestock and food waste assessments, the parameter that has the greatest variability is the methane correction factor (MCF) for the waste management system employed as an alternative to anaerobic digestion. The biogas collection efficiency and the biogas destruction efficiency impact the *BAF* value, as does the global warming potential of CH_4. The total biogas flow rate or the total volatile solids produced (if animal population correlations are used) does not impact the *BAF* value as they impact both the numerator and denominator by a constant factor. However, the relative ratio of CH_4 produced versus CO_2 produced does impact the *BAF* value. Table N-9 presents the results of the sensitivity analysis performed when using biogas measurement data to calculate BA.

Table N-10 presents the results of the sensitivity analysis performed when using animal population data to calculate *BAF*. Sources for the parameter values used here can be found in Table N-8 of Section 4.1.3.

Table N-9. Sensitivity Analysis of Anaerobic Digestion Using Biogas Measurement Data.[1]

Analysis	Key Parameter Varied	Key Parameter Value	*BAF* Value Calculated at the Specified MCF Value			
			MCF=0.05	MCF=0.3	MCF=0.5	MCF=0.8
1	GWP_{CH_4}	21	−0.10	−0.90	−1.54	−2.50
2	GWP_{CH_4}	25	−0.12	−1.08	−1.85	−3.00
3	GWP_{CH_4}	28	−0.13	−1.21	−2.07	−3.37
4	C_{CH_4}	40%	−0.09	−0.88	−1.50	−2.44
5	C_{CH_4}	50%	−0.12	−1.08	−1.85	−3.00
6	C_{CH_4}	60%	−0.14	−1.27	−2.18	−3.55
7	DE	0.99	−0.12	−1.08	−1.85	−3.00
8	DE	0.95	0.03	−0.80	−1.47	−2.47
9	CE	0.99	−0.12	−1.08	−1.85	−3.00
10	CE	0.70	0.47	0.01	−0.35	−0.90

[1] The following central tendency values were used unless specified as the parameter varied. The moisture content was not varied as it has a limited range (1% to 5%) and did not significantly impact the calculated *BAF*.

- GWP_{CH_4} = 25
- C_{CH_4} = 50%
- M (moisture content) = 3%
- DE = 0.99
- CE = 0.99

Note: References for the key parameters and values are presented in Table N-8 of Section 4.1.3.

Table N-10. Sensitivity Analysis of Anaerobic Digestion Using Animal Population Data.[1]

Analysis	Key Parameter Varied	Key Parameter Value	*BAF* Value Calculated at the Specified MCF Value			
			MCF=0.05	MCF=0.3	MCF=0.5	MCF=0.8
1	GWP_{CH_4}	21	−0.09	−0.87	−1.48	−2.41
2	GWP_{CH_4}	25	−0.11	−1.04	−1.79	−2.90
3	GWP_{CH_4}	28	−0.13	−1.17	−2.01	−3.26
4	Bo	0.15	−0.06	−0.54	−0.93	−1.51
5	Bo	0.30	−0.11	−1.04	−1.79	−2.90
6	Bo	0.50	−0.18	−1.65	−2.84	−4.61
7	VolatileCarbon_AT	0.20	−0.16	−1.51	−2.58	−4.20
8	VolatileCarbon_AT	0.30	−0.11	−1.04	−1.79	−2.90
9	VolatileCarbon_AT	0.40	−0.09	−0.80	−1.36	−2.22
10	DE	0.99	−0.11	−1.04	−1.79	−2.90
11	DE	0.95	0.03	−0.78	−1.43	−2.40
12	CE	0.99	−0.11	−1.04	−1.79	−2.90

Analysis	Key Parameter Varied	Key Parameter Value	*BAF* Value Calculated at the Specified MCF Value			
			MCF=0.05	MCF=0.3	MCF=0.5	MCF=0.8
13	CE	0.70	0.46	0.01	−0.35	−0.89

[1] The following central tendency values were used unless specified as the parameter varied.

- GWP_{CH_4} = 25
- Bo = 0.30
- VolatileCarbon_AT = 0.30
- DE = 0.99
- CE = 0.99

Note: References for the key parameters and values are presented in Table N-8 of Section 4.1.3.

The following observations are noted. At the selected central tendency values, the two methodologies yield very similar results. If the ratio for CH_4 generation to CO_2 generation had been exactly the same for both methodologies, identical *BAF* values would be produced. When MCF increases, it directly increases the "Avoided CH_4 emissions" and the *BAF* values go down (or become more negative). Increasing the global warming potential of methane (GWP_{CH_4}), will increase the absolute value of the calculated *BAF* (i.e., if the *BAF* is negative, increasing GWP_{CH_4} will make it more negative; if the *BAF* is positive, increasing GWP_{CH_4} will make *BAF* increase). When CH_4 generation increases at a constant overall "potential CO_2 emissions" rate (increasing C_{CH_4} or increasing Bo), the impact will be similar to increasing the global warming potential of methane (i.e., it will increase the absolute value of the calculated *BAF*). In the biogas measurement method, the CO_2 generation is inversely related to the biogas methane concentration (C_{CH_4}) and is not really an independent variable. In the animal population method, the "potential CO_2 emissions" is a function of the carbon content of the volatile solids (VolatileCarbon_AT) and can vary independently of the maximum methane generation (Bo). Increasing the VolatileCarbon_AT increases the CO_2 emissions relative to CH_4 emissions, so increasing VolatileCarbon_AT acts similar to decreasing C_{CH_4} or Bo. If the fraction of methane emitted from anaerobic digestion, estimated as $1 - DE \times CE$, exceeds the fraction of methane emitted from the alternative waste management system, estimated as MCF, then the *BAF* value will be positive.

5. Livestock Waste Management through Direct Combustion or Thermochemical Processing and Associated GHG Emissions Pathways

Direct combustion of livestock waste presents an alternative to management through anaerobic storage and treatment, or aerobic treatment, such as composting or field spreading as a soil amendment. Direct combustion of livestock waste is currently not a common management practice in the United States. Management applications typically involve combustion of poultry litter for electricity generation, space heating (e.g., of poultry houses), or combined heat and power (Kelleher et al., 2002; Santoianni et al., 2008).[33] There are also emerging thermochemical conversion

[33] Poultry litter is a mixture of animal bedding materials (e.g., straw, wood chips, or corn husks), manure, and feathers (Santoianni et al., 2008).

processes that can be used to convert and capture the energy in livestock waste via pyrolysis, gasification, co-firing, or direct liquefaction (Cantrell et al., 2008; Santoianni et al., 2008).

Direct combustion or thermochemical conversion of livestock waste is not expected to result in a net increase in CO_2e emissions relative to alternative GHG emissions pathways that could be used to manage the livestock waste.[34] Combustion or thermochemical processing is expected to result in net GHG emissions reductions compared to GHG emissions pathways that involve anaerobic storage and treatment of livestock waste. In short, if the livestock waste were not combusted or processed at high temperatures at a stationary source, resulting in biogenic CO_2 emissions, its alternate fate would have resulted in CH_4 and/or CO_2 emissions through anaerobic decay, aerobic decay, or both. Combustion can, however, introduce toxic metals into the environment.

The biomass contained in livestock waste is the digestive byproducts of consumed plant and animal matter. This represents carbon originally contained in plant matter, often in the form of agricultural crops, produced on a short-rotation basis.[35] As a result, the biomass contained in livestock manure that is combusted (with resulting biogenic CO_2 emissions) is typically derived from plant matter CO_2 uptake during annual or short, multi-year growth and harvest cycles.

Stationary source combustion or processing of livestock waste can result in the removal of atmospheric CO_2. For example, ash produced from the combustion of livestock waste can be used as an agricultural fertilizer, and pyrolysis can be used to produce biochar—a process that stabilizes carbon and can result in long-term carbon storage (Cantrell et al., 2008; Santoianni et al., 2008).

5.1. Method for Calculating an Illustrative *BAF* Value Applied to Biogenic Emissions Resulting from Combustion of Livestock Waste

The assessment factor equation can be applied to point source biogenic CO_2 emissions from a stationary source combusting livestock waste. This section provides an illustrative method for calculating a *BAF* value that is applied to point source biogenic CO_2 emissions from a stationary source combusting livestock waste.

Here the biogenic feedstock is livestock waste, in a form suitable for combustion.[36] In applying the assessment factor equation to this feedstock, the avoided GHG emissions reductions that would have occurred in the absence of combustion of livestock waste at a stationary source are accounted for in the *AVOIDEMIT* term of Equation N.1 ($BAF = AVOIDEMIT$). The *AVOIDEMIT* term represents the net GHG emissions reductions that are achieved through combustion of livestock waste, as compared to the emissions pathway from an alternate fate (e.g., treatment via field spreading or in an uncovered anaerobic lagoon). Similar to the other waste-derived biogenic feedstocks, the alternative GHG emissions pathway is accounted for in the numerator of the *AVOIDEMIT* term,

---

[34] In the case of thermochemical processing, this does not include fossil fuel energy inputs used to generate process heat.
[35] This would apply to both plant- and animal-based livestock feeds.
[36] Combustion of biomass with high moisture content can be problematic; pre-drying of livestock waste may be required. Some operations have addressed this problem by mixing livestock waste with woody materials (e.g., saw dust) (Santoianni et al., 2008).

whereas the denominator accounts for the GHG emissions resulting from the actual waste management strategy used.

In practice, as applied here, the *AVOIDEMIT* term contains a ratio of the emissions, in CO_2e, of the alternative livestock waste management process (had that feedstock not been combusted) to the emissions, in tCO_2e, from the combustion of the livestock waste, after accounting for the combustion efficiency of the manure combustor. For the feedstock of livestock waste suitable for combustion, the *AVOIDEMIT* term can be conceptually expressed by the simplified ratio of:

$$\boldsymbol{AVOIDEMIT = 1 - \frac{(\text{emissions from treatment alternative to combustion})}{(\text{emissions from treatment by combustion})}} \qquad \textbf{(EQ N.47)}$$

5.1.1. Calculating the Numerator

In computing *AVOIDEMIT*, the numerator (i.e., emissions from treatment alternative to combustion) can be calculated by assuming that if livestock waste were not managed using combustion, then this waste would have been managed under one or more different waste management systems. For example, the alternative pathway may be associated with waste storage followed by an aerobic land application or it could be anaerobic stored and treated in an uncovered lagoon.[37] The GHGs that would have been generated under these alternative fates can be estimated using methods presented in IPCC (2006b) and EPA (2009b). To estimate the annual CO_2 and CH_4 emissions resulting from a livestock waste management strategy other than combustion, the numerator of the *AVOIDEMIT* term can be estimated using Equation N.48.

Total CO_2e emissions from a livestock waste management alternate to combustion =

$$\textbf{(avoided } \boldsymbol{CO_2} \textbf{ emissions) + (avoided } \boldsymbol{CH_4} \textbf{ emissions)} \qquad \textbf{(EQ. N.48)}$$

The avoided CO_2 emissions from a livestock waste management alternate to combustion is equal to the available carbon in the volatile solids of the livestock waste after removing the amount of carbon which becomes CH_4 and then converting the remaining available carbon to CO_2. This calculation (Equation N.48) is the same as Equation N.25 which was previously used in the calculation of emissions from anaerobic digesters for livestock waste management:

Avoided CO_2 emissions (metric tons CO_2e/year) =

$$\boldsymbol{[(PCO_2 \times 12/44) - (\text{Avoided } CH_4 \text{ emissions}/GWP_{CH_4} \times 12/16)] \times (44/12)} \qquad \textbf{(EQ. N.239)}$$

Where:

PCO_2 = Potential maximum CO_2 emissions, see Equation N.50.

