

Annexes to the Inventory of U.S. Greenhouse Gas Emissions and Sinks

The following nine annexes provide additional information related to the material presented in the main body of this report.

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ANNEX 1 Key Category Analysis

The EPA has identified national key categories based on the estimates compiled in this report to inform prioritization of improvements to make the best use of available resources. Key categories are “... inventory categories which individually, or as a group of categories (for which a common method, emission factor and activity data are applied) are prioritized within the national inventory system because their estimates have a significant influence on a country’s total inventory of greenhouse gases in terms of the absolute level, the trend, or the level of uncertainty in emissions or removals. Whenever the term key category is used, it includes both source and sink categories” (IPCC 2006; IPCC 2019). By definition, key categories are sources or sinks that have the greatest contribution to the absolute overall level of national emissions and removals in any of the years covered by the time series. In addition, when an entire time series of emission and removal estimates is prepared, a determination of key categories must also account for the influence of the trends of individual categories. Therefore, a trend assessment is conducted to identify source and sink categories for that may not be large enough to be identified by the level assessment, but whose trend contributes significantly to the overall *Inventory* trend (IPCC 2019). Finally, a qualitative evaluation of key categories should be performed, in order to capture any key categories that were not identified in either of the quantitative analyses but can be considered key because of the unique country-specific estimation methods.

In sum, this key category analysis includes:

- Approach 1 (including both level and trend assessments);
- Approach 2 (including both level and trend assessments, and incorporating uncertainty analysis); and
- Qualitative approach.

This Annex presents an analysis of key categories, both for sources only and also for sources and sinks (i.e., including Land Use, Land-Use Change and Forestry LULUCF); discusses Approach 1, Approach 2, and qualitative approaches used to identify key categories for the United States; provides level and trend assessment equations; and provides a brief evaluation of IPCC’s quantitative methodologies for defining key categories.

Identification approach. This report’s key category analysis were identified using the IPCC suggested aggregation level as the basis for the analysis, but in some cases the disaggregation does differ. Differences arise from implementation of special considerations identified in Table 4.1 in Volume 1, Chapter 4, of the *2006 IPCC Guidelines* and its *Refinement*. As stated in section 4.2 in Volume 1, Chapter 4 of the *2006 IPCC Guidelines*, “...countries using Approach 2 will probably choose the same level of aggregation that was used for the uncertainty analysis.” In order to retain consistency in the categorization with the uncertainty analysis, the aggregation level for this analysis (i.e. Approach 1, 2 etc.) does reflect some but not all special considerations such as disaggregating for significant subcategories (e.g., for 1.A.1, 3.A, 3.B) and fuel types for the following categories: Fuel Combustion Activities—Water-borne Navigation (1.A.3.d), Fuel Combustion Activities—Other Sectors (1.A.4), Fugitive Emissions from Fuels—Oil (1.B.2.a) and Natural Gas (1.B.2.b), Petrochemical and Carbon Black Production (2.B.8), Direct and Indirect N₂O Emissions (3.D.1 and 3.D.2), land use categories (4.A, 4.B, 4.C, 4.D, 4.E, and 4.F), Solid Waste Disposal (5.A) and Wastewater (5.D). Most other differences stem from additional disaggregation to subcategories consistent with the uncertainty analysis, including within Fuel Combustion Activities—Other Sectors (1.A.4.a Commercial/Institutional and 1.A.4.b Residential), Fossil Fuel Combustion—Non-Specified Stationary (1.A.5.a Incineration of Waste, Non-Energy Use of Fossil Fuels, and U.S. Territories) and Mobile (1.A.5.b Military), Biomass Burning (4.A(V) Forest Fires and 4.C(V) Grass Fires), and Biological Treatment of Solid Waste (5.B.1 Composting and 5.B.2 Anaerobic Digestion at Biogas Facilities). As EPA disaggregates the uncertainty analysis, it will reflect these special considerations in aggregation levels of the key category analysis (e.g., this year EPA disaggregated manure management further into cattle, swine and other and disaggregated harvested wood products (HWP) from other forest land remaining forest land carbon stock change). Similarly, the UN reporting tools also identify key categories using an Approach 1 analysis based largely on the default disaggregation approach provided in Table 4.1 while including special considerations for further disaggregation by fuel type for fuel combustion categories. That said, the identification of key categories from the tool will be largely consistent with those identified in this annex. Differences will be due to the same reasons elaborated above. It is important to

note that a key category analysis can be sensitive to the definitions of the source and sink categories. The EPA has attempted to define source and sink categories by the conventions that would best inform improvement prioritization and still allow comparison with other international key category analyses, so still maintaining the category definitions that constitute how the emissions estimates were calculated for this report. As such, some of the category or subcategory names used in the key category analysis may differ from the names used in the main body of the report.

The Approach 1 level assessment uses a 95 percent cumulative emissions threshold to identify key categories, consistent with the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) and the *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019). The Approach 2 level assessment provides additional insight into why certain source and sink categories are considered key, and how to prioritize inventory improvements to reduce overall uncertainties. The key categories identified by the Approach 2 level assessment may differ from those identified by the Approach 1 assessment. The final set of key categories includes all source and sink categories identified as key by either the Approach 1 or the Approach 2 assessment (as noted in Table 1-4 of the Introduction Chapter).

The Approach 1 trend assessment is the percentage change in total inventory estimate from the base year to the current year. Thus, the source or sink category trend assessment will be large if the source or sink category represents a large percentage of emissions and/or has a trend that is quite different from the overall inventory trend. All categories that fall within that cumulative 95 percent are considered key categories. For Approach 2, the trend assessment for each category from Approach 1 is multiplied by its percent of relative uncertainty. If the uncertainty reported is asymmetrical, the larger uncertainty is used. All categories that fall within that cumulative 90 percent are considered key categories. When source and sink categories are sorted in decreasing order of this calculation, those that fall at the top of the list and cumulatively account for 90 percent of emissions are considered key categories. The final set of key categories includes all source and sink categories identified as key by either the Approach 1 or the Approach 2 assessment, keeping in mind that the two assessments are not mutually exclusive.

Finally, in addition to conducting Approach 1 and 2 level and trend assessments, a qualitative assessment of categories, as described in the *2006 IPCC Guidelines* and the *2019 Refinement to the 2006 IPCC Guidelines*, was conducted to capture any key categories that were not identified by either quantitative method. For this *Inventory*, no additional categories were identified using criteria recommend by IPCC, but EPA continues to review its qualitative assessment on an annual basis.

Analysis and Findings. Documentation of the analyses, including individual and cumulative percentage contributions from key categories, are available as described below.

- **Level Assessment:** Table KCA-1 through Table KCA-4 contain the 1990 and 2023 level assessments for both with and without LULUCF sources and sinks and contain further detail on where each source falls within the analysis. In the tables, Approach 1 key categories are shaded dark gray. Additional key categories identified by the Approach 2 assessment are shaded light gray. Tables are available in electronic format online on the U.S. EPA's web site at <https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2023>.
- **Trend Assessment:** Table KCA-5 through Table KCA-6 contain the trend assessments with and without LULUCF sources and sinks and contain further detail on where each source falls within the analysis. In the tables, similar to the Approach 1 and 2 level assessment tables, the Approach 1 trend assessment key categories are shaded dark gray. Additional key categories identified by the Approach 2 assessment are shaded light gray. Tables are available in electronic format online on the U.S. EPA's web site at <https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2023>.

Table A-1 provides a complete listing of categories by sector/source/sink category code, along with notations on the criteria used in identifying key categories, excluding the LULUCF sources and sinks. Similarly, Table A-2 provides a complete listing of source and sink categories by code/sector, along with notations on the criteria used in identifying key categories, including LULUCF sources and sinks. The notations refer specifically to the year(s) in the *Inventory* time series (i.e., 1990 to 2023) in which each source or sink category reached the threshold for being a key category based on either an Approach 1 or Approach 2 level assessment.

Table A-1: U.S. Greenhouse Gas Inventory Source Categories without LULUCF

Source/Sink Category Code	Greenhouse Gas	1990 Estimate (MMT CO ₂ Eq.)	2023 Estimate (MMT CO ₂ Eq.)	Key Category	ID Criteria ^a	Level in which year(s)? ^b
Energy						
1.A.3.b Transportation: Road	CO ₂	1,157.4	1,455.3	•	L ₁ T ₁ L ₂ T ₂	1990, 2023
1.A.1 Stationary Combustion – Natural Gas - Electricity Generation	CO ₂	175.4	704.5	•	L ₁ T ₁ L ₂ T ₂	1990, 2023
1.A.1 Stationary Combustion - Coal - Electricity Generation	CO ₂	1,546.5	694.6	•	L ₁ T ₁ L ₂ T ₂	1990, 2023
1.A.2 Stationary Combustion - Natural Gas - Industrial	CO ₂	407.4	514.8	•	L ₁ T ₁ L ₂ T ₂	1990, 2023
1.A.4.b Stationary Combustion - Natural Gas - Residential	CO ₂	237.8	247.5	•	L ₁ T ₁ L ₂	1990, 2023
1.A.2 Stationary Combustion - Oil - Industrial	CO ₂	311.2	241.3	•	L ₁ T ₁ L ₂ T ₂	1990, 2023
1.A.4.a Stationary Combustion - Natural Gas - Commercial	CO ₂	142.0	182.8	•	L ₁ T ₁ L ₂ T ₂	1990, 2023
1.A.3.a Transportation: Aviation	CO ₂	187.2	179.7	•	L ₁ L ₂	1990, 2023
1.A.5 Non-Energy Use of Fuels	CO ₂	99.1	107.1	•	L ₁ L ₂ T ₂	1990, 2023
1.A.3.e Transportation: Other	CO ₂	36.0	71.3	•	L ₁ T ₁ T ₂	1990, 2023
1.A.4.a Stationary Combustion - Oil - Commercial	CO ₂	74.3	60.2	•	L ₁ T ₁	1990, 2023 ₁
1.A.4.b Stationary Combustion - Oil - Residential	CO ₂	97.8	59.6	•	L ₁ T ₁ T ₂	1990, 2023
1.B.2 Natural Gas Systems	CO ₂	32.5	37.7	•	L ₁ L ₂	1990, 2023
1.A.2 Stationary Combustion - Coal - Industrial	CO ₂	157.8	36.5	•	L ₁ T ₁ L ₂ T ₂	1990, 2023
1.A.3.d Transportation: Domestic Navigation	CO ₂	39.3	34.6	•	L ₁	1990, 2023
1.A.3.c Transportation: Railways	CO ₂	35.5	30.9	•	L ₁	1990 ₁ , 2023 ₁
1.B.2 Petroleum Systems	CO ₂	9.6	23.3	•	L ₁ T ₁ L ₂ T ₂	2023
1.A.5 Stationary Combustion - Oil - U.S. Territories	CO ₂	19.5	17.9	•	L ₁	1990
1.A.1 Stationary Combustion - Oil - Electricity Generation	CO ₂	97.5	14.7	•	L ₁ T ₁ L ₂ T ₂	1990
5.C.1 Incineration of Waste	CO ₂	12.9	12.4			
1.A.5.b Transportation: Military	CO ₂	13.6	4.6	•	T ₁	
1.A.5 Stationary Combustion - Natural Gas - U.S. Territories	CO ₂	0.0	4.5			

1.A.5 Stationary Combustion - Coal - U.S. Territories	CO ₂	0.5	2.5			
1.B.1 Coal Mining	CO ₂	4.6	2.4			
1.A.4.a Stationary Combustion - Coal - Commercial	CO ₂	12.0	1.1	•	T ₁	
1.A.1 Stationary Combustion - Geothermal Energy	CO ₂	0.5	0.4			
1.C CO ₂ Transport, Injection, and Geological Storage	CO ₂	0.0	0.1			
1.B.2 Abandoned Oil and Gas Wells	CO ₂	+	+			
1.A.4.b Stationary Combustion - Coal - Residential	CO ₂	3.0	0.0	•	T ₂	
1.B.2 Natural Gas Systems	CH ₄	219.6	162.4	•	L ₁ T ₁ L ₂ T ₂	1990, 2023
1.B.1 Fugitive Emissions from Coal Mining	CH ₄	108.1	45.4	•	L ₁ T ₁ L ₂ T ₂	1990, 2023
1.B.2 Petroleum Systems	CH ₄	50.0	38.0	•	L ₁ T ₁ L ₂ T ₂	1990, 2023
1.B.2 Abandoned Oil and Gas Wells	CH ₄	7.8	8.5	•	L ₂	1990, 2023
1.B.1 Fugitive Emissions from Abandoned Underground Coal Mines	CH ₄	8.1	6.1			
1.A.4.b Stationary Combustion - Residential	CH ₄	5.9	4.5	•	L ₂ T ₂	1990, 2023
1.A.2 Stationary Combustion - Industrial	CH ₄	2.1	1.5			
1.A.1 Stationary Combustion - Natural Gas - Electricity Generation	CH ₄	0.1	1.3			
1.A.4.a Stationary Combustion - Commercial	CH ₄	1.2	1.3			
1.A.3.e Transportation: Other	CH ₄	0.8	1.1			
1.A.3.b Transportation: Road	CH ₄	5.8	0.9			
1.A.3.d Transportation: Domestic Navigation	CH ₄	0.4	0.5			
1.A.1 Stationary Combustion - Coal - Electricity Generation	CH ₄	0.4	0.2			
1.A.3.c Transportation: Railways	CH ₄	0.1	0.1			
1.A.5 Stationary Combustion - U.S. Territories	CH ₄	+	+			
1.A.3.a Transportation: Aviation	CH ₄	0.1	+			
5.B.2 Anaerobic Digestion at Biogas Facilities	CH ₄	+	+			
1.A.1 Stationary Combustion - Wood - Electricity Generation	CH ₄	+	+			
1.A.1 Stationary Combustion - Oil - Electricity Generation	CH ₄	+	+			
1.A.5.b Transportation: Military	CH ₄	+	+			
5.C.1 Incineration of Waste	CH ₄	+	+			
1.A.1 Stationary Combustion - Coal - Electricity Generation	N ₂ O	17.9	12.1	•	L ₁ L ₂ T ₂	1990, 2023 ₂
1.A.3.b Transportation: Road	N ₂ O	31.6	8.3	•	L ₁ T ₁ L ₂ T ₂	1990
1.A.3.e Transportation: Other	N ₂ O	4.2	6.0			

1.A.1 Stationary Combustion - Natural Gas - Electricity Generation	N ₂ O	0.3	4.4			
1.A.2 Stationary Combustion - Industrial	N ₂ O	2.8	1.9	•	L ₂	1990
1.A.3.a Transportation: Aviation	N ₂ O	1.5	1.5			
1.A.4.b Stationary Combustion - Residential	N ₂ O	0.9	0.7			
5.C.1 Incineration of Waste	N ₂ O	0.4	0.3			
1.A.4.a Stationary Combustion - Commercial	N ₂ O	0.3	0.3			
1.A.3.c Transportation: Railways	N ₂ O	0.2	0.2			
1.A.3.d Transportation: Domestic Navigation	N ₂ O	0.2	0.2			
1.A.5 Stationary Combustion - U.S. Territories	N ₂ O	+	0.1			
1.B.2 Petroleum Systems	N ₂ O	+	+			
1.A.1 Stationary Combustion - Wood - Electricity Generation	N ₂ O	+	+			
1.B.2 Natural Gas Systems	N ₂ O	+	+			
1.A.1 Stationary Combustion - Oil - Electricity Generation	N ₂ O	0.1	+			
1.A.5.b Transportation: Military	N ₂ O	+	+			
Industrial Processes and Product Use						
2.C.1 Iron and Steel Production & Metallurgical Coke Production	CO ₂	104.7	46.2	•	L ₁ T ₁ L ₂ T ₂	1990, 2023
2.A.1 Cement Production	CO ₂	33.5	40.6	•	L ₁	1990, 2023
2.B.8 Petrochemical Production	CO ₂	20.1	30.5	•	L ₁ T ₁	1990, 2023
2.B.1 Ammonia Production	CO ₂	14.4	12.2			
2.A.2 Lime Production	CO ₂	11.7	11.5			
2.A.4 Other Process Uses of Carbonates	CO ₂	7.1	7.2			
2.B.10 Urea Consumption for Non-Agricultural Purposes	CO ₂	3.8	5.4			
2.H Net Non-EOR Carbon Dioxide Utilization	CO ₂	1.5	2.1			
2.A.3 Glass Production	CO ₂	2.3	1.8			
2.B.7 Soda Ash Production	CO ₂	1.4	1.7			
2.C.2 Ferroalloy Production	CO ₂	2.2	1.2			
2.C.3 Aluminum Production	CO ₂	6.8	1.2			
2.B.6 Titanium Dioxide Production	CO ₂	1.2	1.2			
2.C.6 Zinc Production	CO ₂	0.6	0.9			
2.B.10 Phosphoric Acid Production	CO ₂	1.5	0.9			
2.C.5 Lead Production	CO ₂	0.5	0.5			
2.B.5 Silicon Carbide Production and Consumption	CO ₂	0.2	0.2			
2.C.4 Magnesium Production and Processing	CO ₂	0.1	+			

2.B.5 Silicon Carbide Production and Consumption	CH ₄	+	+			
2.C.2 Ferroalloy Production	CH ₄	+	+			
2.C.1 Iron and Steel Production & Metallurgical Coke Production	CH ₄	+	+			
2.B.8 Petrochemical Production	CH ₄	+	+			
2.B.2 Nitric Acid Production	N ₂ O	10.8	8.3			
2.G N ₂ O from Product Uses	N ₂ O	3.8	3.8			
2.B.4 Caprolactam, Glyoxal, and Glyoxylic Acid Production	N ₂ O	1.5	1.3			
2.B.3 Adipic Acid Production	N ₂ O	13.5	1.2	•	T ₁	
2.E Electronics Industry	N ₂ O	+	0.3			
2.F.1 Emissions from Substitutes for Ozone Depleting Substances: Refrigeration and Air conditioning	HFCs, PFCs	0.0	154.7	•	L ₁ T ₁ L ₂ T ₂	2023
2.F.4 Emissions from Substitutes for Ozone Depleting Substances: Aerosols	HFCs, PFCs	0.2	17.4	•	T ₁ L ₂ T ₂	2023
2.F.2 Emissions from Substitutes for Ozone Depleting Substances: Foam Blowing Agents	HFCs, PFCs	0.0	12.1	•	T ₁	
2.G Electrical Equipment	PFCs, SF ₆	24.6	5.1	•	L ₁ T ₁ T ₂	1990
2.B.9 Fluorochemical Production	PFCs, HFCs, SF ₆ , NF ₃	71.0	4.7	•	L ₁ T ₁ L ₂ T ₂	1990
2.E Electronics Industry	PFCs, HFCs, SF ₆ , NF ₃	3.3	3.9			
2.F.3 Emissions from Substitutes for Ozone Depleting Substances: Fire Protection	HFCs, PFCs	0.0	2.7			
2.F.5 Emissions from Substitutes for Ozone Depleting Substances: Solvents	HFCs, PFCs	0.0	2.2			
2.C.4 Magnesium Production and Processing	SF ₆	5.6	1.1			
2.G Other Product Manufacture and Use	PFCs, HFCs, SF ₆ , NF ₃	1.5	1.0			
2.C.3 Aluminum Production	PFCs, SF ₆	19.3	0.5	•	L ₁ T ₁	1990
2.C.4 Magnesium Production and Processing	HFCs	0.0	+			
Agriculture						
3.G Liming	CO ₂	4.7	5.3			
3.H Urea Fertilization	CO ₂	2.4	5.3			
3.A.1 Enteric Fermentation: Cattle	CH ₄	176.1	180.4	•	L ₁ L ₂	1990, 2023
3.B.1 Manure Management: Cattle	CH ₄	17.8	37.6	•	L ₁ T ₁ L ₂ T ₂	2023
3.B.2 Manure Management: Swine	CH ₄	17.4	24.3	•	L ₁	2023
3.C Rice Cultivation	CH ₄	18.9	18.7	•	L ₁ L ₂	1990, 2023
3.A.4 Enteric Fermentation: Other Livestock	CH ₄	7.0	6.7			

3.B.4 Manure Management: Other Livestock	CH ₄	4.0	3.2			
3.F Field Burning of Agricultural Residues	CH ₄	0.5	0.6			
3.D.1 Direct Agricultural Soil Management	N ₂ O	259.2	266.8	•	L ₁ L ₂	1990, 2023
3.D.2 Indirect Applied Nitrogen	N ₂ O	29.9	29.6	•	L ₁ L ₂	1990, 2023
3.B.1 Manure Management: Cattle	N ₂ O	10.7	12.3			
3.B.3 Manure Management: Poultry	N ₂ O	1.3	2.3			
3.B.2 Manure Management: Swine	N ₂ O	1.1	1.8			
3.B.4 Manure Management: Other Livestock	N ₂ O	0.2	0.4			
3.F Field Burning of Agricultural Residues	N ₂ O	0.2	0.2			
Waste						
5.A MSW Landfills	CH ₄	185.5	100.6	•	L ₁ T ₁ L ₂ T ₂	1990, 2023
5.A Industrial Landfills	CH ₄	12.2	18.9	•	L ₁ L ₂ T ₂	2023
5.D Domestic Wastewater Treatment	CH ₄	16.5	14.0	•	L ₂ T ₂	1990, 2023
5.D Industrial Wastewater Treatment	CH ₄	6.2	7.1			
5.B Composting	CH ₄	0.4	2.6			
5.D Domestic Wastewater Treatment	N ₂ O	14.4	20.3	•	L ₁ T ₁ L ₂ T ₂	1990 ₂ , 2023
5.B Composting	N ₂ O	0.3	1.8			
5.D Industrial Wastewater Treatment	N ₂ O	0.4	0.5			

+ Absolute value does not exceed 0.05 MMT CO₂ Eq.

