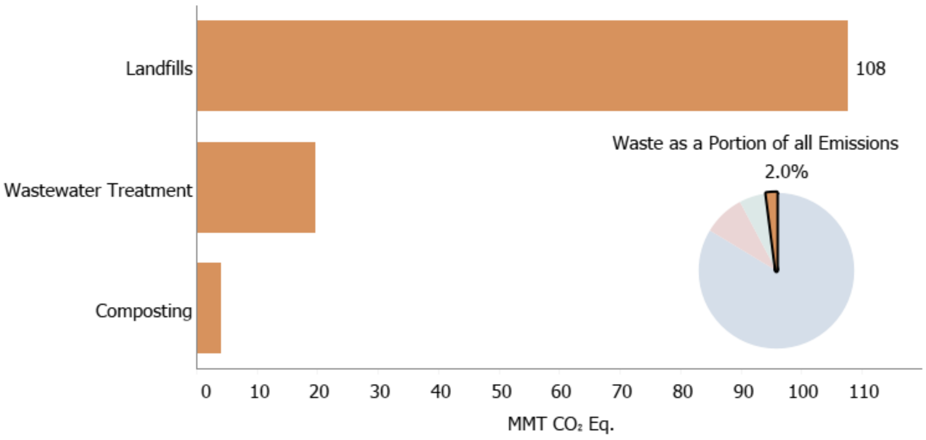
7. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 7-1). Landfills accounted for approximately 16.4 percent of total U.S. anthropogenic methane (CH_4) emissions in 2016, the third largest contribution of any CH_4 source in the United States. Additionally, wastewater treatment and composting of organic waste accounted for approximately 2.3 percent and 0.3 percent of U.S. CH_4 emissions, respectively. Nitrous oxide (N_2O) emissions from the discharge of wastewater treatment effluents into aquatic environments were estimated, as were N_2O emissions from the treatment process itself. Nitrous oxide emissions from composting were also estimated. Together, these waste activities account for 1.9 percent of total U.S. N_2O emissions. Nitrogen oxides (NO_x), carbon monoxide (CO), and non-CH_4 volatile organic compounds (NMVOCs) are emitted by waste activities, and are addressed separately at the end of this chapter. A summary of greenhouse gas emissions from the Waste chapter is presented in Table 7-1 and Table 7-2.

Figure 7-1: 2016 Waste Chapter Greenhouse Gas Sources (MMT CO_2 Eq.)



Overall, in 2016, waste activities generated emissions of 131.5 MMT CO_2 Eq., or 2.0 percent of total U.S. greenhouse gas emissions.[1]

Table 7-1: Emissions from Waste (MMT CO_2 Eq.)

Gas/Source	1990	2005	2012	2013	2014	2015	2016
CH_4	**195.6**	**150.4**	**134.0**	**130.2**	**129.8**	**128.9**	**124.6**
Landfills	179.6	132.7	117.0	113.3	112.7	111.7	107.7

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[1] Emissions reported in the Waste chapter for landfills and wastewater treatment include those from all 50 states, including Hawaii and Alaska, as well as from U.S. Territories to the extent those waste management activities are occurring. Emissions for composting include all 50 states, including Hawaii and Alaska, but not U.S. Territories. Composting emissions from U.S. Territories are assumed to be small.

Wastewater Treatment	15.7	15.8	15.1	14.9	15.0	15.1	14.8
Composting	0.4	1.9	1.9	2.0	2.1	2.1	2.1
N_2O	**3.7**	**6.1**	**6.4**	**6.5**	**6.7**	**6.7**	**6.8**
Wastewater Treatment	3.4	4.4	4.6	4.7	4.8	4.8	5.0
Composting	0.3	1.7	1.7	1.8	1.9	1.9	1.9
Total	**199.3**	**156.4**	**140.4**	**136.7**	**136.5**	**135.6**	**131.5**

Note: Totals may not sum due to independent rounding.

Table 7-2: Emissions from Waste (kt)

Gas/Source	1990	2005	2012	2013	2014	2015	2016
CH_4	**7,825**	**6,016**	**5,361**	**5,208**	**5,190**	**5,155**	**4,984**
Landfills	7,182	5,310	4,680	4,531	4,509	4,467	4,306
Wastewater Treatment	627	631	604	596	598	605	593
Composting	15	75	77	81	84	84	85
N_2O	**12**	**20**	**21**	**22**	**23**	**23**	**23**
Wastewater Treatment	11	15	16	16	16	16	17
Composting	1	6	6	6	6	6	6

Note: Totals may not sum due to independent rounding.

Carbon dioxide (CO_2), CH_4, and N_2O emissions from the incineration of waste are accounted for in the Energy sector rather than in the Waste sector because almost all incineration of municipal solid waste (MSW) in the United States occurs at waste-to-energy facilities where useful energy is recovered. Similarly, the Energy sector also includes an estimate of emissions from burning waste tires and hazardous industrial waste, because virtually all of the combustion occurs in industrial and utility boilers that recover energy. The incineration of waste in the United States in 2016 resulted in 11.0 MMT CO_2 Eq. emissions, more than half of which is attributable to the combustion of plastics. For more details on emissions from the incineration of waste, see Section 7.4.

Box 7-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals

In following the United Nations Framework Convention on Climate Change (UNFCCC) requirement under Article 4.1 to develop and submit national greenhouse gas emission inventories, the emissions and removals presented in this report and this chapter, are organized by source and sink categories and calculated using internationally-accepted methods provided by the Intergovernmental Panel on Climate Change (IPCC) in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)*. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common manner in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement. The use of consistent methods to calculate emissions and removals by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. The presentation of emissions and sinks provided in this Inventory do not preclude alternative examinations, but rather, this Inventory presents emissions and removals in a common format consistent with how countries are to report Inventories under the UNFCCC. The report itself, and this chapter, follows this standardized format, and provides an explanation of the application of methods used to calculate emissions and removals.

Box 7-2: Waste Data from EPA's Greenhouse Gas Reporting Program

On October 30, 2009, the U.S. Environmental Protection Agency (EPA) published a rule requiring annual reporting of greenhouse gas data from large greenhouse gas emission sources in the United States. Implementation of the rule, codified at 40 CFR Part 98, is referred to as EPA's Greenhouse Gas Reporting Program (GHGRP). The rule applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject CO_2 underground for sequestration or other reasons and requires reporting by sources or suppliers in 41 industrial categories. Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. Data reporting by affected facilities includes the reporting of emissions from fuel combustion at that affected facility. In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year.

EPA presents the data collected by its GHGRP through a data publication tool that allows data to be viewed in several formats including maps, tables, charts and graphs for individual facilities or groups of facilities.[2]

EPA's GHGRP dataset and the data presented in this Inventory are complementary. The GHGRP dataset continues to be an important resource for the Inventory, providing not only annual emissions information, but also other annual information, such as activity data and emission factors that can improve and refine national emission estimates and trends over time. GHGRP data also allow EPA to disaggregate national inventory estimates in new ways that can highlight differences across regions and sub-categories of emissions, along with enhancing application of QA/QC procedures and assessment of uncertainties.

EPA uses annual GHGRP data in a number of categories to improve the national estimates presented in this Inventory consistent with IPCC guidelines. Within the Waste Chapter, EPA uses directly reported GHGRP data for net CH_4 emissions from MSW landfills for the years 2010 to 2016 of the Inventory. This data is also used to back-cast emissions from MSW landfills for the years 2005 to 2009.

7.1 Landfills (CRF Source Category 5A1)

In the United States, solid waste is managed by landfilling, recovery through recycling or composting, and combustion through waste-to-energy facilities. Disposing of solid waste in modern, managed landfills is the most commonly used waste management technique in the United States. More information on how solid waste data are collected and managed in the United States is provided in Box 7-3. The municipal solid waste (MSW) and industrial waste landfills referred to in this section are all modern landfills that must comply with a variety of regulations as discussed in Box 7-35. Disposing of waste in illegal dumping sites is not considered to have occurred in years later than 1980 and these sites are not considered to contribute to net emissions in this section for the timeframe of 1990 to the current Inventory year. MSW landfills, or sanitary landfills, are sites where MSW is managed to prevent or minimize health, safety, and environmental impacts. Waste is deposited in different cells and covered daily with soil; many have environmental monitoring systems to track performance, collect leachate, and collect landfill gas. Industrial waste landfills are constructed in a similar way as MSW landfills, but are used to dispose of industrial solid waste, such as RCRA Subtitle D wastes (e.g., non-hazardous industrial solid waste defined in Title 40 of the Code of Federal Regulations or CFR in section 257.2), commercial solid wastes, or conditionally exempt small-quantity generator wastes (EPA 2016a).

After being placed in a landfill, organic waste (such as paper, food scraps, and yard trimmings) is initially decomposed by aerobic bacteria. After the oxygen has been depleted, the remaining waste is available for consumption by anaerobic bacteria, which break down organic matter into substances such as cellulose, amino acids, and sugars. These substances are further broken down through fermentation into gases and short-chain organic compounds that form the substrates for the growth of methanogenic bacteria. These methane (CH_4) producing anaerobic bacteria convert the fermentation products into stabilized organic materials and biogas consisting of approximately 50 percent biogenic carbon dioxide (CO_2) and 50 percent CH_4, by volume. Landfill biogas also contains trace amounts of non-methane organic compounds (NMOC) and volatile organic compounds (VOC) that either result from decomposition byproducts or volatilization of biodegradable wastes (EPA 2008).

Methane and CO_2 are the primary constituents of landfill gas generation and emissions. However, the *2006 IPCC Guidelines* set an international convention to not report biogenic CO_2 from activities in the Waste sector (IPCC 2006). Net carbon dioxide flux from carbon stock changes in landfills are estimated and reported under the Land Use, Land-Use Change, and Forestry (LULUCF) sector (see Chapter 6 of this Inventory). Additionally, emissions of NMOC and VOC are not estimated because they are emitted in trace amounts. Nitrous oxide (N_2O) emissions from

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[2] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

the disposal and application of sewage sludge on landfills are also not explicitly modeled as part of greenhouse gas emissions from landfills. Nitrous oxide emissions from sewage sludge applied to landfills as a daily cover or for disposal are expected to be relatively small because the microbial environment in an anaerobic landfill is not very conducive to the nitrification and denitrification processes that result in N_2O emissions. Furthermore, the *2006 IPCC Guidelines* did not include a methodology for estimating N_2O emissions from solid waste disposal sites "because they are not significant." Therefore, only CH_4 generation and emissions are estimated for landfills under the Waste sector.

Methane generation and emissions from landfills are a function of several factors, including: (1) the total amount and composition of waste-in-place, which is the total waste landfilled annually over the operational lifetime of a landfill; (2) the characteristics of the landfill receiving waste (e.g., size, climate, cover material); (3) the amount of CH_4 that is recovered and either flared or used for energy purposes; and (4) the amount of CH_4 oxidized as the landfill gas – that is not collected by a gas collection system – passes through the cover material into the atmosphere. Each landfill has unique characteristics, but all managed landfills employ similar operating practices, including the application of a daily and intermediate cover material over the waste being disposed of in the landfill to prevent odor and reduce risks to public health. Based on recent literature, the specific type of cover material used can affect the rate of oxidation of landfill gas (RTI 2011). The most commonly used cover materials are soil, clay, and sand. Some states also permit the use of green waste, tarps, waste derived materials, sewage sludge or biosolids, and contaminated soil as a daily cover. Methane production typically begins within the first year after the waste is disposed of in a landfill and will continue for 10 to 60 years or longer as the degradable waste decomposes over time.

In 2016, landfill CH_4 emissions were approximately 107.7 MMT CO_2 Eq. (4,306 kt), representing the third largest source of CH_4 emissions in the United States, behind natural gas systems and enteric fermentation. Emissions from MSW landfills accounted for approximately 95 percent of total landfill emissions, while industrial waste landfills accounted for the remainder. Estimates of operational MSW landfills in the United States have ranged from 1,900 to 2,000 facilities (EPA 2017a; EPA 2017b; Waste Business Journal (WBJ) 2016; WBJ 2010). More recently, the Environment Research & Education Foundation (EREF) conducted a nationwide analysis of MSW management, and counted 1,540 operational MSW landfills in 2013 (EREF 2016). Conversely, there are approximately 3,200 MSW landfills in the United States that have been closed since 1980 (for which a closure date is known, [EPA 2017a; WBJ 2010]). While the number of active MSW landfills has decreased significantly over the past 20 years, from approximately 6,326 in 1990 to 1,540 in the 2013, the average landfill size has increased (EREF 2016; EPA 2017b; BioCycle 2010). With regard to industrial waste landfills, the WBJ database (WBJ 2016) includes approximately 1,200 landfills accepting industrial and/or construction and demolition debris for 2016 (WBJ 2016). Only 172 facilities with industrial waste landfills met the reporting threshold under Subpart TT (Industrial Waste Landfills) of EPA's Greenhouse Gas Reporting Program (GHGRP), indicating that there may be several hundred industrial waste landfills that are not required to report under EPA's GHGRP.

The annual amount of MSW generated and subsequently disposed in MSW landfills varies annually and depends on several factors (e.g., the economy, consumer patterns, recycling and composting programs, inclusion in a garbage collection service). The estimated annual quantity of waste placed in MSW landfills increased 10 percent from approximately 205 MMT in 1990 to 226 MMT in 2000 and then decreased by 11 percent to 205 MMT in 2016 (see Annex 3.14, Table A-251). The total amount of MSW generated is expected to increase as the U.S. population continues to grow, but the percentage of waste landfilled may decline due to increased recycling and composting practices. The estimated quantity of waste placed in industrial waste landfills (from the pulp and paper and food processing sectors) has remained relatively steady since 1990, ranging from 9.7 MMT in 1990 to 10.3 MMT in 2016 (see Annex 3.14, Table A-251). Net CH_4 emissions from MSW landfills have decreased since 1990 (see Table 7-3 and Table 7-4).

In 2016, the Landfill Methane Outreach Program (LMOP) identified 32 new landfill gas-to-energy (LFGE) projects (EPA 2017a) that began operation. While the amount of landfill gas collected and combusted continues to increase, the rate of increase in collection and combustion no longer exceeds the rate of additional CH_4 generation from the amount of organic MSW landfilled as the U.S. population grows.

Landfill gas collection and control is not accounted for at industrial waste landfills in this chapter (see the Methodology discussion for more information).

Table 7-3: CH_4 Emissions from Landfills (MMT CO_2 Eq.)

Activity	1990	2005	2012	2013	2014	2015	2016
MSW CH_4 Generation	205.3	-	-	-	-	-	-
Industrial CH_4 Generation	12.1	15.9	16.5	16.5	16.6	16.6	16.6
MSW CH_4 Recovered	(17.9)	-	-	-	-	-	-
MSW CH_4 Oxidized	(18.7)	-	-	-	-	-	-
Industrial CH_4 Oxidized	(1.2)	(1.6)	(1.6)	(1.7)	(1.7)	(1.7)	(1.7)
MSW net CH_4 Emissions (GHGRP)	-	118.4	102.2	98.4	97.8	96.7	92.7
Total	**179.6**	**132.7**	**117.0**	**113.3**	**112.7**	**111.7**	**107.7**

"-" Not applicable due to methodology change.

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values. For years 1990 to 2004, the Inventory methodology uses the first order decay methodology. A methodological change occurs in year 2005. For years 2005 to 2016, directly reported net CH_4 emissions from the GHGRP data are used plus a scale-up factor to account for emissions from landfill facilities that are not subject to the GHGRP. These data incorporate CH_4 recovered and oxidized. As such, CH_4 generation, CH_4 recovery, and CH_4 oxidized are not calculated separately for 2005 to 2016. See the Time-Series Consistency section of this chapter for more information.

Table 7-4: CH_4 Emissions from Landfills (kt)

Activity	1990	2005	2012	2013	2014	2015	2016
MSW CH_4 Generation	8,214	-	-	-	-	-	-
Industrial CH_4 Generation	484	636	659	661	662	663	664
MSW CH_4 Recovered	(718)	-	-	-	-	-	-
MSW CH_4 Oxidized	(750)	-	-	-	-	-	-
Industrial CH_4 Oxidized	(48)	(64)	(66)	(66)	(66)	(66)	(66)
MSW net CH_4 Emissions (GHGRP)	-	4,737	4,087	3,936	3,913	3,870	3,708
Total	**7,182**	**5,310**	**4,680**	**4,531**	**4,509**	**4,467**	**4,306**

"-" Not applicable due to methodology change.