[37] There are multiple livestock waste management scenarios alternative to combustion of livestock waste. An uncovered anaerobic lagoon would generate the most (see EPA, 2009b, Table A-3). Depending on ambient temperature, CH_4 production in an uncovered anaerobic lagoon ranges from 66% to 80% of the maximum amount of CH_4 that could potentially be produced from the livestock waste. The appropriate alternative livestock waste management scenario should be used when this calculation is made.

(12/44) = molecular weight ratio of C to CO_2 (converts potential CO_2 emissions to carbon).

Avoided CH_4 emissions = avoided CH_4 emissions, metric tons CO_2e/year (see Equation N.53, below).

GWP_{CH_4} = 100-year GWP for CH_4.

(12/16) = molecular weight ratio of C to CH_4 (converts CH_4 emissions to carbon).

(44/12) = molecular weight ratio of CO_2 to C (converts C less that associated with the CH_4 emissions back to CO_2 emissions).

Potential CO_2 emissions can be solved using Equation N.50, which was also used in estimating the emissions associated with livestock waste management via an anaerobic digester:

Potential CO_2 emissions =

$$\boldsymbol{\Sigma_{\text{animal type}} (TVS_{AT} \times VolatileCarbon_{AT} \times (44/12) \times 365 \times 1/1{,}000)} \qquad \textbf{(EQ. N.50)}$$

Where:

$\Sigma_{\text{animal type}}$ = If the alternate waste management system accepts waste from more than one animal type then this calculation must be computed for each animal type and then summed across animal types.

TVS_{AT} = Total volatile solids excreted by animal type (kg/day); the TVS_{AT} equation is presented below (Equation N.51).

$VolatileCarbon_{AT}$ = Fraction of degradable carbon in the volatile solids of the livestock waste (see Equation N.52).

44/12 = molecular weight ratio of CO_2 to C.

365 = number of days per year (i.e., 365 days/year).

1/1,000 = conversion factor from kg to metric tons.

Total volatile solids excreted by animal type (TVS_{AT}) may be calculated using the following equation (previously presented under livestock waste management using anaerobic digester) and referring to tables external to this appendix (Table A-2, EPA, 2009b and Tables JJ-2 and JJ-3, 40 CFR 98.363):

$$\boldsymbol{TVS_{AT} = (Population_{AT} \times TAM_{AT} \times VS_{AT}/1{,}000)} \qquad \textbf{(EQ. N.51)}$$

Where:

TVS_{AT} = Total volatile solids excreted per animal type (kg/day).

$Population_{AT}$ = Average annual animal population (head), by animal type.[38]

TAM_{AT} = Typical animal mass, by animal type; determined using either default values (see EPA, 2009b, Table A-2) or farm specific data (kg/head).

VS_{AT} = Volatile solids excretion rate by animal type, using either default values (see 40 CFR 98.363, Tables JJ-2 and JJ-3) or farm specific data (kg VS/day/kg animal mass).

The fraction of degradable carbon in the volatile solids of the livestock waste ($VolatileCarbon_{AT}$) can be estimated using results from proximate and ultimate analyses[39] of the livestock waste specific to the waste of animal type being managed (see Equation N.52). Data needed to estimate this parameter can be directly measured or, more simply, can be taken from the body of published scientific literature.[40]

$$\mathbf{VolatileCarbon_{AT}} = \frac{\text{Carbon} - \text{Fixed Carbon}}{\text{Volatile Solids}} = \frac{\text{Carbon} - \text{Fixed Carbon}}{\text{Volatile Matter} + \text{Fixed Carbon}} \qquad \textbf{(EQ. N.52)}$$

Where:

$VolatileCarbon_{AT}$ = Fraction of the degradable carbon in the volatile solids of the livestock waste (kg degradable carbon in volatile solids/kg of volatile solids, dry basis).[41]

Carbon = Fraction of carbon in livestock waste (kg carbon in total dried solids/kg of total dried solids), dry basis (from ultimate analysis).

Fixed Carbon = Fraction of dry solids in livestock waste that does not volatilize when heated to 900 °C in nitrogen (kg fixed carbon in total dried solids/kg of total dried solids) but is lost when heated in air at 600 °C, dry basis (from fuels proximate analysis; see Figure N-3).

---

[38] For static populations (e.g., dairy cows, breeding swine), average annual animal populations are estimated using annual animal inventory or equivalent. For growing populations (e.g., meat animals such as beef and veal cattle), average annual animal populations are estimated using the average number of days each animal is kept at the facility and the number of animals produced annually (e.g., growing population = days onsite × (number of animals produced annually / 365)).

[39] Characteristics of a biogenic feedstock can be described using proximate and ultimate analyses based on a sample's complete combustion to CO_2 and liquid water. The proximate analysis gives moisture content, volatile content, carbon remaining (fixed carbon), and mineral ash. The ultimate analysis gives the sample's elemental composition as proportions of carbon, hydrogen, oxygen, nitrogen, and sulfur. Standardized test methods have been developed, for example, see Table 3 in Demirbas (2004).

[40] For example, ASAE Standard D384.2 (2005) is useful for estimating general characteristics of livestock and poultry manure. Li et al. (2008) and Henihan et al. (2003) present specific results of proximate and ultimate analyses of chicken litter characteristics; Sweeten et al. (2002 and 2003) present similar specific results but of cattle manure.

[41] If the mass of fixed carbon is not 100% carbon then the amount of carbon in the volatile solids may be underestimated, thus giving a low-biased estimate of the $VolatileCarbon_{AT}$ term (though the bias is likely small).

Volatile Solids = Fraction of volatile solids in livestock waste (kg volatile solids in total dried solids/kg of total dried solids), dry basis (from waste volatile solids analysis). If only fuels proximate analysis is available, estimate the volatile solids as the sum of the volatile matter and fixed carbon from the fuels proximate analysis (see Figure N-3).

Volatile Matter = fraction of dry solids that does is lost when heated to 900 °C in nitrogen (kg volatile matter/kg of total dried solids), dry basis.

Equation N.53 can be used to estimate the annual avoided CH_4 emissions generated from a manure management strategy alternate to combustion:

Avoided CH_4 emissions (metric tons CO_2e/year) =

$$\Sigma_{\text{animal type}} (TVS_{AT} \times VS_{WMS} \times Days \times B_0 \times MCF_{WMS} \times 0.662 \times 1/1{,}000 \times GWP_{CH_4}) \quad \text{(EQ. N.53)}$$

Where:

$\Sigma_{\text{animal type}}$ = If the alternate waste management system accepts waste from more than one animal type then this calculation must be computed for each animal type and then summed across animal types.

TVS_{AT} = Total volatile solids excreted by animal type (kg/day); (Equation N.51).

VS_{WMS} = Proportion of total manure for each animal type that is managed in each waste management system (assumed to be equivalent to the amount of volatile solids in each waste management system).

Days = Number of days per year (i.e., 365 days/year).

B_0 = Maximum CH_4-producing capacity for each animal type (m^3 CH_4/kg volatile solids; see EPA, 2009b, Table A-2).

MCF_{WMS} = CH_4 conversion factor (proportion represented as a decimal value) for the alternative-scenario, waste management system (see EPA, 2009b, Table A-3).

0.662 = density of CH_4, kg CH_4 / m^3 (at 531.67°R, or 22.22°C, and 1 atm).

1/1000 = conversion factor from kg to metric tons.

GWP_{CH_4} = 100-year GWP of CH_4, 25 (IPCC, 1996).

The maximum amount of CH_4 that could potentially be produced from livestock waste managed under ideal conditions is calculated by multiplying the total volatile solids by the maximum CH_4-producing capacity of the livestock waste (B_0). The B_0 values vary by animal type and diet (see EPA, 2009b, Table A-2). Most manure management systems will not produce the maximum amount of CH_4 possible because the conditions in the systems are not ideal for CH_4 production. The CH_4-

producing potential of a specific livestock waste management system is represented by a methane conversion factor (MCF). The value of this parameter ranges from 0% to 100% and reflects the capability of a system to produce the maximum achievable CH_4 (the higher the MCF, the greater the potential for CH_4 production). For liquid systems (e.g., uncovered anaerobic lagoons), MCF values are temperature dependent: in order to assign the appropriate MCF for the type of liquid system used, the average ambient temperature at the system's location must be known (see EPA, 2009b, Table A-3).

Summing the avoided CO_2 emissions and the avoided CH_4 emissions (Equation N.48, metric tons CO_2e/year) is the final computation in estimating the numerator in the *AVOIDEMIT* term for a livestock waste management strategy alternative to combustion. See Section 5.2.2 for two illustrative example calculations of the numerator in the *AVOIDEMIT* term and its subsequent application in estimating a *BAF*.

5.1.2. Calculating the Denominator

In the derivation of *AVOIDEMIT*, the denominator (emissions from livestock waste treatment by combustion) is based on the carbon content of the point source, stack emissions from the waste combustion unit. The value of the denominator is equal to the CO_2e of the combusted livestock waste, adjusted by the combustion efficiency of the incinerator.[42] This adjustment is to account for the proportion of feedstock that is neither combusted nor emitted to the atmosphere as a point-source emission. Combustion of livestock waste does not create or emit CH_4; the only GHG associated with this process is CO_2. The principal products of livestock waste combustion include CO_2, carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), sulfur oxides (SO_x), inorganic bottom ash, and fly ash (Antares Group Inc. et al., 1999). Carbon monoxide and HC are important indicators of incomplete combustion; with complete combustion, CO_2 is the primary carbon-based emission (Antares Group Inc. et al., 1999).

Total CO_2e emissions from combustion of livestock waste can be computed using the following equation:

CO_2 emissions from incineration of livestock waste (MT CO_2e/year) =

$$\boldsymbol{\Sigma_{\text{animal type}} (TVS_{AT} \times TotalCarbon_{AT} \times DE \times (44/12) \times 365 \times 1/1{,}000)} \qquad \textbf{(EQ. N.244)}$$

Where:

TVS_{AT} = total volatile solids excreted per animal type (kg/day), see Equation N.51.

[42] Combustion efficiency of livestock waste varies with the type of boiler used, moisture content, and particle size of the feedstock. In an efficient combustor, very little carbon in poultry litter is left unburned (Antares Group Inc. et al. 1999). One published value of combustion efficiency for combustion of broiler litter, based on the carbon content in the ash is 96% (Costello, 2007).

$TotalCarbon_{AT}$ = fraction of the carbon in the volatile solids of the livestock waste, see Equation N.55.

DE = livestock waste destruction efficiency (i.e., combustion efficiency of incinerator).

44/12 = molecular weight ratio of CO_2 to C.

365 = number of days per year (i.e., 365 days/year).

1/1,000 = conversion factor from kg to metric tons.

The fraction of total carbon in the volatile solids of the livestock waste ($TotalCarbon_{AT}$) can be estimated using results from proximate and ultimate analyses[43] of the livestock waste specific to the waste of animal type being managed. It is again assumed that there is negligible carbon in the residue, but the fixed carbon is expected to oxidize during the manure combustion process. Thus, it is assumed that all of the combustible carbon exists in the volatile solids fraction of the dried solids. Data needed to estimate this parameter can be directly measured or, more simply, can be taken from the body of published scientific literature.[44]

$$\mathbf{TotalCarbon_{AT}} = \frac{\mathbf{Carbon}}{\mathbf{Volatile\ Solids}} = \frac{\mathbf{Carbon}}{\mathbf{Volatile\ Matter + Fixed\ Carbon}} \qquad \textbf{(EQ. N.255)}$$

Where:

$TotalCarbon_{AT}$ = fraction of carbon in the volatile solids of the livestock waste, (kg carbon in volatile solids/kg of volatile solids, dry basis).