NO (Not Occurring)

^a If the source is a key category for both L₁ and L₂ (as designated in the ID criteria column), it is a key category for both assessments in the years provided unless noted by a subscript, in which case it is a key category for that assessment in that year only (e.g., 1990₂ designates a category is key for the Approach 2 assessment only in 1990). No subscript is noted if the source is key for a single assessment (e.g., if a source is only L₂ for 1990 and 2023 or L₁ for 2023).

Note: LULUCF sources and sinks are not included in the analysis presented in this table. See Table A-2 for the results of the analysis with LULUCF.

Table A-2: U.S. Greenhouse Gas Inventory Source Categories with LULUCF

Source/Sink Category Code	Greenhouse Gas	1990 Emissions (MMT CO ₂ Eq.)	2023 Emissions (MMT CO ₂ Eq.)	Key Category	ID Criteria ^a	Level in which year(s)? ^b
Energy						
1.A.3.b Transportation: Road	CO ₂	1,157.4	1,455.3	•	L ₁ T ₁ L ₂ T ₂	1990, 2023
1.A.1 Stationary Combustion – Natural Gas - Electricity Generation	CO ₂	175.4	704.5	•	L ₁ T ₁ L ₂ T ₂	1990, 2023
1.A.1 Stationary Combustion - Coal - Electricity Generation	CO ₂	1,546.5	694.6	•	L ₁ T ₁ L ₂ T ₂	1990, 2023
1.A.2 Stationary Combustion – Natural Gas - Industrial	CO ₂	407.4	514.8	•	L ₁ T ₁ L ₂ T ₂	1990, 2023

1.A.4.b Stationary Combustion – Natural Gas - Residential	CO ₂	237.8	247.5	•	L ₁ T ₁ L ₂	1990, 2023
1.A.2 Stationary Combustion - Oil - Industrial	CO ₂	311.2	241.3	•	L ₁ T ₁ L ₂ T ₂	1990, 2023
1.A.4.a Stationary Combustion – Natural Gas - Commercial	CO ₂	142.0	182.8	•	L ₁ T ₁ L ₂	1990, 2023
1.A.3.a Transportation: Aviation	CO ₂	187.2	179.7	•	L ₁ L ₂	1990, 2023
1.A.5 Non-Energy Use of Fuels	CO ₂	99.1	107.1	•	L ₁ L ₂ T ₂	1990, 2023
1.A.3.e Transportation: Other	CO ₂	36.0	71.3	•	L ₁ T ₁	1990 ₁ , 2023 ₁
1.A.4.a Stationary Combustion - Oil - Commercial	CO ₂	74.3	60.2	•	L ₁ T ₁	1990 ₁ , 2023 ₁
1.A.4.b Stationary Combustion - Oil - Residential	CO ₂	97.8	59.6	•	L ₁ T ₁	1990 ₁ , 2023 ₁
1.B.2 Natural Gas Systems	CO ₂	32.5	37.7	•	L ₁	1990 ₁ , 2023 ₁
1.A.2 Stationary Combustion - Coal - Industrial	CO ₂	157.8	36.5	•	L ₁ T ₁ L ₂ T ₂	1990, 2023 ₁
1.A.3.d Transportation: Domestic Navigation	CO ₂	39.3	34.6	•	L ₁	1990 ₁ , 2023 ₁
1.A.3.c Transportation: Railways	CO ₂	35.5	30.9	•	L ₁	1990 ₁ , 2023 ₁
1.B.2 Petroleum Systems	CO ₂	9.6	23.3	•	L ₁ T ₁ T ₂	2023 ₁
1.A.5 Stationary Combustion - Oil - U.S. Territories	CO ₂	19.5	17.9	•	L ₁	1990 ₁
1.A.1 Stationary Combustion - Oil - Electricity Generation	CO ₂	97.5	14.7	•	L ₁ T ₁ T ₂	1990 ₁
5.C.1 Incineration of Waste	CO ₂	12.9	12.4			
1.A.5.b Transportation: Military	CO ₂	13.6	4.6	•	T ₁	
1.A.5 Stationary Combustion – Natural Gas - U.S. Territories	CO ₂	0.0	4.5			
1.A.5 Stationary Combustion - Coal - U.S. Territories	CO ₂	0.5	2.5			
1.B.1 Coal Mining	CO ₂	4.6	2.4			
1.A.4.a Stationary Combustion - Coal - Commercial	CO ₂	12.0	1.1	•	T ₁	
1.A.1 Stationary Combustion - Geothermal Energy	CO ₂	0.5	0.4			
1.C CO ₂ Transport, Injection, and Geological Storage	CO ₂	0.0	0.1			
1.B.2 Abandoned Oil and Gas Wells	CO ₂	+	+			
1.A.4.b Stationary Combustion - Coal - Residential	CO ₂	3.0	0.0			
1.B.2 Natural Gas Systems	CH ₄	219.6	162.4	•	L ₁ T ₁ L ₂ T ₂	1990, 2023
1.B.1 Fugitive Emissions from Coal Mining	CH ₄	108.1	45.4	•	L ₁ T ₁ L ₂ T ₂	1990, 2023
1.B.2 Petroleum Systems	CH ₄	50.0	38.0	•	L ₁ T ₁ L ₂	1990, 2023
1.B.2 Abandoned Oil and Gas Wells	CH ₄	7.8	8.5	•	L ₂	1990 ₂ , 2023 ₂
1.B.1 Fugitive Emissions from Abandoned Underground Coal Mines	CH ₄	8.1	6.1			

1.A.4.b Stationary Combustion - Residential	CH ₄	5.9	4.5	•	L ₂ T ₂	1990 ₂ , 2023 ₂
1.A.2 Stationary Combustion - Industrial	CH ₄	2.1	1.5			
1.A.1 Stationary Combustion - Natural Gas - Electricity Generation	CH ₄	0.1	1.3			
1.A.4.a Stationary Combustion - Commercial	CH ₄	1.2	1.3			
1.A.3.e Transportation: Other	CH ₄	0.8	1.1			
1.A.3.b Transportation: Road	CH ₄	5.8	0.9			
1.A.3.d Transportation: Domestic Navigation	CH ₄	0.4	0.5			
1.A.1 Stationary Combustion - Coal - Electricity Generation	CH ₄	0.4	0.2			
1.A.3.c Transportation: Railways	CH ₄	0.1	0.1			
1.A.5 Stationary Combustion - U.S. Territories	CH ₄	+	+			
1.A.3.a Transportation: Aviation	CH ₄	0.1	0.0			
5.B.2 Anaerobic Digestion at Biogas Facilities	CH ₄	+	+			
1.A.1 Stationary Combustion - Wood - Electricity Generation	CH ₄	+	+			
1.A.1 Stationary Combustion - Oil - Electricity Generation	CH ₄	+	+			
1.A.5.b Transportation: Military	CH ₄	+	+			
5.C.1 Incineration of Waste	CH ₄	+	+			
1.A.1 Stationary Combustion - Coal - Electricity Generation	N ₂ O	17.9	12.1			
1.A.3.b Transportation: Road	N ₂ O	31.6	8.3	•	L ₁ T ₁ T ₂	1990
1.A.3.e Transportation: Other	N ₂ O	4.2	6.0			
1.A.1 Stationary Combustion - Natural Gas - Electricity Generation	N ₂ O	0.3	4.4			
1.A.2 Stationary Combustion - Industrial	N ₂ O	2.8	1.9			
1.A.3.a Transportation: Aviation	N ₂ O	1.5	1.5			
1.A.4.b Stationary Combustion - Residential	N ₂ O	0.9	0.7			
5.C.1 Incineration of Waste	N ₂ O	0.4	0.3			
1.A.4.a Stationary Combustion - Commercial	N ₂ O	0.3	0.3			
1.A.3.c Transportation: Railways	N ₂ O	0.2	0.2			
1.A.3.d Transportation: Domestic Navigation	N ₂ O	0.2	0.2			
1.A.5 Stationary Combustion - U.S. Territories	N ₂ O	+	0.1			
1.B.2 Petroleum Systems	N ₂ O	+	+			
1.A.1 Stationary Combustion - Wood - Electricity Generation	N ₂ O	+	+			
1.B.2 Natural Gas Systems	N ₂ O	+	+			
1.A.1 Stationary Combustion - Oil - Electricity Generation	N ₂ O	0.1	+			

1.A.5.b Transportation: Military	N ₂ O	+	+			
Industrial Processes and Product Use						
2.C.1 Iron and Steel Production & Metallurgical Coke Production	CO ₂	104.7	46.2	•	L ₁ T ₁ L ₂ T ₂	1990, 2023 ₁
2.A.1 Cement Production	CO ₂	33.5	40.6	•	L ₁	1990, 2023
2.B.8 Petrochemical Production	CO ₂	20.1	30.5	•	L ₁ T ₁	1990, 2023
2.B.1 Ammonia Production	CO ₂	14.4	12.2			
2.A.2 Lime Production	CO ₂	11.7	11.5			
2.A.4 Other Process Uses of Carbonates	CO ₂	7.1	7.2			
2.B.10 Urea Consumption for Non-Ag Purposes	CO ₂	3.8	5.4			
2.H Net Non-EOR Carbon Dioxide Utilization	CO ₂	1.5	2.1			
2.A.3 Glass Production	CO ₂	2.3	1.8			
2.B.7 Soda Ash Production	CO ₂	1.4	1.7			
2.C.2 Ferroalloy Production	CO ₂	2.2	1.2			
2.C.3 Aluminum Production	CO ₂	6.8	1.2			
2.B.6 Titanium Dioxide Production	CO ₂	1.2	1.2			
2.C.6 Zinc Production	CO ₂	0.6	0.9			
2.B.10 Phosphoric Acid Production	CO ₂	1.5	0.9			
2.C.5 Lead Production	CO ₂	0.5	0.5			
2.B.5 Silicon Carbide Production and Consumption	CO ₂	0.2	0.2			
2.C.4 Magnesium Production and Processing	CO ₂	0.1	+			
2.B.5 Silicon Carbide Production and Consumption	CH ₄	+	+			
2.C.2 Ferroalloy Production	CH ₄	+	+			
2.C.1 Iron and Steel Production & Metallurgical Coke Production	CH ₄	+	+			
2.B.8 Petrochemical Production	CH ₄	+	+			
2.B.2 Nitric Acid Production	N ₂ O	10.8	8.3			
2.G N ₂ O from Product Uses	N ₂ O	3.8	3.8			
2.B.4 Caprolactam, Glyoxal, and Glyoxylic Acid Production	N ₂ O	1.5	1.3			
2.B.3 Adipic Acid Production	N ₂ O	13.5	1.2	•	T ₁	
2.E Electronics Industry	N ₂ O	+	0.3			
2.F.1 Emissions from Substitutes for Ozone Depleting Substances: Refrigeration and Air conditioning	HFCs, PFCs	0.0	154.7	•	L ₁ T ₁ L ₂ T ₂	2023
2.F.4 Emissions from Substitutes for Ozone Depleting Substances: Aerosols	HFCs, PFCs	0.2	17.4	•	T ₁ L ₂ T ₂	2023

2.F.2 Emissions from Substitutes for Ozone Depleting Substances: Foam Blowing Agents	HFCs, PFCs	0.0	12.1	•	T ₁	
2.G Electrical Equipment	PFCs, SF ₆	24.6	5.1	•	L ₁ T ₁ T ₂	1990
2.B.9 Fluorochemical Production	PFCs, HFCs, SF ₆ , NF ₃	71.0	4.7	•	L ₁ T ₁ L ₂ T ₂	1990
2.E Electronics Industry	PFCs, HFCs, SF ₆ , NF ₃	3.3	3.9			
2.F.3 Emissions from Substitutes for Ozone Depleting Substances: Fire Protection	HFCs, PFCs	0.0	2.7			
2.F.5 Emissions from Substitutes for Ozone Depleting Substances: Solvents	HFCs, PFCs	0.0	2.2			
2.C.4 Magnesium Production and Processing	SF ₆	5.6	1.1			
2.G Other Product Manufacture and Use	PFC, HFC, SF ₆ , NF ₃	1.5	1.0			
2.C.3 Aluminum Production	PFCs	19.3	0.5	•	T ₁	
2.C.4 Magnesium Production and Processing	HFCs	0.0	+			
Agriculture						
3.G Liming	CO ₂	4.7	5.3			
3.H Urea Fertilization	CO ₂	2.4	5.3			
3.A.1 Enteric Fermentation: Cattle	CH ₄	176.1	180.4	•	L ₁ L ₂	1990, 2023
3.B.1 Manure Management: Cattle	CH ₄	17.8	37.6	•	L ₁ T ₁ L ₂ T ₂	2023
3.B.2 Manure Management: Swine	CH ₄	17.4	24.3		L ₁	2023
3.C Rice Cultivation	CH ₄	18.9	18.7	•	L ₂	1990 ₂ , 2023 ₂
3.A.4 Enteric Fermentation: Other Livestock	CH ₄	7.0	6.7			
3.B.4 Manure Management: Other Livestock	CH ₄	4.0	3.2			
3.F Field Burning of Agricultural Residues	CH ₄	0.5	0.6			
3.D.1 Direct Agricultural Soil Management	N ₂ O	259.2	266.8	•	L ₁ L ₂	1990, 2023
3.D.2 Indirect Applied Nitrogen	N ₂ O	29.9	29.6	•	L ₁ L ₂	1990, 2023
3.B.1 Manure Management: Cattle	N ₂ O	10.7	12.3			
3.B.3 Manure Management: Poultry	N ₂ O	1.3	2.3			
3.B.2 Manure Management: Swine	N ₂ O	1.1	1.8			
3.B.4 Manure Management: Other Livestock	N ₂ O	0.2	0.4			
3.F Field Burning of Agricultural Residues	N ₂ O	0.2	0.2			

Waste						
5.A MSW Landfills	CH ₄	185.5	100.6	•	L ₁ T ₁ L ₂ T ₂	1990, 2023
5.A Industrial Landfills	CH ₄	12.2	18.9			
5.D Domestic Wastewater Treatment	CH ₄	16.5	14.0			
5.D Industrial Wastewater Treatment	CH ₄	6.2	7.1			
5.B Composting	CH ₄	0.4	2.6			
5.D Domestic Wastewater Treatment	N ₂ O	14.4	20.3	•	L ₁ L ₂ T ₂	1990 ₂ , 2023
5.B Composting	N ₂ O	0.3	1.8			
5.D Industrial Wastewater Treatment	N ₂ O	0.4	0.5			
Land Use, Land Use Change, and Forestry						
4.E.2 Net Land Converted to Settlements	CO ₂	69.5	79.8	•	L ₁ T ₁ L ₂ T ₂	1990, 2023
4.B.2 Net Land Converted to Cropland	CO ₂	48.5	35.6	•	L ₁ T ₁ L ₂ T ₂	1990, 2023
4.C.1 Net Grassland Remaining Grassland	CO ₂	24.0	22.0	•	L ₁ L ₂ T ₂	1990, 2023
4.C.2 Net Land Converted to Grassland	CO ₂	35.6	20.9	•	L ₁ T ₁ L ₂ T ₂	1990, 2023
4.D.2 Net Lands Converted to Wetlands	CO ₂	3.8	0.3			
4.D.1 Net Coastal Wetlands Remaining Coastal Wetlands	CO ₂	-9.8	-10.5			
4.E.1 Net Settlements Remaining Settlements: LYTFS	CO ₂	-24.5	-11.7	•	L ₁ T ₁ L ₂ T ₂	1990
4.B.1 Net Cropland Remaining Cropland	CO ₂	1.0	-30.5	•	L ₁ T ₁ L ₂ T ₂	2023
4.A.1 Net Forest Land Remaining Forest Land: HWP	CO ₂	-123.8	-90.9	•	L ₁ T ₁ L ₂ T ₂	1990, 2023
4.A.2 Net Land Converted to Forest Land	CO ₂	-103.6	-103.8	•	L ₁ L ₂	1990, 2023
4.E.1 Net Settlements Remaining Settlements: C Stocks in Trees and Soils	CO ₂	-86.6	-122.6	•	L ₁ T ₁ L ₂ T ₂	1990, 2023
4.A.1 Net Forest Land Remaining Forest Land: Forest C Pools	CO ₂	-931.1	-789.1	•	L ₁ T ₁ L ₂ T ₂	1990, 2023
4.D.1 Flooded Lands Remaining Flooded Lands	CH ₄	43.9	45.8	•	L ₁	1990 ₁ , 2023 ₁
4.D.1 Coastal Wetlands Remaining Coastal Wetlands	CH ₄	4.2	4.3			
4.A.1 Forest Fires	CH ₄	3.2	3.8			
4.C.1 Grass Fires	CH ₄	0.1	0.4			
4.D.2 Land Converted to Flooded Lands	CH ₄	2.7	0.2			
4.D.2 Land Converted to Coastal Wetlands	CH ₄	0.3	0.2			
4.A.4 Drained Organic Soils	CH ₄	0.0	0.0			
4.D.1 Peatlands Remaining Peatlands	CH ₄	0.0	0.0			
4.E.1 Settlement Soils	N ₂ O	2.1	2.5			
4.A.1 Forest Fires	N ₂ O	2.3	2.4			

4.A.1 Forest Soils	N ₂ O	0.1	0.4
4.C.1 Grass Fires	N ₂ O	0.1	0.3
4.D.1 Coastal Wetlands Remaining Coastal Wetlands	N ₂ O	0.1	0.1
4.A.4 Drained Organic Soils	N ₂ O	0.1	0.1
4.D.1 Peatlands Remaining Peatlands	N ₂ O	+	+

+ Absolute value does not exceed 0.05 MMT CO₂ Eq.

NO (Not Occurring)

^a If the source is a key category for both L₁ and L₂ (as designated in the ID criteria column), it is a key category for both assessments in the years provided unless noted by a subscript, in which case it is a key category only for that assessment in only that year (e.g., 1990₂ designates a category is key for the Approach 2 assessment only in 1990). No subscript is noted if the source is key for a single assessment (e.g., if a source is only L₂ for 1990 and 2023 or L₁ for 2023).

Note: Parentheses indicate negative values (or sequestration).

Methods applied for key categories. Table A-3 indicates the key category rank across approach 1 analyses, the methods applied, and any relevant methodological notes for categories identified as key (i.e., as summarized in Chapter 1.5 of this *Inventory*). Supplemental tables for Annex 1 will be available online at

<https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2023>.