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values. For years 1990 to 2004, the Inventory methodology uses the first order decay methodology. A methodological change occurs in year 2005. For years 2005 to 2016, directly reported net CH_4 emissions from the GHGRP data are used plus a scale-up factor to account for emissions from landfill facilities that are not subject to the GHGRP. These data incorporate CH_4 recovered and oxidized. As such, CH_4 generation and CH_4 recovery are not calculated separately. See the Time-Series Consistency section of this chapter for more information.

Methodology

Methodology Applied for MSW Landfills

Methane emissions from landfills can be estimated using two primary methods. The first method uses the first order decay (FOD) model as described by the *2006 IPCC Guidelines* to estimate CH_4 generation. The amount of CH_4 recovered and combusted from MSW landfills is subtracted from the CH_4 generation, and is then adjusted with an oxidation factor. The oxidation factor represents the amount of CH_4 in a landfill that is oxidized to CO_2 as it passes through the landfill cover (e.g., soil, clay, geomembrane). This method is presented below, and is similar to Equation HH-5 in CFR Part 98.343 for MSW landfills, and Equation TT-6 in CFR Part 98.463 for industrial waste landfills.

$$\mathrm{CH_{4,Solid\ Waste}} = [\mathrm{CH_{4,MSW}} + \mathrm{CH_{4,Ind}} - \mathrm{R}] - \mathrm{Ox}$$

where,

$CH_{4,Solid\ Waste}$ = Net CH_4 emissions from solid waste
$CH_{4,MSW}$ = CH_4 generation from MSW landfills
$CH_{4,Ind}$ = CH_4 generation from industrial waste landfills
R = CH_4 recovered and combusted (only for MSW landfills)

Ox = CH_4 oxidized from MSW and industrial waste landfills before release to the atmosphere

The second method used to calculate CH_4 emissions from landfills, also called the back-calculation method, is based on directly measured amounts of recovered CH_4 from the landfill gas and is expressed below and by Equation HH-8 in CFR Part 98.343. The two parts of the equation consider the portion of CH_4 in the landfill gas that is not collected by the landfill gas collection system, and the portion that is collected. First, the recovered CH_4 is adjusted with the collection efficiency of the gas collection and control system and the fraction of hours the recovery system operated in the calendar year. This quantity represents the amount of CH_4 in the landfill gas that is not captured by the collection system; this amount is then adjusted for oxidation. The second portion of the equation adjusts the portion of CH_4 in the collected landfill gas with the efficiency of the destruction device(s), and the fraction of hours the destruction device(s) operated during the year.

$$CH_4\text{,Solid Waste} = [\left(\frac{R}{CE\ x\ f_{REC}} - R\right) x(1 - OX) + R\ x\ \left(1 - (DE\ x\ f_{Dest})\right)]$$

where,

R = Quantity of recovered CH_4 from Equation HH-4 of EPA’s GHGRP
CE = Collection efficiency estimated at the landfill, considering system coverage, operation, and cover system materials from Table HH-3 of EPA’s GHGRP. If area by soil cover type information is not available, the default value of 0.75 should be used. (percent)
f_{REC} = fraction of hours the recovery system was operating (percent)
OX = oxidation factor (percent)
DE = destruction efficiency (percent)
f_{Dest} = fraction of hours the destruction device was operating (fraction)

The current Inventory uses both methods to estimate CH_4 emissions across the time series. Prior to the previous (1990 through 2015) Inventory, only the FOD method was used. Methodological changes were made to the 1990 through 2015 Inventory to incorporate higher tier data (i.e., directly reported CH_4 emissions to EPA’s GHGRP), which cannot be directly applied to earlier years in the time series without significant bias. The technique used to merge the directly reported GHGRP data with the previous methodology is described as the overlap technique in the Time-Series Consistency chapter of the *2006 IPCC Guidelines*. Additional details on the technique used is included in a technical memorandum (RTI 2017).

A summary of the methodology used to generate the current 1990 through 2016 Inventory estimates for MSW landfills is as follows and also illustrated in Annex Figure A-18:

- **1940 through 1989:** These years are included for historical waste disposal amounts. Estimates of the annual quantity of waste landfilled for 1960 through 1988 were obtained from EPA’s *Anthropogenic Methane Emissions in the United States*, *Estimates for 1990: Report to Congress* (EPA 1993) and an extensive landfill survey by EPA’s Office of Solid Waste in 1986 (EPA 1988). Although waste placed in landfills in the 1940s and 1950s contributes very little to current CH_4 generation, estimates for those years were included in the FOD model for completeness in accounting for CH_4 generation rates and are based on the population in those years and the per capita rate for land disposal for the 1960s. For the Inventory calculations, wastes landfilled prior to 1980 were broken into two groups: wastes disposed in managed, anaerobic landfills (Methane Conversion Factor, MCF, of 1) and those disposed in uncategorized solid waste disposal waste sites (MCF of 0.6). Uncategorized sites represent those sites for which limited information is known about the management practices. All calculations after 1980 assume waste is disposed in managed, anaerobic landfills. The FOD method was applied to estimate annual CH_4 generation. Methane recovery amounts were then subtracted and the result was then adjusted with a 10 percent oxidation factor to derive the net emissions estimates.
- **1990 through 2004:** The Inventory time series begins in 1990. The FOD method is exclusively used for this group of years. The national total of waste generated (based on state-specific landfill waste generation data) and a national average disposal factor for 1989 through 2008 were obtained from the State of Garbage (SOG) survey every two years (i.e., 2002, 2004, and 2006 as published in BioCycle 2006, and 2008 as published in BioCycle 2010). In-between years were interpolated based on population growth. For years 1989 to 2000, directly reported total MSW generation data were used; for other years, the estimated MSW

generation (excluding construction and demolition waste and inerts) were presented in the reports and used in the Inventory. The FOD method was applied to estimate annual CH_4 generation. Landfill-specific CH_4 recovery amounts were then subtracted from CH_4 generation and the result was then adjusted with a 10 percent oxidation factor to derive the net emissions estimates.

- **2005 through 2009:** Emissions for these years are estimated using net CH_4 emissions that are reported by landfill facilities under EPA's GHGRP. Because not all landfills in the United States are required to report to EPA's GHGRP, a 9 percent scale-up factor is applied to the GHGRP emissions for completeness. Supporting information, including details on the technique used to estimate emissions for 2005 to 2009 and to ensure time-series consistency by incorporating the directly reported GHGRP emissions is presented in Annex 3.14 and in RTI (2018). A single oxidation factor is not applied to the annual CH_4 generated as is done for 1990 to 2004 because the GHGRP emissions data are used, which already take oxidation into account. The GHGRP allows facilities to use varying oxidation factors depending on their facility-specific calculated CH_4 flux rate (i.e., 0, 10, 25, or 35 percent). The average oxidation factor from the GHGRP facilities is 19.5 percent.
- **2010 through 2016:** Directly reported net CH_4 emissions to the GHGRP are used with a 9 percent scale-up factor to account for landfills that are not required to report to the GHGRP. A combination of the FOD method and the back-calculated CH_4 emissions were used by the facilities reporting to the GHGRP. Landfills reporting to the GHGRP without gas collection and control apply the FOD method, while most landfills with landfill gas collection and control apply the back-calculation method. As noted above, GHGRP facilities use a variety of oxidation factors; therefore, the average oxidation factor from the GHGRP facilities is 19.5 percent.

A detailed discussion of the data sources and methodology used to calculate CH_4 generation and recovery is provided below. Supporting information, including details on the technique used to ensure time-series consistency by incorporating the directly-reported GHGRP emissions is presented in the Time-Series Consistency section of this chapter and in Annex 3.14.

Description of the Methodology for MSW Landfills as Applied for 1990-2004

National MSW Methane Generation and Disposal Estimates

States and local municipalities across the United States do not consistently track and report quantities of MSW generated or collected for management, nor do they report end-of-life disposal methods to a centralized system. Therefore, national MSW landfill waste generation and disposal data are obtained from secondary data, specifically the SOG surveys, published approximately every two years, with the most recent publication date of 2014. The SOG survey was the only continually updated nationwide survey of waste disposed in landfills in the United States and was the primary data source with which to estimate nationwide CH_4 generation from MSW landfills. Now, EPA's GHGRP waste disposal data and MSW management data published by EREF are available.

The SOG surveys collect data from the state agencies and then apply the principles of mass balance where all MSW generated is equal to the amount of MSW landfilled, combusted in waste-to-energy plants, composted, and/or recycled (BioCycle 2010; Shin 2014). This approach assumes that all waste management methods are tracked and reported to state agencies. Survey respondents are asked to provide a breakdown of MSW generated and managed by landfilling, recycling, composting, and combustion (in waste-to-energy facilities) in actual tonnages as opposed to reporting a percent generated under each waste disposal option. The data reported through the survey have typically been adjusted to exclude non-MSW materials (e.g., industrial and agricultural wastes, construction and demolition debris, automobile scrap, and sludge from wastewater treatment plants) that may be included in survey responses. While these wastes may be disposed of in MSW landfills, they are not the primary type of waste material disposed and are typically inert. In the most recent survey, state agencies were asked to provide already filtered, MSW-only data. Where this was not possible, they were asked to provide comments to better understand the data being reported. All state disposal data are adjusted for imports and exports across state lines where imported waste is included in a state's total while exported waste is not. Methodological changes have occurred over the time frame the SOG survey has been published, and this has affected the fluctuating trends observed in the data (RTI 2013).

State-specific landfill MSW generation data and a national average disposal factor for 1989 through 2008 were obtained from the SOG survey every two years (i.e., 2002, 2004, and 2006 as published in BioCycle 2006, and 2008 as published in BioCycle 2010). The landfill inventory calculations start with hard numbers (where available) as presented in the SOG documentation for the report years 2002, 2004, 2006, and 2008. In-between year waste generation is interpolated using the prior and next SOG report data. For example, waste generated in 2003 = (waste generation in 2002 + waste generation in 2004)/2. The quantities of waste generated across all states are summed and that value is then used as the nationwide quantity of waste generated in each year of the time series. The SOG survey is voluntary and not all states provide data in each survey year. To estimate waste generation for states that did not provide data in any given reporting year, one of the following methods was used (RTI 2013):

- For years when a state-specific waste generation rate was available from the previous SOG reporting year submission, the State-specific waste generation rate for that particular state was used.

  – or –

- For years where a state-specific waste generation rate was not available from the previous SOG reporting year submission, the waste amount is generated using the national average waste generation rate. In other words, Waste Generated = Reporting Year Population × the National Average Waste Generation Rate
    - The National Average Waste Generation Rate is determined by dividing the total reported waste generated across the reporting states by the total population for reporting states.
    - This waste generation rate may be above or below the waste generation rate for the non-reporting states and contributes to the overall uncertainty of the annual total waste generation amounts used in the model.

Use of these methods to estimate solid waste generated by states is a key aspect of how the SOG data was manipulated and why the results differ for total solid waste generated as estimated by SOG and in the Inventory. In the early years (2002 data in particular), SOG made no attempt to fill gaps for non-survey responses. For the 2004 data, the SOG team used proxy data (mainly from the WBJ) to fill gaps for non-reporting states and survey responses.

Another key aspect of the SOG survey is that it focuses on MSW-only data. The data states collect for solid waste typically are representative of total solid waste and not the MSW-only fraction. In the early years of the SOG survey, most states reported total solid waste rather than MSW-only waste. The SOG team, in response, “filtered” the state-reported data to reflect the MSW-only portion.

Also important to note about this data source is that the waste generation data reported by states to the SOG survey fluctuates from year to year. Although some fluctuation is expected, for some states, the year-to-year fluctuations are quite significant (>20 percent increase or decrease in some case) (RTI 2013). The SOG survey reports for these years do not provide additional explanation for these fluctuations and the source data are not available for further assessment. Although exact reasons for the large fluctuations are difficult to obtain without direct communication with states, staff from the SOG team that were contacted speculate that significant fluctuations are present because the particular state could not gather complete information for waste generation (i.e., they are missing part of recycled and composted waste data) during a given reporting year. In addition, SOG team staff speculated that some states may have included C&D and industrial wastes in their previous MSW generation submissions, but made efforts to exclude that (and other non-MSW categories) in more recent reports (RTI 2013).

The most recent SOG survey provides data for 2011 (Shin 2014). The EREF published a report, *MSW Management in the United States*, which includes state-specific landfill MSW generation and disposal data for 2010 and 2013 using a similar methodology as the SOG surveys (EREF 2016). State-specific landfill waste generation data for the years in between the SOG surveys and EREF report (e.g., 2001, 2003, 2005, 2007, and 2009) were either interpolated or extrapolated based on the SOG or EREF data and the U.S. Census population data (U.S. Census Bureau 2016). In the current Inventory methodology, the MSW generation and disposal data are no longer used to estimate CH_4 emissions for the years 2005 to 2016 because EPA’s GHGRP emissions data are now used for those years. The MSW generation and disposal data for these years are still useful for examining general trends in MSW management in the United States.

Estimates of the quantity of waste landfilled from 1989 to 2004 are determined by applying an average national waste disposal factor to the total amount of waste generated (i.e., the SOG data). A national average waste disposal factor is determined for each year an SOG survey is published and equals the ratio of the total amount of waste landfilled in the United States to the total amount of waste generated in the United States. The waste disposal factor is interpolated or extrapolated for the years in-between the SOG surveys, as is done for the amount of waste generated for a given survey year.

The *2006 IPCC Guidelines* recommend at least 50 years of waste disposal data to estimate CH_4 emissions. Estimates of the annual quantity of waste landfilled for 1960 through 1988 were obtained from EPA's *Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress* (EPA 1993) and an extensive landfill survey by EPA's Office of Solid Waste in 1986 (EPA 1988). Although waste placed in landfills in the 1940s and 1950s contributes very little to current CH_4 generation, estimates for those years were included in the FOD model for completeness in accounting for CH_4 generation rates and are based on the population in those years and the per capita rate for land disposal for the 1960s. For calculations in the current Inventory, wastes landfilled prior to 1980 were broken into two groups: wastes disposed in landfills (MCF of 1) and those disposed in uncategorized siteas (MCF of 0.6). All calculations after 1980 assume waste is disposed in managed, modern landfills. See Annex 3.14 for more details.

National Landfill Gas Recovery Estimates for MSW Landfills

The estimated landfill gas recovered per year (R) at MSW landfills for 1990 to 2004 was based on a combination of four databases and including recovery from flares and/or landfill gas-to-energy (LFGE) projects:

- EPA's GHGRP dataset for MSW landfills (EPA 2015a);[3]
- A database developed by the Energy Information Administration (EIA) for the voluntary reporting of greenhouse gases (EIA 2007);
- A database of LFGE projects that is primarily based on information compiled by the EPA LMOP (EPA 2016b);[4] and
- The flare vendor database (contains updated sales data collected from vendors of flaring equipment).

The same landfill may be included one or more times across these four databases. To avoid double or triplecounting CH_4 recovery, the landfills across each database were compared and duplicates identified. A hierarchy of recovery data is used based on the certainty of the data in each database. In summary, the GHGRP > EIA > LFGE > flare vendor database. The rationale for this hierarchy is described below.

EPA's GHGRP MSW landfills database was first introduced as a data source for landfill gas recovery in the 1990 to 2013 Inventory. EPA's GHGRP MSW landfills database contains facility-reported data that undergoes rigorous verification, thus it is considered to contain the least uncertain data of the four CH_4 recovery databases. However, as mentioned earlier, this database is unique in that it only contains a portion of the landfills in the United States (although, presumably the highest emitters since only those landfills that meet a certain CH_4 generation threshold must report) and only contains data for 2010 and later. In the current Inventory methodology, CH_4 recovery for 1990 to 2004 for facilities reporting to EPA's GHGRP has been estimated using the directly reported emissions for those facilities from 2010 to 2015, and an Excel forecasting function so that the GHGRP data source can be applied to earlier years in the time series. Prior to 2005, if a landfill in EPA's GHGRP was also in the LFGE or EIA databases, the landfill gas project information, specifically the project start year, from either the LFGE or EIA databases was used as the cutoff year for the estimated CH_4 recovery in the GHGRP database. For example, if a landfill reporting under EPA's GHGRP was also included in the LFGE database under a project that started in 2002 that is still operational, the CH_4 recovery data in the GHGRP database for that facility was back-calculated to the year 2002 only.

If a landfill in the GHGRP MSW landfills database was also in the EIA, LFGE, and/or flare vendor database, the avoided emissions were only based on EPA's GHGRP MSW landfills database to avoid double or triple counting the recovery amounts. In other words, the CH_4 recovery from the same landfill was not included in the total recovery from the EIA, LFGE, or flare vendor databases.

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[3] The 2015 GHGRP dataset is used to estimate landfill gas recovery from MSW landfills for the years 1990 to 2004 of the Inventory. This database is no longer updated because the methodology has changed such that the directly reported net methane emissions from the GHGRP are used and landfill gas recovery is not separately estimated.