Carbon = fraction of carbon in livestock waste (kg carbon in total dried solids/kg of total dried solids), dry basis (from ultimate analysis).

Volatile Solids = fraction of volatile solids in livestock waste (kg volatile solids in total dried solids/kg of total dried solids), dry basis (from waste volatile solids analysis). If only fuels proximate analysis is available, estimate the volatile solids as the sum of the volatile matter and fixed carbon from the fuels proximate analysis (see Figure N-3).

---

[43] Characteristics of a biogenic feedstock can be described using proximate and ultimate analyses based on a sample's complete combustion to CO_2 and liquid water. The proximate analysis gives moisture content, volatile content, carbon remaining (fixed carbon), and mineral ash. The ultimate analysis gives the sample's elemental composition as proportions of carbon, hydrogen, oxygen, nitrogen, and sulfur. Standardized test methods have been developed, for example, see Table 3 in Demirbas (2004).

[44] For example, ASAE Standard D384.2 (2005) is useful for estimating general characteristics of livestock and poultry manure. Li et al. (2008) and Henihan et al. (2003) present specific results of proximate and ultimate analyses of chicken litter characteristics; Sweeten et al. (2002 and 2003) present similar specific results but of cattle manure.

Volatile Matter = fraction of dry solids that does is lost when heated to 900 °C in nitrogen (kg volatile matter/kg of total dried solids), dry basis (from fuels proximate analysis; see Figure N-3)

Fixed Carbon = fraction of dry solids in livestock waste that does not volatilize when heated to 900 °C in nitrogen (kg fixed carbon in total dried solids/kg of total dried solids) but is lost when heated in air at 600 °C, dry basis (from fuels proximate analysis; see Figure N-3).

After solving for the numerator and the denominator of the *AVOIDEMIT* term, the *BAF* can be calculated using Equation N.1. See Section 5.2.2 for two illustrative example calculations of the numerator and denominator in the *AVOIDEMIT* term and its subsequent application in estimating a *BAF* for livestock waste management by way of direct combustion.

Several parameters are presented and used in the equations in the remainder of this section. Table N-11 presents the parameters used, typical or default values, ranges presented in the literature, and references.

Table N-11. Summary of Parameters Used When Calculating an Illustrative *BAF* for Livestock Waste Management through Combustion.

Parameter Description	Symbol	Value	Range	Units	Comments	Reference (for value column)
Typical animal mass, by animal type	TAM_{AT}	604	Numerous	kg/head	Determined using either default values or farm-specific data	EPA, 2009b, Table A-2; IPCC, 2006, Table 10A4-10A9
Volatile solids excretion rate by animal type	VS_{AT}	9.34	Depends on the type of animal group	kg VS/day/kg animal mass	Value presented is used in the example calculations in Section 4.0.[1]	EPA, 2009b, Table A-2; EPA, 2013c, Tables JJ-2 and JJ-3
Maximum CH_4-producing capacity for each animal type	B_0	0.24	0.17 to 0.78	m^3 CH_4 /kg volatile solids	Value presented is for dairy cows	EPA, 2009b, Table A-2
Density of CH_4	--	0.662	--	kg CH_4/m^3	At 532°R, or 22.22°C, and 1 atm	EPA, 2009b
Destruction efficiency	DE	0.96	0.90 to 0.9977	decimal percent		EPA, 2009b, Table A-4

Parameter Description	Symbol	Value	Range	Units	Comments	Reference (for value column)
Fraction of volatile solids in livestock waste	Volatile Carbon_AT		0.20 to 0.40	kg volatile solids in total dried solids/kg of total dried solids, dry basis	Value is determined from waste volatile solids analysis[2]	Sweeten et al., 2002

[1] VS_{AT} can be determined using either default values or farm-specific data.

[2] If only fuels proximate analysis is available, estimate the volatile solids as the sum of the volatile matter and fixed carbon from the fuels proximate analysis (see Figure N-3).

5.2. Example *AVOIDEMIT* and *BAF* Calculations for Direct Combustion of Livestock Waste

Two example scenarios of alternative management for poultry litter are presented here. Both examples are set in northern Georgia and consist of 400,000 broilers (chickens).[45] In the first example, the alternative management strategy is to store the chicken litter as a solid prior to its application as a soil amendment; the chicken litter would be stored for approximately 1 year prior to its land application (EPA, 2001).[46] In the second example, the alternative management strategy, although not as commonly used, is to store and manage the chicken litter from broilers in an uncovered anaerobic lagoon.[47] Several of the calculated parameter values can be used in both scenarios (i.e., TVS_{AT}, $VolatileCarbon_{AT}$, and the potential maximum CO_2 emissions).

5.2.1. Example Calculation for Direct Combustion and Land Application of Livestock Waste

Step 1: Calculating the Avoided CH_4 from the Alternate Treatment

To calculate the numerator of the *AVOIDEMIT* term, the total volatile solids must be estimated in order to calculate the avoided CH_4 emissions. Parameters in Equation N.48 can be estimated using a hypothetical example of an operation set in northern Georgia, consisting of 400,000 broilers per year, with a typical animal mass of 0.9 kg, and a volatile solids excretion rate of 15 kg VS/day/1000 kg animal mass (see 40 CFR 98.363, Table JJ-2). Equation N.51 may be used to calculate total volatile solids excreted per animal type:

[45] Regional differences in ambient temperature affect the value of the CH_4 conversion factor (MCF_{WMS}) used to calculate avoided CH_4 emissions. Therefore, the geographic location of the manure management system has an effect on the amount of generated emissions and the value of the *BAF*. However, the number of animals (e.g., broilers) whose waste is managed does not have an effect on the value of the *BAF*.

[46] Large quantities of poultry litter are removed from the poultry house during annual clean-out. If possible, the annual clean-out typically is timed to coincide with the time land is available for land application (EPA, 2001).

[47] Although chicken litter from broilers can be managed in anaerobic lagoons, it is more common to use this management strategy for pullets.

$$\mathbf{TVS_{AT} = (Population_{AT} \times TAM_{AT} \times VS_{AT}/1{,}000)}$$

$$\mathbf{= 400{,}000 \times 0.9\ kg \times 15\ kgVS/day/kg\ animal\ mass/1{,}000}$$

$$\mathbf{= 5{,}400\ kg/day}$$

With TVS_{AT} estimated, the avoided CH_4 emissions resulting from a poultry litter management strategy other than an anaerobic digester can be calculated. In this hypothetical example set in a temperate region (e.g., northern Georgia) with an average temperature of 16ºC, the alternative fate could have been to store the chicken litter as a solid prior to its application as a soil amendment; the chicken litter would be stored for approximately 1 year prior to its land application (EPA, 2001).

In this first hypothetical scenario, the only litter-producing animal type is broilers, and the only alternate waste management system of the poultry production with litter is solid storage prior to land application. When calculating the avoided CH_4 emissions associated with the alternative fate of chicken litter under this scenario, several parameters are needed, including the maximum CH_4-producing capacity for broilers (see EPA, 2009b, Table A-2, for the appropriate default value; for broilers, $B_0 = 0.36\ m^3\ CH_4/kg$); and a CH_4 conversion factor for the alternative-scenario's waste management system (see EPA, 2009b, Table A-3; for solid storage in a temperate climate, $MCF_{WMS} = 0.04$). Equation N.53 can be used to calculate the avoided CH_4 emissions:

Avoided CH_4 emissions (metric tons CO_2e per year)

$$\mathbf{= 25 \times (TVS_{AT} \times VS_{WMS} \times 365\ days/year \times B_0 \times MCF_{WMS} \times 0.662\ kg\ CH_4/m^3 \times 1\ metric\ ton/1{,}000\ kg)}$$

$$\mathbf{= 25 \times (5{,}400 \times 1 \times 365 \times 0.36\ m^3\ CH_4/kg \times 0.04 \times 0.662 \times 1/1{,}000)}$$

$$\mathbf{= 469.7287\ MT\ CO_2e\ per\ year.}$$

Step 2: Calculating the Avoided CO_2 from the Alternate Treatment

To estimate the avoided CO_2 emissions from a poultry litter management strategy other than combustion, the fraction of degradable carbon in the volatile solids of the chicken litter must be calculated. For the scenarios presented here (Section 5.2), data (results from proximate and ultimate analyses of poultry litter) from Li et al. (2008) can be used to populate parameters in Equation N.48. Because Li et al. (2008) presented results of the proximate analysis on a wet basis, those parameters must be converted to a dry basis by dividing each of them by the proportion of the dry content of the chicken litter (i.e., divide the fixed carbon and the volatile solids each by (1–moisture content)). In the $VolatileCarbon_{AT}$ term, the fixed carbon is removed from the total carbon in the poultry litter because the fixed carbon is assumed not to degrade. Using these data, Equation N.52 can be parameterized as follows:

$$\mathbf{VolatileCarbon_{AT} = \frac{Carbon - Fixed\ Carbon}{Volatile\ Solids} = \frac{Carbon - Fixed\ Carbon}{Volatile\ Matter + Fixed\ Carbon}}$$

$$= \frac{\mathbf{0.282 - 0.0688}}{\mathbf{0.6516 + 0.0688}}$$

$$= \mathbf{0.2959}$$

With TVS_{AT} and $VolatileCarbon_{AT}$ estimated, the potential maximum CO_2 emissions (Equation N.50) resulting from a chicken litter management strategy alternative to combustion can then be estimated. In this scenario, the alternate fate is solid manure storage for approximately 1 year before it is ultimately used as a land application. Because waste management is limited to litter from only one animal type (broilers), Equation N.50 only needs to be calculated once, as follows:

Potential CO_2 emissions

$$= (\mathbf{TVS_{AT} \times VolatileCarbon_{AT} \times (44/12) \times 365\ days/year \times 1\ metric\ ton/1{,}000\ kg})$$

$$= \mathbf{5{,}400 \times 0.2959 \times (44/12) \times 365 \times 1/1{,}000}$$

$$= \mathbf{2{,}138.4693\ MT\ CO_2\ per\ year}$$

With estimates of both the potential CO_2 emissions and the avoided CH_4 emissions, the avoided CO_2 emissions resulting from an aerobic poultry litter management strategy can be calculated. For this calculation the total potential CO_2 emissions from the decomposition of TVS_{AT} must first be converted to carbon. From this is subtracted the CH_4 emissions after converting them to carbon. The result is then converted back to CO_2 (see Equation N.49):

Avoided CO_2 emissions

$$= \mathbf{((Potential\ CO_2\ emissions \times 12/44) - (Avoided\ CH_4\ emissions/25 \times 12/16)) \times (44/12)}$$

$$= \mathbf{((2{,}138.4693 \times 12/44) - (469.7287 / 25 \times 12/16)) \times (44/12)}$$

$$= \mathbf{2{,}086.7990\ MT\ CO_2\ per\ year}$$

Step 3: Calculating the CO_2e from the Alternate Fate (Numerator)

The final calculation in solving for the numerator of the *AVOIDEMIT* term for this scenario of chicken litter management is to sum the estimated, avoided CH_4 and the avoided CO_2 emissions (Equation N.48). This summation represents the total avoided CO_2e emissions (in metric tons CO_2e per year) that result from storage of the solid litter:

Total avoided CO_2e emissions

$$= \mathbf{(avoided\ CO_2\ emissions) + (avoided\ CH_4\ emissions)}$$

$$= \mathbf{2{,}086.7990 + 469.7287}$$

$$= \mathbf{2{,}556.5277\ metric\ tons\ CO_2e\ per\ year.}$$

Step 4: Calculating the CO_2e from the Anaerobic Digester (Denominator)

Equation N.54 can be used to calculate the denominator of the *AVOIDEMIT* term. In both of the scenarios presented here, poultry litter management is limited to that from only one animal type (i.e., broilers). The above calculated values for total volatile solids excreted per broiler (TVS_{AT}) is still applicable. For combustion, however, the fraction of total carbon, rather than degradable carbon, in the volatile solids must be calculated. Using Equation N.55, fraction of carbon in the volatile solids of the poultry litter ($TotalCarbon_{AT}$) is calculated as:

$$\mathbf{TotalCarbon_{AT}} = \frac{\textbf{Carbon}}{\textbf{Volatile Solids}} = \frac{\textbf{Carbon}}{\textbf{Volatile Matter + Fixed Carbon}}$$

$$= \frac{\mathbf{0.282}}{\mathbf{0.6516+0.0688}}$$

$$= \mathbf{0.3914}$$

Given these values, the total CO_2e emissions from combusting the litter from the 400,000 broilers assuming a 96% destruction efficiency of the waste[48] is calculated as:

CO_2 emissions from incineration of poultry litter (metric tons CO_2e/year)

$$= \mathbf{TVS_{AT} \times TotalCarbon_{AT} \times (44/12) \times DE \times days/year \times 1\ metric\ ton/1{,}000kg}$$

$$= \mathbf{5{,}400 \times 0.3914 \times (44/12) \times 0.96 \times 365 \times 1/1{,}000}$$

$$= \mathbf{2{,}715.5019\ metric\ tons\ CO_2e\ per\ year}$$

Step 5: Calculating the *BAF* Value

After solving for the numerator and the denominator of the *AVOIDEMIT* term associated with this litter management strategy (i.e., litter storage prior to a land application), the *BAF* can be calculated using Equation N.1 and Equation N.2:

BAF = AVOIDEMIT

$$= 1 - \frac{\mathbf{2{,}556.5277\ metric\ tons\ CO_2e/year}}{\mathbf{2{,}715.5019\ metric\ tons\ CO_2e/year}}$$

$$= \mathbf{0.06}$$

[48] Combustion efficiency of livestock waste varies with the type of boiler used, moisture content, and particle size of the feedstock. In an efficient combustor, very little carbon in poultry litter is left unburned (Antares Group Inc. et al., 1999). One published value of combustion efficiency for combustion of broiler litter, based on the carbon content in the ash is 96% (Costello, 2007).

The *BAF* is small, but positive, indicating that the alternate disposal scenario of storing the chicken litter as a solid prior to its application as a soil amendment has emissions similar to, but slightly lower than manure combustion.

5.2.2. Calculation for Direct Combustion and an Uncovered Anaerobic Lagoon

The second scenario presented is an alternate management strategy of this chicken litter via storage and treatment in an open anaerobic lagoon.[49] An uncovered anaerobic lagoon is capable of generating more CH_4 than is management via solid storage prior to land application. As a result the calculated avoided CH_4 emissions and the avoided CO_2 emissions will differ. However, between these two scenarios, the calculated values for TVS_{AT} (5,400 kg/day), $VolatileCarbon_{AT}$ (0.2959), and the potential maximum CO_2 emissions (2,138.4693 metric tons CO_2 per year) would not be different; those values calculated above, can be imported into the equations needed to calculate the avoided CH_4 emissions and the avoided CO_2 emissions (Equations N.53, and N.49, respectively).

Step 1: Calculating the Avoided CH_4 Emissions from the Alternate Fate

When calculating the avoided CH_4 emissions associated with the alternate fate of the chicken litter under this scenario, several parameters are needed, including the maximum CH_4-producing capacity for broilers (see EPA, 2009b, Table A-2, for the appropriate default value; for broilers, B_0 = 0.36 m^3 CH_4/kg; this is the same as under the previous example); and a CH_4 conversion factor for the alternative-scenario's waste management system (see EPA, 2009b, Table A-3; for an uncovered anaerobic lagoon in a temperate climate of 16°C, MCF_{WMS} = 0.75). The following equation (Equation N.53) can be used to calculate the avoided CH_4 emissions for treatment of this chicken litter via an uncovered anaerobic lagoon:

Avoided CH_4 emissions (metric tons CO_2e /year)

$$= 25 \times (TVS_{AT} \times VS_{WMS} \times 365 \text{ days/year} \times B_0 \times MCF_{WMS} \times 0.662 \text{ kg } CH_4/m^3 \times 1 \text{ metric ton}/1{,}000 \text{ kg})$$

$$= 25 \times (5{,}400 \text{ kg/day} \times 1 \times 365 \times 0.36 \text{ m}^3 \text{ } CH_4/\text{kg} \times 0.75 \times 0.662 \text{ kg } CH_4/m^3 \times 1/1{,}000)$$

$$= 8{,}807.4135 \text{ MT } CO_2e \text{ per year}$$

Step 2: Calculating the CO_2 Emissions from the Alternate Fate

With estimates of both the potential CO_2 emissions and the avoided CH_4 emissions, the avoided CO_2 emissions resulting from an uncovered anaerobic lagoon poultry litter management strategy can be calculated. For this calculation, the total potential CO_2 emissions from the decomposition of TVS_{AT} must first be converted to carbon. From this is subtracted the CH_4 emissions after converting them to carbon. The result is then converted back to CO_2 (see Equation N.49):

---

[49] As previously mentioned, chicken litter from broilers can be managed in anaerobic lagoons, though it is more common to use this management strategy for pullets.

Avoided CO_2 emissions

$$= ((\text{Potential } CO_2 \text{ emissions} \times 12/44) - (\text{Avoided } CH_4 \text{ emissions}/21 \times 12/16)) \times (44/12)$$

$$= ((2{,}138.4693 \times 12/44) - (7{,}398.2273/21 \times 12/16)) \times (44/12)$$

$$= 1{,}169.6538 \text{ MT CO2 per year}$$

Step 3: Calculating the CO_2e Emissions from the Alternate Fate

Summing the estimated, avoided CH_4 and CO_2 emissions (both in metric tons CO_2e per year) that result from an uncovered, anaerobic lagoon management strategy for poultry litter (Equation N.25), the numerator of the *AVOIDEMIT* term for this scenario can be computed as:

Total avoided CO_2e emissions

$$= (\text{avoided } CO_2 \text{ emissions}) + (\text{avoided } CH_4 \text{ emissions})$$

$$= 1{,}169.6538 + 8{,}807.4135$$

$$= 9{,}977.0673 \text{ MT } CO_2\text{e per year}$$

Step 4: Calculating the *BAF* Value

The denominator of the *AVOIDEMIT* term represents the CO_2e emissions associated with combustion of the poultry litter (in this case, litter from 400,000 broilers). The computed value of the denominator was previously calculated using Equation N.54 and is unchanged by the alternate fate of the managed poultry litter. Therefore, both the numerator and the denominator of the *AVOIDEMIT* term associated with this waste management strategy (i.e., an uncovered anaerobic lagoon) have been calculated. The *BAF* can be computed using Equations N.1 and N.2:

$$\boldsymbol{BAF = AVOIDEMIT}$$

$$= 1 - \frac{9{,}977.0673}{2{,}715.5019}$$

$$= -2.67$$

5.3. Sensitivity Analysis for Livestock Waste Management through Direct Combustion

Table N-12 presents the results of the sensitivity analysis performed for the direct combustion of livestock waste. Sources for the parameter values used here can be found in Table N-11 of Section 5.1.2. The parameter that has the greatest variability is the methane correction factor (MCF) for the waste management system employed as an alternative to direct livestock waste combustion. Increasing the MCF decreases the *BAF* (including making negative *BAF* values more negative). Increasing the GWP of CH_4 (GWP_CH_4) also decreases the *BAF* value. The methane generation potential (Bo) and the volatile carbon content (VolatileCarbon_AT) of the waste has a similar affect; increasing Bo or VolatileCarbon_AT decreases *BAF*. The total carbon content (TotalCarbon_AT) is only used in the denominator of the emission ratio term of *AVOIDEMIT*, so increasing

TotalCarbon_AT increases *BAF* (including making negative *BAF* less negative). In the same manner, the waste combustor destruction efficiency (DE) only impacts the denominator. Since the destruction efficiency here reflects the fraction of the total carbon that is oxidized in the combustor, lowering DE reduces the emissions in the denominator causes *BAF* to decrease (or become more negative).

Table N-12. Sensitivity Analysis of Anaerobic Digestion using Animal Population Data.[1]

Analysis	Key Parameter Varied	Key Parameter Value	*BAF* Value Calculated at the Specified MCF Value			
			MCF=0.05	MCF=0.3	MCF=0.5	MCF=0.8
1	GWP_{CH_4}	21	0.21	−0.35	−0.80	−1.47
2	GWP_{CH_4}	25	0.18	−0.50	−1.05	−1.87
3	GWP_{CH_4}	28	0.16	−0.61	−1.23	−2.16
4	Bo	0.15	0.25	−0.09	−0.36	−0.77
5	Bo	0.30	0.18	−0.50	−1.05	−1.87
6	Bo	0.50	0.09	−1.05	−1.96	−3.32
7	VolatileCarbon_AT	0.20	0.41	−0.27	−0.82	−1.64
8	VolatileCarbon_AT	0.30	0.18	−0.50	−1.05	−1.87
9	VolatileCarbon_AT	0.40	−0.04	−0.73	−1.27	−2.09
10	TotalCarbon_AT	0.30	−0.23	−1.25	−2.07	−3.30
11	TotalCarbon_AT	0.45	0.18	−0.50	−1.05	−1.87
12	TotalCarbon_AT	0.60	0.39	−0.13	−0.53	−1.15
13	DE	0.99	0.19	−0.48	−1.03	−1.84
14	DE	0.98	0.18	−0.50	−1.05	−1.87
15	DE	0.95	0.16	−0.55	−1.11	−1.96

[1] The following central tendency values were used unless specified as the parameter varied.

- GWP_{CH_4} = 25
- Bo = 0.30
- VolatileCarbon_AT = 0.30
- TotalCarbon_AT = 0.45
- DE = 0.99.

Note: References for the key parameters and values are presented in Table N-11 of Section 5.1.2.

6. Wastewater Disposal in Wastewater Treatment Facilities and Associated GHG Emission Pathways

Wastewater from domestic and industrial sources is treated to remove soluble organic matter, suspended solids, pathogenic organisms, and chemical contaminants from the wastewater prior to its discharge into natural water systems. In the United States, approximately 20% of domestic wastewater is treated in septic systems or other onsite systems, while the rest is collected and treated centrally (EPA, 2014b). Centralized wastewater treatment systems, such as publicly owned treatment works, may include a variety of processes, ranging from treatment in lagoons to advanced tertiary treatment technology for removing nutrients. In the United States, there are approximately 14,780 wastewater treatment plants (Lono-Batura et al., 2012).