Table A-3: Summary of 2023 Key Categories with Rank and Methods Applied by Sector

Source/Sink Category Code	Greenhouse Gas	2023 Level A1 Ranking with LULUCF	2023 Trend A1 Ranking with LULUCF	Methods Applied	Notes
Energy					
1.A.3.b Transportation: Road	CO ₂	1	3	T2, M	
1.A.1 Stationary Combustion - Natural Gas - Electricity Generation	CO ₂	3	2	T2	
1.A.1 Stationary Combustion - Coal - Electricity Generation	CO ₂	4	1	T2	
1.A.2 Stationary Combustion - Natural Gas - Industrial	CO ₂	5	7	T2	
1.A.4.b Stationary Combustion - Natural Gas - Residential	CO ₂	7	37	T2	
1.A.2 Stationary Combustion - Oil - Industrial	CO ₂	8	10	T2	
1.A.4.a Stationary Combustion - Natural Gas - Commercial	CO ₂	9	15	T2	
1.A.3.a Transportation: Aviation	CO ₂	11	41	T2, T3	
1.A.5 Non-Energy Use of Fuels	CO ₂	15	39	T2	
1.A.3.e Transportation: Other	CO ₂	20	18	T2	
1.A.4.a Stationary Combustion - Oil - Commercial	CO ₂	21	27	T2	
1.A.4.b Stationary Combustion - Oil - Residential	CO ₂	22	16	T2	
1.B.2 Natural Gas Systems	CO ₂	28	48	CS	
1.A.2 Stationary Combustion - Coal - Industrial	CO ₂	30	6	T2	
1.A.3.d Transportation: Domestic Navigation	CO ₂	32	50	T2, M	
1.A.3.c Transportation: Railways	CO ₂	33	51	T2	
1.B.2 Petroleum Systems	CO ₂	38	28	CS	
1.A.5 Stationary Combustion - Oil - U.S. Territories	CO ₂	44	72	T2	
1.A.1 Stationary Combustion - Oil - Electricity Generation	CO ₂	46	9	T2	
1.A.5.b Transportation: Military	CO ₂	55	38	T2	
1.A.4.a Stationary Combustion - Coal - Commercial	CO ₂	59	34	T2	

1.A.4.b Stationary Combustion - Coal - Residential	CO ₂	61	57	T2	
1.B.2 Natural Gas Systems	CH ₄	28	48	CS	
1.B.1 Fugitive Emissions from Coal Mining	CH ₄	25	12	T2, T3	
1.B.2 Petroleum Systems	CH ₄	38	28	CS	
1.B.2 Abandoned Oil and Gas Wells	CH ₄	51	85	CS	
1.A.4.b Stationary Combustion - Residential	CH ₄	56	76	T1	Tier 1 default EFs are used because country-specific EFs are not available and IPCC T1 defaults felt to be representative.
1.A.1 Stationary Combustion - Coal - Electricity Generation	N ₂ O	4	1	T2	
1.A.3.b Transportation: Road	N ₂ O	1	3	T2, M	
1.A.2 Stationary Combustion - Industrial	N ₂ O	57	81	T1	Tier 1 default EFs are used because country-specific EFs are not available and IPCC T1 defaults felt to be representative.
Industrial Processes and Product Use				T2, M	
2.C.1 Iron and Steel Production & Metallurgical Coke Production	CO ₂	23	13	T1, T2, CS	Tier 1 is used for sinter production, pellet production and DRI Production due to insufficient data. Together, emissions from these subcategories contribute 15 percent of total 2.C.1 emissions in 2023. More information is available under the Methodology and Time-Series Consistency section of Chapter 4.18.
2.A.1 Cement Production	CO ₂	26	42	T2	
2.B.8 Petrochemical Production	CO ₂	35	35	T1, CS	Tier 1 is used for estimating CO ₂ and CH ₄ from acrylonitrile due to data CBI. Data reported under EPA's GHGRP is considered CBI and cannot be published for this subcategory. Acrylonitrile emissions are 4 percent of total petrochemical emissions in 2023. More information is available under the Methodology and Time-Series Consistency section of Chapter 4.13.
2.B.3 Adipic Acid Production	N ₂ O	58	31	T3	
2.F.1 Emissions from Substitutes for Ozone Depleting Substances: Refrigeration and Air conditioning	HFCs, PFCs	13	4	T2, T3	
2.F.4 Emissions from Substitutes for Ozone Depleting Substances: Aerosols	HFCs, PFCs	45	25	T2, T3	

2.F.2 Emissions from Substitutes for Ozone Depleting Substances: Foam Blowing Agents	HFCs, PFCs	49	32	T2, T3	
2.G Electrical Equipment	PFCs, SF ₆	53	23	M, T2, T3	
2.B.9 Fluorochemical Production	PFCs, HFCs, SF ₆ , NF ₃	54	11	T1, T3	Tier 1 is used to estimate emissions from fluorochemical production facilities that do not report their emissions under the GHG Reporting Program (GHGRP) due to lack of publicly available data to apply higher tiers. These facilities account for less than 3 percent of U.S. fluorochemical production. More information is available in the Methodology section of Chapter 4.15.
2.C.3 Aluminum Production	PFCs	60	24	M, T1, T2	Tier 1 is used for estimating emissions from low voltage anode effects (LVAE) because data are not available to support higher-Tiered methods. LVAE emissions were estimated using methods from the <i>2019 Refinement</i> to reflect the latest science and improve completeness. LVAE emissions accounted for 2 percent of total emissions from aluminum production in 2022. More information is available under the Methodology and Time-Series Consistency section of Chapter 4.20.
Agriculture					
3.A.1 Enteric Fermentation: Cattle	CH ₄	10	54	M, T2	
3.B.1 Manure Management: Cattle	CH ₄	29	22	M, T1, T2	Specific parameters where a Tier 2 method is applicable due to available data, a Tier 2 method is used, some of which are modeled (M) within the Cattle Enteric Fermentation Model (CEFM). Other parameters follow the Tier 1 approach or default emission factors, largely due to data availability. More information is available under the Methodology and Time-Series Consistency discussion in section 5.2.
3.B.2 Manure Management: Swine	CH ₄	37	43	T1, T2	Specific parameters where a Tier 2 method is applicable due to available data, a Tier 2 method is used. Other parameters follow the Tier 1 approach or default emission factors (e.g., Tier 1 MCFs for dry systems), largely due to data availability. More information is available under the Methodology and Time-Series Consistency discussion in Section 5.2.

3.C Rice Cultivation	CH ₄	43	103	T1, T3	Tier 1 method is used for rice when grown in rotation with crops that are not simulated by DayCent, such as vegetable crops, and areas converted between agriculture (i.e., cropland and grassland) and other land uses. Tier 1 method is also used to estimate CH ₄ emissions from organic soils (i.e., Histosols) and from areas with very gravelly, cobbly, or shaley soils (greater than 35 percent by volume). DayCent has not been tested for modeling these conditions. Tier 3 is used for other conditions. More information is available under the Methodology and Time-Series Consistency section of Section 5.3.
3.D.1 Direct Agricultural Soil Management	CH ₄	6	40	T1, T3, CS	Tier 1 is applied as follows: 1) Mineral cropland soils where DayCent has not been parametrized. 2) Non-manure commercial organic amendments added to cropland soils. 3) Drained organic soils on croplands and grasslands. 4) Biosolids (sewage sludge) additions to grasslands. 5) PRP manure on federal grasslands.
3.D.2 Indirect Applied Nitrogen	N ₂ O	36	96	T1, T3	Tier 1 is applied as follows: 1) Nitrogen volatilization for croplands/grasslands not simulated by DayCent. 2) Tier 1 IPCC EF is applied to nitrogen volatilization data generated by DayCent and the volatilization data for croplands/grassland not simulated by DayCent. 3) Nitrogen leaching/runoff for croplands/grasslands not simulated by DayCent. 4) Tier 1 IPCC EF is applied to N leaching/runoff data generated by DayCent and the leaching/runoff data for croplands/grassland not simulated by DayCent.
Waste					
5.A MSW Landfills	CH ₄	17	8	T2, T3	
5.A Industrial Landfills	CH ₄	42	44	M	
5.D Domestic Wastewater Treatment	CH ₄	47	61	T1, T2, CS	Significant pathways for domestic wastewater treatment CH ₄ (65%) emissions are estimated using Tier 2 methodologies. Centralized treatment (aerobic, anerobic) is estimated with a Tier 1 methodology due to lack of country-specific methodologies, data and emission factors.
5.D Domestic Wastewater Treatment	N ₂ O	47	61	T1, T2, T3, CS	Significant pathways for domestic wastewater treatment N ₂ O (85%) emissions are estimated using Tier 2 methodologies. Centralized treatment

					(anerobic) and septic systems are estimated with a Tier 1 methodology due to lack of country-specific methodologies, data and emission factors.
Land Use, Land-Use Change, and Forestry					
4.E.2 Net Land Converted to Settlements	CO ₂	19	36	T2	
4.B.2 Net Land Converted to Cropland	CO ₂	31	29	T2, T3, CS	
4.C.1 Net Grassland Remaining Grassland	CO ₂	39	68	T2, T3, CS	
4.C.2 Net Land Converted to Grassland	CO ₂	40	26	T2, T3, CS	
4.E.1 Net Settlements Remaining Settlements: LYTFS	CO ₂	50	30	T2, T3, CS	
4.B.1 Net Cropland Remaining Cropland	CO ₂	34	20	T2, T3, CS	
4.A.1 Net Forest Land Remaining Forest Land: HWP	CO ₂	18	19	T2, T3, CS	
4.A.2 Net Land Converted to Forest Land	CO ₂	16	106	T2, T3, CS	
4.E.1 Net Settlements Remaining Settlements: C Stocks in Trees and Soils	CO ₂	14	17	T2, T3, CS	
4.A.1 Net Forest Land Remaining Forest Land: Forest C Pools	CO ₂	2	5	T2	
4.D.1 Flooded Lands Remaining Flooded Lands	CH ₄	24	70	T2, T3, CS	See the Planned Improvements section in Section 6.8. Work has been underway to develop country-specific emission factors.

References

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The Intergovernmental Panel on Climate Change. [Calvo Buendía, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds.)]. Published: IPCC, Switzerland.

IPCC (2006) Volume 1, Chapter 4: Methodological Choice and Identification of Key Categories, 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendía, K. Miwa, T. Negara, and K. Tanabe (eds.). Hayman, Kanagawa, Japan.

ANNEX 2 Methodology and Data for Estimating CO₂ Emissions from Fossil Fuel Combustion

2.1. Methodology for Estimating Emissions of CO₂ from Fossil Fuel Combustion

Carbon dioxide (CO₂) emissions from fossil fuel combustion were estimated using a “bottom-up” methodology characterized by eight steps. These steps are described below.

Step 1: Determine Total Fuel Consumption by Fuel Type and Sector

The bottom-up methodology used by the United States for estimating CO₂ emissions from fossil fuel combustion is conceptually similar to the approach recommended by the Intergovernmental Panel on Climate Change (IPCC) for countries that intend to develop detailed, sector-based emission estimates in line with a Tier 2 method in the 2006 *IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). Total consumption data and adjustments to consumption are presented in Columns 2 through 13 of Table A-4.

Adjusted consumption data for years 1990, 1995, 2000, 2005, 2010, and 2015 through 2023 are presented in columns 2 through 8 of Table A-4 through Table A-18 with totals by fuel type in column 8 and totals by end-use sector in the last rows.¹ Fuel consumption data for the bottom-up approach were obtained directly from the Energy Information Administration (EIA) of the U.S. Department of Energy. These data were first gathered in physical units, and then converted to their energy equivalents (see Annex 6.4 Constants, Units, and Conversions). The EIA data were collected through a variety of consumption surveys at the point of delivery or use and qualified with survey data on fuel production, imports, exports, and stock changes. Individual data elements were supplied by a variety of sources within EIA. Most information was taken from published reports, although some data were drawn from unpublished energy studies and databases maintained by EIA.

Energy use data were aggregated by sector (i.e., residential, commercial, industrial, transportation, electric power, and U.S. Territories), primary fuel type (e.g., coal, natural gas, and petroleum), and secondary fuel type (e.g., motor gasoline, distillate fuel). The 2023 total adjusted fossil energy consumption across all sectors, including U.S. Territories, and energy types was 69,497.5 trillion British thermal units (Tbtu), as indicated in the last entry of Column 13 in Table A-4. This total excludes fuel used for non-energy purposes and fuel consumed as international bunkers, both of which were deducted in earlier steps.

Electricity use information was allocated to each sector based on EIA’s distribution of electricity retail sales to ultimate customers (i.e., residential, commercial, industrial, and other). Because the “other” fuel use includes sales to both the commercial and transportation sectors, EIA’s limited transportation electricity use data were subtracted from “other” electricity use and reported separately, and the remaining “other” electricity use was consequently combined with the commercial electricity data. Further information on these electricity end uses is described in EIA’s *Monthly Energy Review* (EIA 2025). Within the transportation sector, electricity use from electric vehicle charging in commercial and residential locations, not specifically reported by EIA, was calculated and re-allocated from the residential and commercial sectors to the transportation sector, for the years 2010 to present. The methodology for estimating electricity consumption by electric vehicles is outlined in Browning (2018).

¹ Adjusted consumption data for other years in the time series are available along with all other data tables for this report on U.S. EPA’s website at <https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks>.

There are also three basic differences between the consumption data presented in Table A-4 and Table A-5 through Table A-18 and those recommended in the IPCC (2006) emission inventory methodology.

First, consumption data in the U.S. *Inventory* are presented using higher heating values (HHV)² rather than the lower heating values (LHV)³ reflected in the IPCC (2006) emission inventory methodology. This convention is followed because data obtained from EIA are based on HHV. Of note, however, is that EIA renewable energy statistics are often published using LHV. The difference between the two conventions relates to the treatment of the heat energy that is consumed in the process of evaporating the water contained in the fuel. The simplified convention used by the International Energy Agency for converting from HHV to LHV is to multiply the energy content by 0.95 for petroleum and coal and by 0.9 for natural gas.

Second, while EIA's energy use data for the United States includes only the 50 U.S. states and the District of Columbia, the data in this report includes energy use within U.S. Territories. Therefore, estimates for U.S. Territories⁴ were added to domestic consumption of fossil fuels. Energy use data from U.S. Territories are presented in Column 7 of Table A-5 through Table A-18. It is reported separately from domestic sectoral consumption, because it is collected separately by EIA with no sectoral disaggregation.

Energy consumption data for U.S. territories is based on the following data by fuel type. Coal and coke: Puerto Rico and US Virgin Islands consumption values are deduced from Global Trade Tracker trade data. All other territories do not have coal consumption. Natural gas: Puerto Rico consumption data is deduced from trade data from Vortexa and DOE's Office of Fossil Energy. There is no natural gas consumption in the other U.S. territories. Electricity: consumption is set equal to generation + imports - exports - distribution losses. Fossil fuel generation are sourced from UN and renewables generation are sourced from the International Renewable Energy Agency (IRENA). Petroleum: American Samoa and Northern Mariana Islands consumption data are estimated from UN trade data. Guam, Puerto Rico, and US Virgin Islands consumption data are estimated internally using EIA surveys and supplemented with EIA's company level imports.

Third, there were a number of modifications made in this report that may cause consumption information herein to differ from figures given in the cited literature. These are (1) the reallocation of select amounts of coking coal, petroleum coke, natural gas, residual fuel oil, and other oil (>401 degrees Fahrenheit) for processes accounted for in the Industrial Processes and Product Use chapter, (2) corrections for synthetic natural gas production, (3) subtraction of other fuels used for non-energy purposes, and (4) subtraction of international bunker fuels. These adjustments are described in the following steps.

Step 2: Subtract Uses Accounted for in the Industrial Processes and Product Use Chapter

Portions of the fuel consumption data for seven fuel categories—coking coal, distillate fuel, industrial other coal, petroleum coke, natural gas, residual fuel oil, and other oil (>401 degrees Fahrenheit)—were reallocated to the Industrial Processes and Product Use (IPPU) chapter, as these portions were consumed as raw materials during non-energy related industrial processes. Emissions from these fuels used as raw materials are presented in the Industrial Processes and Product Use chapter and are removed from the energy and non-energy use estimates within the Energy chapter.

- Coking coal is used as a raw material (specifically as a reducing agent) in the blast furnace process to produce iron and steel, lead, and zinc and therefore is not used as a fuel for this process.
- Similarly, petroleum coke is used in multiple processes as a raw material and is thus not used as a fuel in those applications. The processes in which petroleum coke is used include (1) ferroalloy production,

²Also referred to as gross calorific values (GCV).

³Also referred to as net calorific values (NCV).

⁴Fuel consumption by U.S. Territories (i.e., American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other U.S. Pacific Islands) is included in this report.

(2) aluminum production (for the production of C anodes and cathodes), (3) titanium dioxide production (in the chloride process), (4) ammonia production, and (5) silicon carbide.

- Natural gas consumption is used as a feedstock for the production of ammonia.
- Residual fuel oil and other oil (>401 degrees Fahrenheit) are both used in the production of C black.
- Natural gas, distillate fuel, coal, and net imports of metallurgical coke are used to produce pig iron through the reduction of iron ore in the production of iron and steel.

Examples of iron and steel production adjustments in allocating emissions in Energy and IPPU sectors:

The consumption of coking coal, natural gas, distillate fuel, and coal used in iron and steel production are adjusted within the Energy chapter to avoid double counting of emissions from consumption of these fuels during activities in IPPU related sectors. These fuels are adjusted based on activity data utilized in calculating emissions estimates within the Iron and Steel Production section. Iron and steel production is an industrial process in which coal coke is used as a raw material rather than as a fuel;⁵ as such, the total use of industrial coking coal, as reported by EIA, is adjusted downward to account for this consumption within the iron and steel category. In this case, if the reported amount of coking coal used in these processes is greater than the amount of coking coal consumption reported by the EIA, the excess amount of coking coal used in these processes that is greater than the amount reported from consumption is subtracted from the industrial other coal fuel type.

In 2023, 15,849 thousand tons of coking coal were consumed,⁶ resulting in an Energy sector adjustment of 392 TBtu. Natural gas, fuel oil, and coal are other fossil fuels also used in the production of iron and steel; therefore, the consumption of these fuels in industrial processes is subtracted from the industrial fossil fuel combustion sector to account for the amount of fuel used in the iron and steel calculation. In 2023, the iron and steel industry consumed 2,286 tons of coal (bituminous), 49,062 million ft³ of natural gas, and 2,153 thousand gallons of distillate fuel as fuel. This resulted in Energy chapter adjustments of roughly 55 TBtu for coal, 51 TBtu for natural gas, and 0.3 TBtu for distillate fuel. In addition, an additional 65 TBtu is adjusted to account for coking coal consumed for industrial processes other than iron and steel, lead, and zinc production in 2023.

Step 3: Adjust for Conversion of Fossil Fuels and Exports

First, ethanol has been added to the motor gasoline stream for many years, but prior to 1993 this addition was not captured in EIA motor gasoline statistics. Starting in 1993, ethanol was included in gasoline statistics. Carbon dioxide emissions from ethanol added to motor gasoline are not included specifically in summing energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF, therefore, fuel consumption estimates are adjusted to remove ethanol. Thus, motor gasoline consumption statistics given in this report exclude ethanol and may be slightly lower than in EIA sources for finished gasoline that includes ethanol.

Second, EIA distillate fuel oil consumption statistics include “biodiesel” and “other renewable diesel fuel” consumption starting in 2009. Carbon dioxide emissions from biodiesel and other renewable diesel added to diesel fuel are not included specifically in summing energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF, therefore, fuel consumption estimates are adjusted to remove biodiesel and other renewable diesel fuel. Thus, distillate fuel oil consumption statistics for the transportation sector in this report may be slightly lower than in EIA sources.

Third, a portion of industrial “other” coal that is accounted for in EIA coal combustion statistics is actually used to make “synthetic natural gas” via coal gasification at the Dakota Gasification Plant, a synthetic natural gas plant. The plant produces synthetic natural gas and byproduct CO₂. Since October 2000, a portion of the CO₂ produced

⁵ In addition to iron and steel, lead and zinc production are also industrial processes in which coal coke is used as a raw material. Iron and steel, lead and zinc production accounts for the major portion of consumption of coal coke in the United States.

⁶ Coking coal includes non-imported coke consumption from the iron and steel, lead, and zinc industries.

by the coal gasification plant has been exported to Canada by pipeline. The energy in this synthetic natural gas enters the natural gas distribution stream, however it is accounted for in EIA coal combustion statistics.⁷ The exported CO₂ is not emitted to the atmosphere in the United States, and therefore the energy associated with the amount of CO₂ exported is subtracted from industrial other coal.