[4] The LFGE database was not updated for the current (1990 to 2016) Inventory because the methodology does not use this database for years 2005 and later, thus the LMOP 2016 database is the most recent year reflected in the LFGE database for the Inventory.

If a landfill in the EIA database was also in the LFGE and/or the flare vendor database, the CH_4 recovery was based on the EIA data because landfill owners or operators directly reported the amount of CH_4 recovered using gas flow concentration and measurements, and because the reporting accounted for changes over time.

If both the flare data and LFGE recovery data were available for any of the remaining landfills (i.e., not in the EIA or GHGRP databases), then the avoided emissions were based on the LFGE data, which provides reported landfill-specific data on gas flow for direct use projects and project capacity (i.e., megawatts) for electricity projects. The LFGE database is based on the most recent EPA LMOP database (published annually). The remaining portion of avoided emissions is calculated by the flare vendor database, which estimates CH_4 combusted by flares using the midpoint of a flare's reported capacity. New flare vendor sales data have not been collected since 2015 because these data are not used for estimates beyond 2005 in the time series. Given that each LFGE project is likely to also have a flare, double counting reductions from flares and LFGE projects in the LFGE database was avoided by subtracting emission reductions associated with LFGE projects for which a flare had not been identified from the emission reductions associated with flares (referred to as the flare correction factor). A further explanation of the methodology used to estimate the landfill gas recovered can be found in Annex 3.14.

A destruction efficiency of 99 percent was applied to CH_4 recovered to estimate CH_4 emissions avoided due to the combusting of CH_4 in destruction devices (i.e., flares) in the EIA, LFGE, and flare vendor databases. The median value of the reported destruction efficiencies to the GHGRP was 99 percent for all reporting years (2010 through 2015). For the other three recovery databases, the 99 percent destruction efficiency value selected was based on the range of efficiencies (86 to greater than 99 percent) recommended for flares in EPA's *AP-42 Compilation of Air Pollutant Emission Factors,* Draft Section 2.4, Table 2.4-3 (EPA 2008). A typical value of 97.7 percent was presented for the non-CH_4 components (i.e., VOC and NMOC) in test results (EPA 2008). An arithmetic average of 98.3 percent and a median value of 99 percent are derived from the test results presented in EPA (2008). Thus, a value of 99 percent for the destruction efficiency of flares has been used in the Inventory methodology. Other data sources supporting a 99 percent destruction efficiency include those used to establish New Source Performance Standards (NSPS) for landfills and in recommendations for shutdown flares used by the EPA LMOP.

National MSW Landfill Methane Oxidation Estimates

The amount of CH_4 oxidized by the landfill cover at MSW landfills was assumed to be 10 percent of the CH_4 generated that is not recovered (IPCC 2006; Mancinelli and McKay 1985; Czepiel et al. 1996) for the years 1990 to 2004.

National MSW Net Emissions Estimates

Net CH_4 emissions are calculated by subtracting the CH_4 recovered and CH_4 oxidized from CH_4 generated at MSW landfills.

Description of the Methodology for MSW Landfills as Applied for 2005 to 2009

The Inventory methodology uses directly reported net CH_4 emissions for the 2010 to 2016 reporting years from the GHGRP to back-cast emissions for 2005 to 2009. The emissions for 2005 to 2009 are recalculated each year the Inventory is published to account for the additional year of reported data and any revisions that facilities make to past GHGRP reports. When EPA verifies the greenhouse gas reports, comparisons are made with data submitted in earlier reporting years and errors may be identified in these earlier year reports. Facility representatives may submit revised reports for any reporting year in order to correct these errors. Facilities reporting to the GHGRP that do not have landfill gas collection and control systems use the FOD method. Facilities with landfill gas collection and control must use both the FOD method and a back-calculation approach. The back-calculation approach starts with the amount of CH_4 recovered and works back through the system to account for gas not collected by the landfill gas collection and control system (i.e., the collection efficiency).

A scale-up factor to account for emissions from landfills that do not report to EPA's GHGRP is also applied annually. In theory, national MSW landfill emissions should equal the net CH_4 emissions reported to the GHGRP plus net CH_4 emissions from landfills that do not report to the GHGRP. EPA estimated a scale-up factor of 9 percent. The rationale behind the 9 percent scale-up factor is included in Annex 3.14 and in RTI (2018) .

The GHGRP data allow facilities to apply a range of oxidation factors (0.0, 0.10, 0.25, or 0.35) based on the calculated CH_4 flux at the landfill. Therefore, one oxidation factor is not applied for this time frame, as is done for 1990 to 2004. The average oxidation factor across the GHGRP data is 19.5 percent.

Description of the Methodology for MSW Landfills as Applied for 2010 to 2016

Directly reported CH_4 emissions to the GHGRP are used for 2010 to 2016 plus the 9 percent scale-up factor to account for emissions from landfills that do not report to the GHGRP. The average oxidation factor across the GHGRP data is 19.5 percent.

Description of the First Order Decay Methodology for Industrial Waste Landfills

Emissions from industrial waste landfills are estimated from industrial production data (ERG 2017), waste disposal factors, and the FOD method. There are currently no data sources that track and report the amount and type of waste disposed of in the universe of industrial waste landfills in the United States. EPA's GHGRP provides some insight into waste disposal in industrial waste landfills, but is not comprehensive. Data reported to the GHGRP on industrial waste landfills suggests that most of the organic waste which would result in methane emissions is disposed at pulp and paper and food processing facilities. Of the 172 facilities that report to subpart TT of the GHGRP, 93 (54 percent) are in the North American Industrial Classification System (NAICS) for Pulp, Paper, and Wood Products (NAICS 321 and 322) and 12 (7 percent) are in Food Manufacturing (NAICS 311) (EPA 2017b). Based on this limited information, the Inventory methodology assumes most of the organic waste placed in industrial waste landfills originates from the food processing (meat, vegetables, fruits) and pulp and paper sectors (EPA 1993a), thus estimates of industrial landfill emissions focused on these two sectors. The amount of waste landfilled is assumed to be a fraction of production that is held constant over the time series as explained in Annex 3.14. The composition of waste disposed of in industrial waste landfills is expected to be more consistent in terms of composition and quantity than that disposed of in MSW landfills.

Landfill CH_4 recovery is not accounted for in industrial waste landfills. Data collected through EPA's GHGRP for industrial waste landfills (Subpart TT) show that only two of the 176 facilities, or 1 percent of facilities, have active gas collection systems (EPA 2017b). However, because EPA's GHGRP is not a national database and comprehensive data regarding gas collection systems have not been published for industrial waste landfills, assumptions regarding a percentage of landfill gas collection systems, or a total annual amount of landfill gas collected for the non-reporting industrial waste landfills have not been made for the Inventory methodology.

The amount of CH_4 oxidized by the landfill cover at industrial waste landfills was assumed to be 10 percent of the CH_4 generated (IPCC 2006; Mancinelli and McKay 1985; Czepiel et al. 1996) for all years.

Uncertainty and Time-Series Consistency

Several types of uncertainty are associated with the estimates of CH_4 emissions from MSW and industrial waste landfills when the FOD method is applied directly for 1990 to 2004 in the Waste Model and, to some extent, in the GHGRP methodology. The approach used in the MSW emission estimates assumes that the CH_4 generation potential (L_o) and the rate of decay that produces CH_4 from MSW, as determined from several studies of CH_4 recovery at MSW landfills, are representative of conditions at U.S. MSW landfills. When this top-down approach is applied at the nationwide level, the uncertainties are assumed to be less than when applying this approach to individual landfills and then aggregating the results to the national level. In other words, the FOD method as applied in this Inventory is not facility-specific modeling and while this approach may over- or under-estimate CH_4 generation at some landfills if used at the facility-level, the result is expected to balance out because it is being applied nationwide. There is also a high degree of uncertainty and variability associated with the FOD model, particularly when a homogeneous waste composition and hypothetical decomposition rates are applied to heterogeneous landfills (IPCC 2006). There is less uncertainty in the GHGRP data because this methodology is facility-specific, uses directly measured CH_4 recovery data (when applicable), and allows for a variety of landfill gas collection efficiencies, destruction efficiencies, and/or oxidation factors to be used. An uncertainty factor of 8 percent is applied to the directly reported CH_4 emissions to EPA's GHGRP.

Uncertainty also exists in the scale-up factor applied for years 2005 to 2009 and in the back-casted emissions estimates for 2005 to 2009. As detailed in RTI (2018), limited information is available for landfills that do not report to the GHGRP. RTI developed an initial list of landfills that do not report to the GHGRP with the intent of quantifying the total waste-in-place for these landfills that would equal the scale-up factor. Input was provided by industry, LMOP, and additional EPA support. However, gaps still exist and assumptions were made for many landfills in order to estimate the scale-up factor. Additionally, a simple methodology was used to back-cast emissions for 2005 to 2009 using the GHGRP emissions from 2010 to 2016. This methodology does not factor in annual landfill to landfill changes in landfill CH_4 generation and recovery. Because of this, an uncertainty factor of 25 percent is applied to emissions for 2005 to 2009.

With regard to the time series and as stated in *2006 IPCC Guidelines Volume 1: Chapter 5 Time-Series Consistency* (IPCC 2006), "the time series is a central component of the greenhouse gas inventory because it provides information on historical emissions trends and tracks the effects of strategies to reduce emissions at the national level. All emissions in a time series should be estimated consistently, which means that as far as possible, the time series should be calculated using the same method and data sources in all years" (IPCC 2006). This chapter however, recommends against back-casting emissions back to 1990 with a limited set of data and instead provides guidance on techniques to splice, or join methodologies together. One of those techniques is referred to as the overlap technique. The overlap technique is recommended when new data become available for multiple years. This was the case with the GHGRP data, where directly reported CH_4 emissions data became available for more than 1,200 MSW landfills beginning in 2010. The GHGRP emissions data had to be merged with emissions from the FOD method to avoid a drastic change in emissions in 2010, when the datasets were combined. EPA also had to consider that according to IPCC's good practice, efforts should be made to reduce uncertainty in Inventory calculations and that, when compared to the GHGRP data, the FOD method presents greater uncertainty.

In evaluating the best way to combine the two datasets, EPA considered either using the FOD method from 1990 to 2009, or using the FOD method for a portion of that time and back-casting the GHGRP emissions data to a year where emissions from the two methodologies aligned. Plotting the back-casted GHGRP emissions against the emissions estimates from the FOD method showed an alignment of the data in 2004 and later years which facilitated the use of the overlap technique while also reducing uncertainty. Therefore, EPA decided to back-cast the GHGRP emissions from 2009 to 2005 only, in order to merge the datasets and adhere to the IPCC *Good Practice Guidance*.

Aside from the uncertainty in estimating landfill CH_4 generation, uncertainty also exists in the estimates of the landfill gas oxidized. Facilities directly reporting to the GHGRP can use oxidation factors ranging from 0 to 35 percent, depending on their facility-specific CH_4 flux. As recommended by the *2006 IPCC Guidelines* for managed landfills, a 10 percent default oxidation factor is applied in the Inventory for both MSW landfills (those not reporting to the GHGRP) and industrial waste landfills regardless of climate, the type of cover material, and/or presence of a gas collection system. The number of published field studies measuring the rate of oxidation has increased substantially since the *2006 IPCC Guidelines* were published and, as discussed in the Potential Improvements section, efforts are being made to review the literature and revise this value, as appropriate.

Another significant source of uncertainty lies with the estimates of CH_4 recovered by flaring and gas-to-energy projects at MSW landfills that are sourced from the Inventory's CH_4 recovery databases (used for years 1990 to 2004). Four CH_4 recovery databases are used to estimate nationwide CH_4 recovery for MSW landfills for 1990 to 2004; whereas directly reported CH_4 recovery is used for facilities reporting to the GHGRP for years 2005 to 2015. The GHGRP MSW landfills database was added as a fourth recovery database starting with the 1990 through 2013 Inventory report. Relying on multiple databases for a complete picture introduces uncertainty because the coverage and characteristics of each database differs, which increases the chance of double counting avoided emissions. Additionally, the methodology and assumptions that go into each database differ. For example, the flare database assumes the midpoint of each flare capacity at the time it is sold and installed at a landfill; the flare may be achieving a higher capacity, in which case the flare database would underestimate the amount of CH_4 recovered.

The LFGE database was updated annually until 2015. The flare database was populated annually until 2015 by the voluntary sharing of flare sales data by select vendors, which likely underestimated recovery for landfills not included in the three other recovery databases used by the Inventory. The EIA database has not been updated since 2006 and has, for the most part, been replaced by the GHGRP MSW landfills database. To avoid double counting and to use the most relevant estimate of CH_4 recovery for a given landfill, a hierarchical approach is used among the four databases. GHGRP data and the EIA data are given precedence because facility data were directly reported; the LFGE data are given second priority because CH_4 recovery is estimated from facility-reported LFGE system characteristics; and the flare data are given the lowest priority because this database contains minimal information about the flare, no site-specific operating characteristics, and includes smaller landfills not included in the other three databases (Bronstein et al. 2012). The coverage provided across the databases most likely represents the complete universe of landfill CH_4 gas recovery; however, the number of unique landfills between the four databases does differ.

The *2006 IPCC Guidelines* default value of 10 percent for uncertainty in recovery estimates was used for two of the four recovery databases in the uncertainty analysis where metering of landfill gas was in place (for about 64 percent of the CH_4 estimated to be recovered). This 10 percent uncertainty factor applies to the LFGE database; 12 percent to the EIA database; and 1 percent for the GHGRP MSW landfills dataset because of the supporting information provided and rigorous verification process. For flaring without metered recovery data (the flare database), a much higher uncertainty value of 50 percent is used. The compounding uncertainties associated with the four databases in addition to the uncertainties associated with the FOD method and annual waste disposal quantities leads to the large upper and lower bounds for MSW landfills presented in Table 7-5.

The lack of landfill-specific information regarding the number and type of industrial waste landfills in the United States is a primary source of uncertainty with respect to the industrial waste generation and emission estimates. The approach used here assumes that most of the organic waste disposed of in industrial waste landfills that would result in CH_4 emissions consists of waste from the pulp and paper and food processing sectors. However, because waste generation and disposal data are not available in an existing data source for all U.S. industrial waste landfills, a straight disposal factor is applied over the entire time series to the amount of waste generated to determine the amounts disposed. Industrial waste facilities reporting under EPA's GHGRP do report detailed waste stream information, and these data have been used to improve, for example, the DOC value used in the Inventory methodology for the pulp and paper sector. A 10 percent oxidation factor is also applied to CH_4 generation estimates for industrial waste landfills, and carries the same amount of uncertainty as with the factor applied to CH_4 generation for MSW landfills.

The results of the *2006 IPCC Guidelines* Approach 2 quantitative uncertainty analysis are summarized in Table 7-5. There is considerable uncertainty for the MSW landfills estimates due to the number of data sources used, each with its own uncertainty factor.

Table 7-5: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Landfills ($MMT CO_2$ Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Total Landfills	**CH_4**	**107.7**	**82.6**	**131.9**	**-23%**	**23%**
MSW	CH_4	92.7	69.6	116.5	-25%	26%
Industrial	CH_4	14.9	10.3	18.7	-31%	25%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. QA/QC plan, which is in accordance with Vol. 1 Chapter 6 of *2006 IPCC Guidelines* (see Annex 8 for more details). QA/QC checks are performed for the transcription of the published data set (e.g., EPA's GHGRP dataset) used to populate the Inventory data set in terms of completeness and accuracy against the reference source. Additionally, all datasets used for this category have been checked to ensure they are of appropriate quality and are representative of U.S. conditions. The primary calculation spreadsheet is tailored from the *2006 IPCC Guidelines* waste model and has been verified previously using the original, peer-reviewed IPCC waste model. All model input values and calculations were verified by secondary QA/QC review. Stakeholder engagements sessions in 2016 and 2017 were used to gather input on methodological improvements and facilitate an external expert review on the methodology, activity data, and emission factors.

Category-specific checks include the following:

- Evaluation of the secondary data sources used as inputs to the Inventory dataset to ensure they are appropriately collected and are reliable;
- Cross-checking the data (activity data and emissions estimates) with previous years to ensure the data are reasonable, and that any significant variation can be explained through the activity data;
- Conducting literature reviews to evaluate the appropriateness of country-specific emission factors (e.g., DOC values, precipitation zones with respect to the application of the k values) given findings from recent peer-reviewed studies; and
- Reviewing secondary datasets to ensure they are nationally complete and supplementing where necessary (e.g., using a scale-up factor to account for emissions from landfills that do not report to EPA's GHGRP).