Soluble organic matter in wastewater is generally removed via biological processes in which microorganisms biodegrade the organic matter under aerobic or anaerobic conditions. Sludges (also referred to as wastewater biosolids after they have been treated) are the product of most wastewater treatment systems (Bogner et al., 2007; RTI International, 2010). Carbon dioxide, CH_4 and N_2O can be produced and released to the atmosphere at various stages between the initial point of wastewater collection and its final disposal, including wastewater transport, sewage treatment processes, and anaerobic digestion of wastewater or sludges (Bogner et al., 2007). In the United States, domestic and industrial wastewater treatment accounted for approximately 2.3% of CH_4 emissions in 2012 (totaling 12.8 Tg CO_2e) and 1.2% of N_2O emissions (totaling 5.0 Tg CO_2e) (EPA, 2014b).

Methane is microbially produced under anaerobic conditions. Domestic wastewater CH_4 emissions originate from both septic systems and from centralized treatment systems. Within centralized systems, CH_4 emissions can arise from aerobic systems that are not well managed (resulting in anaerobic conditions) or that are designed to have periods of anaerobic activity (e.g., constructed wetlands), anaerobic systems (e.g., anaerobic lagoons), a mixed aerobic and anaerobic systems (e.g., facultative lagoons with surface aerobic zones and deeper anaerobic zones), and from anaerobic digesters if captured biogas is released through leaks, venting, or incomplete combustion (Bogner et al., 2007; RTI International, 2010; EPA, 2014b). During collection and treatment, wastewater may be accidentally or deliberately managed under anaerobic conditions. Wastewater and wastewater sludge may be further biodegraded under aerobic conditions or anaerobic conditions, including anaerobic digestion, agricultural reuse, or incineration (Bogner et al., 2007; EPA, 2014b).

N_2O is an intermediate product of microbial nitrogen cycling; it is generated via the treatment of domestic wastewater during both nitrification and denitrification of the nitrogen present, usually in the form of urea, ammonia, and proteins. These compounds are converted to nitrate (NO_3) through the aerobic process of nitrification. Denitrification occurs under anoxic conditions, and involves the biological conversion of nitrate into N_2 (EPA, 2014b). The amount of nitrogen present in the influent wastewater determines the N_2O generation potential.

Collection of biogas generated in the wastewater treatment process is primarily, if not entirely, restricted to treatment systems using anaerobic digesters. Anaerobic digesters are used to enhance the degradation process of wastewater and wastewater sludge, thereby producing biogas. If the CH_4 generated by an anaerobic wastewater treatment process or anaerobic sludge digestion process is captured and combusted (in a flare or other combustion device), then CH_4 is destroyed and converted to CO_2, resulting in a net decrease in GHG emissions. N_2O is not a product of wastewater treatment via an anaerobic digester.

It is unknown how many U.S. wastewater treatment facilities use anaerobic digesters to treat wastewater and wastewater sludge. However, a survey of 5,128 U.S. wastewater treatment facilities (of the 14,780 facilities) concluded that at least 1,238 (24% of this subsample) treat sludge using anaerobic digesters and collect the biogas produced (Lono-Batura et al., 2012). The majority of wastewater treatment facilities that use anaerobic digesters are large (treating over one million gallons per day). However, this represents less than 40% of the large wastewater treatment facilities in the U.S; this sector has potential to expand (Lono-Batura et al., 2012). Collected biogas from waste water treatment facilities is most commonly flared, though some wastewater treatment facilities use it for energy generation or sell it for use off-site; several facilities reported releasing the collected biogas directly to the atmosphere (Lono-Batura et al., 2012). Because anaerobic digesters enhance the waste degradation process, thereby increasing the rate of CH_4 generation, biogas produced in an anaerobic digester and released directly to the atmosphere without combustion would result in greater CH_4 emissions than had the treatment not utilized an anaerobic digester.

6.1. Method for Calculating an Illustrative *BAF* Value Applied to Biogenic Emissions Resulting from Combustion of Biogas from Wastewater Treatment

The assessment factor equation can be applied to point source biogenic emissions that result from the combustion of biogas from an anaerobic digester used for wastewater treatment. An illustrative method is provided for calculating a *BAF* value that can be applied to point source biogenic emissions from anaerobic digesters used for the treatment of wastewater. Wastewater treatment via an anaerobic digester is the only treatment method that results in point source emissions.

Here the biogenic feedstock is biogas that is collected from an anaerobic digester used for waste water treatment. Biogas combustion, whether biogas is flared or used as a fuel to generate energy, oxidizes the CH_4 contained in biogas to CO_2. This results in a net reduction of GHG emissions relative to an alternate GHG emissions pathway in which biogas produced through the anaerobic treatment of wastewater is not captured and combusted, but instead is released to the atmosphere as an indirect emission.

In instances where the alternate GHG emissions pathway involves uncontrolled anaerobic treatment of wastewater, use of anaerobic digester systems typically results in substantial net GHG emissions reductions. However, because anaerobic digesters are designed to enhance CH_4 generation, poor design, operation, or maintenance of anaerobic digesters can result in significant indirect CH_4 emissions. For example, CH_4 can leak from a digester cover or can be vented during digester start-ups, shutdowns, and malfunctions (Bogner et al., 2007; EPA, 2008b; Climate Action Reserve, 2013). However, under normal working conditions, GHG emissions from controlled biological treatment in an anaerobic digester are small relative to indirect CH_4 emissions from uncontrolled anaerobic storage and treatment systems (Bogner et al., 2007, and references therein).

In instances where the alternative GHG emissions pathway involves aerobic treatment of wastewater, use of an anaerobic digestion system with biogas capture and combustion in most instances would not be expected to result in a net increase of GHG emissions. In these instances, wastewater and sludges either would have decayed aerobically, producing CO_2 as the primary decay product (e.g., in a shallow lagoon or in an aeration tank associated with activated sludge wastewater treatment processes), or they would have decayed anaerobically, producing both CH_4 and CO_2 (e.g., in a deep, open lagoon).

In applying the assessment factor equation (*BAF* = *AVOIDEMIT*; Equation N.1), net GHG emissions reductions from the use of an anaerobic digester (where the generated biogas is collected and destroyed) are accounted for in the *AVOIDEMIT* term. In practice, as applied here, the *AVOIDEMIT* term is a ratio expressed in units of CO_2e avoided (i.e., the emissions, in CO_2e, resulting from an alternative wastewater treatment scenario of aerobic, anaerobic, or a combination of aerobic and anaerobic treatment) per units of CO_2e removed via combustion (i.e., the emissions, in CO_2e, of the biogas generated in an anaerobic digester—accounting for biogas collection and combustion efficiencies). For the biogas feedstock collected from the treatment of wastewater in an anaerobic digester, the *AVOIDEMIT* term can be conceptually expressed using the simplified ratio of:

$$\boldsymbol{AVOIDMENT = 1 - \frac{(\textbf{emissions from treatment alternative to an anaerobic digester})}{(\textbf{emissions from treatment in an anaerobic digester})}} \quad \textbf{(EQ N.56)}$$

6.1.1. Calculating the Numerator

In computing *AVOIDEMIT*, the numerator (i.e., emissions from a treatment alternative to an anaerobic digester) can be calculated by building upon the methods developed for EPA by RTI International (2010). To compute the emissions profile of the treatment method that is alternate to an anaerobic digester, the CO_2e emissions resulting from the alternate treatments of wastewater and wastewater sludge must be summed:

$$\textbf{\textit{AVOIDEMIT} numerator} = \mathbf{CO_2WW + CO_2S + (GWP_{CH_4} \times (CH_4WW + CH_4S))} \quad \textbf{(EQ. N.267)}$$

Where:

CO_2WW	= CO_2 emission rate from wastewater treatment (MT CO_2/year), see Equation N.58.
CO_2S	= CO_2 emission rate from wastewater sludge treatment (MT CO_2/year), see Equation N.61.
GWP_{CH_4}	= Global warming potential for methane, 25 (IPCC, 2007)
CH_4WW	= CH_4 emission rate from wastewater treatment (MT CH_4/year), see Equation N.59.
CH_4S	= CH_4 emission rate from wastewater sludge treatment (MT CO_2/year), see Equation N.62.

CO_2 and CH_4 emissions from the aerobic treatment of wastewater can be calculated using the following two equations:

$$\mathbf{CO_2WW = 10^{-6} \times OpHrs \times Q_{ww} \times OD \times Eff_{OD} \times \frac{44}{32} \times \left[\left(1 - MCF_{WW} \times BG_{CH_4}\right)(1-\lambda)\right]}$$

(EQ. N.278)

$$\mathbf{CH_4WW = 10^{-6} \times OpHrs \times Q_{ww} \times OD \times Eff_{OD} \times \frac{16}{32} \times \left[\left(MCF_{WW} \times BG_{CH_4}\right)(1-\lambda)\right]}$$

(EQ. N.59)

Where:

CO_2WW = CO_2 emission rate (MT CO_2/year).

CH_4WW = CH_4 emission rate (MT CH_4/year).

10^{-6} = Units conversion factor (MT/g).

OpHrs = Hours wastewater treatment system is operated per year.

Q_{ww} = Wastewater influent flow rate (m^3/hr).

OD = Oxygen demand[50] of influent wastewater to the biological treatment unit (mg/L = g/m^3).

Eff_{OD} = Oxygen demand removal efficiency of the biological treatment unit.

44/32 = Molar mass ratio of CO_2 to O_2; representing the conversion factor for maximum CO_2 generation per unit of oxygen demand.

16/32 = Molar mass ratio of CH_4 to O_2; representing the conversion factor for maximum CH_4 generation per unit of oxygen demand.

MCF_{ww} = CH_4 correction factor for wastewater treatment unit, indicating the fraction of the influent oxygen demand that is converted anaerobically in the wastewater treatment unit.[51]

BG_{CH_4} = Fraction of C as CH_4 in generated biogas (default is 0.65).

λ = Sludge biomass yield, expressed as g C converted to sludge per g C consumed in the wastewater treatment process (see Equation N.60).

The variable representing sludge biomass yield (λ) in Equations N.58 and N.59 is an estimate of the net sludge generated from the wastewater treatment process, as calculated with Equation N.60.

$$\boldsymbol{\lambda = \frac{Q_s \times MLVSS_s \times 0.53}{Q_{ww} \times OD \times Eff_{od} \times \frac{12}{32}}}$$ **(EQ. N.60)**

Where:

[50] Determined as either the 5-day biochemical oxygen demand (BOD5) or the chemical oxygen demand (COD). The BOD5 and COD are two measures of the amount of degradable organic content in wastewater.
[51] MCF_{ww} value ranges from 0 to 0.8 (see Table N-4). A MCF_{ww} value of zero (no CH_4 emissions) is assigned to well-managed aerobic decomposition systems.

λ = Sludge biomass yield, expressed as g C converted to sludge per g C consumed in the wastewater treatment process.

Q_s = Wastewater sludge flow rate (m^3/hr).

Q_{ww} = Wastewater influent flow rate (m^3/hr).

$MVVSS_s$ = Mixed liquor volatile suspended solids concentration of the waste sludge stream (mg/L).

OD = Oxygen demand of influent wastewater to the biological treatment unit (mg/L).

Eff_{OD} = Oxygen demand removal efficiency of the biological treatment unit.

0.53 = Correction factor for carbon content of the sludge biomass.[52]

12/32 = Molar mass ratio of C to O_2; representing the conversion factor for maximum C consumption per unit of oxygen demand.

If the flow rate of the sludge waste stream is not directly measured then estimated representative values for sludge biomass yield can be used as an alternative to Equation N.60. Illustrative representative values for sludge biomass yield are specific to the treatment system used (Table N-13).