Step 4: Adjust Sectoral Allocation of Distillate Fuel Oil and Motor Gasoline

EPA conducted a separate bottom-up analysis of transportation fuel consumption based on data from the Federal Highway Administration (FHWA). The FHWA data indicated that the amount of distillate and motor gasoline consumption allocated to the transportation sector in the EIA statistics should be adjusted (FHWA 1996 through 2024). Therefore, for the estimates presented in the U.S. *Inventory*, the transportation sector's distillate fuel and motor gasoline consumption were adjusted to match the value obtained from the bottom-up analysis. As the total distillate and motor gasoline consumption estimate from EIA are considered to be accurate at the national level, the distillate and motor gasoline consumption totals for the residential, commercial, and industrial sectors were adjusted proportionately.

Step 5: Subtract Consumption for Non-Energy Use

U.S. aggregate energy statistics include consumption of fossil fuels for non-energy purposes. Depending on the end-use, non-energy uses of fossil fuels can result in long term storage of some or all of the C contained in the fuel. For example, asphalt made from petroleum can sequester up to 100 percent of the C contained in the petroleum feedstock for extended periods of time. Other non-energy fossil fuel products, such as lubricants or plastics also store C, but can lose or emit some of this C when they are used and/or burned as waste. As the emission pathways of C used for non-energy purposes are vastly different than fuel combustion, these emissions are estimated separately in the Carbon Emitted in Products from Non-Energy Uses of Fossil Fuels section in this chapter. Therefore, the amount of fuels used for non-energy purposes, shown in Table A-19, was subtracted from total fuel consumption.

Step 6: Subtract Consumption of International Bunker Fuels

Emissions from international transport activities, or international bunker fuel consumption, are not included in national totals and instead reported separately, consistent with the IPCC (2006) guidelines. EIA energy statistics, however, include these bunker fuels jet fuel for aircraft, and distillate fuel oil and residual fuel oil for marine shipping as part of fuel consumption by the transportation end-use sector. Therefore, the amount of consumption for international bunker fuels was estimated and subtracted from total fuel consumption (see Table A-20). Emissions from international bunker fuels have been estimated separately and not included in national totals.⁸

Step 7: Determine the C Content of All Fuels

The C content of combusted fossil fuels was estimated by multiplying adjusted energy consumption (Columns 2 through 8 of Table A-5 through Table A-18) by fuel-specific C content coefficients (see Table A-21) that reflect the amount of C per unit of energy in each fuel. The C content coefficients used in the *Inventory* were derived in part by EIA and EPA from detailed fuel information and are similar to the C content coefficients contained in the IPCC's default methodology (IPCC 2006), with modifications reflecting fuel qualities specific to the United States.

For geothermal electricity production, C content was estimated by multiplying net generation for each geotype (see Table A-25) by technology-specific C content coefficients (see Table A-21). For industrial energy and non-energy hydrocarbon gas liquids (HGL)⁹ consumption, annually variable C contents were estimated by multiplying

⁷ To avoid double-counting, EIA's MER statistics account for supplemental gaseous fuels (including synthetic natural gas) in their primary energy category (i.e., coal, petroleum, or biomass) (EIA 2024a).

⁸ Refer to the International Bunker Fuels section of the Energy chapter and Annex 3.3 for a description of the methodology for distinguishing between international and domestic fuel consumption.

⁹ EIA defines HGL as "a group of hydrocarbons including ethane, propane, normal butane, isobutane, and natural gasoline, and their associated olefins, including ethylene, propylene, butylene, and isobutylene" (EIA 2024a).

annual energy and non-energy consumption for each HGL component (e.g., ethane, ethylene, propane, propylene) by its respective C content coefficient (see Table A-21).

Step 8: Estimate CO₂ Emissions

Actual CO₂ emissions in the United States were summarized by major fuel (i.e., coal, petroleum, natural gas, geothermal) and consuming sector (i.e., residential, commercial, industrial, transportation, electric power, and U.S. Territories). Emission estimates are expressed in million metric tons of carbon dioxide equivalents (MMT CO₂ Eq.). To convert from C content to CO₂ emissions, the fraction of C that is oxidized was applied. This fraction was 100 percent based on 2006 IPCC Guidelines.

To determine total emissions by final end-use sector, emissions from electric power were distributed to each end-use sector according to its share of aggregate electricity use (see Table A-23). This pro-rated approach to allocating emissions from electric power may overestimate or underestimate emissions for particular sectors due to differences in the average C content of fuel mixes burned to generate electricity.

To provide a more detailed accounting of emissions from transportation, fuel consumption data by vehicle type and transportation mode were used to allocate emissions by fuel type calculated for the transportation end-use sector. Additional information on the allocation is available in Annex 3.1.

Box A-1: Uses of Greenhouse Gas Reporting Program Data in Reporting Emissions from Industrial Sector Fossil Fuel Combustion

As described in the calculation methodology, total fossil fuel consumption for each year is based on aggregated end-use sector consumption published by the EIA. The availability of facility-level combustion emissions through EPA's Greenhouse Gas Reporting Program (GHGRP) has provided an opportunity to better characterize the industrial sector's energy consumption and emissions in the United States, through a disaggregation of EIA's industrial sector fuel consumption data from select industries.

For EPA's GHGRP 2010 through 2023 reporting years, facility-level fossil fuel combustion emissions reported through EPA's GHGRP were categorized and distributed to specific industry types by utilizing facility-reported NAICS codes (as published by the U.S. Census Bureau). As noted previously in this report, the definitions and provisions for reporting fuel types in EPA's GHGRP include some differences from the *Inventory*'s use of EIA national fuel statistics to for consistency with reporting guidelines. The IPCC has provided guidance on aligning facility-level reported fuels and fuel types published in national energy statistics, which guided this exercise.¹⁰

As with previous *Inventory* reports, this year's effort represents an attempt to align, reconcile, and coordinate the facility-level reporting of fossil fuel combustion emissions under EPA's GHGRP with the national-level approach presented in this report. Consistent with recommendations for reporting the *Inventory* under IPCC guidelines, progress was made on certain fuel types for specific industries and has been included in the common data tables that are submitted along with this report.¹¹ The efforts in reconciling fuels focus on standard, common fuel types (e.g., natural gas, distillate fuel oil) where the fuels in EIA's national statistics aligned well with facility-level GHGRP data. For these reasons, the current information should be viewed as an initial attempt at this exercise. Additional efforts will be made for future *Inventory* reports to improve the mapping of fuel types, and examine ways to reconcile and coordinate any differences between facility-level data and national statistics.

This year's analysis includes the full time series. Analyses were conducted linking GHGRP facility-level reporting with the information published by EIA in its MECS data in order to disaggregate the full 1990 through 2023 time series. It is believed that the current analysis has led to improvements in the presentation of data in the *Inventory*, but further work will be conducted, and future improvements will be realized in subsequent *Inventory* reports. This includes incorporating the latest MECS data as it becomes available.

¹⁰ See Section 4 "Use of Facility-Level Data in Good Practice National Greenhouse Gas Inventories" of the IPCC meeting report, and specifically the section on using facility-level data in conjunction with energy data, available at: http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

¹¹ See <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html>.

Table A-4: 2023 Energy Consumption Data by Fuel Type (TBtu) and Adjusted Energy Consumption Data

1	2	3	4	5	6	7	8	9	10	11	12	13
	Total Consumption (TBtu) ^a							Adjustments (TBtu) ^b				Total Adjusted Consumption (TBtu)
Fuel Type	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Bunker Fuel	Unadjusted NEU Consumption			
									Ind.	Trans.	Terr.	
Total Coal	NO	11.6	455.8	0.0	7,247.3	27.6	7,742.4		74.9	0.0		7,667.5
Residential Coal	NO						NO					NO
Commercial Coal		11.6					11.6					11.6
Industrial Other Coal			390.4				390.4		9.5			380.9
Transportation Coal				NO			NO					NO
Electric Power Coal					7,247.3		7,247.3					7,247.3
U.S. Territory Coal (bit)						27.6	27.6					27.6
Natural Gas	4,676.6	3,454.6	10,457.6	1,355.6	13,314.1	84.7	33,343.1		729.3			32,613.8
Total Petroleum	876.0	859.7	8,326.4	25,184.8	175.5	246.3	35,668.7	1,339.7	5,070.1	97.5	1.0	29,160.4
Asphalt & Road Oil			891.8				891.8		891.8			0.0
Aviation Gasoline				21.2			21.2					21.2
Distillate Fuel Oil	387.1	268.2	963.9	6,452.0	52.9	72.2	8,196.3	94.0	5.8			8,096.4
Jet Fuel				3,421.5		34.6	3,456.1	943.9				2,512.2
Kerosene	17.1	2.6	2.2			0.1	22.0					22.0
LPG (Propane)	471.8	188.6		11.1			671.6					671.6
HGL			3,452.1			10.3	3,462.4		3,216.8			245.6
Lubricants			86.3	97.5		1.0	184.8		86.3	97.5	1.0	0.0
Motor Gasoline		397.5	249.7	14,658.5		64.2	15,369.8					15,369.8
Residual Fuel		2.7	0.0	523.0	64.1	63.9	653.7	301.8				351.9
Other Petroleum												0.0
AvGas Blend Components			(0.6)				(0.6)					(0.6)
Crude Oil			0.0				0.0					0.0
MoGas Blend Components			0.0				0.0					0.0
Misc. Products			176.2			0.0	176.2		176.2		0.0	0.0
Naphtha (<401 deg. F)			271.8				271.8		271.8			0.0
Other Oil (>401 deg. F)			119.6				119.6		119.6			0.0
Pentanes Plus			0.0				0.0		0.0			0.0
Petroleum Coke		0.1	510.1		58.5		568.7		47.7			521.1
Still Gas			1,505.0				1,505.0		155.8			1,349.2
Special Naphtha			89.2				89.2		89.2			0.0
Unfinished Oils			0.0				0.0					0.0
Waxes			9.0				9.0		9.0			0.0
Geothermal					55.8		55.8					55.8
Total (All Fuels)	5,552.5	4,326.0	19,239.7	26,540.4	20,792.8	358.7	76,810.1	1,339.7	5,874.3	97.5	1.0	69,497.5

NO (Not Occurring)

^a Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-19), and international bunker fuel consumption (see Table A-20).

^b Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table A-5: 2023 Energy Consumption Data and CO₂ Emissions from Fossil Fuel Combustion by Fuel Type

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Adjusted Consumption (TBtu) ^a							Emissions ^b (MMT CO ₂ Eq.) from Energy Use							
Fuel Type	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	
Total Coal	NO	11.6	380.9	NO	7,247.3	27.6	7,667.5	NO	1.1	36.5		694.6	2.5	734.7	
Residential Coal	NO						NO	NO						NO	
Commercial Coal		11.6					11.6		1.1					1.1	
Industrial Other Coal			380.9				380.9			36.5				36.5	
Transportation Coal				NO			NO				NO			NO	
Electric Power Coal					7,247.3		7,247.3					694.6		694.6	
U.S. Territory Coal (bit)						27.6	27.6						2.5	2.5	
Natural Gas	4,676.6	3,454.6	9,728.2	1,355.6	13,314.1	84.7	32,613.8	247.5	182.8	514.8	71.7	704.5	4.5	1,725.8	
Total Petroleum	876.0	859.7	3,256.3	23,747.6	175.5	245.3	29,160.4	59.6	60.2	241.3	1,704.7	14.7	17.9	2,098.5	
Asphalt & Road Oil															
Aviation Gasoline				21.2			21.2				1.5			1.5	
Distillate Fuel Oil	387.1	268.2	958.1	6,357.9	52.9	72.2	8,096.4	28.7	19.9	71.0	471.3	3.9	5.4	600.2	
Jet Fuel				2,477.6		34.6	2,512.2				178.9		2.5	181.4	
Kerosene	17.1	2.6	2.2			0.1	22.0	1.2	0.2	0.2			+	1.6	
LPG (Propane)	471.8	188.6		11.1			671.6	29.7	11.9		0.7			42.2	
HGL			235.3			10.3	245.6			15.3			0.7	16.0	
Lubricants															
Motor Gasoline		397.5	249.7	14,658.5		64.2	15,369.8		28.1	17.6	1,035.7		4.5	1,086.0	
Residual Fuel		2.7		221.2	64.1	63.9	351.9		0.2		16.6	4.8	4.8	26.4	
Other Petroleum															
AvGas Blend Components			(0.6)				(0.6)			(+)				(+)	
Crude Oil															
MoGas Blend Components															
Misc. Products															
Naphtha (<401 deg. F)															
Other Oil (>401 deg. F)															
Pentanes Plus															
Petroleum Coke		0.1	462.5		58.5		521.1		+	47.2		6.0		53.2	
Still Gas			1,349.2				1,349.2			90.0				90.0	
Special Naphtha															
Unfinished Oils															
Waxes															
Geothermal					55.8		55.8					0.4		0.4	
Total (All Fuels)	5,552.5	4,326.0	13,365.5	25,103.1	20,792.8	357.6	69,497.5	307.1	244.2	792.6	1,776.5	1,414.2	24.9	4,559.4	

+ Does not exceed 0.05 TBtu or 0.05 MMT CO₂ Eq.

NO (Not Occurring)

NA (Not Available)

^a Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-19), and international bunker fuel consumption (see Table A-20).

^b Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table A-6: 2022 Energy Consumption Data and CO₂ Emissions from Fossil Fuel Combustion by Fuel Type

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Adjusted Consumption (TBtu) ^a							Emissions ^b (MMT CO ₂ Eq.) from Energy Use							
Fuel Type	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	
Total Coal	NO	14.5	449.6	NO	8,885.5	31.9	9,381.5	NO	1.4	43.0		851.5	2.9	898.8	
Residential Coal	NO						NO	NO						NO	
Commercial Coal		14.5					14.5		1.4					1.4	
Industrial Other Coal			449.6				449.6			43.0				43.0	
Transportation Coal				NO			NO				NO			NO	
Electric Power Coal					8,885.5		8,885.5					851.5		851.5	
U.S. Territory Coal (bit)						31.9	31.9						2.9	2.9	
Natural Gas	5,139.9	3,634.9	9,628.7	1,367.1	12,459.2	51.3	32,281.0	272.0	192.3	509.5	72.3	659.3	2.7	1,708.2	
Total Petroleum	929.0	933.9	3,344.4	23,410.3	243.9	245.1	29,106.6	63.2	65.4	247.1	1,681.2	20.5	17.8	2,095.3	
Asphalt & Road Oil															
Aviation Gasoline				22.3			22.3				1.5			1.5	
Distillate Fuel Oil	416.2	288.4	1,035.7	6,431.2	83.4	72.1	8,327.1	30.9	21.4	76.8	476.7	6.2	5.3	617.3	
Jet Fuel				2,282.3		34.7	2,317.0				164.8		2.5	167.3	
Kerosene	8.5	1.3	1.1			0.1	11.0	0.6	0.1	0.1			+	0.8	
LPG (Propane)	504.3	201.6		11.1			717.1	31.7	12.7		0.7			45.1	
HGL			229.6			10.3	239.8			14.9			0.7	15.6	
Lubricants															
Motor Gasoline		438.8	275.7	14,358.5		64.1	15,137.0		31.0	19.5	1,014.5		4.5	1,069.5	
Residual Fuel		3.2	3.0	304.9	75.6	63.8	450.6		0.2	0.2	22.9	5.7	4.8	33.8	
Other Petroleum															
AvGas Blend Components			(0.7)				(0.7)			(+)				(+)	
Crude Oil															
MoGas Blend Components															
Misc. Products															
Naphtha (<401 deg. F)															
Other Oil (>401 deg. F)															
Pentanes Plus															
Petroleum Coke		0.5	439.7		84.8		525.0		+	44.9		8.7		53.6	
Still Gas			1,360.4				1,360.4			90.8				90.8	
Special Naphtha															
Unfinished Oils															
Waxes															
Geothermal					54.9		54.9					0.4		0.4	
Total (All Fuels)	6,069.0	4,583.2	13,422.7	24,777.5	21,643.4	328.3	70,824.1	335.2	259.2	799.7	1,753.6	1,531.7	23.5	4,702.8	

+ Does not exceed 0.05 TBtu or 0.05 MMT CO₂ Eq.

NO (Not Occurring)

NA (Not Available)

^a Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-19), and international bunker fuel consumption (see Table A-20).

^b Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table A-7: 2021 Energy Consumption Data and CO₂ Emissions from Fossil Fuel Combustion by Fuel Type

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Adjusted Consumption (TBtu) ^a							Emissions ^b (MMT CO ₂ Eq.) from Energy Use							
Fuel Type	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	
Total Coal	NO	14.9	449.7	NO	9,497.7	31.3	9,993.6	NO	1.4	43.0		910.1	2.9	957.4	
Residential Coal	NO						NO	NO						NO	
Commercial Coal		14.9					14.9		1.4					1.4	
Industrial Other Coal			449.7				449.7			43.0				43.0	
Transportation Coal				NO			NO				NO			NO	
Electric Power Coal					9,497.7		9,497.7					910.1		910.1	
U.S. Territory Coal (bit)						31.3	31.3						2.9	2.9	
Natural Gas	4,888.9	3,409.2	9,473.3	1,232.2	11,582.6	74.1	30,660.3	258.6	180.4	501.2	65.2	612.8	3.9	1,622.1	
Total Petroleum	874.8	799.4	3,179.7	23,511.3	205.0	238.3	28,808.5	59.4	55.7	236.3	1,688.4	17.7	17.3	2,074.8	
Asphalt & Road Oil															
Aviation Gasoline				21.6			21.6				1.5			1.5	
Distillate Fuel Oil	381.2	264.1	948.1	6,484.0	59.8	71.1	8,208.3	28.3	19.6	70.3	480.6	4.4	5.3	608.5	
Jet Fuel				2,113.6		34.4	2,148.0				152.6		2.5	155.1	
Kerosene	9.4	1.4	1.5			0.5	12.8	0.7	0.1	0.1			+	0.9	
LPG (Propane)	484.1	217.0		9.8			710.9	30.4	13.6		0.6			44.7	
HGL			217.7			10.1	227.8			14.2			0.7	14.9	
Lubricants															
Motor Gasoline		313.5	221.2	14,559.9		73.1	15,167.6		22.2	15.6	1,028.7		5.2	1,071.7	
Residual Fuel		3.2	1.8	322.6	57.3	49.2	434.1		0.2	0.1	24.2	4.3	3.7	32.6	
Other Petroleum															
AvGas Blend Components			(0.8)				(0.8)			(0.1)				(0.1)	
Crude Oil															
MoGas Blend Components															
Misc. Products															
Naphtha (<401 deg. F)															
Other Oil (>401 deg. F)															
Pentanes Plus															
Petroleum Coke		0.2	466.9		87.9		555.0		+	47.7		9.0		56.7	
Still Gas			1,323.4				1,323.4			88.3				88.3	
Special Naphtha															
Unfinished Oils															
Waxes															
Geothermal					54.5		54.5					0.4		0.4	
Total (All Fuels)	5,763.7	4,223.5	13,102.7	24,743.6	21,339.8	343.8	69,517.0	318.0	237.5	780.5	1,753.5	1,540.9	24.1	4,654.6	

+ Does not exceed 0.05 TBtu or 0.05 MMT CO₂ Eq.

NO (Not Occurring)

NA (Not Available)

^a Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-19), and international bunker fuel consumption (see Table A-20).