A primary focus of the QA/QC checks in past Inventories was to ensure that CH_4 recovery estimates were not double-counted and that all LFGE projects and flares were included in the respective project databases. QA/QC checks performed in the past for the recovery databases were not performed in this Inventory, because new data were not added to the recovery databases in this Inventory year. For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., combination of electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred.[5]

Recalculations Discussion

Recalculations to the back-casted GHGRP emissions for 2005 to 2009 were performed, and the scale-up factor applied to years 2005 to the current year (2016) was revised. These recalculations decreased net emissions for MSW landfills from 2005 to 2015 when compared to the previous Inventory report.

First, the GHGRP data for all available years is used to back-cast emissions for 2005 to 2009. Revisions to the individual facility reports submitted to the GHGRP can be made at any time and a portion of facilities have revised their reports since 2010 for various reasons, resulting in changes to the total net CH_4 emissions for MSW landfills. Each Inventory year, the back-casted emissions for 2005 to 2009 will be recalculated using the most recently verified data from the GHGRP. Changes in these data result in changes to the back-casted emissions.

Second, the scale-up factor was revised from 12.5 percent to 9 percent. The scale-up factor to supplement directly reported emissions from the GHGRP was first applied in the 1990 to 2015 Inventory. The initial scale-up factor of 12.5 percent was developed as a rough estimate with the intent of it being refined after engaging with stakeholders and completing various data analyses. EPA has since investigated options to develop a more precise scale-up factor to apply to the GHGRP data and has refined the scale-up factor to 9 percent as detailed in RTI 2018. The revised scale-up factor was developed after extracting data on the first year of waste acceptance, annual waste disposal, and total waste-in-place from the LMOP database and WBJ Directory 2016 for landfills that are not reporting to the GHGRP. EPA created a database of non-reporting landfills and sought input from various stakeholders (industry and LMOP). Stakeholders were asked to review the database of non-reporting landfills and to provide input on the following: whether the landfill reported to the GHGRP (and reporting identification number), if the landfill was considered an MSW or other landfill, whether the landfill was open or closed, first year of waste acceptance, closure year (for closed landfills), estimated closure year (for active landfills), geographical coordinates (latitude and longitude), and annual waste acceptance data or total waste-in-place.

The revised scale-up factor of 9 percent is based on the total waste-in-place from readily available information for landfills that do not report to the GHGRP. It is the ratio of the "non-reporting landfills waste-in-place" to the sum total of the GHGRP waste-in-place and the non-reporting landfills waste-in-place.

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[5] See <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

Planned Improvements

EPA has engaged in stakeholder outreach through a series of webinars since December 2016 to increase the transparency in the Inventory methodology and to identify ideas and supplemental data sources that can lead to methodological improvements. The areas where EPA is actively working on improvements include the oxidation factor for 1990 to 2004, the DOC value for 1990 to 2004, the decay rate (k value) for 1990 to 2004, and the scale-up factor.

EPA is continuing to investigate options to adjust the oxidation factor from the 10 percent currently used for 1990 to 2004 to another value or approach such as the binned approach used in the GHGRP (e.g., 10 percent, 25 percent, or 35 percent based on methane flux). The oxidation factor currently applied in the later portion of the time series (2005 to 2016) averages at 19.5 percent due to the use of the GHGRP data while the earlier portion of the time series applies the default of 10 percent.

The Inventory currently uses one value of 0.20 for the DOC for years 1990 to 2004. With respect to improvements to the DOC value, EPA developed a database with MSW characterization data from individual studies across the United States. EPA will review this data against the Inventory time series to assess the validity of the current DOC value and how it is applied in the FOD method. Waste characterization studies vary greatly in terms of the granularity of waste types included and the spatial boundaries of each study (e.g., one landfill, a metro area, statewide). EPA also notes the longer term recommendation from industry stakeholders regarding the DOC values used in the GHGRP, in the context of new information on the composition of waste disposed in MSW landfills; these newer values could then be reflected in the 2005 and later years of the Inventory.

EPA will review the k values for the three climate types (dry, moderate, and wet) against new data and other landfill gas models, and how they are applied to the percentage of the population assigned to these climate types. EPA will also assess the uncertainty factor applied to these k values in the Waste Model. A 30 percent uncertainty factor is applied to each k value in the Monte Carlo analysis, which is consistent with that recommended by the IPCC (2006).

With respect to the scale-up factor, EPA will periodically assess the impact to the waste-in-place and emissions data from facilities that have resubmitted annual reports during any reporting years, are new reporting facilities, and from facilities that have stopped reporting to the GHGRP to ensure national estimates are as complete as possible. Facilities may stop reporting to the GHGRP when they meet the “off-ramp” provisions (reported less than 15,000 metric tons of CO_2 equivalent for 3 consecutive years or less than 25,000 metric tons of CO_2 equivalent for 5 consecutive years). If warranted, EPA will revise the scale-up factor to reflect newly acquired information to ensure completeness of the Inventory.

EPA also plans to investigate revisions to the destruction efficiencies for flares and the fluctuation in natural gas pricing and other potential factors that are impacting the development of new LFGTE projects for inclusion in a future Inventory report, as appropriate.

Box 7-3: Nationwide Municipal Solid Waste Data Sources

Municipal solid waste generated in the United States can be managed through landfilling, recycling, composting, and combustion with energy recovery. There are three main sources for nationwide solid waste management data in the United States:

- The *BioCycle* and Earth Engineering Center of Columbia University’s SOG in America surveys [no longer published];
- The EPA’s *Advancing Sustainable Materials Management* reports; and
- The EREF’s MSW Generation in the United States reports.

The SOG surveys and, now EREF, collect state-reported data on the amount of waste generated and the amount of waste managed via different management options: landfilling, recycling, composting, and combustion. The survey asks for actual tonnages instead of percentages in each waste category (e.g., residential, commercial, industrial, construction and demolition, organics, tires) for each waste management option. If such a breakdown is not available, the survey asks for total tons landfilled. The data are adjusted for imports and exports across state lines so that the principles of mass balance are adhered to, whereby the amount of waste managed does not exceed the amount of waste generated. The SOG and EREF reports present survey data aggregated to the state level.

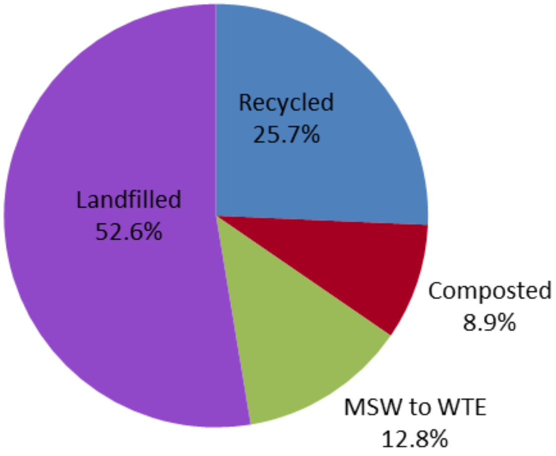
The EPA *Advancing Sustainable Materials Management* reports use a materials flow methodology, which relies heavily on a mass balance approach. Data are gathered from industry associations, key businesses, similar industry sources, and government agencies (e.g., the Department of Commerce and the U.S. Census Bureau) and are used to estimate tons of materials and products generated, recycled, combusted with energy recovery or landfilled nationwide. The amount of MSW generated is estimated by estimating production and then adjusting these values by addressing the imports and exports of produced materials to other countries. MSW that is not recycled, composted, or combusted is assumed to be landfilled. The data presented in the report are nationwide totals.

In this Inventory, emissions from solid waste management are presented separately by waste management option, except for recycling of waste materials. Emissions from recycling are attributed to the stationary combustion of fossil fuels that may be used to power on-site recycling machinery, and are presented in the stationary combustion chapter in the Energy sector, although the emissions estimates are not called out separately. Emissions from solid waste disposal in landfills and the composting of solid waste materials are presented in the Landfills and Composting sections in the Waste sector of this report. In the United States, almost all incineration of MSW occurs at waste-to-energy (WTE) facilities or industrial facilities where useful energy is recovered, and thus emissions from waste incineration are accounted for in the Incineration chapter of the Energy sector of this report.

Box 7-4: Overview of the Waste Sector

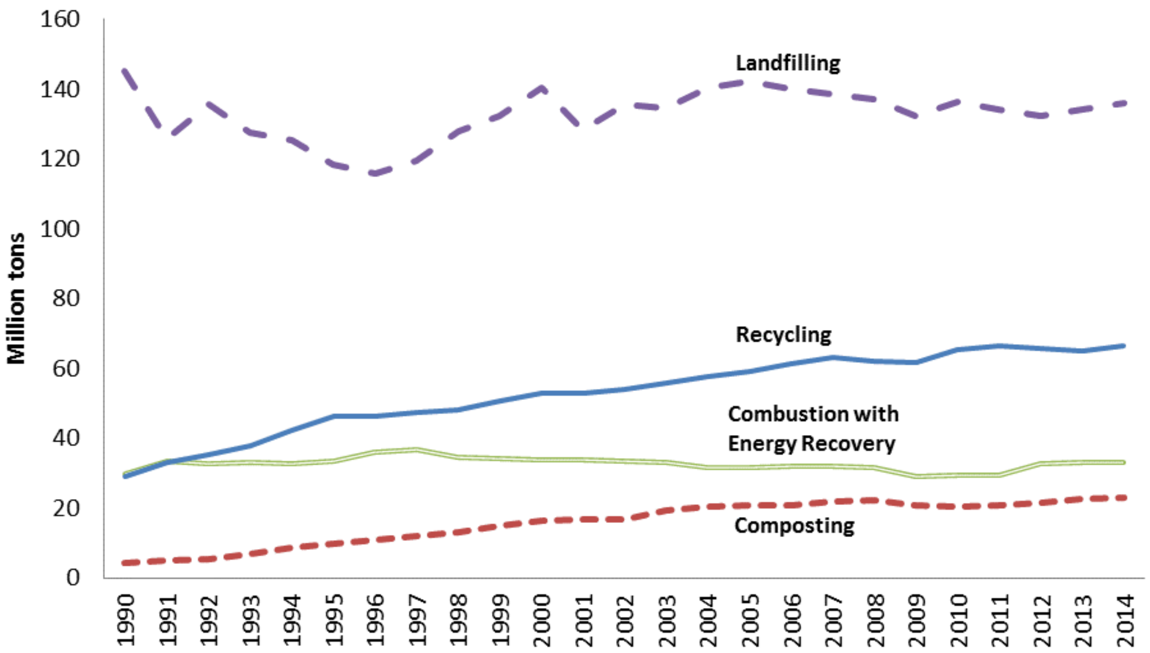
As shown in Figure 7-2 and Figure 7-3, landfilling of MSW is currently and has been the most common waste management practice. A large portion of materials in the waste stream are recovered for recycling and composting, which is becoming an increasingly prevalent trend throughout the country. Materials that are composted and recycled would have previously been disposed in a landfill.

Figure 7-2: Management of Municipal Solid Waste in the United States, 2014



Source: EPA (2016c)
Note: 2014 is the latest year of available data.

Figure 7-3: MSW Management Trends from 1990 to 2014



Source: EPA (2016c).
Note: 2014 is the latest year of available data.

Table 7-6 presents a typical composition of waste disposed of at a typical MSW landfill in the United States over time. It is important to note that the actual composition of waste entering each landfill will vary from that presented in Table 7-6. Understanding how the waste composition changes over time, specifically for the degradable waste types (i.e., those types known to generate CH_4 as they break down in a modern MSW landfill), is important for estimating greenhouse gas emissions. Increased diversion of degradable materials so that they are not disposed of in landfills reduces the CH_4 generation potential and CH_4 emissions from landfills. For certain degradable waste types (i.e., paper and paperboard), the amounts discarded have decreased over time due to an increase in waste diversion through recycling and composting (see Table 7-6 and Figure 7-4). As shown in Figure 7-4, the diversion of food scraps has been consistently low since 1990 because most cities and counties do not practice curbside collection of these materials. Neither Table 7-6 nor Figure 7-4 reflect the frequency of backyard composting of yard trimmings and food waste because this information is largely not collected nationwide and is hard to estimate.

Table 7-6: Materials Discarded[a] in the Municipal Waste Stream by Waste Type from 1990 to 2014 (Percent)[b]

Waste Type	1990	2005	2010	2011[c]	2012	2013	2014
Paper and Paperboard	30.0%	24.7%	16.1%	14.7%	14.7%	15.0%	14.3%
Glass	6.0%	5.8%	5.1%	5.1%	5.2%	5.2%	5.2%
Metals	7.2%	7.9%	9.0%	8.9%	9.2%	9.5%	9.4%
Plastics	9.5%	16.4%	17.9%	17.9%	18.2%	18.4%	18.5%
Rubber and Leather	3.2%	2.9%	3.2%	3.8%	3.2%	3.1%	3.1%
Textiles	2.9%	5.3%	6.5%	6.8%	7.1%	7.4%	7.7%
Wood	6.9%	7.5%	8.2%	8.2%	8.2%	8.0%	8.1%
Other[d]	1.4%	1.8%	2.1%	2.0%	2.0%	1.9%	1.9%
Food Scraps	13.6%	18.5%	21.0%	21.4%	21.0%	21.0%	21.6%
Yard Trimmings	17.6%	7.0%	8.6%	8.8%	8.7%	8.1%	7.9%
Miscellaneous Inorganic Wastes	1.7%	2.2%	2.3%	2.4%	2.4%	2.4%	2.3%

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[a] Discards after materials and compost recovery. In this table, discards include combustion with energy recovery. Does not include construction & demolition debris, industrial process wastes, or certain other wastes.

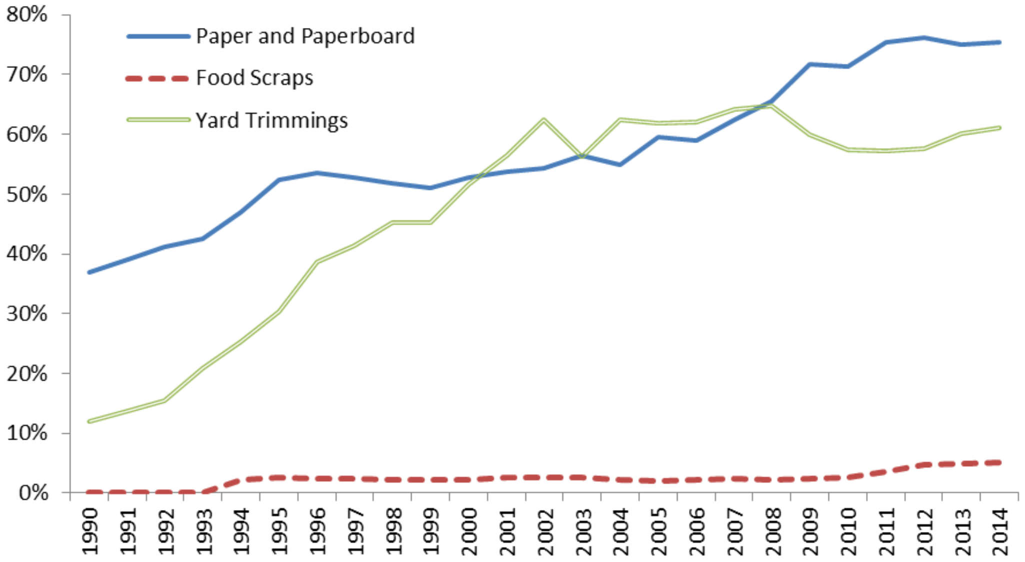
[b] Data for all years except 2011 are from the EPA's *Advancing Sustainable Materials Management: 2014 Tables and Figures* report (Table 4) published in December 2016 (EPA 2016c).

[c] 2011 data are not included in the most recent *Advancing Sustainable Materials Management* report (2014), thus data from the 2013 report (Table 3) was kept in place for 2011 (EPA 2015b).

[d] Includes electrolytes in batteries and fluff pulp, feces, and urine in disposable diapers. Details may not add to totals due to rounding.

Note: 2014 is the latest year of available data.

Figure 7-4: Percent of Degradable Materials Diverted from Landfills from 1990 to 2014 (Percent)



Source: (EPA 2016c).

Note: 2014 is the latest year of available data.