Table N-13. Illustrative Representative Values for Methane Correction Factor (MCF) and Biomass Yield (λ) by Treatment System for both Wastewater and Sludge Treatment Processes (from RTI International, 2010).

Wastewater Treatment Process	MCF	λ
Aerated treatment process (e.g., activated sludge system), well managed	0	0.65
Aerated treatment process, overloaded (i.e., anoxic areas)	0.3	0.45
Anaerobic treatment process (e.g., anaerobic digester)	0.8	0.1
Facultative lagoon, shallow (< 2 m deep)	0.2	0
Facultative lagoon, deep (≥ 2 m deep)	0.8	0
Sludge Treatment Process		
Aerobic sludge digestion	0	Use λ from wastewater treatment process
Anaerobic sludge digestion (e.g., anaerobic digester)	0.8	

Emissions from the treatment of solids (i.e., sludge generated in the wastewater treatment system), whether sludge is treated aerobically or anaerobically, can be calculated using the following equations:

[52] Carbon accounts for 53% of the sludge biomass weight (dry basis).

$$\mathbf{CO_2S = 10^{-6} \times OpHrs \times Q_{ww} \times OD \times Eff_{OD} \times \frac{44}{32} \times \left[\lambda\left(1 - MCF_S \times BG_{CH_4}\right)\right]} \quad \textbf{(EQ. N.61)}$$

$$\mathbf{CH_4S = 10^{-6} \times OpHrs \times Q_{ww} \times OD \times Eff_{OD} \times \frac{16}{32} \times \left[\lambda\left(MCF_S \times BG_{CH_4}\right)\right]} \quad \textbf{(EQ. N.62)}$$

Where:

CO_2S = CO_2 emission rate (MT CO_2/year).

CH_4S = CH_4 emission rate (MT CH_4/year).

10^{-6} = Units conversion factor (MT/g).

OpHrs = Hours wastewater treatment system is operated per year.[53]

Q_{ww} = Wastewater influent flow rate (m^3/hr).

OD = Oxygen demand[54] of influent wastewater to the biological treatment unit (mg/L = g/m^3).

Eff_{OD} = Oxygen demand removal efficiency of the biological treatment unit.

44/32 = Molar mass ratio of CO_2 to O_2; representing the conversion factor for maximum CO_2 generation per unit of oxygen demand.

16/32 = Molar mass ratio of CH_4 to O_2; representing the conversion factor for maximum CH_4 generation per unit of oxygen demand.

λ = Sludge biomass yield, expressed as g C converted to sludge per g C consumed in the wastewater treatment process (see Equation N.60).

MCF_S = CH_4 correction factor for sludge digestion, indicating the fraction of the treated sludge that is converted anaerobically in the wastewater treatment unit.[55]

BG_{CH_4} = Fraction of C as CH_4 in generated biogas (default is 0.65).

6.1.2. Calculating the Denominator

In computing *AVOIDEMIT*, the denominator (i.e., emissions from the treatment of wastewater and sludge in an anaerobic digester such that the generated biogas is captured and combusted) can be calculated by building upon the methods developed for EPA by RTI International (2010). To compute the emissions profile associated with the anaerobic treatment of wastewater and wastewater sludge in an anaerobic digester, the CO_2e emissions resulting from these treatments

[53] A wastewater system may operate continuously except for when it is down for maintenance, 10% of the year (e.g., 365 × 24 × 0.9 = 8760 hours).
[54] Determined as either the 5-day biochemical oxygen demand (BOD5) or the chemical oxygen demand (COD). The BOD5 and COD are two measures of the amount of degradable organic content in wastewater.
[55] MCF_{ww} value ranges from 0 to 0.8 (see table 3-1, RTI International, 2010). A MCF_{ww} value of zero (no CH_4 emissions) is assigned to well-managed aerobic decomposition systems.

must be summed while simultaneously accounting for biogas destruction efficiency (via combustion) and biogas collection efficiency:

$$\textbf{\textit{AVOIDEMIT} denominator} = CO_2WW + CO_2S + 25\times((CH_4WW - CH_4WWD + CH_4WWL) + (CH_4S - CH_4SD + CH_4SL)) + (CH_4WWD \times 44/16) + (CH_4SD \times 44/16) \qquad \textbf{(EQ. N.63)}$$

Where:

CO_2WW = CO_2 emission rate from wastewater treatment (MT CO_2/year), see Equation N.58.

CO_2S = CO_2 emission rate from wastewater sludge treatment (MT CO_2/year), see Equation N.61.

CH_4WW = CH_4 emission rate from wastewater treatment (MT CH_4/year), see Equation N.59.

CH_4WWD = CH_4 emission rate from wastewater treatment, adjusted for biogas destruction efficiency (MT CH_4/year).[56]

CH_4WWL = CH_4 emission rate from wastewater treatment, adjusted for biogas collection efficiency (MT CH_4/year).[57]

CH_4S = CH_4 emission rate from wastewater sludge treatment (metric ton CO_2/year), see Equation N.62.

CH_4SD = CH_4 emission rate from wastewater sludge treatment, adjusted for biogas destruction efficiency (MT CH_4/year).[58]

CH_4SL = CH_4 emission rate from wastewater sludge treatment, adjusted for biogas collection efficiency (MT CH_4/year).[59]

44/16 = molecular weight ratio of CO_2 to CH_4.

After solving for the numerator and the denominator of the *AVOIDEMIT* term, the *BAF* can be calculated using Equation N.1. See Section 6.2 for an illustrative example calculation of the numerator and denominator in the *AVOIDEMIT* term and its subsequent application in estimating a *BAF* for the management of wastewater and wastewater sludge.

Several parameters are presented and used in the equations in the remainder of this section.

---

[56] Assuming biogas destruction efficiency is 0.99 then $CH_4WWD = 0.99 \times CH_4WW$.
[57] Assuming biogas collection efficiency is 0.99 then $CH_4WWL = (1-0.99) \times CH_4WW$.
[58] Assuming biogas destruction efficiency is 0.99 then $CH_4SD = 0.99 \times CH_4S$.
[59] Assuming biogas collection efficiency is 0.99 then $CH_4SL = (1-0.99) \times CH_4S$.

Table N-14presents the parameters used, typical or default values, ranges presented in the literature, and references.

Table N-14. Summary of Parameters Used When Calculating an Illustrative *BAF* for Wastewater Treatment.

Parameter Description	Symbol	Value	Range	Units	Comments	Reference (for value column)
Oxygen demand of the influent wastewater to the biological treatment unit	OD	–	–	mg/L or g/m^3	Determined through either the BOD5 or the COD tests.	NA
Oxygen demand removal efficiency of the biological treatment unit	Eff_{OD}	–	–	Decimal percent	Determined by the wastewater treatment facility.	NA
Fraction of C as CH_4 in generated biogas	BG_{CH_4}	0.65	0.40 to 0.70	Decimal percent		EPA, 2013c
Sludge biomass yield	λ	–	0 to 0.65	Expressed as g C converted to sludge per g C consumed in the wastewater treatment process	See Equation N.60	RTI International, 2010
Aerated treatment process (e.g., activated sludge system), well managed	λ	0.65				Muller et al., 2003; Munz, 2008; Choubert et al., 2009; RTI International, 2010
Aerated treatment process, overloaded (i.e., anoxic areas)	λ	0.45				Muller et al., 2003; Ammary, 2004; Munz, 2008; Choubert et al., 2009; RTI International, 2010
Anaerobic treatment process (e.g., anaerobic digester)	λ	0.1				Ammary, 2004; Low and Chase, 1999; RTI International, 2010
Facultative lagoon, shallow (< 2 m deep)	λ	0				RTI International, 2010
Facultative lagoon, deep (≥ 2 m deep)	λ	0				RTI International, 2010

Parameter Description	Symbol	Value	Range	Units	Comments	Reference (for value column)
WW: Aerated treatment process (e.g., activated sludge system), well managed	MCF_{ww}	0	0 to 0.8	Fraction	Indicating the fraction of the influent oxygen demand that is converted anaerobically in the wastewater treatment unit	IPCC, 2006; RTI International, 2010
WW: Aerated treatment process, overloaded (i.e., anoxic areas)	MCF_{ww}	0.3				
WW: Anaerobic treatment process (e.g., anaerobic digester)	MCF_{ww}	0.8				
WW: Facultative lagoon, shallow (< 2 m deep)	MCF_{ww}	0.2				
WW: Facultative lagoon, deep (≥ 2 m deep)	MCF_{ww}	0.8				
Sludge: Aerobic sludge digestion	MCF_{S}	0				
Sludge: Anaerobic sludge digestion (e.g., anaerobic digestion)	MCF_{S}	0.8				
Biogas destruction efficiency	DE; included in CH_4WWD and CH_4SD	0.99	0.90 to 0.9977	Decimal percent		EPA, 2010d; EPA, 2011a; EPA, 2013c
Biogas collection efficiency	CE; included in CH_4WWL and CH_4SD	0.99	0.70 to 0.99	Decimal percent	0.99 is used for an enclosed vessel, anaerobic sludge digester	EPA, 2010d, Table 6-1

6.2. Example *AVOIDEMIT* and *BAF* Calculations for the Collected Biogas from Treatment of Wastewater and Wastewater Sludge

This example calculation of the *BAF* is for a hypothetical wastewater treatment system that uses an anaerobic digester to treat wastewater and another anaerobic digester to treat sludge. In this scenario the wastewater treatment system has an average flow rate of 1 million gallons per day (or 157.71 m^3/hr), an inlet 5-day biochemical oxygen demand (BOD5) of 500 g/m^3, and the treatment system has a 95% BOD5 removal efficiency.

Step 1: Calculating the Numerator

To calculate the numerator of *AVOIDEMIT*, the emissions from a treatment alternative to an anaerobic digester, must be computed. In this hypothetical example, the treatment alternative to an anaerobic digester would be a shallow (< 2 m deep), facultative lagoon. For this example, it is assumed that the wastewater system would operate continuously throughout the year (365 × 24 = 8760 hours). Treatment of wastewater sludge is assumed to be outside of the lagoon such that there is no sludge biomass yield (λ = 0). Emissions from this alternate treatment pathway can be computed using Equation N.57. However, values to populate Equation N.57 must first be calculated using Equations N.58 and N.59 (because λ = 0, Equations N.61 and N.62 are equal to zero, thus dropping out of Equation N.57).

CO_2 emissions from the wastewater treatment system (a shallow, facultative lagoon) are calculated using Equation N.58, (MCF_{ww} = 0.2 and λ = 0):

$$\boldsymbol{CO_2WW = 10^{-6} \times \frac{HO}{yr} \times Q_{WW} \times OD \times Eff_{OD} \times \frac{44}{32} \times \left[\left(1 - MCF_{WW} \times BG_{CH_4}\right)(1 - \lambda)\right]}$$

$$\mathbf{= 10^{-6} \times 8760 \times 157.71 \times 500 \times 0.95 \times (44/32) \times [(1 - 0.2 \times 0.65)\ (1 - 0)]}$$

$$\mathbf{= 785.0167\ MT\ CO_2\ per\ year}$$

CH_4 emissions from the wastewater treatment system (a shallow, facultative lagoon) are calculated using Equation N.59, (MCF_{ww} = 0.2 and λ = 0):

$$\boldsymbol{CH_4WW = 10^{-6} \times \frac{HO}{yr} \times Q_{WW} \times OD \times Eff_{OD} \times \frac{16}{32} \times \left[\left(MCF_{WW} \times BG_{CH_4}\right)(1 - \lambda)\right]}$$

$$\mathbf{= 10\text{-}6 \times 8760 \times 157.71 \times 500 \times 0.95 \times (16/32) \times [(0.2 \times 0.65)(1 - 0)]}$$

$$\mathbf{= 42.6550\ MT\ CH_4\ per\ year.}$$

The numerator of *AVOIDEMIT* can now be solved using Equation N.57:

$$\mathbf{\textit{AVOIDEMIT}\ numerator = CO_2WW + CO_2S + (25 \times (CH_4WW + CH_4S))}$$

$$\mathbf{= 785.0108 + 0 + 25 \times (42.6547 + 0)}$$

$$\mathbf{= 1{,}851.38\ MT\ CO_2e\ per\ year}$$

Step 2: Calculating the Denominator

To calculate the denominator of *AVOIDEMIT*, the emissions from wastewater and wastewater sludge treatment using an anaerobic digester, must be computed. Emissions from this treatment pathway can be computed using Equation N.63. However, values to populate Equation N.63 must first be calculated using Equations N.58, N.59, N.61, and N.62.