^b Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table A-8: 2020 Energy Consumption Data and CO₂ Emissions from Fossil Fuel Combustion by Fuel Type

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Adjusted Consumption (TBtu) ^a							Emissions ^b (MMT CO ₂ Eq.) from Energy Use							
Fuel Type	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	
Total Coal	NO	14.5	448.5	NO	8,229.3	33.4	8,725.7	NO	1.4	43.0		788.2	3.1	835.6	
Residential Coal	NO						NO	NO						NO	
Commercial Coal		14.5					14.5		1.4					1.4	
Industrial Other Coal			448.5				448.5			43.0				43.0	
Transportation Coal				NO			NO				NO			NO	
Electric Power Coal					8,229.3		8,229.3					788.2		788.2	
U.S. Territory Coal (bit)						33.4	33.4						3.1	3.1	
Natural Gas	4,845.7	3,278.5	9,283.6	1,111.2	11,999.8	50.0	30,568.8	256.4	173.5	491.1	58.8	634.8	2.6	1,617.2	
Total Petroleum	863.6	780.2	3,085.9	21,091.9	184.4	228.3	26,234.3	58.4	54.4	229.3	1,514.2	16.2	16.6	1,889.1	
Asphalt & Road Oil															
Aviation Gasoline				20.2			20.2				1.4			1.4	
Distillate Fuel Oil	357.8	242.1	929.8	6,035.8	44.3	68.0	7,677.8	26.5	17.9	68.9	447.4	3.3	5.0	569.1	
Jet Fuel				1,670.2		33.6	1,703.8				120.6		2.4	123.0	
Kerosene	10.8	1.7	3.0			0.1	15.7	0.8	0.1	0.2			+	1.1	
LPG (Propane)	494.9	201.0		8.6			704.6	31.1	12.6		0.5			44.3	
HGL			204.3			9.6	213.9			13.3			0.6	13.9	
Lubricants															
Motor Gasoline		332.9	241.3	13,259.6		70.0	13,903.7		23.5	17.0	936.9		4.9	982.4	
Residual Fuel		2.3		97.5	52.7	47.1	199.6		0.2		7.3	4.0	3.5	15.0	
Other Petroleum															
AvGas Blend Components			(0.8)				(0.8)			(0.1)				(0.1)	
Crude Oil															
MoGas Blend Components															
Misc. Products															
Naphtha (<401 deg. F)															
Other Oil (>401 deg. F)															
Pentanes Plus															
Petroleum Coke		0.1	448.9		87.4		536.5		+	45.8		8.9		54.8	
Still Gas			1,259.4				1,259.4			84.0				84.0	
Special Naphtha															
Unfinished Oils															
Waxes															
Geothermal					54.2		54.2					0.4		0.4	
Total (All Fuels)	5,709.3	4,073.2	12,818.0	22,203.1	20,467.7	311.8	65,583.0	314.8	229.3	763.4	1,573.0	1,439.6	22.3	4,342.3	

+ Does not exceed 0.05 TBtu or 0.05 MMT CO₂ Eq.

NO (Not Occurring)

NA (Not Available)

^a Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-19), and international bunker fuel consumption (see Table A-20).

^b Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table A-9: 2019 Energy Consumption Data and CO₂ Emissions from Fossil Fuel Combustion by Fuel Type

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Adjusted Consumption (TBtu) ^a							Emissions ^b (MMT CO ₂ Eq.) from Energy Use							
Fuel Type	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	
Total Coal	NO	16.7	517.1	NO	10,181.3	38.6	10,753.7	NO	1.6	49.4		973.5	3.6	1,028.1	
Residential Coal	NO						NO	NO						NO	
Commercial Coal		16.7					16.7		1.6					1.6	
Industrial Other Coal			517.1				517.1			49.4				49.4	
Transportation Coal				NO			NO				NO			NO	
Electric Power Coal					10,181.3		10,181.3					973.5		973.5	
U.S. Territory Coal (bit)						38.6	38.6						3.6	3.6	
Natural Gas	5,208.0	3,647.3	9,481.8	1,114.1	11,658.4	71.3	31,181.0	275.5	192.9	501.5	58.9	616.6	3.8	1,649.3	
Total Petroleum	995.3	815.4	3,461.8	24,498.9	188.6	240.8	30,200.8	67.4	57.2	258.9	1,757.7	16.2	17.5	2,174.9	
Asphalt & Road Oil															
Aviation Gasoline				23.4			23.4				1.6			1.6	
Distillate Fuel Oil	421.2	292.9	1,073.1	6,393.0	53.9	71.6	8,305.6	31.2	21.7	79.6	474.0	4.0	5.3	615.8	
Jet Fuel				2,496.0		34.6	2,530.5				180.3		2.5	182.8	
Kerosene	10.8	1.8	1.4			0.5	14.5	0.8	0.1	0.1			+	1.1	
LPG (Propane)	563.4	182.0		12.5			757.9	35.4	11.4		0.8			47.7	
HGL			225.1			10.2	235.3			14.7			0.7	15.3	
Lubricants															
Motor Gasoline		336.1	242.7	15,381.1		74.1	16,034.1		23.7	17.1	1,086.5		5.2	1,132.7	
Residual Fuel		2.3		192.9	58.8	49.8	303.8		0.2		14.5	4.4	3.7	22.8	
Other Petroleum															
AvGas Blend Components			(1.2)				(1.2)			(0.1)				(0.1)	
Crude Oil															
MoGas Blend Components															
Misc. Products															
Naphtha (<401 deg. F)															
Other Oil (>401 deg. F)															
Pentanes Plus															
Petroleum Coke		0.2	545.9		75.9		622.0		+	55.7		7.8		63.5	
Still Gas			1,374.7				1,374.7			91.7				91.7	
Special Naphtha															
Unfinished Oils															
Waxes															
Geothermal					52.8		52.8					0.4		0.4	
Total (All Fuels)	6,203.4	4,479.4	13,460.7	25,613.0	22,081.0	350.7	72,188.2	342.9	251.7	809.8	1,816.6	1,606.7	24.8	4,852.6	

+ Does not exceed 0.05 TBtu or 0.05 MMT CO₂ Eq.

NO (Not Occurring)

NA (Not Available)

^a Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-19), and international bunker fuel consumption (see Table A-20).

^b Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table A-10: 2018 Energy Consumption Data and CO₂ Emissions from Fossil Fuel Combustion by Fuel Type

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Adjusted Consumption (TBtu) ^a							Emissions ^b (MMT CO ₂ Eq.) from Energy Use							
Fuel Type	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	
Total Coal	NO	18.7	568.5	NO	12,053.0	27.7	12,668.0	NO	1.8	54.4		1,152.9	2.6	1,211.6	
Residential Coal	NO						NO	NO						NO	
Commercial Coal		18.7					18.7		1.8					1.8	
Industrial Other Coal			568.5				568.5			54.4				54.4	
Transportation Coal				NO			NO				NO			NO	
Electric Power Coal					12,053.0		12,053.0					1,152.9		1,152.9	
U.S. Territory Coal (bit)						27.7	27.7						2.6	2.6	
Natural Gas	5,174.4	3,638.3	9,325.3	962.2	10,921.5	62.4	30,084.1	273.8	192.5	493.5	50.9	577.9	3.3	1,592.0	
Total Petroleum	955.5	740.8	3,506.8	24,561.9	260.4	278.0	30,303.4	65.1	52.0	262.6	1,762.2	22.2	20.1	2,184.2	
Asphalt & Road Oil															
Aviation Gasoline				22.4			22.4				1.5			1.5	
Distillate Fuel Oil	440.7	280.5	1,082.1	6,427.8	80.6	85.4	8,397.2	32.7	20.8	80.2	476.6	6.0	6.3	622.6	
Jet Fuel				2,385.1		40.4	2,425.5				172.3		2.9	175.2	
Kerosene	8.2	1.3	1.6			0.4	11.6	0.6	0.1	0.1			+	0.9	
LPG (Propane)	506.5	176.0		12.6			695.1	31.8	11.1		0.8			43.7	
HGL			204.0			8.8	212.8			13.3			0.6	13.8	
Lubricants															
Motor Gasoline		279.5	205.6	15,527.5		119.1	16,131.8		19.7	14.5	1,097.0		8.4	1,139.7	
Residual Fuel		3.1		186.5	78.3	23.8	291.7		0.2		14.0	5.9	1.8	21.9	
Other Petroleum															
AvGas Blend Components			(1.6)				(1.6)			(0.1)				(0.1)	
Crude Oil															
MoGas Blend Components															
Misc. Products															
Naphtha (<401 deg. F)															
Other Oil (>401 deg. F)															
Pentanes Plus															
Petroleum Coke		0.4	569.8		101.5		671.6		+	58.2		10.4		68.6	
Still Gas			1,445.3				1,445.3			96.4				96.4	
Special Naphtha															
Unfinished Oils															
Waxes															
Geothermal					54.5		54.5					0.4		0.4	
Total (All Fuels)	6,129.9	4,397.8	13,400.6	25,524.1	23,289.3	368.2	73,109.9	338.9	246.3	810.5	1,813.1	1,753.4	25.9	4,988.2	

+ Does not exceed 0.05 TBtu or 0.05 MMT CO₂ Eq.

NO (Not Occurring)

NA (Not Available)

^a Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-19), and international bunker fuel consumption (see Table A-20).

^b Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table A-11: 2017 Energy Consumption Data and CO₂ Emissions from Fossil Fuel Combustion by Fuel Type

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Adjusted Consumption (TBtu) ^a							Emissions ^b (MMT CO ₂ Eq.) from Energy Use							
Fuel Type	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	
Total Coal	NO	20.7	614.6	NO	12,622.2	25.0	13,282.4	NO	2.0	58.7		1,207.1	2.3	1,270.1	
Residential Coal	NO						NO	NO						NO	
Commercial Coal		20.7					20.7		2.0					2.0	
Industrial Other Coal			614.6				614.6			58.7				58.7	
Transportation Coal				NO			NO				NO			NO	
Electric Power Coal					12,622.2		12,622.2					1,207.1		1,207.1	
U.S. Territory Coal (bit)						25.0	25.0						2.3	2.3	
Natural Gas	4,563.5	3,272.9	8,846.5	798.6	9,555.2	48.1	27,084.7	241.5	173.2	468.1	42.3	505.6	2.5	1,433.2	
Total Petroleum	773.6	814.5	3,391.3	24,220.4	217.7	292.3	29,710.0	52.5	57.2	253.5	1,738.1	18.9	21.1	2,141.3	
Asphalt & Road Oil															
Aviation Gasoline				20.9			20.9				1.4			1.4	
Distillate Fuel Oil	334.5	249.7	926.1	6,287.9	54.7	68.8	7,921.7	24.8	18.5	68.6	465.9	4.1	5.1	586.9	
Jet Fuel				2,377.2		43.9	2,421.0				171.7		3.2	174.9	
Kerosene	8.4	1.2	1.1			0.4	11.2	0.6	0.1	0.1			+	0.8	
LPG (Propane)	430.7	155.7		12.4			598.8	27.1	9.8		0.8			37.6	
HGL			193.7			8.8	202.5			12.6			0.6	13.2	
Lubricants															
Motor Gasoline		403.7	295.7	15,302.8		129.1	16,131.3		28.5	20.9	1,081.8		9.1	1,140.4	
Residual Fuel		3.8	2.8	219.3	65.8	41.3	333.0		0.3	0.2	16.5	4.9	3.1	25.0	
Other Petroleum															
AvGas Blend Components			(0.2)				(0.2)			(+)				(+)	
Crude Oil															
MoGas Blend Components															
Misc. Products															
Naphtha (<401 deg. F)															
Other Oil (>401 deg. F)															
Pentanes Plus															
Petroleum Coke		0.5	553.0		97.2		650.8		0.1	56.5		9.9		66.4	
Still Gas			1,419.0				1,419.0			94.7				94.7	
Special Naphtha															
Unfinished Oils															
Waxes															
Geothermal					54.3		54.3					0.4		0.4	
Total (All Fuels)	5,337.1	4,108.0	12,852.4	25,019.0	22,449.5	365.4	70,131.5	294.0	232.4	780.4	1,780.3	1,732.0	25.9	4,845.1	

+ Does not exceed 0.05 TBtu or 0.05 MMT CO₂ Eq.

NO (Not Occurring)

NA (Not Available)

^a Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-19), and international bunker fuel consumption (see Table A-20).

^b Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table A-12: 2016 Energy Consumption Data and CO₂ Emissions from Fossil Fuel Combustion by Fuel Type

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Adjusted Consumption (TBtu) ^a							Emissions ^b (MMT CO ₂ Eq.) from Energy Use							
Fuel Type	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	
Total Coal	NO	23.7	662.1	NO	12,996.4	35.5	13,717.7	NO	2.3	63.2		1,242.0	3.3	1,310.8	
Residential Coal	NO						NO	NO						NO	
Commercial Coal		23.7					23.7		2.3					2.3	
Industrial Other Coal			662.1				662.1			63.2				63.2	
Transportation Coal				NO			NO				NO			NO	
Electric Power Coal					12,996.4		12,996.4					1,242.0		1,242.0	
U.S. Territory Coal (bit)						35.5	35.5						3.3	3.3	
Natural Gas	4,505.8	3,223.5	8,770.1	757.2	10,301.3	63.6	27,621.5	238.4	170.5	464.0	40.1	545.0	3.4	1,461.3	
Total Petroleum	804.9	838.7	3,482.6	23,959.5	243.9	269.6	29,599.2	54.8	59.1	261.1	1,717.8	21.5	19.5	2,133.8	
Asphalt & Road Oil															
Aviation Gasoline				20.5			20.5				1.4			1.4	
Distillate Fuel Oil	361.3	271.1	955.0	6,104.1	54.9	80.2	7,826.6	26.8	20.1	70.8	452.4	4.1	5.9	580.1	
Jet Fuel				2,297.8		29.6	2,327.4				166.0		2.1	168.1	
Kerosene	13.7	2.1	2.3			0.4	18.4	1.0	0.2	0.2			+	1.3	
LPG (Propane)	429.9	150.0		11.8			591.7	27.0	9.4		0.7			37.2	
HGL			206.2			8.2	214.4			13.4			0.5	13.9	
Lubricants															
Motor Gasoline		410.8	287.2	15,352.9		105.0	16,155.9		29.0	20.3	1,084.4		7.4	1,141.1	
Residual Fuel		4.4	2.1	172.4	70.7	46.2	295.8		0.3	0.2	12.9	5.3	3.5	22.2	
Other Petroleum															
AvGas Blend Components			(0.3)				(0.3)			(+)				(+)	
Crude Oil															
MoGas Blend Components															
Misc. Products															
Naphtha (<401 deg. F)															
Other Oil (>401 deg. F)															
Pentanes Plus															
Petroleum Coke		0.3	591.4		118.3		710.1		+	60.4		12.1		72.5	
Still Gas			1,438.6				1,438.6			96.0				96.0	
Special Naphtha															
Unfinished Oils															
Waxes															
Geothermal					54.0		54.0					0.4		0.4	
Total (All Fuels)	5,310.7	4,086.0	12,914.8	24,716.7	23,595.6	368.7	70,992.4	293.2	231.9	788.3	1,757.9	1,808.9	26.2	4,906.3	

+ Does not exceed 0.05 TBtu or 0.05 MMT CO₂ Eq.

NO (Not Occurring)

NA (Not Available)

^a Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-19), and international bunker fuel consumption (see Table A-20).

^b Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table A-13: 2015 Energy Consumption Data and CO₂ Emissions from Fossil Fuel Combustion by Fuel Type

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Adjusted Consumption (Tbtu) ^a							Emissions ^b (MMT CO ₂ Eq.) from Energy Use							
Fuel Type	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	
Total Coal	NO	31.1	732.3	NO	14,138.3	35.9	14,937.6	NO	3.0	69.8		1,351.4	3.3	1,427.5	
Residential Coal	NO						NO	NO						NO	
Commercial Coal		31.1					31.1		3.0					3.0	
Industrial Other Coal			732.3				732.3			69.8				69.8	
Transportation Coal				NO			NO				NO			NO	
Electric Power Coal					14,138.3		14,138.3					1,351.4		1,351.4	
U.S. Territory Coal (bit)						35.9	35.9						3.3	3.3	
Natural Gas	4,776.9	3,315.6	8,688.1	744.8	9,926.5	57.4	27,509.4	252.7	175.4	459.6	39.4	525.2	3.0	1,455.4	
Total Petroleum	943.1	940.7	3,503.8	23,421.8	276.0	305.7	29,391.0	64.9	66.4	263.5	1,679.0	23.7	22.2	2,119.7	
Asphalt & Road Oil															
Aviation Gasoline				21.1			21.1				1.5			1.5	
Distillate Fuel Oil	487.3	318.2	1,026.9	6,154.7	70.4	78.8	8,136.2	36.1	23.6	76.1	456.3	5.2	5.8	603.3	
Jet Fuel				2,180.9		36.0	2,217.0				157.5		2.6	160.1	
Kerosene	10.1	1.4	1.7			0.1	13.4	0.7	0.1	0.1			+	1.0	
LPG (Propane)	445.7	148.0		10.0			603.7	28.0	9.3		0.6			38.0	
HGL			220.6			8.1	228.6			14.3			0.5	14.8	
Lubricants															
Motor Gasoline		468.6	321.4	14,998.5		113.0	15,901.4		33.1	22.7	1,058.8		8.0	1,122.5	
Residual Fuel		4.0		56.6	93.9	69.6	224.0		0.3		4.2	7.0	5.2	16.8	
Other Petroleum															
AvGas Blend Components			(0.3)				(0.3)			(+)				(+)	
Crude Oil															
MoGas Blend Components															
Misc. Products															
Naphtha (<401 deg. F)															
Other Oil (>401 deg. F)															
Pentanes Plus															
Petroleum Coke		0.5	600.8		111.7		713.0		0.1	61.3		11.4		72.8	
Still Gas			1,332.9				1,332.9			88.9				88.9	
Special Naphtha															
Unfinished Oils															
Waxes															
Geothermal					54.3		54.3					0.4		0.4	
Total (All Fuels)	5,720.0	4,287.4	12,924.2	24,166.6	24,395.0	399.0	71,892.2	317.6	244.8	793.0	1,718.4	1,900.6	28.5	5,002.9	

+ Does not exceed 0.05 Tbtu or 0.05 MMT CO₂ Eq.

NO (Not Occurring)

NA (Not Available)

^a Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-19), and international bunker fuel consumption (see Table A-20).

^b Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table A-14: 2010 Energy Consumption Data and CO₂ Emissions from Fossil Fuel Combustion by Fuel Type

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Adjusted Consumption (TBtu) ^a							Emissions ^b (MMT CO ₂ Eq.) from Energy Use							
Fuel Type	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	
Total Coal	NO	69.7	993.0	NO	19,133.5	34.7	20,230.8	NO	6.6	94.2		1,827.2	3.2	1,931.2	
Residential Coal	NO						NO	NO						NO	
Commercial Coal		69.7					69.7		6.6					6.6	
Industrial Other Coal			993.0				993.0			94.2				94.2	
Transportation Coal				NO			NO				NO			NO	
Electric Power Coal					19,133.5		19,133.5					1,827.2		1,827.2	
U.S. Territory Coal (bit)						34.7	34.7						3.2	3.2	
Natural Gas	4,878.1	3,164.7	7,669.9	719.0	7,527.6	27.8	23,987.1	258.9	168.0	407.1	38.2	399.5	1.5	1,273.1	
Total Petroleum	1,099.9	695.5	3,848.9	23,028.4	370.3	407.7	29,450.6	75.6	49.7	289.8	1,658.5	31.4	29.8	2,134.9	
Asphalt & Road Oil															
Aviation Gasoline				27.0			27.0				1.9			1.9	
Distillate Fuel Oil	540.9	376.8	1,101.4	5,729.4	79.7	66.4	7,894.7	40.1	28.0	81.7	425.2	5.9	4.9	585.9	
Jet Fuel				2,096.4		36.6	2,133.0				151.4		2.6	154.0	
Kerosene	29.1	4.8	7.3			7.5	48.7	2.1	0.4	0.5			0.5	3.6	
LPG (Propane)	529.8	140.0		4.6			674.4	33.3	8.8		0.3			42.4	
HGL			197.7			15.7	213.3			12.9			1.0	13.9	
Lubricants															
Motor Gasoline		111.8	559.7	14,898.8		112.9	15,683.2		7.9	39.8	1,059.3		8.0	1,115.0	
Residual Fuel		61.7	25.9	272.2	154.1	168.7	682.5		4.6	1.9	20.4	11.6	12.7	51.2	
Other Petroleum															
AvGas Blend Components			(0.2)				(0.2)			(+)				(+)	
Crude Oil															
MoGas Blend Components															
Misc. Products															
Naphtha (<401 deg. F)															
Other Oil (>401 deg. F)															
Pentanes Plus															
Petroleum Coke		0.3	633.0		136.6		770.0		+	64.6		13.9		78.6	
Still Gas			1,324.0				1,324.0			88.3				88.3	
Special Naphtha															
Unfinished Oils															
Waxes															
Geothermal					51.9		51.9					0.4		0.4	
Total (All Fuels)	5,978.0	3,929.8	12,511.8	23,747.3	27,083.3	470.2	73,720.5	334.5	224.3	791.1	1,696.6	2,258.6	34.5	5,339.6	

+ Does not exceed 0.05 TBtu or 0.05 MMT CO₂ Eq.