Box 7-5: Description of a Modern, Managed Landfill

Modern, managed landfills are well-engineered facilities that are located, designed, operated, and monitored to ensure compliance with federal, state, and tribal regulations. MSW landfills must be designed to protect the environment from contaminants which may be present in the solid waste stream. Additionally, many new landfills collect and destroy landfill gas through flares or landfill gas-to-energy projects. Requirements for affected MSW landfills may include:

- Siting requirements to protect sensitive areas (e.g., airports, floodplains, wetlands, fault areas, seismic impact zones, and unstable areas);
- Design requirements for new landfills to ensure that Maximum Contaminant Levels (MCLs) will not be exceeded in the uppermost aquifer (e.g., composite liners and leachate collection systems);
- Leachate collection and removal systems;
- Operating practices (e.g., daily and intermediate cover, receipt of regulated hazardous wastes, use of landfill cover material, access options to prevent illegal dumping, use of a collection system to prevent stormwater run-on/run-off, record-keeping);
- Air monitoring requirements (explosive gases);
- Groundwater monitoring requirements;
- Closure and post-closure care requirements (e.g., final cover construction); and
- Corrective action provisions.

Specific federal regulations that affected MSW landfills must comply with include the 40 CFR Part 258 (Subtitle D of RCRA), or equivalent state regulations and the NSPS 40 CFR Part 60 Subpart WWW. Additionally, state and tribal requirements may exist.[6]

7.2 Wastewater Treatment (CRF Source Category 5D)

Wastewater treatment processes can produce anthropogenic methane (CH_4) and nitrous oxide (N_2O) emissions. Wastewater from domestic and industrial sources is treated to remove soluble organic matter, suspended solids, pathogenic organisms, and chemical contaminants.[7] Treatment may either occur on site, most commonly through septic systems or package plants, or off site at centralized treatment systems. In the United States, approximately 19 percent of domestic wastewater is treated in septic systems or other on-site systems, while the rest is collected and treated centrally (U.S. Census Bureau 2015). Centralized wastewater treatment systems may include a variety of processes, ranging from lagooning to advanced tertiary treatment technology for removing nutrients. Some wastewater may also be treated through the use of constructed (or semi-natural) wetland systems, though it is much less common in the United States (ERG 2016). Constructed wetlands may be used as the primary method of wastewater treatment, or as a tertiary treatment step following settling and biological treatment. Constructed wetlands develop natural processes that involve vegetation, soil, and associated microbial assemblages to trap and treat incoming contaminants (IPCC 2014).

Soluble organic matter is generally removed using biological processes in which microorganisms consume the organic matter for maintenance and growth. The resulting biomass (sludge) is removed from the effluent prior to discharge to the receiving stream. Microorganisms can biodegrade soluble organic material in wastewater under aerobic or anaerobic conditions, where the latter condition produces CH_4. During collection and treatment, wastewater may be accidentally or deliberately managed under anaerobic conditions. In addition, the sludge may be further biodegraded under aerobic or anaerobic conditions. The generation of N_2O may also result from the treatment of domestic wastewater during both nitrification and denitrification of the nitrogen (N) 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 (without free oxygen), and involves the biological conversion of nitrate into dinitrogen gas (N_2). Nitrous oxide can be an intermediate product of both processes, but has typically been associated with denitrification. Recent research suggests that higher emissions of N_2O may in fact originate from nitrification (Ahn et al. 2010). Other more recent research suggests that N_2O may also result from other types of wastewater treatment operations (Chandran 2012).

The principal factor in determining the CH_4 generation potential of wastewater is the amount of degradable organic material in the wastewater. Common parameters used to measure the organic component of the wastewater are the biochemical oxygen demand (BOD) and chemical oxygen demand (COD). Under the same conditions, wastewater with higher COD (or BOD) concentrations will generally yield more CH_4 than wastewater with lower COD (or BOD) concentrations. BOD represents the amount of oxygen that would be required to completely consume the organic matter contained in the wastewater through aerobic decomposition processes, while COD measures the total material available for chemical oxidation (both biodegradable and non-biodegradable). The BOD value is most commonly expressed in milligrams of oxygen consumed per liter of sample during 5 days of incubation at 20°C, or BOD_5. Because BOD is an aerobic parameter, it is preferable to use COD to estimate CH_4 production, since CH_4 is produced only in anaerobic conditions. The principal factor in determining the N_2O generation potential of

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[6] For more information regarding federal MSW landfill regulations, see <http://www.epa.gov/osw/nonhaz/municipal/landfill/msw_regs.htm>.

[7] Throughout the Inventory, emissions from domestic wastewater also include any commercial and industrial wastewater collected and co-treated with domestic wastewater.

wastewater is the amount of N in the wastewater. The variability of N in the influent to the treatment system, as well as the operating conditions of the treatment system itself, also impact the N_2O generation potential.

In 2016, CH_4 emissions from domestic wastewater treatment were 8.9 MMT CO_2 Eq. (357 kt CH_4). Emissions remained fairly steady from 1990 through 1999, but have decreased since that time due to decreasing percentages of wastewater being treated in anaerobic systems, generally including reduced use of on-site septic systems and central anaerobic treatment systems (EPA 1992, 1996, 2000, and 2004; U.S. Census Bureau 2015). In 2016, CH_4 emissions from industrial wastewater treatment were estimated to be 5.9 MMT CO_2 Eq. (236 kt CH_4). Industrial emission sources have generally increased across the time series through 1999 and then fluctuated up and down with production changes associated with the treatment of wastewater from the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, and petroleum refining industries. Table 7-7 and Table 7-8 provide CH_4 emission estimates from domestic and industrial wastewater treatment.

With respect to N_2O, the United States identifies two distinct sources for N_2O emissions from domestic wastewater: emissions from centralized wastewater treatment processes, and emissions from effluent from centralized treatment systems that has been discharged into aquatic environments. The 2016 emissions of N_2O from centralized wastewater treatment processes and from effluent were estimated to be 0.4 MMT CO_2 Eq. (1.2 kt N_2O) and 4.6 MMT CO_2 Eq. (15.4 kt N_2O), respectively. Total N_2O emissions from domestic wastewater were estimated to be 5.0 MMT CO_2 Eq. (16.6 kt N_2O). Nitrous oxide emissions from wastewater treatment processes gradually increased across the time series as a result of increasing U.S. population and protein consumption. Nitrous oxide emissions are not estimated from industrial wastewater treatment because there is no IPCC methodology provided or industrial wastewater emission factors available. Table 7-7 and Table 7-8 provide N_2O emission estimates from domestic wastewater treatment.

Table 7-7: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (MMT CO_2 Eq.)

Activity	1990	2005	2012	2013	2014	2015	2016
CH_4	**15.7**	**15.8**	**15.1**	**14.9**	**15.0**	**15.1**	**14.8**
Domestic	10.5	10.1	9.3	9.1	9.2	9.3	8.9
Industrial[a]	5.1	5.7	5.8	5.8	5.7	5.8	5.9
N_2O	**3.4**	**4.4**	**4.6**	**4.7**	**4.8**	**4.8**	**5.0**
Centralized WWTP	0.2	0.3	0.3	0.3	0.3	0.3	0.4
Domestic Effluent	3.2	4.1	4.3	4.3	4.5	4.5	4.6
Total	**19.1**	**20.2**	**19.7**	**19.6**	**19.8**	**20.0**	**19.8**

[a] Industrial activity includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, and petroleum refining industries.

Note: Totals may not sum due to independent rounding.

Table 7-8: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (kt)

Activity	1990	2005	2012	2013	2014	2015	2016
CH_4	**627**	**631**	**604**	**596**	**598**	**605**	**593**
Domestic	422	404	372	365	369	374	357
Industrial[a]	205	227	232	231	229	231	236
N_2O	**11**	**15**	**16**	**16**	**16**	**16**	**17**
Centralized WWTP	1	1	1	1	1	1	1
Domestic Effluent	11	14	14	15	15	15	15

[a] Industrial activity includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, and petroleum refining industries.

Note: Totals may not sum due to independent rounding.

Methodology

Domestic Wastewater CH_4 Emission Estimates

Domestic wastewater CH_4 emissions originate from both septic systems and from centralized treatment systems, such as publicly owned treatment works (POTWs). Within these centralized systems, CH_4 emissions can arise from aerobic systems that are not well managed or that are designed to have periods of anaerobic activity (e.g., constructed wetlands and facultative lagoons), anaerobic systems (anaerobic lagoons and anaerobic reactors), and from anaerobic digesters when the captured biogas is not completely combusted. The methodological equations are:

$$\textit{Emissions from Septic Systems} = \text{A}$$
$$= US_{POP} \times (\%\ \text{onsite}) \times (EF_{SEPTIC}) \times 1/10^{9} \times 365.25$$

$$\textit{Emissions from Centrally Treated Aerobic Systems (other than Constructed Wetlands)} + \textit{Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands Only)} + \textit{Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands used as Tertiary Treatment)} = \text{B}$$

where,

$$\textit{Emissions from Centrally Treated Aerobic Systems (other than Constructed Wetlands)}$$
$$= [(\%\ \text{collected}) \times (\text{total } BOD_5 \text{ produced}) \times (\%\ \text{aerobic}_{OTCW}) \times (\%\ \text{aerobic w/out primary}) + (\%\ \text{collected}) \times (\text{total } BOD_5 \text{ produced}) \times (\%\ \text{aerobic}_{OTCW}) \times (\%\ \text{aerobic w/primary}) \times (1\text{-}\%\ \text{BOD removed in prim. treat.})] \times (\%\ \text{operations not well managed}) \times (B_o) \times (\text{MCF-aerobic\_not\_well\_man})$$

$$\textit{Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands Only)}$$
$$= [(\%\ \text{collected}) \times (\text{total } BOD_5 \text{ produced}) \times (\%\text{aerobic}_{CW})] \times (B_o) \times (\text{MCF-constructed wetlands})$$

$$\textit{Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands used as Tertiary Treatment)}$$
$$= [(\text{POTW\_flow\_CW}) \times (BOD_{CW,INF}) \times 3.79] \times 1/10^{6} \times 365.25$$

$$\textit{Emissions from Centrally Treated Anaerobic Systems} = \text{C}$$
$$= \{[(\%\ \text{collected}) \times (\text{total } BOD_5 \text{ produced}) \times (\%\ \text{anaerobic}) \times (\%\ \text{anaerobic w/out primary})] + [(\%\ \text{collected}) \times (\text{total } BOD_5 \text{ produced}) \times (\%\ \text{anaerobic}) \times (\%\ \text{anaerobic w/primary}) \times (1\text{-}\%\ \text{BOD removed in prim. treat.})]\} \times (B_o) \times (\text{MCF-anaerobic})$$

$$\textit{Emissions from Anaerobic Digesters} = \text{D}$$
$$= [(\text{POTW\_flow\_AD}) \times (\text{digester gas})/(100)] \times 0.0283 \times (\text{FRAC\_}CH_4) \times 365.25 \times (\text{density of } CH_4) \times (1\text{-DE}) \times 1/10^{9}$$

$$\text{Total Domestic } CH_4 \text{ Emissions from Wastewater (kt)} = \text{A} + \text{B} + \text{C} + \text{D}$$

where,

US_{POP} = U.S. population
% onsite = Flow to septic systems / total flow
% collected = Flow to POTWs / total flow
% aerobic_{OTCW} = Flow to aerobic systems, other than wetlands only / total flow to POTWs
% aerobic_{CW} = Flow to aerobic systems, constructed wetlands used as sole treatment / total flow to POTWs
% anaerobic = Flow to anaerobic systems / total flow to POTWs
% aerobic w/out primary = Percent of aerobic systems that do not employ primary treatment
% aerobic w/primary = Percent of aerobic systems that employ primary treatment
% BOD removed in prim. treat. = Percent of BOD removed in primary treatment
% operations not well managed = Percent of aerobic systems that are not well managed and in which some anaerobic degradation occurs
% anaerobic w/out primary = Percent of anaerobic systems that do not employ primary treatment

% anaerobic w/primary = Percent of anaerobic systems that employ primary treatment
EF_{SEPTIC} = Methane emission factor – septic systems
Total BOD_5 produced = kg BOD/capita/day × U.S. population × 365.25 days/yr
$BOD_{CW,INF}$ = BOD concentration in wastewater entering the constructed wetland
B_o = Maximum CH_4-producing capacity for domestic wastewater
$1/10^6$ = Conversion factor, kg to kt
365.25 = Days in a year
3.79 = Conversion factor, liters to gallons
MCF-aerobic_not_well_man. = CH_4 correction factor for aerobic systems that are not well managed
MCF-anaerobic = CH_4 correction factor for anaerobic systems
MCF-constructed wetlands = CH_4 correction factor for surface flow constructed wetlands
DE = CH_4 destruction efficiency from flaring or burning in engine
POTW_flow_CW = Wastewater flow to POTWs that use constructed wetlands as tertiary treatment (MGD)
POTW_flow_AD = Wastewater influent flow to POTWs that have anaerobic digesters (MGD)
digester gas = Cubic feet of digester gas produced per person per day
100 = Wastewater flow to POTW (gallons/person/day)
0.0283 = Conversion factor, ft^3 to m^3
$FRAC\_CH_4$ = Proportion of CH_4 in biogas
662 = Density of CH_4 (g CH_4/m^3 CH_4)
$1/10^9$ = Conversion factor, g to kt

Emissions from Septic Systems:

Methane emissions from septic systems were estimated by multiplying the U.S. population by the percent of wastewater treated in septic systems (about 19 percent) and an emission factor (10.7 g CH_4/capita/day) (Leverenz et al. 2010), and then converting the result to kt/year. U.S. population data were taken from the U.S. Census Bureau International Database (U.S. Census Bureau 2017) and include the populations of the United States, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the U.S. Virgin Islands. Table 7-9 presents U.S. population for 1990 through 2016.

Emissions from Centrally Treated Aerobic and Anaerobic Systems:

Methane emissions from POTWs were estimated by multiplying the total BOD_5 produced in the United States by the percent of wastewater treated centrally (about 81 percent) (U.S. Census Bureau 2015), the relative percentage of wastewater treated by aerobic and anaerobic systems (other than constructed wetlands), the relative percentage of wastewater facilities with primary treatment (EPA 1992, 1996, 2000, and 2004), the percentage of BOD_5 treated after primary treatment (67.5 percent, 32.5 percent removed in primary treatment) (Metcalf & Eddy 2003), the maximum CH_4-producing capacity of domestic wastewater (B_o, 0.6 kg CH_4/kg BOD) (IPCC 2006), and the relative methane conversion factors (MCF) not well managed aerobic (0.3) (IPCC 2006), and anaerobic (0.8) (IPCC 2006) systems.

Table 7-9 presents total BOD_5 produced for 1990 through 2016. The proportions of domestic wastewater treated onsite versus at centralized treatment plants were based on data from the 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, 2007, 2009, 2011, 2013, and 2015 *American Housing Surveys* conducted by the U.S. Census Bureau (U.S. Census Bureau 2015), with data for intervening years obtained by linear interpolation and 2016 forecasted using 1990 to 2015 data. The percent of wastewater flow to aerobic and anaerobic systems, the percent of aerobic and anaerobic systems that do and do not employ primary treatment, and the wastewater flow to POTWs that have anaerobic digesters were obtained from the 1992, 1996, 2000, and 2004 Clean Watersheds Needs Survey (EPA 1992, 1996, 2000, and 2004). Data for intervening years were obtained by linear interpolation and the years 2005 through 2016 were forecasted from the rest of the time series. The percent of wastewater flow to aerobic systems that use only constructed wetlands and wastewater flow to POTWs that use constructed wetlands as tertiary treatment were obtained from the 1992, 1996, 2000, 2004, 2008, and 2012 Clean Watersheds Needs Survey (EPA 1992, 1996, 2000, 2004, 2008b, and 2012). Data for intervening years were obtained by linear interpolation and the years 2013 through 2016 were forecasted from the rest of the time series. The BOD_5 production rate (0.09 kg/capita/day) and the percent BOD_5 removed by primary treatment for domestic wastewater were obtained from Metcalf & Eddy (2003).

Table 7-9: U.S. Population (Millions) and Domestic Wastewater BOD_5 Produced (kt)

Year	Population	BOD_5
1990	253	8,333
2005	300	9,853
2012	318	10,458
2013	320	10,534
2014	323	10,615
2015	325	10,696
2016	328	10,780

Sources: U.S. Census Bureau (2017); Metcalf & Eddy (2003).

For constructed wetlands, an MCF of 0.4 was used, which is the IPCC suggested MCF for surface flow wetlands. This is the most conservative factor for constructed wetlands and was recommended by IPCC (2014) when the type of constructed wetland is not known. A BOD_5 concentration of 30 mg/L was used for wastewater entering constructed wetlands used as tertiary treatment based on U.S. secondary treatment standards for POTWs. These standards are based on plants generally utilizing simple settling and biological treatment (EPA 2013).

All aerobic systems are assumed to be well-managed as there are currently no data available to quantify the number of systems that are not well-managed. In addition, methane emissions were calculated for systems that treat wastewater with constructed wetlands and systems that use constructed wetlands as tertiary treatment; however, constructed wetlands are a relatively small portion of wastewater treated centrally (<0.1 percent).