CO_2 emissions from the wastewater treatment system (an anaerobic digester) are calculated using Equation N.58, (MCF_{ww} = 0.8 and λ = 0.1):

$$CO_2WW = 10^{-6} \times \frac{HO}{yr} \times Q_{WW} \times OD \times Eff_{OD} \times \frac{44}{32} \times \left[\left(1 - MCF_{WW} \times BG_{CH_4}\right)(1-\lambda)\right]$$

$$= 10^{-6} \times 8760 \times 157.71 \times 500 \times 0.95 \times (44/32) \times [(1 - 0.8 \times 0.65)(1 - 0.1)]$$

$$= 389.8014 \text{ MT } CO_2 \text{ per year}$$

CH_4 emissions from the wastewater treatment system (an anaerobic digester) are calculated using Equation N.59, (MCF_{ww} = 0.8 and λ = 0.1):

$$CH_4WW = 10^{-6} \times \frac{HO}{yr} \times Q_{WW} \times OD \times Eff_{OD} \times \frac{16}{32} \times \left[\left(MCF_{WW} \times BG_{CH_4}\right)(1-\lambda)\right]$$

$$= 10^{-6} \times 8760 \times 157.71 \times 500 \times 0.95 \times (16/32) \times [(0.8 \times 0.65)(1 - 0.1)]$$

$$= 153.558 \text{ MT } CH_4 \text{ per year.}$$

CO_2 emissions from the wastewater sludge treatment system (an anaerobic digester) are calculated using Equation N.61, (MCF_S = 0.8 and λ = 0.1):

$$CO_2S = 10^{-6} \times \frac{HO}{yr} \times Q_{WW} \times OD \times Eff_{OD} \times \frac{44}{32} \times \left[\lambda\left(1 - MCF_S \times BG_{CH_4}\right)\right]$$

$$= 10^{-6} \times 8760 \times 157.71 \times 500 \times 0.95 \times (44/32) \times [0.1(1 - 0.8 \times 0.65)]$$

$$= 43.3113 \text{ MT } CO_2 \text{ per year}$$

CH_4 emissions from the wastewater sludge treatment system (an anaerobic digester) are calculated using Equation N.62, (MCF_S = 0.8 and λ = 0.1):

$$CH_4S = 10^{-6} \times \frac{HO}{yr} \times Q_{WW} \times OD \times Eff_{OD} \times \frac{16}{32} \times \left[\lambda\left(MCF_S \times BG_{CH_4}\right)\right]$$

$$= 10^{-6} \times 8760 \times 157.71 \times 500 \times 0.95 \times (16/32) \times [0.1(0.8 \times 0.65)]$$

$$= 17.0620 \text{ MT } CH_4 \text{ per year.}$$

Next, the calculated emissions associated with treatment of wastewater and wastewater sludge in an anaerobic digester can be used to populate Equation N.63:

$$\textbf{\textit{AVOIDEMIT} denominator} =$$

$$\mathbf{CO_2WW + CO_2S}$$

$$\mathbf{+\ 25\times\ ((CH_4WW - CH_4WWD + CH_4WWL) + (CH_4S - CH_4SD + CH_4SL))}$$

$$\mathbf{+\ CH_4WWD \times 44/16 + CH_4SD \times 44/16}$$

Assuming biogas destruction efficiency is 0.99, then:

- $CH_4WWD = 0.99 \times CH_4WW$, and
- $CH_4SD = 0.99 \times CH_4S$.

Assuming biogas collection efficiency is 0.99, then:

- $CH_4WWL = (1–0.99) \times CH_4WW$, and
- $CH_4SL = (1–0.99) \times CH_4S$.

Applying these assumptions, the denominator of *AVOIDEMIT* can be expressed as:

$$\begin{aligned}\textbf{\textit{AVOIDEMIT} denominator} &= \mathbf{CO_2WW + CO_2S}\\ &\mathbf{+\ 25\times\ (CH_4WW - (0.99 \times CH_4WW) + ((1-0.99) \times CH_4WW))}\\ &\mathbf{+\ 25\times\ (CH_4S - (0.99 \times CH_4S) + ((1-0.99) \times CH_4S))}\\ &\mathbf{+\ (0.99 \times CH_4WW \times 44/16) + (0.99 \times CH_4S \times 44/16)}\end{aligned}$$

$$\begin{aligned}\textbf{\textit{AVOIDEMIT} denominator} &= \mathbf{389.8014 + 43.3113}\\ &\mathbf{+\ 25\times\ (153.558 - (0.99 \times 153.558) + ((1 - 0.99) \times 153.558))}\\ &\mathbf{+\ 25\times\ (17.0620 - (0.99 \times 17.0620) + ((1 - 0.99) \times 17.0620))}\\ &\mathbf{+\ (0.99 \times 153.558 \times 44/16) + (0.99 \times 17.0620 \times 44/16)}\\ &\mathbf{= 982.9357\ MT\ CO_2e\ per\ year.}\end{aligned}$$

Step 3: Calculating the *BAF* Value

After solving for the numerator and the denominator of the *AVOIDEMIT* term associated with wastewater management, the *BAF* can be calculated using Equations N.1 and N.2:

$$\boldsymbol{BAF = AVOIDEMIT}$$

$$\mathbf{= 1 - \frac{1{,}851.38}{982.9357}}$$

$$\mathbf{= -0.88}$$

A negative calculated *BAF* value, such as that above, indicates that a biogas feedstock produced in an anaerobic digester from the treatment of wastewater and wastewater sludge, and used by a stationary source results in net CO_2e emissions reductions.

6.3. Sensitivity Analysis for Wastewater Treatment

A simple sensitivity analysis on the key parameters in the wastewater treatment methodology is presented in Table N-15 for the actual fate of wastewater treatment in an anaerobic digester and the alternate fate of placing the waste in a shallow, facultative lagoon. Key parameters impacting the *BAF* include the DE and CE for the anaerobic digester, and the GWP for CH_4 (21, 25, and 28). In each of the six analyses, the DE of the biogas was adjusted between 95% and 99%, and the CE was adjusted to 75%, 90%, and 99%, representing a range of low to high performing biogas collection system efficiencies. Sources for the parameter values used here can be found in Table N-14of Section 6.1.2. The inputs used in the analyses are equivalent to those shown in the example calculations in Section 6.2 of this appendix.

The *BAF* values are positive when performing the calculations with a CE lower than 78% despite the DE value (95% or 99%) used. Higher CEs yield negative *BAF* values regardless of the GWP, indicating that wastewater management through anaerobic digestion may be a better treatment option with respect to CO_2 and CH_4 emissions pathways. The turning point for the *BAF* values with respect to either a 95% of 99% DE is presented in Analyses 7 through 18. Note that, in order for a net CO_2e emissions reduction to occur, the anaerobic digester may require a CE of at least 80% to 85%.

Table N-15. Sensitivity Analysis for Wastewater Treatment.

Analysis	Key Parameter and Value		*BAF*		
	CE	DE	GWP=21	GWP=25	GWP=28
1	0.75	0.99	0.081	0.077	0.075
2	0.75	0.95	0.140	0.142	0.144
3	0.85	0.99	−0.143	−0.172	−0.191
4	0.85	0.95	−0.053	−0.069	−0.079
5	0.99	0.99	−0.734	−0.884	−0.993
6	0.99	0.95	−0.537	−0.631	−0.698
7[a]	0.79	0.99	0.003		
8[a]	0.80	0.99	−0.019		
9[b]	0.78	0.99		0.015	
10[b]	0.79	0.99		−0.008	
11[c]	0.78	0.99			0.009
12[c]	0.79	0.99			−0.016
13[d]	0.82	0.95	0.013		
14[d]	0.83	0.95	−0.008		
15[e]	0.82	0.95		0.005	
16[e]	0.83	0.95		−0.019	
17[f]	0.81	0.95			0.023
18[f]	0.82	0.95			−0.001

[a] The point at which the *BAF* changes from negative to positive with a GWP of 21 and DE = 0.99.

[b] The point at which the *BAF* changes from negative to positive with a GWP of 25 and DE = 0.99.

[c] The point at which the *BAF* changes from negative to positive with a GWP of 28 and DE = 0.99.
[d] The point at which the *BAF* changes from negative to positive with a GWP of 21 and DE = 0.95.
[e] The point at which the *BAF* changes from negative to positive with a GWP of 25 and DE = 0.95.
[f] The point at which the *BAF* changes from negative to positive with a GWP of 28 and DE = 0.95.
Note: References for the key parameters and values are presented in Section 6.1.

7. References

Ammary, B. Y. 2004. Nutrient requirements in biological industrial wastewater treatment. *African Journal of Biotechnology* 3(4): 236-238.

Antares Group Inc., T. R. Miles Technical Consulting Inc., and Foster Wheeler Development Corporation. 1999. Economic and technical feasibility of energy production from poultry litter and nutrient filter biomass on the Lower Delmarva Peninsula. http://www.nrbp.org/pdfs/pub20a.pdf. Accessed 06 June 2013.

ASAE (2005). Standard D384.2. Manure Production and Characteristics. American Society of Agricultural Engineers.

Astrup, T., J. Møller, and T. Fruergaard. 2009. Incineration and co-combustion of waste: accounting of greenhouse gases and global warming contributions. Waste Management and Research 00:1-11.

ASTM Standard E870, 2013 Book of Standards Volume 11. Available at http://www.astm.org/Standards/E870.htm

Barlaz, M. A. 1998. Carbon storage during biodegradation of municipal solid waste components in laboratory-scale landfills. Global Biogeochemical Cycles 12:373-380.

Barlaz, M. A. 2006. Forest products decomposition in municipal solid waste landfills. Waste Management 26:321-333.

Bogner, J. 1992. Anaerobic burial of refuse in landfills: increased atmospheric methane and implications for increased carbon storage. Ecological Bulletins 42:98-108.

Bogner, J., M. Abdelrafie Ahmed, C. Diaz, A. Faaij, Q. Gao, S. Hashimoto, K. Mareckova, R. Pipatti, and T. Zhang. Waste Management. *In* Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, and L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Cantrell, K. B., T. Ducey, K. S. Ro, and P. G. Hunt. 2008. Livestock waste-to-bioenergy generation opportunities. Bioresource Technology, 99:7941-7953.

Chanton, J., D. K. Powelson, and R. B. Green. 2009. Methane oxidation in landfill cover soils: is a 10% default value reasonable? Journal of Environmental Quality, 38:654-663.