NO (Not Occurring)

NA (Not Available)

^a Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-19), and international bunker fuel consumption (see Table A-20).

^b Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table A-15: 2005 Energy Consumption Data and CO₂ Emissions from Fossil Fuel Combustion by Fuel Type

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Adjusted Consumption (TBtu) ^a							Emissions ^b (MMT CO ₂ Eq.) from Energy Use							
Fuel Type	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	
Total Coal	8.4	97.0	1,246.0	NO	20,737.2	32.7	22,121.3	0.8	9.3	117.8		1,982.8	3.0	2,113.7	
Residential Coal	8.4						8.4	0.8						0.8	
Commercial Coal		97.0					97.0		9.3					9.3	
Industrial Other Coal			1,246.0				1,246.0			117.8				117.8	
Transportation Coal				NO			NO				NO			NO	
Electric Power Coal					20,737.2		20,737.2					1,982.8		1,982.8	
U.S. Territory Coal (bit)						32.7	32.7						3.0	3.0	
Natural Gas	4,946.4	3,073.2	7,314.7	623.9	6,014.5	24.3	21,997.0	262.2	162.9	387.8	33.1	318.9	1.3	1,166.2	
Total Petroleum	1,366.4	760.7	4,554.4	25,369.9	1,222.1	649.5	33,923.0	95.9	54.9	342.0	1,825.5	98.0	47.6	2,463.8	
Asphalt & Road Oil															
Aviation Gasoline				35.4			35.4				2.4			2.4	
Distillate Fuel Oil	769.1	402.9	1,119.4	6,193.8	114.5	136.5	8,736.3	57.4	30.1	83.6	462.6	8.5	10.2	652.5	
Jet Fuel				2,620.4		65.5	2,685.9				189.2		4.7	194.0	
Kerosene	83.8	21.6	39.1			5.8	150.2	6.1	1.6	2.9			0.4	11.0	
LPG (Propane)	513.5	131.6		28.2			673.3	32.3	8.3		1.8			42.3	
HGL			338.8			10.6	349.5			21.8			0.7	22.5	
Lubricants															
Motor Gasoline		88.6	689.5	16,235.7		200.2	17,213.9		6.3	48.8	1,150.1		14.2	1,219.4	
Residual Fuel		115.8	223.2	256.4	876.5	230.9	1,702.8		8.7	16.8	19.3	65.8	17.3	127.9	
Other Petroleum															
AvGas Blend Components			8.3				8.3			0.6				0.6	
Crude Oil															
MoGas Blend Components															
Misc. Products															
Naphtha (<401 deg. F)															
Other Oil (>401 deg. F)															
Pentanes Plus															
Petroleum Coke		0.3	706.6		231.1		938.0		+	72.1		23.6		95.8	
Still Gas			1,429.4				1,429.4			95.4				95.4	
Special Naphtha															
Unfinished Oils															
Waxes															
Geothermal					50.1		50.1					0.5		0.5	
Total (All Fuels)	6,321.2	3,930.9	13,115.0	25,993.8	28,024.0	706.5	78,091.5	358.9	227.1	847.6	1,858.6	2,400.1	51.9	5,744.1	

+ Does not exceed 0.05 TBtu or 0.05 MMT CO₂ Eq.

NO (Not Occurring)

NA (Not Available)

^a Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-19), and international bunker fuel consumption (see Table A-20).

^b Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table A-16: 2000 Energy Consumption Data and CO₂ Emissions from Fossil Fuel Combustion by Fuel Type

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Adjusted Consumption (TBtu) ^a							Emissions ^b (MMT CO ₂ Eq.) from Energy Use							
Fuel Type	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	
Total Coal	11.4	91.9	1,361.6	NO	20,220.2	5.2	21,690.2	1.1	8.8	128.5		1,926.4	0.5	2,065.2	
Residential Coal	11.4						11.4	1.1						1.1	
Commercial Coal		91.9					91.9		8.8					8.8	
Industrial Other Coal			1,361.6				1,361.6			128.5				128.5	
Transportation Coal				NO			NO				NO			NO	
Electric Power Coal					20,220.2		20,220.2					1,926.4		1,926.4	
U.S. Territory Coal (bit)						5.2	5.2						0.5	0.5	
Natural Gas	5,104.6	3,251.5	8,636.6	672.0	5,293.4	12.7	22,970.8	270.8	172.5	458.2	35.7	280.8	0.7	1,218.6	
Total Petroleum	1,425.4	766.7	3,985.2	24,295.9	1,144.1	491.2	32,108.7	99.8	55.3	300.6	1,756.6	88.5	35.9	2,336.6	
Asphalt & Road Oil															
Aviation Gasoline				36.3			36.3				2.5			2.5	
Distillate Fuel Oil	775.2	420.7	1,000.1	5,442.4	174.7	87.5	7,900.6	58.0	31.5	74.8	406.9	13.1	6.5	590.7	
Jet Fuel				2,698.9		68.6	2,767.5				194.9		5.0	199.9	
Kerosene	94.6	29.7	15.6			2.4	142.2	6.9	2.2	1.1			0.2	10.4	
LPG (Propane)	555.6	150.6		11.9			718.1	34.9	9.5		0.7			45.1	
HGL			396.9			7.9	404.8			25.6			0.5	26.1	
Lubricants															
Motor Gasoline		74.1	249.9	15,663.0		186.3	16,173.3		5.3	17.8	1,118.2		13.3	1,154.6	
Residual Fuel		91.6	190.3	443.5	870.8	138.6	1,734.8		6.9	14.3	33.3	65.4	10.4	130.3	
Other Petroleum															
AvGas Blend Components			3.8				3.8			0.3				0.3	
Crude Oil															
MoGas Blend Components															
Misc. Products															
Naphtha (<401 deg. F)															
Other Oil (>401 deg. F)															
Pentanes Plus															
Petroleum Coke		0.2	697.3		98.6		796.2		+	71.2		10.1		81.3	
Still Gas			1,431.2				1,431.2			95.5				95.5	
Special Naphtha															
Unfinished Oils															
Waxes															
Geothermal					48.1		48.1					0.5		0.5	
Total (All Fuels)	6,541.4	4,110.2	13,983.4	24,967.9	26,705.8	509.1	76,817.7	371.7	236.5	887.2	1,792.2	2,296.2	37.0	5,620.9	

+ Does not exceed 0.05 TBtu or 0.05 MMT CO₂ Eq.

NO (Not Occurring)

NA (Not Available)

^a Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-19), and international bunker fuel consumption (see Table A-20).

^b Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table A-17: 1995 Energy Consumption Data and CO₂ Emissions from Fossil Fuel Combustion by Fuel Type

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Adjusted Consumption (TBtu) ^a							Emissions ^b (MMT CO ₂ Eq.) from Energy Use							
Fuel Type	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	
Total Coal	17.5	116.8	1,557.0	NO	17,466.3	4.7	19,162.2	1.7	11.2	147.2		1,659.9	0.4	1,820.4	
Residential Coal	17.5						17.5	1.7						1.7	
Commercial Coal		116.8					116.8		11.2					11.2	
Industrial Other Coal			1,557.0				1,557.0			147.2				147.2	
Transportation Coal				NO			NO				NO			NO	
Electric Power Coal					17,466.3		17,466.3					1,659.9		1,659.9	
U.S. Territory Coal (bit)						4.7	4.7						0.4	0.4	
Natural Gas	4,954.2	3,096.0	8,700.5	724.0	4,302.0		21,776.6	262.8	164.2	461.5	38.4	228.2		1,155.0	
Total Petroleum	1,259.3	724.1	4,008.0	21,528.1	754.5	290.4	28,564.4	88.7	52.4	298.8	1,542.3	58.7	21.1	2,062.0	
Asphalt & Road Oil															
Aviation Gasoline				39.6			39.6				2.7			2.7	
Distillate Fuel Oil	789.7	418.0	964.1	4,383.3	108.0	62.5	6,725.6	58.4	30.9	71.3	324.2	8.0	4.6	497.4	
Jet Fuel				2,427.1		57.2	2,484.4				172.1		4.1	176.2	
Kerosene	74.3	22.1	15.4			2.0	113.9	5.4	1.6	1.1			0.1	8.3	
LPG (Propane)	395.3	108.9		17.8			521.9	24.9	6.8		1.1			32.8	
HGL			383.3			2.3	385.6			24.5			0.1	24.7	
Lubricants															
Motor Gasoline		33.5	370.5	14,273.1		84.5	14,761.5		2.4	26.3	1,013.1		6.0	1,047.7	
Residual Fuel		141.5	284.7	387.3	566.0	81.9	1,461.3		10.6	21.4	29.1	42.5	6.1	109.7	
Other Petroleum															
AvGas Blend Components			5.3				5.3			0.4				0.4	
Crude Oil			14.5				14.5			1.1				1.1	
MoGas Blend Components															
Misc. Products															
Naphtha (<401 deg. F)															
Other Oil (>401 deg. F)															
Pentanes Plus															
Petroleum Coke		0.1	600.7		80.6		681.4		+	61.3		8.2		69.6	
Still Gas			1,369.5				1,369.5			91.4				91.4	
Special Naphtha															
Unfinished Oils															
Waxes															
Geothermal					45.6		45.6					0.4		0.4	
Total (All Fuels)	6,231.0	3,936.9	14,265.6	22,252.1	22,568.4	295.0	69,548.9	353.1	227.8	907.5	1,580.7	1,947.2	21.5	5,037.8	

+ Does not exceed 0.05 TBtu or 0.05 MMT CO₂ Eq.

NO (Not Occurring)

NA (Not Available)

^a Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-19), and international bunker fuel consumption (see Table A-20).

^b Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table A-18: 1990 Energy Consumption Data and CO₂ Emissions from Fossil Fuel Combustion by Fuel Type

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Adjusted Consumption (TBtu) ^a							Emissions ^b (MMT CO ₂ Eq.) from Energy Use							
Fuel Type	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	Res.	Comm.	Ind.	Trans.	Elec.	Terr.	Total	
Total Coal	31.1	124.5	1,668.1	NO	16,261.0	5.4	18,090.1	3.0	12.0	157.8		1,546.5	0.5	1,719.8	
Residential Coal	31.1						31.1	3.0						3.0	
Commercial Coal		124.5					124.5		12.0					12.0	
Industrial Other Coal			1,668.1				1,668.1			157.8				157.8	
Transportation Coal				NO			NO				NO			NO	
Electric Power Coal					16,261.0		16,261.0					1,546.5		1,546.5	
U.S. Territory Coal (bit)						5.4	5.4						0.5	0.5	
Natural Gas	4,486.6	2,679.6	7,687.2	679.2	3,308.5		18,841.1	237.8	142.0	407.4	36.0	175.4		998.6	
Total Petroleum	1,375.7	1,022.5	4,171.9	19,974.7	1,289.4	268.2	28,102.4	97.8	74.3	311.2	1,432.9	97.5	19.5	2,033.3	
Asphalt & Road Oil															
Aviation Gasoline				45.0			45.0				3.1			3.1	
Distillate Fuel Oil	959.2	525.4	1,098.5	3,554.8	96.5	56.4	6,290.8	70.9	38.9	81.2	262.9	7.1	4.2	465.2	
Jet Fuel				2,587.7		48.6	2,636.3				184.1		3.5	187.5	
Kerosene	63.9	11.8	12.3			2.0	90.0	4.7	0.9	0.9			0.1	6.6	
LPG (Propane)	352.6	102.4		22.9			477.9	22.2	6.4		1.4			30.0	
HGL			309.7			6.9	316.6			19.8			0.4	20.2	
Lubricants															
Motor Gasoline		153.0	254.8	13,464.1		75.9	13,947.7		10.9	18.1	958.9		5.4	993.3	
Residual Fuel		229.8	364.1	300.3	1,162.6	78.5	2,135.3		17.3	27.3	22.6	87.3	5.9	160.3	
Other Petroleum															
AvGas Blend Components			0.2				0.2			+				+	
Crude Oil			50.9				50.9			3.8				3.8	
MoGas Blend Components			53.7				53.7			3.8				3.8	
Misc. Products															
Naphtha (<401 deg. F)															
Other Oil (>401 deg. F)															
Pentanes Plus															
Petroleum Coke			591.2		30.4		621.5			60.4		3.1		63.5	
Still Gas			1,436.5				1,436.5			95.8				95.8	
Special Naphtha															
Unfinished Oils															
Waxes															
Geothermal					52.7		52.7					0.5		0.5	
Total (All Fuels)	5,893.3	3,826.5	13,527.2	20,654.0	20,911.6	273.6	65,086.3	338.6	228.3	876.5	1,468.9	1,820.0	20.0	4,752.2	

+ Does not exceed 0.05 TBtu or 0.05 MMT CO₂ Eq.

NO (Not Occurring)

NA (Not Available)

^a Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-19), and international bunker fuel consumption (see Table A-20).

^b Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table A-19: Unadjusted Non-Energy Fuel Consumption (TBtu)

Sector/Fuel Type	1990	1995	2000	2005	2010	2016	2017	2018	2019	2020	2021	2022	2023
Industry	4,436.4	4,880.4	5,401.2	5,331.7	4,610.5	5,066.7	5,269.1	5,595.7	5,533.9	5,492.2	5,738.0	5,715.2	5,874.3
Industrial Coking Coal	0.0	37.8	53.5	80.4	64.8	89.6	113.0	124.7	113.0	79.4	77.5	46.4	65.4
Industrial Other Coal	7.6	10.5	11.5	11.0	9.6	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
Natural Gas to Chemical Plants, Other Uses	305.9	371.0	401.7	270.4	310.0	532.0	631.1	730.8	732.2	731.5	731.5	730.8	729.3
Asphalt & Road Oil	1,170.2	1,178.2	1,275.7	1,323.2	877.8	853.4	849.2	792.8	843.9	832.3	898.1	916.1	891.8
HGL	1,219.6	1,546.2	1,756.2	1,602.5	1,853.0	2,273.6	2,306.3	2,595.9	2,579.1	2,693.0	2,865.8	3,010.8	3,216.8
Lubricants	186.3	177.8	189.9	160.2	135.9	135.1	124.9	122.0	118.3	111.1	113.5	115.0	86.3
Pentanes Plus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Naphtha (<401 deg. F)	347.8	373.0	613.5	698.7	490.6	420.0	436.2	447.1	396.7	354.6	354.8	265.5	271.8
Other Oil (>401 deg. F)	753.9	801.0	722.2	708.0	452.5	222.5	262.9	239.1	234.1	217.0	216.9	127.7	119.6
Still Gas	36.7	47.9	17.0	67.7	147.8	166.1	163.8	166.9	158.7	145.4	152.8	157.1	155.8
Petroleum Coke	123.1	120.6	98.7	186.9	61.0	61.2	57.0	58.9	56.4	46.2	48.1	45.0	47.7
Special Naphtha	107.1	70.8	97.4	62.5	26.1	93.6	100.3	92.0	95.6	86.6	81.2	89.2	89.2
Other (Wax/Misc.)													
Distillate Fuel Oil	7.0	8.0	11.7	16.0	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8
Waxes	33.3	40.6	33.1	31.4	17.1	12.8	10.2	12.4	10.4	9.2	11.8	13.0	9.0
Miscellaneous Products	137.8	97.1	119.2	112.8	158.7	191.3	198.8	198.0	180.2	170.7	170.8	183.4	176.2
Transportation	176.0	167.9	179.4	151.3	154.8	154.4	142.0	137.0	131.3	115.6	119.0	129.9	97.5
Lubricants	176.0	167.9	179.4	151.3	154.8	154.4	142.0	137.0	131.3	115.6	119.0	129.9	97.5
U.S. Territories	50.8	55.4	140.8	114.9	27.4	10.5	3.5	3.6	3.6	3.5	3.5	1.0	1.0
Lubricants	0.7	2.0	3.1	4.6	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Other Petroleum (Misc. Prod.)	50.1	53.4	137.7	110.3	26.4	9.5	2.4	2.5	2.6	2.5	2.5	0.0	0.0
Total	4,663.3	5,103.8	5,721.4	5,598.0	4,792.7	5,231.5	5,414.6	5,736.2	5,668.9	5,611.4	5,860.6	5,846.1	5,972.8

Note: These values are unadjusted non-energy fuel use provided by EIA. They have not yet been adjusted to remove petroleum feedstock exports and processes accounted for in the Industrial Processes and Product Use chapter. Totals may not sum due to independent rounding.

Table A-20: International Bunker Fuel Consumption (TBtu)

Fuel Type	1990	1995	2000	2005	2010	2016	2017	2018	2019	2020	2021	2022	2023
Aviation Jet Fuel	541.8	705.1	881.5	854.4	866.4	1,052.1	1,104.2	1,147.7	1,112.0	563.7	721.5	945.6	943.9
Marine Residual Fuel Oil	715.7	523.2	444.1	581.0	619.8	450.7	445.3	417.6	336.2	294.0	292.3	325.2	301.8
Marine Distillate Fuel Oil	158.0	125.7	85.9	126.9	128.2	117.5	121.3	134.4	136.3	105.0	100.1	96.8	94.0
Total	1,415.5	1,354.0	1,411.4	1,562.3	1,614.4	1,620.3	1,670.8	1,699.7	1,584.5	962.6	1,113.9	1,367.5	1,339.7

Note: Further information on the calculation of international bunker fuel consumption of aviation jet fuel is provided in Annex 3.3 Methodology for Estimating Emissions from Commercial Aircraft Jet Fuel Consumption. Totals may not sum due to independent rounding.

Table A-21: C Content Coefficients by Year (MMT C/QBtu)

Fuel Type	1990	1995	2000	2005	2010	2016	2017	2018	2019	2020	2021	2022	2023
Coal													
Residential Coal ^a	26.19	26.13	26.00	26.04	25.75	26.01	26.09	26.09	26.11	26.21	26.16	26.18	26.38
Commercial Coal	26.19	26.13	26.00	26.04	25.75	26.01	26.09	26.09	26.11	26.21	26.16	26.18	26.38
Industrial Coking Coal	25.53	25.57	25.63	25.60	25.58	25.57	25.56	25.59	25.59	25.60	25.60	25.61	25.59
Industrial Other Coal	25.81	25.79	25.74	25.79	25.86	26.03	26.06	26.08	26.07	26.13	26.10	26.10	26.12
Electric Power Coal ^b	25.94	25.92	25.98	26.08	26.05	26.06	26.08	26.09	26.08	26.12	26.13	26.13	26.15
U.S. Territory Coal (bit)	25.14	25.14	25.14	25.14	25.14	25.14	25.14	25.14	25.14	25.14	25.14	25.14	25.14
Natural Gas													
Pipeline Natural Gas ^d	14.46	14.47	14.47	14.46	14.48	14.43	14.43	14.43	14.43	14.43	14.43	14.43	14.43
Petroleum													
Asphalt & Road Oil	20.55	20.55	20.55	20.55	20.55	20.55	20.55	20.55	20.55	20.55	20.55	20.55	20.55
Aviation Gasoline	18.86	18.86	18.86	18.86	18.86	18.86	18.86	18.86	18.86	18.86	18.86	18.86	18.86
Distillate Fuel Oil No. 2 ^{c,d}	20.17	20.17	20.39	20.37	20.24	20.21	20.21	20.22	20.22	20.22	20.22	20.22	20.22
Jet Fuel ^d	19.40	19.34	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70
Kerosene	19.96	19.96	19.96	19.96	19.96	19.96	19.96	19.96	19.96	19.96	19.96	19.96	19.96
LPG (Propane)	17.15	17.15	17.15	17.15	17.15	17.15	17.15	17.15	17.15	17.15	17.15	17.15	17.15
HGL (Energy Use) ^d	17.40	17.45	17.57	17.58	17.75	17.71	17.75	17.74	17.78	17.76	17.79	17.76	17.77
HGL (Non-Energy Use) ^d	17.21	17.21	17.19	17.21	17.10	17.03	17.00	16.95	16.93	16.86	16.88	16.81	16.81
Lubricants	20.20	20.20	20.20	20.20	20.20	20.20	20.20	20.20	20.20	20.20	20.20	20.20	20.20
Motor Gasoline ^d	19.42	19.36	19.47	19.32	19.39	19.26	19.28	19.27	19.27	19.27	19.27	19.27	19.27
Residual Fuel Oil No. 6 ^{a,c}	20.48	20.48	20.48	20.48	20.48	20.48	20.48	20.48	20.48	20.48	20.48	20.48	20.48
Other Petroleum													
AvGas Blend Components	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87
Crude Oil ^d	20.15	20.21	20.22	20.31	20.31	20.31	20.31	20.31	20.31	20.31	20.31	20.31	20.31
MoGas Blend Components ^{b,d}	19.42	19.36	19.33	19.36	19.46	19.46	19.46	19.46	19.46	19.46	19.46	19.46	19.46
Misc. Products ^e	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other Petroleum Liquids	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
Naphtha (<401 deg. F)	18.55	18.55	18.55	18.55	18.55	18.55	18.55	18.55	18.55	18.55	18.55	18.55	18.55
Other Oil (>401 deg. F)	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17	20.17
Pentanes Plus	18.24	18.24	18.24	18.24	18.24	18.24	18.24	18.24	18.24	18.24	18.24	18.24	18.24
Petroleum Coke	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85
Still Gas	18.20	18.20	18.20	18.20	18.20	18.20	18.20	18.20	18.20	18.20	18.20	18.20	18.20

Special Naphtha	19.74	19.74	19.74	19.74	19.74	19.74	19.74	19.74	19.74	19.74	19.74	19.74	19.74
Unfinished Oils ^d	20.15	20.21	20.22	20.31	20.31	20.31	20.31	20.31	20.31	20.31	20.31	20.31	20.31
Waxes	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80	19.80
Geothermal^f													
Flash Steam	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18
Dry Steam	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22
Binary	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Binary/Flash Steam	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

^a EIA discontinued collection of residential sector coal consumption data in 2008, because consumption of coal in the residential sector is extremely limited. Therefore, the number cited here is developed from commercial/institutional consumption.