Emissions from Anaerobic Digesters:

Total CH_4 emissions from anaerobic digesters were estimated by multiplying the wastewater influent flow to POTWs with anaerobic digesters, the cubic feet of digester gas generated per person per day divided by the flow to POTWs, the fraction of CH_4 in biogas (0.65), the density of CH_4 (662 g CH_4/m^3 CH_4) (EPA 1993a), one minus the destruction efficiency from burning the biogas in an energy/thermal device (0.99 for enclosed flares) and then converting the results to kt/year.

The CH_4 destruction efficiency for CH_4 recovered from sludge digestion operations, 99 percent, was selected based on the range of efficiencies (98 to 100 percent) recommended for flares in *AP-42 Compilation of Air Pollutant Emission Factors*, Chapter 2.4 (EPA 1998), efficiencies used to establish New Source Performance Standards (NSPS) for landfills, along with data from CAR (2011), Sullivan (2007), Sullivan (2010), and UNFCCC (2012). The cubic feet of digester gas produced per person per day (1.0 ft^3/person/day) and the proportion of CH_4 in biogas (0.65) come from Metcalf & Eddy (2014). The wastewater flow to a POTW (100 gal/person/day) was taken from the Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers, "*Recommended Standards for Wastewater Facilities (Ten-State Standards)*" (2004).

Table 7-10 presents domestic wastewater CH_4 emissions for both septic and centralized systems, including anaerobic digesters, in 2016.

Table 7-10: Domestic Wastewater CH_4 Emissions from Septic and Centralized Systems (2016, MMT CO_2 Eq. and Percent)

	CH_4 Emissions (MMT CO_2 Eq.)	% of Domestic Wastewater CH_4
Septic Systems	6.0	66.7%
Centrally-Treated Aerobic Systems	0.1	1.1%
Centrally-Treated Anaerobic Systems	2.7	29.8%
Anaerobic Digesters	0.2	2.3%
Total	**8.9**	**100%**

Note: Totals may not sum due to independent rounding.

Industrial Wastewater CH_4 Emission Estimates

Methane emission estimates from industrial wastewater were developed according to the methodology described in the *2006 IPCC Guidelines*. Industry categories that are likely to produce significant CH_4 emissions from wastewater treatment were identified and included in the Inventory. The main criteria used to identify these industries are whether they generate high volumes of wastewater, whether there is a high organic wastewater load, and whether the wastewater is treated using methods that result in CH_4 emissions. The top five industries that meet these criteria are pulp and paper manufacturing; meat and poultry processing; vegetables, fruits, and juices processing; starch-based ethanol production; and petroleum refining. Wastewater treatment emissions for these sectors for 2016 are displayed in Table 7-11 below. Table 7-12 contains production data for these industries.

Table 7-11: Industrial Wastewater CH_4 Emissions by Sector (2016, MMT CO_2 Eq. and Percent)

	CH_4 Emissions (MMT CO_2 Eq.)	% of Industrial Wastewater CH_4
Meat & Poultry	4.5	76.8%
Pulp & Paper	0.9	15.8%
Fruit & Vegetables	0.1	2.4%
Petroleum Refineries	0.1	2.5%
Ethanol Refineries	0.1	2.5%
Total	**5.9**	**100%**

Note: Totals may not sum due to independent rounding.

Table 7-12: U.S. Pulp and Paper, Meat, Poultry, Vegetables, Fruits and Juices, Ethanol, and Petroleum Refining Production (MMT)

Year	Pulp and Paper[a]	Meat (Live Weight Killed)	Poultry (Live Weight Killed)	Vegetables, Fruits and Juices	Ethanol	Petroleum Refining
1990	128.9	27.3	14.6	38.7	2.5	702.4
2005	138.5	31.4	25.1	42.9	11.7	818.6
2012	124.7	33.8	26.1	45.6	39.5	856.1
2013	120.8	33.6	26.5	45.1	39.7	878.7
2014	123.2	32.2	26.9	45.3	42.8	903.9
2015	121.8	32.8	27.7	44.6	44.2	914.5
2016	121.4	34.2	28.3	43.3	45.8	925.3

[a] Pulp and paper production is the sum of woodpulp production plus paper and paperboard production.
Sources: Lockwood-Post (2002); FAO (2017a); USDA (2017a); Cooper (2017); EIA (2017).

Methane emissions from these categories were estimated by multiplying the annual product output by the average outflow, the organics loading (in COD) in the outflow, the maximum CH_4 producing potential of industrial wastewater (B_o), and the percentage of organic loading assumed to degrade anaerobically in a given treatment system (MCF). Ratios of BOD:COD in various industrial wastewaters were obtained from EPA (1997a) and used to estimate COD loadings. The B_o value used for all industries is the IPCC default value of 0.25 kg CH_4/kg COD (IPCC 2006).

For each industry, the percent of plants in the industry that treat wastewater on site, the percent of plants that have a primary treatment step prior to biological treatment, and the percent of plants that treat wastewater anaerobically were defined. The percent of wastewater treated anaerobically onsite (TA) was estimated for both primary treatment ($\%TA_p$) and secondary treatment ($\%TA_s$). For plants that have primary treatment in place, an estimate of COD that is removed prior to wastewater treatment in the anaerobic treatment units was incorporated. The values used in the %TA calculations are presented in Table 7-13 below.

The methodological equations are:

$$\mathrm{CH_4\ (industrial\ wastewater)} = [\mathrm{P} \times \mathrm{W} \times \mathrm{COD} \times \%\mathrm{TA_p} \times \mathrm{B_o} \times \mathrm{MCF}] + [\mathrm{P} \times \mathrm{W} \times \mathrm{COD} \times \%\mathrm{TA_s} \times \mathrm{B_o} \times \mathrm{MCF}]$$

$$\%TA_p = [\%Plants_o \times \%WW_{a,p} \times \%COD_p]$$

$$\%TA_s = [\%Plants_a \times \%WW_{a,s} \times \%COD_s] + [\%Plants_t \times \%WW_{a,t} \times \%COD_s]$$

where,

CH_4 (industrial wastewater) = Total CH_4 emissions from industrial wastewater (kg/year)
P = Industry output (metric tons/year)
W = Wastewater generated (m^3/metric ton of product)
COD = Organics loading in wastewater (kg/m^3)
$\%TA_p$ = Percent of wastewater treated anaerobically on site in primary treatment
$\%TA_s$ = Percent of wastewater treated anaerobically on site in secondary treatment
$\%Plants_o$ = Percent of plants with onsite treatment
$\%WW_{a,p}$ = Percent of wastewater treated anaerobically in primary treatment
$\%COD_p$ = Percent of COD entering primary treatment
$\%Plants_a$ = Percent of plants with anaerobic secondary treatment
$\%Plants_t$ = Percent of plants with other secondary treatment
$\%WW_{a,s}$ = Percent of wastewater treated anaerobically in anaerobic secondary treatment
$\%WW_{a,t}$ = Percent of wastewater treated anaerobically in other secondary treatment
$\%COD_s$ = Percent of COD entering secondary treatment
B_o = Maximum CH_4 producing potential of industrial wastewater (kg CH_4/kg COD)
MCF = CH_4 correction factor, indicating the extent to which the organic content (measured as COD) degrades anaerobically

Alternate methodological equations for calculating %TA were used for secondary treatment in the pulp and paper industry to account for aerobic systems with anaerobic portions. These equations are:

$$\%TA_a = [\%Plants_a \times \%WW_{a,s} \times \%COD_s]+[\%Plant_{s,t} \times \%WW_{a,t} \times COD_s]$$

$$\%TA_{a,t} = [\%Plants_{a,t} \times \%WW_{a,s} \times \%COD_s]$$

where,

$\%TA_a$ = Percent of wastewater treated anaerobically on site in secondary treatment
$\%TA_{a,t}$ = Percent of wastewater treated in aerobic systems with anaerobic portions on site in secondary treatment
$\%Plants_a$ = Percent of plants with anaerobic secondary treatment
$\%Plants_{a,t}$ = Percent of plants with partially anaerobic secondary treatment
$\%WW_{a,s}$ = Percent of wastewater treated anaerobically in anaerobic secondary treatment
$\%WW_{a,t}$ = Percent of wastewater treated anaerobically in other secondary treatment
$\%COD_s$ = Percent of COD entering secondary treatment

As described below, the values presented in Table 7-13 were used in the emission calculations and are described in detail in ERG (2008), ERG (2013a), and ERG (2013b).

Table 7-13: Variables Used to Calculate Percent Wastewater Treated Anaerobically by Industry (Percent)

Variable	Industry						
	Pulp and Paper	**Meat Processing**	**Poultry Processing**	**Fruit/ Vegetable Processing**	**Ethanol Production – Wet Mill**	**Ethanol Production – Dry Mill**	**Petroleum Refining**
$\%TA_p$	0	0	0	0	0	0	0
$\%TA_s$	0	33	25	4.2	33.3	75	23.6
$\%TA_a$	2.2	0	0	0	0	0	0
$\%TA_{a,t}$	11.8	0	0	0	0	0	0
$\%Plants_o$	0	100	100	11	100	100	100
$\%Plants_a$	5	33	25	5.5	33.3	75	23.6
$\%Plants_{a,t}$	28	0	0	0	0	0	0
$\%Plants_t$	35	67	75	5.5	66.7	25	0

$\%WW_{a,p}$	0	0	0	0	0	0	0
$\%WW_{a,s}$	100	100	100	100	100	100	100
$\%WW_{a,t}$	0	0	0	0	0	0	0
$\%COD_p$	100	100	100	100	100	100	100
$\%COD_s$	42	100	100	77	100	100	100

Note: Due to differences in data availability and methodology, zero values in the table are for calculation purposes only and may indicate unavailable data.
Sources: ERG (2008); ERG (2013a); and ERG (2013b).

Pulp and Paper. Wastewater treatment for the pulp and paper industry typically includes neutralization, screening, sedimentation, and flotation/hydrocycloning to remove solids (World Bank 1999; Nemerow and Dasgupta 1991). Secondary treatment (storage, settling, and biological treatment) mainly consists of lagooning. In determining the percent that degrades anaerobically, both primary and secondary treatment were considered. In the United States, primary treatment is focused on solids removal, equalization, neutralization, and color reduction (EPA 1993b). The vast majority of pulp and paper mills with on-site treatment systems use mechanical clarifiers to remove suspended solids from the wastewater. About 10 percent of pulp and paper mills with treatment systems use settling ponds for primary treatment and these are more likely to be located at mills that do not perform secondary treatment (EPA 1993b). However, because the vast majority of primary treatment operations at U.S. pulp and paper mills use mechanical clarifiers, and less than 10 percent of pulp and paper wastewater is managed in primary settling ponds that are not expected to have anaerobic conditions, negligible emissions are assumed to occur during primary treatment.

Approximately 42 percent of the BOD passes on to secondary treatment, which consists of activated sludge, aerated stabilization basins, or non-aerated stabilization basins. Based on EPA's *OAQPS Pulp and Paper Sector Survey*, 5.3 percent of pulp and paper mills reported using anaerobic secondary treatment for wastewater and/or pulp condensates (ERG 2013a). Twenty-eight percent of mills also reported the use of quiescent settling ponds. Using engineering judgment, these systems were determined to be aerobic with possible anaerobic portions. For the truly anaerobic systems, an MCF of 0.8 is used, as these are typically deep stabilization basins. For the partially anaerobic systems, an MCF of 0.2 is used, which is the *2006 IPCC Guidelines*-suggested MCF for shallow lagoons.

A time series of CH_4 emissions for 1990 through 2001 was developed based on production figures reported in the Lockwood-Post Directory (Lockwood-Post 2002). Data from the Food and Agricultural Organization of the United Nations (FAO) database FAOSTAT were used for 2002 through 2015 (FAO 2017a). A time series of the overall wastewater outflow for 1990 through 1994 varies based on data outlined in ERG (2013a) to reflect historical wastewater flow. Wastewater generation rates for 1995, 2000, and 2002 were estimated from the 2014 *American Forest and Paper Association* (AF&PA) *Sustainability Report* (AF&PA 2014). Wastewater generation rates for 2004, 2006, 2008, 2010, 2012, and 2014 were estimated from the 2016 AF&PA Sustainability Report (AF&PA 2016). Data for intervening years were obtained by linear interpolation, while 2015 and 2016 were forecasted using 1990 to 2014 and 1990 to 2015 data, respectively. The average BOD concentrations in raw wastewater was estimated to be 0.4 grams BOD/liter (EPA 1997b; EPA 1993b; World Bank 1999). The COD:BOD ratio used to convert the organic loading to COD for pulp and paper mills was 2 (EPA 1997a).

Meat and Poultry Processing. The meat and poultry processing industry makes extensive use of anaerobic lagoons in sequence with screening, fat traps, and dissolved air flotation when treating wastewater on site. About 33 percent of meat processing operations (EPA 2002) and 25 percent of poultry processing operations (U.S. Poultry 2006) perform on-site treatment in anaerobic lagoons. The IPCC default B_o of 0.25 kg CH_4/kg COD and default MCF of 0.8 for anaerobic lagoons were used to estimate the CH_4 produced from these on-site treatment systems. Production data, in carcass weight and live weight killed for the meat and poultry industry, were obtained from the USDA *Agricultural Statistics Database and the Agricultural Statistics Annual Reports* (USDA 2017a). Data collected by EPA's Office of Water provided estimates for wastewater flows into anaerobic lagoons: 5.3 and 12.5 m^3/metric ton for meat and poultry production (live weight killed), respectively (EPA 2002). The loadings are 2.8 and 1.5 g BOD/liter for meat and poultry, respectively. The COD:BOD ratio used to convert the organic loading to COD for both meat and poultry facilities was 3 (EPA 1997a).

Vegetables, Fruits, and Juices Processing. Treatment of wastewater from fruits, vegetables, and juices processing includes screening, coagulation/settling, and biological treatment (lagooning). The flows are frequently seasonal, and robust treatment systems are preferred for on-site treatment. Effluent is suitable for discharge to POTWs. This industry is likely to use lagoons intended for aerobic operation, but the large seasonal loadings may develop limited anaerobic zones. In addition, some anaerobic lagoons may also be used (Nemerow and Dasgupta 1991). Consequently, 4.2 percent of these wastewater organics are assumed to degrade anaerobically. The IPCC default B_o of 0.25 kg CH_4/kg COD and default MCF of 0.8 for anaerobic treatment were used to estimate the CH_4 produced from these on-site treatment systems. The USDA National Agricultural Statistics Service (USDA 2017a, 2017c) provided production data for potatoes, other vegetables, citrus fruit, non-citrus fruit, and grapes processed for wine. Outflow and BOD data, presented in Table 7-14, were obtained from EPA (1974) for potato, citrus fruit, and apple processing, and from EPA (1975) for all other commodities. The COD:BOD ratio used to convert the organic loading to COD for all fruit, vegetable, and juice facilities was 1.5 (EPA 1997a).

Table 7-14: Wastewater Flow (m^3/ton) and BOD Production (g/L) for U.S. Vegetables, Fruits, and Juices Production

Commodity	Wastewater Outflow (m^3/ton)	BOD (g/L)
Vegetables		
Potatoes	10.27	1.765
Other Vegetables	8.55	0.776
Fruit		
Apples	3.66	1.371
Citrus Fruits	10.11	0.317
Non-citrus Fruits	12.42	1.204
Grapes (for wine)	2.78	1.831

Sources: EPA (1974); EPA (1975).

Ethanol Production. Ethanol, or ethyl alcohol, is produced primarily for use as a fuel component, but is also used in industrial applications and in the manufacture of beverage alcohol. Ethanol can be produced from the fermentation of sugar-based feedstocks (e.g., molasses and beets), starch- or grain-based feedstocks (e.g., corn, sorghum, and beverage waste), and cellulosic biomass feedstocks (e.g., agricultural wastes, wood, and bagasse). Ethanol can also be produced synthetically from ethylene or hydrogen and carbon monoxide. However, synthetic ethanol comprises only about 2 percent of ethanol production, and although the U.S. Department of Energy (DOE) predicts cellulosic ethanol to greatly increase in the coming years, currently it is only in an experimental stage in the United States. Currently, ethanol is mostly made from sugar and starch crops, but with advances in technology, cellulosic biomass is increasingly used as ethanol feedstock (DOE 2013).