Chanton, J., T. Abichou, C. Langford, G. Hater, R. Green, D. Goldsmith, and N. Swan. 2011a. Landfill methane oxidation across climate types in the U.S. Environmental Science and Technology. 45:313-319.

Chanton, J., T. Abichou, C. Langford, K. Spokas, G. Hater, R. Green, D. Goldsmith, and M. A. Barlaz. 2011b. Observations on the methane oxidation capacity of landfill soils. Waste Management 31:914-925.

Choubert, J-M.; A. Marquot; A-E. Stricker; Y. Racault; S. Gillot; and A. Heduit. 2009. Anoxic and aerobic values for the yield coefficient of the heterotrophic biomass: determination at full-scale plants and consequences on simulations. *Water SA* 35(1):103-109.

Climate Action Reserve. 2013. U.S. livestock project protocol, version 4.0. http://www.climateactionreserve.org/wp-content/uploads/2009/03/U.S._Livestock_Project_Protocol_V4.0.pdf

Costello, T. A. 2007. Feasibility of On-Farm Broiler Litter Combustion. The Poultry Site. http://www.thepoultrysite.com/articles/797/feasibility-of-onfarm-broiler-litter-combustion

Demirbas, A. 2004. Combustion characteristics of different biomass fuels. Progress in Energy and Combustion Science, 30:219–230.

EPA. 1996. Standards of performance for new stationary sources and guidelines for control of existing sources: municipal solid waste landfills. Federal Register, 61(49)9905-9944.

EPA. 2001. Development document for the proposed revisions to the national pollutant discharge elimination system regulation and the effluent guidelines for concentrated animal feeding operations. Energy and Analysis Division, Office of Science and Technology.

EPA. 2008a. AP 42, Fifth Edition, Volume I, Chapter 2: Solid Waste Disposal, Draft Section 2.4: Municipal Solid Waste Landfills. October 2008. http://www.epa.gov/ttn/chief/ap42/ch02/draft/d02s04.pdf.

EPA. 2008b. Climate Leaders greenhouse gas inventory protocol offset project methodology for managing manure with biogas recovery systems. Version 1.3 http://www.epa.gov/climateleadership/documents/resources/ClimateLeaders_DraftManureOffsetProtocol.pdf

EPA. 2009a. Technical support document for the landfill sector: proposed rule for mandatory reporting of greenhouse gases. http://www.epa.gov/ghgreporting/documents/pdf/archived/tsd/TSD-Landfill-sector.pdf

EPA. 2009b. Technical support document for manure management systems: proposed rule for mandatory reporting of greenhouse gases. http://www.epa.gov/ghgreporting/documents/pdf/archived/tsd/TSD%20manure_020409.pdf

EPA. 2010a. Landfill Gas Energy Project Development Handbook. Chapter 1, Landfill gas energy basics. http://www.epa.gov/lmop/documents/pdfs/pdh_chapter1.pdf

EPA. 2010b. Landfill Gas Energy Project Development Handbook. Chapter 2, Landfill gas modeling. http://epa.gov/lmop/documents/pdfs/pdh_chapter2.pdf

EPA. 2010c. Technical Support Document for Revision of Certain Provisions: Proposed Rule for Mandatory Reporting of Greenhouse Gases. http://www.epa.gov/ghgreporting/documents/pdf/2010/MRR-Revisions_TSD.pdf

EPA. 2010d. Technical Support Document for Industrial Wastewater Treatment: Final Rule for Mandatory Reporting of Greenhouse Gases. http://www.epa.gov/ghgreporting/documents/pdf/2010/Subpart-II_TSD.pdf

EPA. 2011a. Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from Municipal Solid Waste Landfills. http://www.epa.gov/nsr/ghgdocs/landfills.pdf

EPA. 2011b. Environmental Management System Glossary. http://ofmpub.epa.gov/sor_internet/registry/termreg/searchandretrieve/glossariesandkeywordlists/search.do?details=&glossaryName=EMS%20Glossary

EPA. 2012a. http://www.epa.gov/lmop/basic-info/index.html#a04 Landfill Methane Outreach Program, Basic Information, Landfill Gas Energy. Accessed 25 October 2012.

EPA. 2012b. http://www.epa.gov/lmop/projects-candidates/lfge-calculator.html LFG Energy Benefits Calculator. Accessed 1 November 2012.

EPA. 2012c. U.S. anaerobic digester status: A 2011 snapshot. AgSTAR. http://www.epa.gov/agstar/documents/2011_digester_update.pdf

EPA. 2013a. http://www.epa.gov/lmop/projects-candidates/index.html Landfill Methane Outreach Program. Accessed 29 April 2013.

EPA. 2013b. Operating anaerobic digester projects. AgSTAR EPA partnership program. http://www.epa.gov/agstar/projects/. Accessed 30 April 2013.

EPA. 2013c. 2013 revisions to the greenhouse gas reporting rule and proposed confidentiality determinations for new or substantially revised data elements. 40 CFR Part 98. http://www.gpo.gov/fdsys/pkg/FR-2013-04-02/pdf/2013-06093.pdf

EPA. 2014a. Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2012. http://www.epa.gov/waste/nonhaz/municipal/pubs/2012_msw_dat_tbls.pdf

EPA. 2014b. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2012. http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html

Henihan, A. M., M. J. Leahy, J. J. Leahy, E. Cummins, and B. P. Kelleher. 2003. Emissions modeling of fluidised bed co-combustion of poultry litter and peat. Bioresource Technology, 87:289-294.

Hilger, H. H., M. A. Barlaz. 2001. Anaerobic decomposition of refuse in landfills and methane oxidation in landfill cover soils. Manual of Environmental Microbiology, 2nd Edition, Am. Soc. Microbiol., Washington, D.C., p. 696-718.

ICF. 2008. Revised data for landfill carbon storage in yard trimmings and coated paper, and implications for waste management GHG emission factors and US GHG Inventory. Memorandum to Sara Hartwell (EPA/OSW), Jennifer Brady (EPA/OSW), Tom Wirth (EPA), Melissa Weitz (EPA), Kim Klunich (EPA), Ken Skog (USDA), and Dennis Jackson (Environment Canada). April 21, 2008.

IPCC. 1996. Climate Change 1995: The Science of Climate Change. Intergovernmental Panel on Climate Change, J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell. (eds.). Cambridge University Press. Cambridge, United Kingdom.

IPCC. 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds). Bracknell, UK: IGES, Japan, National Greenhouse Gas Inventories Programme. http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.htm.

IPCC. 2006a. Guidelines for national greenhouse gas inventories. Volume 5: Waste. Chapter 3: Solid waste disposal. Intergovernmental Panel on Climate Change. http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_3_Ch3_SWDS.pdf

IPCC. 2006b. Guidelines for national greenhouse gas inventories. Volume 4: Agriculture, Forestry and Other Land Use. Chapter 10: Emissions from livestock and manure management. Intergovernmental Panel on Climate Change. http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_10_Ch10_Livestock.pdf

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. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press. Cambridge, United Kingdom. 996 pp.

Kelleher, B. P., J. J. Leahy, A. M. Henihan, T. F. O'Dwyer, D. Sutton, and M. J. Leahy. 2002. Advances in poultry litter disposal technology—a review. Bioresource Technology, 83:27-36.

Li, A., A. Wu, S. Deng, and W. Pan. 2008. Effect of co-combustion of chicken litter and coal on emissions in a laboratory-scale fluidized bed combustor. Fuel Processing Technology, 89:7-12.

Lono-Batura, M., Y. Qi, and N. Beecher. 2012. Biogas production and potential from U.S. wastewater treatment. Biocycle, December issue:46-49.

Low, E. W. and H. A. Chase. 1999. Reducing production of excess biomass during wastewater treatment. *Water Research* 37(5):1119-1132.

Manfredi, S., and T.H. Christensen. 2009. Environmental assessment of solid waste landfilling technologies by means of LCA-modeling. Waste Management, 29:32-43.

Manfredi, S., D. Tonini, T.H. Christensen, and H. Scharff. 2009. Landfilling of waste: accounting of greenhouse gases and global warming contributions. Waste Management and Research, 27:825-836.

Micales J. A., and K. E. Skog. 1997. The decomposition of forest products in landfills. International Biodeterioration and Biodegradation, 39:145-158.

Muller, A.; M. C. Wentzel; R. E. Loewenthal; and G. A. Ekama. 2003. Heterotroph anoxic yield in anoxic aerobic activated sludge systems treating municipal wastewater. *Water Research* 37(10): 2435-2441.

Munz, G.; R. Gori; L. Cammil; and C. Lubello. 2008. Characterization of tannery wastewater and biomass in a membrane bioreactor using respirometric analysis. *Bioresource Technology* 99(19):8612-8618.

New Zealand Ministry for the Environment. 2010. Recommendations for methodologies for ETS landfill gas emission reporting. Prepared by Tonkin & Taylow Ltd. June 2010. http://www.climatechange.govt.nz/consultation/waste/recommendations-for-methodologies/recommendations.pdf.

RTI International. 2010. Greenhouse gas emissions estimation methodologies for biogenic emissions from selected source categories: solid waste disposal, wastewater treatment, ethanol fermentation. *Draft* submitted to EPA from Research Triangle Institute International. RTI project number 0210426.004.018. EPA contract number EP-D-06-118.

Rubber Manufacturer's Association. 2013. Data from July 25, 2013 presentation made by the Rubber Manufacturer's Association to the Environmental Protection Agency's Office of Air and Radiation, Office of Atmospheric Programs, Climate Change Division.

Santoianni, D. A., M. F. Bingham, D. M. Woodward, and J. C. Kinnell. 2008. Power from animal waste—economic, technical, and regulatory landscape in the United States. Journal of Energy Utility Environment Conference, 2:1-37.

Solid Waste Industry for Climate Solutions (SWICS). 2009. Current MSW Industry Position and State-of-the-Practice on LFG Collection Efficiency, Methane Oxidation, and Carbon Sequestration in Landfills. Prepared by SCS Engineers. Version 2.2, Revised January 2009. http://www.scsengineers.com/Papers/Sullivan_SWICS_White_Paper_Version_2.2_Final.pdf

Spokas, K. A., and J. E. Bogner. 2011. Limits and dynamics of methane oxidation in landfill cover soils. Waste Management, 31:823-832.

Spokas, K. Bogner, J. Chanton J.P., Morcet M., Aran C., Graff C., Moreau-Le Golvan Y., and Hebe I. 2006. Methane mass balance at three landfill sites: what is the efficiency of capture by gas collection systems? Waste Management, 26:515-525.

Staley, B. and M. A. Barlaz. 2009. Composition of Municipal Solid Waste in the U.S. and Implications for Carbon Sequestration and Methane Yield. Journal of Environmental Engineering, 135(10):901-909.

Sweeten, J. M., K. Annamalai, K. Heflin, and M. Freeman. 2002. Cattle feedlot manure quality for combustion in coal/manure blends. American Society for Agricultural Engineers. Paper Number 024092, written for American Society of Agricultural Engineers, Annual International Meeting. http://cabel.tamu.edu/Pdfs/pap23.pdf

Sweeten, J. M., K. Annamalai, B. Thien, L. A. McDonald. 2003. Co-firing of coal and cattle feedlot biomass (FB) fuels. Part I. Feedlot biomass (cattle manure) fuel quality and characteristics. Fuel. 82:1167-1182.

Wang, X., J. M. Padgett, F. B. De la Cruz, and M. A. Barlaz. 2011. Wood biodegradation in laboratory-scale landfills. Environmental Science and Technology, 45:6864-6871.