^b Content for utility coal used in the electric power calculations. All coefficients based on higher heating value. Higher heating value (gross heating value) is the total amount of heat released when a fuel is burned. Coal, crude oil, and natural gas all include chemical compounds of carbon and hydrogen. When those fuels are burned, the carbon and hydrogen combine with oxygen in the air to produce CO₂ and water. Some of the energy released in burning goes into transforming the water into steam and is usually lost. The amount of heat spent in transforming the water into steam is counted as part of gross heat content. Lower heating value (net heating value), in contrast, does not include the heat spent in transforming the water into steam. Using a simplified methodology based on International Energy Agency defaults, higher heating value can be converted to lower heating value for coal and petroleum products by multiplying by 0.95 and for natural gas by multiplying by 0.90. Carbon content coefficients are presented in higher heating value because U.S. energy statistics are reported by higher heating value.

^c Distillate fuel oil No. 2 and residual fuel oil No. 6 are the only fuel oils used in the CO₂ from fossil fuel combustion calculations.

^d C contents vary annually based on changes in fuel composition.

^e The miscellaneous products category reported by EIA is assumed to be mostly petroleum refinery sulfur compounds that do not contain carbon (EIA 2019).

^f C contents based on geotype (i.e., flash steam and dry steam) were obtained from EPA's *Emissions & Generation Resource Integrated Database (eGRID) 2019 Technical Support Document* (EPA 2021). C contents were obtained in pounds CO₂/megawatt hour and were applied to net generation by geotype (in megawatt hours) from EIA (2025). C contents were converted to MMT Carbon/QBtu in this table.

Sources: Non-variable C coefficients from EIA (2009), EPA (2010), and EPA (2020). Coal C content coefficients calculated from USGS (1998), PSU (2010), Gunderson (2019), IGS (2019), ISGS (2019), EIA (1990 through 2001), EIA (2001 through 2024a), and EIA (2001 through 2024); pipeline natural gas C content coefficients calculated from EIA (2025) and EPA (2010); petroleum carbon contents from EPA (2010), EIA (1994), EIA (2009), EPA (2020), and ICF (2020). See Annex 2.2 for information on how these C content coefficients are calculated.

Table A-22: CO₂ Content Coefficients by Year (MMT CO₂/Qbtu)

Fuel Type	1990	1995	2000	2005	2010	2016	2017	2018	2019	2020	2021	2022	2023
Coal													
Residential Coal ^a	96.02	95.79	95.33	95.47	94.42	94.65	94.90	94.98	94.91	95.27	95.38	95.65	95.68
Commercial Coal	96.02	95.79	95.33	95.47	94.42	94.65	94.90	94.98	94.91	95.27	95.38	95.65	95.68
Industrial Coking Coal	93.62	93.74	93.97	93.87	93.80	93.77	93.76	93.79	93.74	93.75	93.75	93.73	93.85
Industrial Other Coal	94.62	94.55	94.37	94.58	94.83	94.90	95.10	95.06	95.13	95.35	95.46	95.55	95.63
Electric Power Coal ^b	95.11	95.03	95.27	95.61	95.50	95.50	95.55	95.51	95.48	95.58	95.57	95.63	95.65
U.S. Territory Coal (bit)	92.18	92.18	92.18	92.18	92.18	92.18	92.18	92.18	92.18	92.18	92.18	92.18	92.18
Natural Gas													
Pipeline Natural Gas ^d	53.00	53.04	53.05	53.01	53.08	53.09	53.06	53.03	52.97	52.91	52.91	52.92	52.92
Petroleum													
Asphalt & Road Oil	75.36	75.36	75.36	75.36	75.36	75.36	75.36	75.36	75.36	75.36	75.36	75.36	75.36
Aviation Gasoline	69.14	69.14	69.14	69.14	69.14	69.14	69.14	69.14	69.14	69.14	69.14	69.14	69.14
Distillate Fuel Oil No. 2 ^{c,d}	73.96	73.96	74.76	74.69	74.21	74.14	74.14	74.18	74.18	74.15	74.12	74.09	74.15
Jet Fuel ^d	71.13	70.91	72.22	72.22	72.22	72.22	72.22	72.22	72.22	72.22	72.22	72.22	72.22
Kerosene	73.20	73.20	73.20	73.20	73.20	73.20	73.20	73.20	73.20	73.20	73.20	73.20	73.20
LPG (Propane)	62.87	62.87	62.87	62.87	62.87	62.87	62.87	62.87	62.87	62.87	62.87	62.87	62.87
HGL (Energy Use) ^d	63.81	63.98	64.41	64.48	65.08	65.02	64.78	64.67	64.95	64.85	64.93	65.07	65.04
HGL (Non-Energy Use) ^d	63.09	63.10	63.02	63.09	62.69	62.56	62.58	62.58	62.50	62.50	62.45	62.32	62.16
Lubricants	74.06	74.06	74.06	74.06	74.06	74.06	74.06	74.06	74.06	74.06	74.06	74.06	74.06
Motor Gasoline ^d	71.22	70.98	71.39	70.84	71.10	71.06	70.95	70.69	70.62	70.59	70.63	70.69	70.65
Residual Fuel Oil No. 6 ^{a,c}	75.09	75.09	75.09	75.09	75.09	75.09	75.09	75.09	75.09	75.09	75.09	75.09	75.09
Other Petroleum													
AvGas Blend Components	69.19	69.19	69.19	69.19	69.19	69.19	69.19	69.19	69.19	69.19	69.19	69.19	69.19
Crude Oil ^d	73.87	74.09	74.13	74.49	74.45	74.45	74.45	74.45	74.45	74.45	74.45	74.45	74.45
MoGas Blend Components ^{b, d}	71.22	70.98	70.87	71.00	71.34	71.34	71.34	71.34	71.34	71.34	71.34	71.34	71.34
Misc. Products ^e	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other Petroleum Liquids	73.33	73.33	73.33	73.33	73.33	73.33	73.33	73.33	73.33	73.33	73.33	73.33	73.33
Naphtha (<401 deg. F)	68.02	68.02	68.02	68.02	68.02	68.02	68.02	68.02	68.02	68.02	68.02	68.02	68.02
Other Oil (>401 deg. F)	73.96	73.96	73.96	73.96	73.96	73.96	73.96	73.96	73.96	73.96	73.96	73.96	73.96

Pentanes Plus	66.88	66.88	66.88	66.88	66.88	66.88	66.88	66.88	66.88	66.88	66.88	66.88	66.88
Petroleum Coke	102.11	102.11	102.11	102.11	102.11	102.11	102.11	102.11	102.11	102.11	102.11	102.11	102.11
Still Gas	66.72	66.72	66.72	66.72	66.72	66.72	66.72	66.72	66.72	66.72	66.72	66.72	66.72
Special Naphtha	72.37	72.37	72.37	72.37	72.37	72.37	72.37	72.37	72.37	72.37	72.37	72.37	72.37
Unfinished Oils ^d	73.87	74.09	74.13	74.49	74.45	74.45	74.45	74.45	74.45	74.45	74.45	74.45	74.45
Waxes	72.58	72.58	72.58	72.58	72.58	72.58	72.58	72.58	72.58	72.58	72.58	72.58	72.58
Geothermal^f													
Flash Steam	7.98	7.98	7.98	7.98	7.98	7.98	7.98	7.98	7.98	7.98	7.98	7.98	7.98
Dry Steam	11.81	11.81	11.81	11.81	11.81	11.81	11.81	11.81	11.81	11.81	11.81	11.81	11.81

^a EIA discontinued collection of residential sector coal consumption data in 2008, because consumption of coal in the residential sector is extremely limited. Therefore, the number cited here is developed from commercial/institutional consumption.

^b Content for utility coal used in the electric power calculations. All coefficients based on higher heating value. Higher heating value (gross heating value) is the total amount of heat released when a fuel is burned. Coal, crude oil, and natural gas all include chemical compounds of carbon and hydrogen. When those fuels are burned, the carbon and hydrogen combine with oxygen in the air to produce CO₂ and water. Some of the energy released in burning goes into transforming the water into steam and is usually lost. The amount of heat spent in transforming the water into steam is counted as part of gross heat content. Lower heating value (net heating value), in contrast, does not include the heat spent in transforming the water into steam. Using a simplified methodology based on International Energy Agency defaults, higher heating value can be converted to lower heating value for coal and petroleum products by multiplying by 0.95 and for natural gas by multiplying by 0.90. CO₂ content coefficients are presented in higher heating value because U.S. energy statistics are reported by higher heating value.

^c Distillate fuel oil No. 2 and residual fuel oil No. 6 are the only fuel oils used in the CO₂ from fossil fuel combustion calculations.

^d C contents vary annually based on changes in fuel composition.

^e The miscellaneous products category reported by EIA is assumed to be mostly petroleum refinery sulfur compounds that do not contain carbon (EIA 2019).

^f C contents based on geotype (i.e., flash steam and dry steam) were obtained from EPA's *Emissions & Generation Resource Integrated Database (eGRID) 2019 Technical Support Document* (EPA 2021). C contents were obtained in pounds CO₂/megawatt hour and were applied to net generation by geotype (in megawatt hours) from EIA (2025). CO₂ contents for binary and binary/flash geotypes are zero and have been excluded from this table.

Notes: CO₂ content coefficients calculated based on C content coefficients in Table A-21. Coefficients assume 100% oxidation of C to CO₂. See Annex 2.2 for information on how C content coefficients are calculated.

Table A-23: Electricity Consumption by End-Use Sector (Billion Kilowatt-Hours)

End-Use Sector	1990	1995	2000	2005	2010	2016	2017	2018	2019	2020	2021	2022	2023
Residential	924	1,043	1,192	1,359	1,446	1,410	1,377	1,467	1,438	1,462	1,467	1,503	1,441
Commercial	838	953	1,159	1,275	1,330	1,367	1,353	1,381	1,360	1,287	1,327	1,389	1,406
Industrial	1,070	1,163	1,235	1,169	1,103	1,117	1,125	1,145	1,146	1,097	1,140	1,160	1,146
Transportation ^a	5	5	5	8	8	9	9	10	10	9	10	12	14
Total	2,837	3,164	3,592	3,811	3,887	3,902	3,864	4,003	3,954	3,855	3,944	4,065	4,007

^a Includes electricity used for electric vehicle charging in the residential and commercial sectors.

Note: Does not include the U.S. Territories.

Source: Retail sales of electricity to end-users obtained from EIA (2025). Industrial electricity consumption includes direct use. Totals may not sum due to independent rounding.

Table A-24: Electric Power Generation by Fuel Type (Percent)

Fuel Type	1990	1995	2000	2005	2010	2016	2017	2018	2019	2020	2021	2022	2023
Coal	54.1%	52.7%	53.3%	51.1%	46.0%	31.4%	30.9%	28.4%	24.2%	19.9%	22.6%	20.3%	16.6%
Natural Gas	10.7%	13.1%	14.2%	17.5%	22.7%	32.7%	30.9%	34.0%	37.3%	39.5%	37.3%	38.8%	42.2%
Nuclear	19.9%	21.1%	20.7%	20.0%	20.3%	20.6%	20.8%	20.1%	20.4%	20.5%	19.7%	18.9%	19.2%
Renewables	11.3%	10.9%	8.8%	8.3%	10.0%	14.7%	16.8%	16.8%	17.6%	19.5%	19.8%	21.4%	21.5%
Petroleum	4.1%	2.1%	2.9%	3.0%	0.9%	0.6%	0.5%	0.6%	0.4%	0.4%	0.5%	0.5%	0.4%
Other Gases ^a	0.0%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
<i>Net Electricity Generation (Billion kWh)^b</i>	2,905	3,197	3,643	3,902	3,971	3,918	3,878	4,020	3,966	3,852	3,955	4,076	4,031

+ Does not exceed 0.05 percent.

^a Other gases include blast furnace gas, propane gas, and other manufactured and waste gases derived from fossil fuels.

^b Represents net electricity generation from the electric power sector. Excludes net electricity generation from commercial and industrial combined-heat-and-power and electricity-only plants. Net electricity generation differs from the total presented in Table A-23 (i.e., end-use consumption of electricity) due to electricity transmitted across U.S. borders, as well as transmission and distribution losses.

Notes: Does not include electricity generation from purchased steam as the fuel used to generate the steam cannot be determined. Does not include non-renewable waste (i.e., municipal solid waste from non-biogenic sources, and tire-derived fuels).

Source: EIA (2025).

Table A-25: Geothermal Net Generation by Geotype (Billion Kilowatt-Hours)

Geotype	1990	1995	2000	2005	2010	2016	2017	2018	2019	2020	2021	2022	2023
Binary	0.08	0.28	0.24	0.68	2.41	3.62	3.56	3.84	4.34	4.22	4.77	4.76	5.50
Flash Steam	6.15	7.63	7.43	7.93	6.83	6.65	6.69	6.39	5.92	6.05	5.68	5.78	5.38
Dry Steam	9.21	5.47	6.43	6.09	5.98	5.55	5.67	5.73	5.21	5.61	5.52	5.54	5.48
Total	15.43	13.38	14.09	14.69	15.22	15.83	15.93	15.97	15.47	15.89	15.97	16.09	16.37

Source: EIA (2024).

Note: Totals may not sum due to independent rounding.

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2.2. Methodology for Estimating the Carbon Content of Fossil Fuels

This sub-annex presents the background and methodology for estimating the carbon (C) content of fossil fuels combusted in the United States. The C content of a particular fossil fuel represents the maximum potential emissions to the atmosphere if all C in the fuel is oxidized during combustion. The C content coefficients used in this report were developed using methods first outlined in the U.S. Energy Information Administration's (EIA) *Emissions of Greenhouse Gases in the United States: 1987-1992* (1994) and were developed primarily by EIA. EPA has updated many of the C content coefficients based on carbon dioxide (CO₂) emission factors developed for the Mandatory Reporting of Greenhouse Gases Rule, signed in September 2009 (EPA 2009b, 2010). In addition, EPA has revised many of the C content coefficients to vary annually across the time series to account for the annual variability in carbon content (or composition) of each fuel type as it is consumed in the United States (ICF 2020; USGS 1998; PSU 2010; Gunderson 2019; IGS 2019; ISGS 2019; Martel and Angello 1977; ASTM 1985; NIPER 1990 through 2009; Green & Perry ed. 2008; Wauquier ed. 1995; EPA (2009b; 2010; 2013; 2020a); and EIA (1994; 2008a; 2009a; 2024b; 1990 through 2001; 2001 through 2024a; 2001 through 2024b)). This sub-annex presents a time-series analysis of changes in U.S. C content coefficients for coal, petroleum products, and natural gas. A summary of C content coefficients used in this report appears in Table A-26.

Though the methods for estimating C contents for coal, natural gas, and petroleum products differ in their details, they each follow the same basic approach. First, because C coefficients are presented in terms of mass per unit energy (i.e., million metric tons C per quadrillion Btu or MMT C/QBtu), those fuels that are typically described in volumetric units (i.e., petroleum products and natural gas) are converted to units of mass using an estimated density. Second, C contents are derived from fuel sample data, using descriptive statistics to estimate the C share of the fuel by weight. The heat content of the fuel is then estimated based on the sample data, or where sample data are unavailable or unrepresentative, by default values that reflect the characteristics of the fuel as defined by market requirements. A discussion of each fuel appears below.

The C content of coal is described first; approximately one-sixth of all U.S. C emissions from fossil fuel combustion are associated with coal consumption. The methods and sources for estimating the C content of natural gas are provided next. Approximately one-third of U.S. greenhouse gas emissions from fossil fuel combustion are attributable to natural gas consumption. Finally, this sub-annex examines C contents of petroleum products. U.S. energy use statistics account for more than 20 different petroleum products.

Coal

Although the IPCC (2006) guidelines provide C contents for coal according to rank, it was necessary to develop C content coefficients by consuming sector to match the format in which coal consumption is reported by EIA. Because the C content of coal varies by the state in which it was mined and by coal rank, and because the sources of coal for each consuming sector vary by year, the weighted average C content for coal combusted in each consuming sector also varies over time. A time series of C contents by coal rank and consuming sector appears in Table A-26.¹²

Methodology

The methodology for developing C contents for coal by consuming sector consists of four steps. An additional step has been taken to calculate C contents by coal rank to facilitate comparison with IPCC default values.

Step 1: Determine Carbon Contents by Rank and by State of Origin

Carbon contents by rank and state of origin are estimated on the basis of 8,672 coal samples, 6,588 of which were collected by the U.S. Geological Survey (USGS) (1998), 504 samples that come from the Pennsylvania State University database (PSU 2010), and the remainder from individual State Geological Surveys. Samples obtained directly from individual State Geological Surveys include 908 samples from the Montana Bureau of Mines & Geology (Gunderson 2019), 745 samples from the Indiana Geological Survey Coal Quality Database (IGS 2019),

¹² For a comparison to earlier estimated carbon contents see Chronology and Explanation of Changes in Individual Carbon Content Coefficients of Fossil Fuels near the end of this Annex.

and 460 samples from the Illinois State Geological Survey (ISGS 2019). Because the data obtained directly from the State Geological Surveys for these three states included both samples collected by the USGS and additional samples, these data were used to determine C content coefficients for these states instead of the USGS and Pennsylvania State University data.

These coal samples are classified according to rank and state of origin. For each rank in each state, the average heat content and C content of the coal samples are calculated based on the proximate (heat) and ultimate (percent carbon) analyses of the samples. Dividing the C content (reported in pounds of CO₂) by the heat content (reported in million Btu or MMBtu) yields an average C content coefficient. This coefficient is then converted into units of MMT C/QBtu.

Step 2: Determine Weighted Average Carbon Content by State

Carbon contents by rank and origin calculated in Step 1 are then weighted by the annual share of state production that was each rank. State production by rank is obtained from the EIA. This step yields a single carbon content per state that varies annually based on production by coal type. However, most coal-producing states produce only one rank of coal. For these states the weighted factor equals the carbon content calculated in Step 1 and is constant across the time series.

Step 3: Allocate Sectoral Consumption by State of Origin

U.S. energy statistics¹³ through 2023 provide data on the origin of coal used in four areas: 1) the electric power industry, 2) industrial coking, 3) all other industrial uses, and 4) the residential and commercial end-use sectors.¹⁴ Because U.S. energy statistics do not provide the distribution of coal rank consumed by each consuming sector, it is assumed that each sector consumes a representative mixture of coal ranks from a particular state that matches the mixture of all coal produced in that state during the year. Thus, the weighted state-level factor developed in Step 2 is applied.