Ethanol is produced from corn (or other starch-based feedstocks) primarily by two methods: wet milling and dry milling. Historically, the majority of ethanol was produced by the wet milling process, but now the majority is produced by the dry milling process. The dry milling process is cheaper to implement, and has become more efficient in recent years (Rendleman and Shapouri 2007). The wastewater generated at ethanol production facilities is handled in a variety of ways. Dry milling facilities often combine the resulting evaporator condensate with other process wastewaters, such as equipment wash water, scrubber water, and boiler blowdown and anaerobically treat this wastewater using various types of digesters. Wet milling facilities often treat their steepwater condensate in anaerobic systems followed by aerobic polishing systems. Wet milling facilities may treat the stillage (or processed stillage) from the ethanol fermentation/distillation process separately or together with steepwater and/or wash water. Methane generated in anaerobic digesters is commonly collected and either flared or used as fuel in the ethanol production process (ERG 2006).

Available information was compiled from the industry on wastewater generation rates, which ranged from 1.25 gallons per gallon ethanol produced (for dry milling) to 10 gallons per gallon ethanol produced (for wet milling) (Ruocco 2006a; Ruocco 2006b; Merrick 1998; Donovan 1996; NRBP 2001). COD concentrations were found to be about 3 g/L (Ruocco 2006a; Merrick 1998; White and Johnson 2003). One hundred percent of plants were estimated to have onsite wastewater treatment, and the variables used to calculate percent wastewater treated anaerobically are presented in Table 7-13. A default MCF of 0.8 for anaerobic treatment was used to estimate the CH_4 produced from these on-site treatment systems. The amount of CH_4 recovered through the use of biomethanators was estimated, and a 99 percent destruction efficiency was used. Biomethanators are anaerobic reactors that use microorganisms under anaerobic conditions to reduce COD and organic acids and recover biogas from wastewater (ERG 2006). Methane emissions were then estimated as follows:

$$\text{Methane} = [\text{Production} \times \text{Flow} \times \text{COD} \times 3.785 \times ([\%\text{Plants}_o \times \%\text{WW}_{a,p} \times \%\text{COD}_p] + [\%\text{Plants}_a \times \%\text{WW}_{a,s} \times \%\text{COD}_s] + [\%\text{Plants}_t \times \%\text{WW}_{a,t} \times \%\text{COD}_s]) \times \text{B}_o \times \text{MCF} \times \%\ \text{Not Recovered}] + [\text{Production} \times \text{Flow} \times 3.785 \times \text{COD} \times ([\%\text{Plants}_o \times \%\text{WW}_{a,p} \times \%\text{COD}_p] + [\%\text{Plants}_a \times \%\text{WW}_{a,s} \times \%\text{COD}_s] + [\%\text{Plants}_t \times \%\text{WW}_{a,t} \times \%\text{COD}_s]) \times \text{B}_o \times \text{MCF} \times (\%\ \text{Recovered}) \times (1\text{-DE})] \times 1/10^9$$

where,

Production = Gallons ethanol produced (wet milling or dry milling)
Flow = Gallons wastewater generated per gallon ethanol produced
COD = COD concentration in influent (g/l)
3.785 = Conversion factor, gallons to liters
$\%\text{Plants}_o$ = Percent of plants with onsite treatment
$\%\text{WW}_{a,p}$ = Percent of wastewater treated anaerobically in primary treatment
$\%\text{COD}_p$ = Percent of COD entering primary treatment
$\%\text{Plants}_a$ = Percent of plants with anaerobic secondary treatment
$\%\text{Plants}_t$ = Percent of plants with other secondary treatment
$\%\text{WW}_{a,s}$ = Percent of wastewater treated anaerobically in anaerobic secondary treatment
$\%\text{WW}_{a,t}$ = Percent of wastewater treated anaerobically in other secondary treatment
$\%\text{COD}_s$ = Percent of COD entering secondary treatment
B_o = Maximum methane producing capacity (g CH_4/g COD)
MCF = Methane conversion factor
% Recovered = Percent of wastewater treated in system with emission recovery
% Not Recovered = 1 - percent of wastewater treated in system with emission recovery
DE = Destruction efficiency of recovery system
$1/10^9$ = Conversion factor, g to kt

A time series of CH_4 emissions for 1990 through 2016 was developed based on production data from the Renewable Fuels Association (Cooper 2017).

Petroleum Refining. Petroleum refining wastewater treatment operations have the potential to produce CH_4 emissions from anaerobic wastewater treatment. EPA's Office of Air and Radiation performed an Information Collection Request (ICR) for petroleum refineries in 2011.[8] Of the responding facilities, 23.6 percent reported using non-aerated surface impoundments or other biological treatment units, both of which have the potential to lead to anaerobic conditions (ERG 2013b). In addition, the wastewater generation rate was determined to be 26.4 gallons per barrel of finished product (ERG 2013b). An average COD value in the wastewater was estimated at 0.45 kg/m^3 (Benyahia et al. 2006). A default MCF of 0.3 was used for partially aerobic systems.

The equation used to calculate CH_4 generation at petroleum refining wastewater treatment systems is presented below:

$$\text{Methane} = \text{Flow} \times \text{COD} \times \%\text{TA} \times \text{B}_o \times \text{MCF}$$

where,

Flow = Annual flow treated through anaerobic treatment system (m^3/year)
COD = COD loading in wastewater entering anaerobic treatment system (kg/m^3)
%TA = Percent of wastewater treated anaerobically on site
B_o = Maximum methane producing potential of industrial wastewater (kg CH_4/kg COD)
MCF = Methane conversion factor

A time series of CH_4 emissions for 1990 through 2016 was developed based on production data from the EIA 2017.

Domestic Wastewater N_2O Emission Estimates

Nitrous oxide emissions from domestic wastewater (wastewater treatment) were estimated using the IPCC (2006) methodology and supplemented with IPCC (2014) methodology to include constructed wetland emissions, including

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[8] Available online at <https://www.epa.gov/stationary-sources-air-pollution/comprehensive-data-collected-petroleum-refining-sector>

calculations that take into account N removal with biosolids, non-consumption and industrial/commercial wastewater N, and emissions from advanced and constructed wetlands at centralized wastewater treatment plants:

- In the United States, a certain amount of N is removed with biosolids, which is applied to land, incinerated, or landfilled (N_{SLUDGE}). The value for N discharged into aquatic environments as effluent is reduced to account for the biosolids application.
- The *2006 IPCC Guidelines* use annual, per capita protein consumption (kg protein/person-year). For this Inventory, the amount of protein available to be consumed is estimated based on per capita annual food availability data and its protein content, and then that data is adjusted using a factor to account for the fraction of protein actually consumed.
- Small amounts of gaseous nitrogen oxides are formed as byproducts in the conversion of nitrate to N gas in anoxic biological treatment systems. Approximately 7 g N_2O is generated per capita per year if wastewater treatment includes intentional nitrification and denitrification (Scheehle and Doorn 2001). Analysis of the use of treatment systems in the United States that include denitrification has shown a significant increase in the time period between 2004 and 2012, from serving populations totaling 2.4 million people to 21.3 million people (EPA 2004 and EPA 2012). This is consistent with efforts throughout the United States to improve nutrient removal at centralized treatment systems in response to specific water quality concerns. Based on an emission factor of 7 g per capita per year, and data from CWNS 2004, 2008, and 2012, approximately 21.2 metric tons of additional N_2O may have been emitted via denitrification in 2004, while about 186 metric tons may have been emitted via denitrification in both 2008 and 2012. Similar analyses were completed for each year in the Inventory using data from CWNS on the amount of wastewater in centralized systems treated in denitrification units. Plants without intentional nitrification or denitrification are assumed to generate 3.2 g N_2O per capita per year.
- Constructed wetlands may be used as the sole treatment unit at a centralized wastewater treatment plant or may serve as tertiary treatment after simple settling and biological treatment. Emissions from all constructed wetland systems were included in the estimates of emissions from centralized wastewater treatment plant processes and effluent from these plants. The emission factor of 0.0013 kg N_2O-N/kg N produced for constructed wetlands is from IPCC (2014).
- N_2O emissions from wastewater treatment plants are estimated, and as such, the N associated with these emissions is subtracted from the amount of N estimated to be discharged into aquatic environments as effluent, consistent with the *2006 IPCC Guidelines*.

Nitrous oxide emissions from domestic wastewater were estimated using the following methodology:

$$N_2O_{TOTAL} = N_2O_{PLANT} + N_2O_{EFFLUENT}$$

$$N_2O_{PLANT} = N_2O_{NIT/DENIT} + N_2O_{WOUT\ NIT/DENIT} + N_2O_{CW\ ONLY} + N_2O_{CW\ TERTIARY}$$

$$N_2O_{NIT/DENIT} = [(US_{POPND}) \times EF_2 \times F_{IND\text{-}COM}] \times 1/10^9$$

$$N_2O_{WOUT\ NIT/DENIT} = \{[(US_{POP} \times WWTP) - US_{POPND} - US_{POPCW}] \times 10^6 \times F_{IND\text{-}COM} \times EF_1\} \times 1/10^9$$

$$N_2O_{CW\ ONLY} = \{[(US_{POPCW} \times 10^6 \times \text{Protein} \times F_{NPR} \times F_{NON\text{-}CON} \times F_{IND\text{-}COM}) \times EF_4] \times 44/28\} \times 1/10^6$$

$$N_2O_{CW\ TERTIARY} = \{[(N_{CW,INF} \times \text{POTW\_flow\_CW} \times 3.79 \times 365.25) \times EF_4] \times 44/28\} \times 1/10^6$$

$$N_2O_{EFFLUENT} = [(US_{POP} \times WWTP \times \text{Protein} \times F_{NPR} \times F_{NON\text{-}CON} \times F_{IND\text{-}COM}) - N_{SLUDGE} - (N_2O_{PLANT} \times 10^6 \times 28/44)] \times EF_3 \times 44/28 \times 1/10^6$$

where,

N_2O_{TOTAL} = Annual emissions of N_2O (kt)
N_2O_{PLANT} = N_2O emissions from centralized wastewater treatment plants (kt)
$N_2O_{NIT/DENIT}$ = N_2O emissions from centralized wastewater treatment plants with nitrification/denitrification (kt)
$N_2O_{WOUT\ NIT/DENIT}$ = N_2O emissions from centralized wastewater treatment plants without nitrification/denitrification (kt)
$N_2O_{CW\ ONLY}$ = N_2O emissions from centralized wastewater treatment plants with constructed wetlands only (kt)

$N_2O_{CW\ TERTIARY}$ = N_2O emissions from centralized wastewater treatment plants with constructed wetlands used as tertiary treatment (kt)
$N_2O_{EFFLUENT}$ = N_2O emissions from wastewater effluent discharged to aquatic environments (kt)
US_{POP} = U.S. population
US_{POPND} = U.S. population that is served by biological denitrification
US_{POPCW} = U.S. population that is served by only constructed wetland systems
WWTP = Fraction of population using WWTP (as opposed to septic systems)
POTW_flow_CW = Wastewater flow to POTWs that use constructed wetlands as tertiary treatment (MGD)
EF_1 = Emission factor – plants without intentional denitrification
EF_2 = Emission factor – plant with intentional nitrification or denitrification
Protein = Annual per capita protein consumption (kg/person/year)
$N_{CW,INF}$ = Influent nitrogen concentration to constructed wetlands used as tertiary treatment (mg/L)
F_{NPR} = Fraction of N in protein (kg N/kg protein)
$F_{NON\text{-}CON}$ = Factor for non-consumed protein added to wastewater
$F_{IND\text{-}COM}$ = Factor for industrial and commercial co-discharged protein into the sewer
N_{SLUDGE} = N removed with sludge, kg N/year
EF_3 = Emission factor (kg N_2O -N/kg sewage-N produced) – from effluent
EF_4 = Emission factor (kg N_2O -N/kg N produced) – constructed wetlands
3.79 = Conversion factor, liters to gallons
44/28 = Molecular weight ratio of N_2O to N_2
$1/10^6$ = Conversion factor, kg to Gg
$1/10^9$ = Conversion factor, g to Gg

U.S. population data were taken from the U.S. Census Bureau International Database (U.S. Census Bureau 2017) and include the populations of the United States, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the U.S. Virgin Islands. The fraction of the U.S. population using wastewater treatment plants is based on data from the 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, 2007, 2009, 2011, 2013, and 2015 *American Housing Survey* (U.S. Census Bureau 2015). Data for intervening years were obtained by linear interpolation and 2016 was forecasted using 1990 to 2015 data. The emission factor (EF_1) used to estimate emissions from wastewater treatment for plants without intentional nitrification or denitrification was taken from IPCC (2006), while the emission factor (EF_2) used to estimate emissions from wastewater treatment for plants with intentional nitrification or denitrification was taken from Scheehle and Doorn (2001). The emission factor (EF_4) used to estimate emissions from surface flow constructed wetlands (0.0013 kg N_2O -N/kg N produced) was taken from IPCC (2014). Data on annual per capita protein intake were provided by the U.S. Department of Agriculture Economic Research Service (USDA 2017b) and FAO (2017b). Protein consumption data was used directly from USDA for 1990 to 2010 and 2011 through 2013 was calculated using FAO data and a scaling factor. 2014 through 2016 were extrapolated from data for 1990 through 2013. An emission factor to estimate emissions from effluent (EF_3) has not been specifically estimated for the United States, thus the default IPCC value (0.005 kg N_2O-N/kg sewage-N produced) was applied (IPCC 2006). The fraction of N in protein (0.16 kg N/kg protein) was also obtained from IPCC (2006). The factor for non-consumed protein (1.2) and the factor for industrial and commercial co-discharged protein (1.25) were obtained from IPCC (2006). The amount of nitrogen removed by denitrification systems was taken from EPA (2008a), while the population served by denitrification systems was estimated from Clean Watersheds Needs Survey (EPA 1992, 1996, 2000, 2004, 2008b, and 2012). Sludge generation was obtained from EPA (1999) for 1988, 1996, and 1998 and from Beecher et al. (2007) for 2004. Intervening years were interpolated, and estimates for 2005 through 2016 were forecasted from the rest of the time series. The influent nitrogen concentration to constructed wetlands used as tertiary treatment (25 mg/L) was obtained from Metcalf & Eddy (2014). An estimate for the N removed as sludge (N_{SLUDGE}) was obtained by determining the amount of sludge disposed by incineration, by land application (agriculture or other), through surface disposal, in landfills, or through ocean dumping (EPA 1993b; Beecher et al. 2007; McFarland 2001; EPA 1999). In 2016, 295 kt N was removed with sludge. Table 7-15 presents the data for U.S. population, population served by biological denitrification, population served by wastewater treatment plants, available protein, protein consumed, and nitrogen removed with sludge.

Table 7-15: U.S. Population (Millions), Population Served by Biological Denitrification (Millions), Fraction of Population Served by Wastewater Treatment (percent), Available Protein (kg/person-year), Protein Consumed (kg/person-year), and Nitrogen Removed with Sludge (kt-N/year)

Year	Population	Population$_{ND}$	WWTP Population	Available Protein	Protein Consumed	N Removed with Sludge
1990	253	2.0	75.6	43.1	33.2	214.2
2005	300	7.1	78.8	44.9	34.7	261.1
2012	318	21.3	81.0	43.3	33.4	282.6
2013	320	19.8	81.4	43.3	33.4	285.6
2014	323	20.8	80.8	44.8	34.6	288.7
2015	325	21.8	80.2	44.8	34.5	291.8
2016	328	22.8	81.4	44.7	34.5	294.8

Sources: Population: U.S. Census Bureau (2017); Population$_{ND}$: EPA (1992), EPA (1996), EPA (2000), EPA (2004), EPA (2008b), EPA (2012); WWTP Population: U.S. Census Bureau (2015); Available Protein: USDA (2017b); N Removed with sludge: Beecher et al. (2007), McFarland (2001), EPA (1999), EPA (1993c).

Uncertainty and Time-Series Consistency

The overall uncertainty associated with both the 2016 CH_4 and N_2O emission estimates from wastewater treatment and discharge was calculated using the *2006 IPCC Guidelines* Approach 2 methodology (IPCC 2006). Uncertainty associated with the parameters used to estimate CH_4 emissions include that of numerous input variables used to model emissions from domestic wastewater, and wastewater from pulp and paper manufacturing, meat and poultry processing, fruits and vegetable processing, ethanol production, and petroleum refining. Uncertainty associated with the parameters used to estimate N_2O emissions include that of biosolids disposal, total U.S. population, average protein consumed per person, fraction of N in protein, non-consumption nitrogen factor, emission factors per capita and per mass of sewage-N, and for the percentage of total population using centralized wastewater treatment plants. Uncertainty associated with constructed wetlands parameters including U.S. population served by constructed wetlands, and emission and conversion factors are from IPCC (2014), whereas uncertainty associated with POTW flow to constructed wetlands and influent BOD and nitrogen concentrations were based on expert judgment.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 7-16. Methane emissions from wastewater treatment were estimated to be between 11.0 and 18.0 MMT CO_2 Eq. at the 95 percent confidence level (or in 19 out of 20 Monte Carlo Stochastic Simulations). This indicates a range of approximately 26 percent below to 22 percent above the 2016 emissions estimate of 14.8 MMT CO_2 Eq. Nitrous oxide emissions from wastewater treatment were estimated to be between 1.3 and 10.5 MMT CO_2 Eq., which indicates a range of approximately 75 percent below to 112 percent above the 2016 emissions estimate of 5.0 MMT CO_2 Eq.

Table 7-16: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Wastewater Treatment (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Wastewater Treatment	**CH_4**	**14.8**	**11.0**	**18.0**	**-26%**	**+22%**
Domestic	CH_4	8.9	6.6	11.2	-26%	+26%
Industrial	CH_4	5.9	3.1	8.6	-48%	+45%
Wastewater Treatment	**N_2O**	**5.0**	**1.3**	**10.5**	**-75%**	**+112%**

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

General QA/QC procedures were applied to activity data, documentation, and emission calculations consistent with the U.S. QA/QC plan, which is in accordance with Vol. 1 Chapter 6 of *2006 IPCC Guidelines* (see Annex 8 for more details). This effort included a general or Tier 1 analysis, including the following checks:

- Checked for transcription errors in data input;
- Ensured references were specified for all activity data used in the calculations;
- Checked a sample of each emission calculation used for the source category;
- Checked that parameter and emission units were correctly recorded and that appropriate conversion factors were used;
- Checked for temporal consistency in time series input data for each portion of the source category;
- Confirmed that estimates were calculated and reported for all portions of the source category and for all years;
- Investigated data gaps that affected trends of emissions estimates; and
- Compared estimates to previous estimates to identify significant changes.

All transcription errors identified were corrected and documented. The QA/QC analysis did not reveal any systemic inaccuracies or incorrect input values.

Recalculations Discussion

Population data were updated to reflect revised U.S. Census Bureau datasets which resulted in changes to 2010 through 2015 values (U.S. Census Bureau 2017). In addition, the 2015 *American Housing Survey* became available which resulted in updated values for the percent of wastewater treatment collected versus treatment onsite for both 2014 and 2015 (U.S. Census Bureau 2015).

EPA evaluated pulp and paper wastewater generation rates in the *2016 American Forest & Paper Association Sustainability Report* based on the National Council of Air and Stream Improvement's (NCASI) recommendation, and determined updates to current Inventory data were appropriate. EPA updated values for 2004, 2006, 2008, 2010, 2012, and 2014 with data provided in the 2016 report. EPA also used the *2014 AF&PA Sustainability Report* to update the 1995, 2000, and 2002 values to more accurately reflect industry data. Data for intervening years were obtained by linear interpolation and the years 2015 and 2016 were forecasted from the rest of the time series. This change resulted in updated values for pulp and paper wastewater generation rates (m^3/ton) for 1995 through 2015.

Planned Improvements

EPA will continue to investigate the following improvements to the wastewater emissions estimates in the Inventory*:*

- Continue working with the NCASI to determine if there are sufficient data available to update the estimates of organic loading in pulp and paper wastewaters treated on-site;
- Investigate updated sources of activity data for wastewater treatment system type to distinguish between aerobic, anaerobic, and other systems with the potential to generate CH_4. This includes re-evaluating a methodology that was developed so that the 2008 and 2012 CWNS data could be used in estimating emissions from constructed wetlands to determine if it could be extended to all types of systems; and
- Continue reviewing other industrial wastewater treatment sources for those industries believed to discharge significant loads of BOD or COD, including dairy processing and brewery wastewater.

In addition, EPA will continue to monitor potential sources for updating Inventory data, including:

- WEF biosolid data as a potential source of digester, sludge, and biogas data from POTWs;
- Reports based on international research and other countries' inventory submissions to inform potential updates to the Inventory's emission factors, methodologies, or included industries;
- Research by groups such as the Water Environment Research Federation (WERF) on emissions from various types of municipal treatment systems, country-specific N_2O emission factors, and flare efficiencies;

- Data collected by WERF that indicate septic soil systems are a source of N_2O for the potential development of appropriate emission factors for septic system N_2O emissions;
- Sources of data for development of a country-specific methodology for N_2O emissions associated with on-site industrial wastewater treatment operations, including the appropriateness of using IPCC's default factor for domestic wastewater (0.005 kg N_2O-N/kg N);
- Sources of data for updating the factor for industrial and commercial co-discharged protein to determine if the IPCC factor currently used (1.25) is underestimating the contribution of industrial wastewater to N_2O emissions;
- Additional data sources for improving the uncertainty of the estimate of N entering municipal treatment systems; and
- Data to update the value used for N content of sludge, the amount of sludge produced, and sludge disposal practices, along with increasing the transparency of the fate of sludge produced in wastewater treatment.

A refinement of the *2006 IPCC Guidelines* is currently underway to incorporate abundant new scientific and empirical knowledge published since 2006 which the IPCC should take into account, particularly with respect to data for emission factor development. For wastewater treatment, this refinement includes a review of methane and nitrous oxide emission factors, and an assessment of adding methodologies to account for nitrous oxide emissions from both domestic and industrial wastewater. EPA will continue to monitor the status of this refinement for potential updates to the wastewater inventory methodology.

These planned improvements were described in greater detail in the previous Inventory report; please see Section 7.2 of the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2015*.

7.3 Composting (CRF Source Category 5B1)

Composting of organic waste, such as food waste, garden (yard) and park waste, and wastewater treatment sludge and/or biosolids, is common in the United States. Advantages of composting include reduced volume of the waste, stabilization of the waste, and destruction of pathogens in the waste. The end products of composting, depending on its quality, can be recycled as a fertilizer and soil amendment, or be disposed of in a landfill.

Composting is an aerobic process and a large fraction of the degradable organic carbon in the waste material is converted into carbon dioxide (CO_2). Methane (CH_4) is formed in anaerobic sections of the compost, which are created when there is excessive moisture or inadequate aeration (or mixing) of the compost pile. This CH_4 is then oxidized to a large extent in the aerobic sections of the compost. The estimated CH_4 released into the atmosphere ranges from less than 1 percent to a few percent of the initial C content in the material (IPCC 2006). Depending on how well the compost pile is managed, nitrous oxide (N_2O) emissions can be produced. The formation of N_2O depends on the initial nitrogen content of the material and is mostly due to nitrogen oxide (NO_x) denitrification during the later composting stages. Emissions vary and range from less than 0.5 percent to 5 percent of the initial nitrogen content of the material (IPCC 2006). Animal manures are typically expected to generate more N_2O than, for example, yard waste, however data are limited.

From 1990 to 2016, the amount of waste composted in the United States increased from 3,810 kt to 21,163 kt. There was some fluctuation in the amount of waste composted between 2006 to 2009. Since then, the annual quantity has increased and is now at an all-time high for the Inventory time series (see Table 7-19). A peak of 20,049 kt composted was observed in 2008, followed by a steep drop the following year to 18,824 kt composted, presumably driven by the economic crisis. Since then, the amount of waste composted has gradually increased, and when comparing 2010 to 2016, a 16 percent increase in waste composted is observed. Emissions of CH_4 and N_2O from composting from 2010 to 2015 have increased by the same percentage. In 2016, CH_4 emissions from composting (see Table 7-17 and Table 7-18) were 2.1 MMT CO_2 Eq. (85 kt), and N_2O emissions from composting were 1.9 MMT CO_2 Eq. (6 kt). The wastes composted primarily include yard trimmings (grass, leaves, and tree and brush trimmings) and food scraps from the residential and commercial sectors (such as grocery stores; restaurants; and school, business, and factory cafeterias). The composted waste quantities reported here do not include backyard composting or agricultural composting.

The growth in composting since the 1990s and specifically over the past decade is attributable primarily to the following factors: (1) the enactment of legislation by state and local governments that discouraged the disposal of yard trimmings in landfills, (2) yard trimming collection and yard trimming drop off sites provided by local solid waste management districts/divisions, (3) an increased awareness of the environmental benefits of composting, and (4) loans or grant programs to establish or expand composting infrastructure. Most bans or diversion laws on the disposal of yard trimmings were initiated in the early 1990s by state or local governments (U.S. Composting Council 2010). California, for example, enacted a waste diversion law for organics including yard trimmings and food scraps in 1999 (AB939) that required jurisdictions to divert 50 percent of the waste stream by 2000, or be subjected to fines. By 2010, 25 states, representing about 50 percent of the nation's population, had enacted such legislation (ILSR 2014; BioCycle 2010). There are many more initiatives at the metro and municipal level across the United States. More than 3,280 composting facilities exist in the United States with most (71 percent) composting yard trimmings only (ISLR 2014).

Table 7-17: CH_4 and N_2O Emissions from Composting (MMT CO_2 Eq.)

Activity	1990	2005	2012	2013	2014	2015	2016
CH_4	0.4	1.9	1.9	2.0	2.1	2.1	2.1
N_2O	0.3	1.7	1.7	1.8	1.9	1.9	1.9
Total	**0.7**	**3.5**	**3.7**	**3.9**	**4.0**	**4.0**	**4.0**

Table 7-18: CH_4 and N_2O Emissions from Composting (kt)

Activity	1990	2005	2012	2013	2014	2015	2016
CH_4	15.2	74.6	77.4	81.4	83.5	84.2	84.7
N_2O	1.1	5.6	5.8	6.1	6.3	6.3	6.3

Methodology

Methane and N_2O emissions from composting depend on factors such as the type of waste composted, the amount and type of supporting material (such as wood chips and peat) used, temperature, moisture content (e.g., wet and fluid versus dry and crumbly), and aeration during the composting process.

The emissions shown in Table 7-17 and Table 7-18 were estimated using the IPCC default (Tier 1) methodology (IPCC 2006), which is the product of an emission factor and the mass of organic waste composted (note: no CH_4 recovery is expected to occur at composting operations in the emission estimates presented):

$$E_i = M \times EF_i$$

where,

E_i = CH_4 or N_2O emissions from composting, kt CH_4 or N_2O,
M = mass of organic waste composted in kt,
EF_i = emission factor for composting, 4 t CH_4/kt of waste treated (wet basis) and 0.3 t N_2O/kt of waste treated (wet basis) (IPCC 2006), and
i = designates either CH_4 or N_2O.

Estimates of the quantity of waste composted (M) are presented in Table 7-19 for select years. Estimates of the quantity composted for 1990, 2005, 2010, and 2012 to 2014 were taken from EPA's *Advancing Sustainable Materials Management: Facts and Figures* 2014 (EPA 2016); the estimate of the quantity composted for 2011 was taken from EPA's *Municipal Solid Waste In The United States: 2012 Facts and Figures* (EPA 2014); estimates of the quantity composted for 2015 and 2016 were extrapolated using the 2014 quantity composted and a ratio of the U.S. population growth between 2014 and 2015, and 2015 to 2016 (U.S. Census Bureau 2016 and 2017).

Table 7-19: U.S. Waste Composted (kt)

Activity	1990	2005	2012	2013	2014	2015	2016
Waste Composted	3,810	18,643	19,351	20,358	20,884	21,052	21,163

Uncertainty and Time-Series Consistency

The estimated uncertainty from the *2006 IPCC Guidelines* is ±50 percent for the Approach 1 methodology. Emissions from composting in 2015 were estimated to be between 2.0 and 6.0 MMT CO_2 Eq., which indicates a range of 50 percent below to 50 percent above the actual 2016 emission estimate of 4.0 MMT CO_2 Eq. (see Table 7-20).

Table 7-20: Approach 1 Quantitative Uncertainty Estimates for Emissions from Composting (MMT CO_2 Eq. and Percent)

Source	Gas	2016 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Composting	CH_4, N_2O	4.0	2.0	6.0	-50%	+50%

QA/QC and Verification

General QA/QC procedures were applied to data gathering and input, documentation, and calculations consistent with the U.S. QA/QC plan, which is in accordance with Vol. 1 Chapter 6 of *2006 IPCC Guidelines* (see Annex 8 for more details).

Recalculations Discussion

No recalculations were made in this Inventory year. The composting estimates will be updated pending the release of a new EPA *Advancing Sustainable Materials Management: Facts and Figures* report.

Planned Improvements

For future Inventories, additional efforts will be made to improve the estimates of CH_4 and N_2O emissions from composting. For example, a literature search on emission factors and composting systems and management techniques has been completed and will be documented in a technical memorandum for the 1990 through 2017 Inventory. The purpose of this literature review was to compile all published emission factors specific to various composting systems and composted materials. This information will be used to determine whether the emission factors used in the current methodology should be revised, or expanded to account for geographical differences and/or differences in composting systems used. For example, outdoor composting processes in arid regions typically require the addition of moisture compared to similar composting processes in wetter climates. Additionally, composting systems that primarily compost food waste may generate CH_4 at different rates than those that compost yard trimmings because the food waste may have a higher moisture content and more readily degradable material. Further cooperation with estimating emissions in cooperation with the LULUCF Settlements section will also be investigated.

7.4 Waste Incineration (CRF Source Category 5C1)

As stated earlier in this chapter, carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) emissions from the incineration of waste are accounted for in the Energy sector rather than in the Waste sector because almost all incineration of municipal solid waste (MSW) in the United States occurs at waste-to-energy facilities where useful energy is recovered. Similarly, the Energy sector also includes an estimate of emissions from burning waste tires and hazardous industrial waste, because virtually all of the combustion occurs in industrial and utility boilers that recover energy. The incineration of waste in the United States in 2016 resulted in 11.0 MMT CO_2 Eq., over half of which (5.9 MMT CO_2 Eq.) is attributable to the combustion of plastics. For more details on emissions from the incineration of waste, see Section 3.3 of the Energy chapter.

Additional sources of emissions from waste incineration include non-hazardous industrial waste incineration and medical waste incineration. As described in Annex 5 of this report, data are not readily available for these sources and emission estimates are not provided. An analysis of the likely level of emissions was conducted based on a 2009 study of hospital/ medical/ infectious waste incinerator (HMIWI) facilities in the United States (RTI 2009). Based on that study's information of waste throughput and an analysis of the fossil-based composition of the waste, it was determined that annual greenhouse gas emissions for medical waste incineration would be below 500 kt CO_2 Eq. per year and considered insignificant for the purposes of Inventory reporting under the UNFCCC. More information on this analysis is provided in Annex 5.

7.5 Waste Sources of Indirect Greenhouse Gases

In addition to the main greenhouse gases addressed above, waste generating and handling processes are also sources of indirect greenhouse gas emissions. Total emissions of nitrogen oxides (NO_x), carbon monoxide (CO), and non-CH_4 volatile organic compounds (NMVOCs) from waste sources for the years 1990 through 2016 are provided in Table 7-21.

Table 7-21: Emissions of NO_x, CO, and NMVOC from Waste (kt)

Gas/Source	1990		2005		2012	2013	2014	2015	2016
NO_x	**+**		**2**		**2**	**2**	**2**	**2**	**2**
Landfills	+		2		2	2	2	2	2
Wastewater Treatment	+		0		0	0	0	0	0
Miscellaneous[a]	+		0		0	0	0	0	0
CO	**1**		**7**		**6**	**8**	**9**	**9**	**9**
Landfills	1		6		6	7	8	8	8
Wastewater Treatment	+		+		+	1	1	1	1
Miscellaneous[a]	+		0		0	0	0	0	0
NMVOCs	**673**		**114**		**45**	**51**	**57**	**57**	**57**
Wastewater Treatment	57		49		19	22	25	25	25
Miscellaneous[a]	557		43		17	19	22	22	22
Landfills	58		22		8	10	11	11	11

+ Does not exceed 0.5 kt.

[a] Miscellaneous includes TSDFs (Treatment, Storage, and Disposal Facilities under the Resource Conservation and Recovery Act [42 U.S.C. § 6924, SWDA § 3004]) and other waste categories.

Note: Totals may not sum due to independent rounding.

Methodology

Emission estimates for 1990 through 2016 were obtained from data published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site (EPA 2016), and disaggregated based on EPA (2003). Emission estimates for 2012 and 2013 for non-electric generating units (EGU) were updated to the most recent available data in EPA (2016). Emission estimates for 2012 and 2013 for non-mobile sources are recalculated emissions by interpolation from 2016 in EPA (2016). Emission estimates of these gases were provided by sector, using a "top down" estimating procedure—emissions were calculated either for individual sources or for many sources combined, using basic activity data (e.g., the amount of raw material processed) as an indicator of emissions.

National activity data were collected for individual categories from various agencies. Depending on the category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

Uncertainty and Time-Series Consistency

No quantitative estimates of uncertainty were calculated for this source category. Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2016. Details on the emission trends through time are described in more detail in the Methodology section, above.