Step 4: Weight Sectoral Carbon Contents to Reflect the Rank and State of Origin of Coal Consumed

Sectoral C contents are calculated by multiplying the share of coal purchased from each state by the state's weighted C content estimated in Step 2. The resulting partial C contents are then totaled across all states to generate a national sectoral C content.

Equation A-1: C Content for Coal by Consuming Sector

$$C_{\text{sector}} = S_{\text{state1}} \times C_{\text{state1}} + S_{\text{state2}} \times C_{\text{state2}} + \dots + S_{\text{state50}} \times C_{\text{state50}}$$

where,

C_{sector}	=	The C content by consuming sector;
S_{state}	=	The portion of consuming sector coal consumption attributed to production from a given state;
C_{state}	=	The estimated weighted C content of all ranks produced in a given state.

¹³ U.S. Energy Information Administration (EIA). *Annual Coal Distribution Report (2001-2019b)*; *Coal Industry Annual (1990-2001)*.

¹⁴ In 2008, EIA began collecting and reporting data on commercial and institutional coal consumption, rather than residential and commercial consumption. Thus, the residential/commercial coal coefficient reported in Table A-21 for 2009 to the present represents the mix of coal consumed by commercial and institutional users. Currently, only an extremely small amount of coal is consumed in the U.S. residential sector.

Table A-26: Carbon Content Coefficients for Coal by Consuming Sector and Coal Rank (MMT C/QBtu) (1990-2023)

Consuming Sector	1990	1995	2000	2005	2010	2016	2017	2018	2019	2020	2021	2022	2023
Electric Power	25.94	25.92	25.98	26.08	26.05	26.06	26.08	26.09	26.08	26.12	26.13	26.13	26.15
Industrial Coking	25.53	25.57	25.63	25.60	25.58	25.57	25.56	25.59	25.59	25.60	25.60	25.61	25.59
Other Industrial	25.81	25.79	25.74	25.79	25.86	26.03	26.06	26.08	26.07	26.13	26.10	26.10	26.12
Residential/ Commercial ^a	26.19	26.13	26.00	26.04	25.75	26.01	26.09	26.09	26.11	26.21	26.16	26.18	26.38
Coal Rank^b													
Anthracite	28.28	28.28	28.28	28.28	28.28	28.28	28.28	28.28	28.28	28.28	28.28	28.28	28.28
Bituminous	25.38	25.42	25.45	25.45	25.42	25.40	25.40	25.41	25.41	25.43	25.43	25.43	25.43
Sub-bituminous	26.46	26.47	26.46	26.48	26.47	26.49	26.20	26.49	26.49	26.49	26.49	26.49	26.48
Lignite	26.58	26.59	26.61	26.62	26.63	26.64	26.67	26.76	26.75	26.77	26.80	26.80	26.82

^a In 2008, EIA began collecting consumption data for commercial and institutional consumption rather than commercial and residential consumption.

^b Emission factors for coal rank are weighted based on production in each state.

Sources: C content coefficients calculated from USGS (1998), PSU (2010), Gunderson (2019), IGS (2019), ISGS (2019), EIA (1990 through 2001; 2001 through 2024a; 2001 through 2024b).

Step 5: Develop National-Level Carbon Contents by Rank for Comparison to IPCC Defaults

Although not used to calculate emissions, national-level C contents by rank are more easily compared to C contents of other countries than are sectoral C contents. This step requires weighting the state-level C contents by rank developed under Step 1 by overall coal production by state and rank. Each state-level C content by rank is multiplied by the share of national production of that rank that each state represents. The resulting partial C contents are then summed across all states to generate an overall C content for each rank.

Equation A-2: C Content for Coal by Rank

$$N_{\text{rank}} = P_{\text{rank1}} \times C_{\text{rank1}} + P_{\text{rank2}} \times C_{\text{rank2}} + \cdots + P_{\text{rankn}} \times C_{\text{rankn}}$$

where,

- N_{rank} = The national C content by rank;
- P_{rank} = The portion of U.S. coal production of a given rank attributed to each state; and
- C_{rank} = The estimated C content of a given rank in each state.

Data Sources

The ultimate analysis of coal samples was based on 8,672 coal samples, 6,588 of which are from USGS (1998), 504 from the Pennsylvania State University Coal Database (PSU 2010), and the remainder from individual State Geological Surveys. Samples obtained directly from individual State Geological Surveys include 908 samples from the Montana Bureau of Mines & Geology (Gunderson 2019), 745 samples from the Indiana Geological Survey Coal Quality Database (IGS 2019), and 460 samples from the Illinois State Geological Survey (ISGS 2019). Because the data obtained directly from the State Geological Surveys for these three states included both samples collected by the USGS and additional samples, these data were used to determine C content coefficients for these states instead of the USGS and Pennsylvania State University data. Data contained in the USGS's CoalQual Database are derived primarily from samples taken between 1973 and 1989, and were largely reported in State Geological Surveys. Data in the PSU Coal Database are mainly from samples collected by PSU since 1967 and are housed at the PSU Sample Bank. Additional samples that were not contained in the USGS's CoalQual Database, many of which were more recent samples taken after 1989, were obtained directly from the State Geological Surveys for Montana, Illinois, and Indiana. Whole-seam channel samples provided by PSU, Illinois, and Indiana, and both whole-seam channel and drill core samples provided by Montana, were included in the development of carbon factors.

Data on coal consumption by sector and state of origin, as well as coal production by state and rank, were obtained from EIA. EIA's *Annual Coal Report* (EIA 2001 through 2024a) is the source for state coal production by rank from 2001 through 2023. In prior years, EIA reported this data in its *Coal Industry Annual* (EIA 1990 through 2001). Data for coal consumption by state of origin and consuming sector for 2001 through 2023 was obtained from the EIA's *Annual Coal Distribution Report* (EIA 2001 through 2024b). For 1990 through 2000, end-use data was obtained from the *Coal Industry Annual* (EIA 1990 through 2001).

Uncertainty

Carbon contents vary considerably by state. Bituminous coal production and sub-bituminous coal production represented 45.5 percent and 46.9 percent of total U.S. supply in 2023, respectively. Of the states that have been producing bituminous coal since 1990, state average C content coefficients for bituminous coal vary from a low of 85.58 kg CO₂ per MMBtu in Texas to a high of 96.36 kg CO₂ per MMBtu in Arkansas. The next lowest average emission factor for bituminous coal is found in Missouri (91.71 kg CO₂ per MMBtu). In 2023, Missouri production accounted for 0.05 percent of overall bituminous production. More than 50 percent of bituminous coal was produced in three states in 2023: West Virginia, Kentucky, and Pennsylvania, and this share has remained fairly constant since 1990. These three states show a variation in C content for bituminous coals of ±0.7 percent, based on more than 2,000 samples (see Table A-27).

Similarly, the C content coefficients for sub-bituminous coal range from 91.29 kg CO₂ per MMBtu in Utah to 98.09 kg CO₂ per MMBtu in Alaska. However, Utah has no recorded production of sub-bituminous coal since 1990. Production of sub-bituminous coal in Alaska has made up less than 1 percent of total sub-bituminous production

since 1990, with even this small share declining over time. Wyoming has represented between 75 percent and 90 percent of total sub-bituminous coal production in the United States throughout the time series (1990 through 2023). Thus, the C content coefficient for Wyoming (97.21 kg CO₂ per MMBtu), based on 503 samples, dominates the national average.

The interquartile range of C content coefficients among samples of sub-bituminous coal in Wyoming was ± 1.5 percent from the mean. Similarly, this range among samples of bituminous coal from West Virginia, Kentucky, and Pennsylvania was ± 1.2 percent or less for each state. The large number of samples and the low variability within the sample set of the states that represent the predominant source of supply of U.S. coal suggest that the uncertainty in this factor is very low, on the order of ± 1.0 percent.

For comparison, J. Quick (2010) completed an analysis similar in methodology to that used here, in order to generate national average C emission factors as well as county-level factors. This study's rank-based national average factors have a maximum deviation from the factors developed in this *Inventory* report of 0.78 percent, which is for sub-bituminous (range: -0.32 to +0.78 percent). This corroboration further supports the assertion of minimal uncertainty in the application of the rank-based factors derived for the purposes of this *Inventory*.

Table A-27: Variability in Carbon Content Coefficients by Rank Across States (Kilograms CO₂ Per MMBtu)

State	Number of Samples	Bituminous	Sub-bituminous	Anthracite	Lignite
Alabama	951	92.84			99.10
Alaska	91	98.32	98.09		98.65
Arizona	15	93.94	97.34		
Arkansas	77	96.36			94.97
Colorado	317	94.37	96.52		101.10
Georgia	35	95.00			
Idaho	1		94.90		
Illinois	460	92.53			
Indiana	745	92.30			
Iowa	100	91.87			
Kansas	29	90.91			
Kentucky	897	92.61			
Louisiana	1				96.01
Maryland	47	94.29			
Massachusetts	3			114.82	
Michigan	3				92.87
Mississippi	8				98.18
Missouri	111	91.71			
Montana	908	96.01	96.61		98.34
Nebraska	6	103.59			
Nevada	2	94.41			99.86
New Mexico	185	94.28	94.88	103.92	
North Dakota	202		93.97		99.47
Ohio	674	91.84			
Oklahoma	63	92.33			
Pennsylvania	849	93.33		103.68	
Tennessee	61	92.81			
Texas	64	85.58	94.19		96.46
Utah	169	95.75	91.29		
Virginia	465	93.51		98.54	
Washington	18	94.53	97.35	102.53	106.55
West Virginia	612	93.84			
Wyoming	503	94.80	97.21		
U.S. Average	8,672	93.46	96.01	102.15	98.95

Note: “-” Indicates no sample data available. Average is weighted by number of samples.

Sources: Calculated from USGS (1998) and PSU (2010), Gunderson (2019), IGS (2019), and ISGS (2019).

Natural Gas

Natural gas is predominantly composed of methane (CH_4), which is 75 percent C by weight and contains 14.2 MMT C/QBtu (higher heating value), but it may also contain many other compounds that can lower or raise its overall C content. These other compounds may be divided into two classes: (1) natural gas liquids (NGLs) and (2) non-hydrocarbon gases. The most common NGLs are ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), and, to a lesser extent, pentane (C_5H_{12}) and hexane (C_6H_{14}). Because the NGLs have more C atoms than CH_4 (which has only one), their presence increases the overall C content of natural gas. NGLs have a commercial value greater than that of CH_4 , and therefore are usually separated from raw natural gas at gas processing plants and sold as separate products. Ethane is typically used as a petrochemical feedstock, propane and butane have diverse uses, and natural gasoline¹⁵ contributes to the gasoline/naphtha “octane pool,” used primarily to make motor gasoline.

Raw natural gas can also contain varying amounts of non-hydrocarbon gases, such as CO_2 , nitrogen, helium and other noble gases, and hydrogen sulfide. The share of non-hydrocarbon gases is usually less than 5 percent of the total, but there are individual natural gas reservoirs where the share can be much larger. The treatment of non-hydrocarbon gases in raw gas varies. Hydrogen sulfide is always removed. Inert gases are removed if their presence is substantial enough to reduce the energy content of the gas below pipeline specifications (see Step 1, below). Otherwise, inert gases will usually be left in the natural gas. Because the raw gas that is usually flared (see Step 2, below) contains NGLs and CO_2 , it will typically have a higher overall C content than gas that has been processed and moved to end-use customers via transmission and distribution pipelines.

Methodology

The methodology for estimating the C contents of pipeline and flared natural gas can be described in five steps.

Step 1: Define pipeline-quality natural gas

In the United States, pipeline-quality natural gas is required to have an energy content greater than 970 Btu per cubic foot, but less than 1,100 Btu per cubic foot. Hydrogen sulfide content must be negligible. Typical pipeline-quality natural gas is about 95 percent CH_4 , 3 percent NGLs, and 2 percent non-hydrocarbon gases, of which approximately half is CO_2 .

However, there remains a range of gas compositions that are consistent with pipeline specifications. The minimum C content coefficient for natural gas would match that for pure CH_4 , which equates to an energy content of 1,005 Btu per standard cubic foot. Gas compositions with higher or lower Btu content tend to have higher C emission factors, because the “low” Btu gas has a higher content of inert gases (including CO_2 offset with more NGLs), while “high” Btu gas tends to have more NGLs.

Step 2: Define flared gas

Every year, a certain amount of natural gas is flared in the United States. There are several reasons that gas is flared:

- There may be no market for some batches of natural gas, the amount may be too small or too variable, or the quality might be too poor to justify treating the gas and transporting it to market (such is the case when gas contains large shares of CO_2). Most natural gas that is flared for these reasons is “rich” associated gas, with relatively high energy content, high NGL content, and a high C content.
- Gas treatment plants may flare substantial volumes of natural gas because of “process upsets,” because the gas is “off spec,” or possibly as part of an emissions control system. Gas flared at processing plants may be of variable quality.

¹⁵ A term used in the gas processing industry to refer to a mixture of liquid hydrocarbons (mostly pentanes and heavier hydrocarbons) extracted from natural gas.

Data on the energy content of flare gas, as reported by states to EIA, indicate an average energy content of 1,130 Btu per standard cubic foot (EIA 1994). Flare gas may have an even higher energy content than reported by EIA since rich associated gas can have energy contents as high as 1,300 to 1,400 Btu per cubic foot.

Step 3: Determine a relationship between carbon content and heat content

A relationship between C content and heat content may be used to develop a C content coefficient for natural gas consumed in the United States. In 1994, EIA examined the composition (including C contents) of 6,743 samples of pipeline-quality natural gas from utilities and/or pipeline companies in 26 cities located in 19 states. To demonstrate that these samples were representative of actual natural gas “as consumed” in the United States, their heat content was compared to that of the national average. For the most recent year, the average heat content of natural gas consumed in the United States was 1,036 Btu per cubic foot, and has varied by less than 1 percent (1,027 to 1,038 Btu per cubic foot) over the past 10 years. Meanwhile, the average heat content of the 6,743 samples was 1,027 Btu per cubic foot, and the median heat content was 1,031 Btu per cubic foot. Thus, the average heat content of the sample set falls within the typical range of natural gas consumed in the United States, suggesting that these samples continue to be representative of natural gas “as consumed” in the United States. The average and median composition of these samples appear in Table A-28.

Table A-28: Composition of Natural Gas (Percent)

Compound	Average	Median
Methane	93.07	95.00
Ethane	3.21	2.79
Propane	0.59	0.48
Higher Hydrocarbons	0.32	0.30
Non-hydrocarbons	2.81	1.43
Higher Heating Value (Btu per cubic foot)	1,027	1,031

Source: Gas Technology Institute (1992).

Carbon contents were calculated for a series of sub-samples based on their CO₂ content and heat content. Carbon contents were calculated for the groups of samples with less than 1.0 percent (n=5,181) and less than 1.5 percent CO₂ only (n=6,522) and those with less than 1.0 or 1.5 percent CO₂ and less than 1,050 Btu/cf (n=4,888 and 6,166, respectively). These stratifications were chosen to exclude samples with CO₂ content and heat contents outside the range of pipeline-quality natural gas. In addition, hexane was removed from the samples since it is usually stripped out of raw natural gas before delivery because it is a valuable natural gas liquid used as a feedstock for gasoline. The average carbon contents for the four separate sub-samples are shown below in Table A-29.

Table A-29: Carbon Content of Pipeline-Quality Natural Gas by CO₂ and Heat Content (MMT C/QBtu)

Sample	Average Carbon Content
Full Sample	14.48
< 1.0% CO ₂	14.43
< 1.5% CO ₂	14.47
< 1.0 % CO ₂ and <1,050 Btu/cf	14.42
< 1.5 % CO ₂ and <1,050 Btu/cf	14.47

Source: EPA (2010).

Step 4: Apply carbon content coefficients developed in Step 3 to pipeline natural gas

A regression analysis was performed on the sub-samples in to further examine the relationship between carbon (C) content and heat content (both on a per cubic foot basis). The regression used carbon content as the dependent

variable and heat content as the independent variable. The resulting R-squared values¹⁶ for each of the sub-samples ranged from 0.79 for samples with less than 1.5 percent CO₂ and under 1,050 Btu/cf to 0.91 for samples containing less than 1.0 percent CO₂ only. However, the sub-sample with less than 1.5 percent CO₂ and 1,050 Btu/cf was chosen as the representative sample for two reasons. First, it most accurately reflects the range of CO₂ content and heat content of pipeline quality natural gas. Secondly, the R-squared value, although it is the lowest of the sub-groups tested, remains relatively high. This high R-squared indicates a low percentage of variation in C content as related to heat content. The regression for this sub-sample resulted in the following equation:

Equation A-3: C Content of Pipeline and Flared Natural Gas

$$C \text{ Content} = (0.011 \times \text{Heat Content}) + 3.5341$$

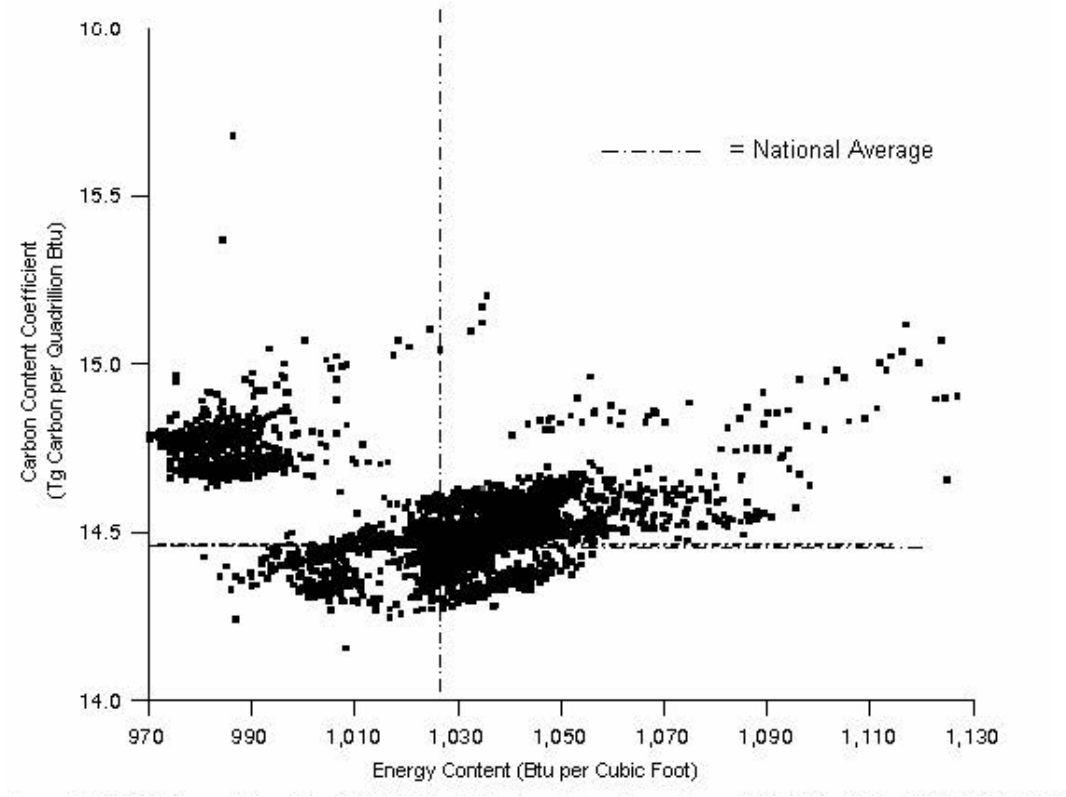
This equation was used to estimate the annual predicted carbon content of natural gas from 1990 to 2023 based on the EIA’s national average pipeline-quality gas heat content for each year (EIA 2024). The table of average C contents for each year is shown below in Table A-30.

Table A-30: Carbon Content Coefficients for Natural Gas (MMT Carbon/QBtu)

Fuel Type	1990	1995	2000	2005	2010	2016	2017	2018	2019	2020	2021	2022	2023
Natural Gas	14.46	14.47	14.47	14.46	14.48	14.43	14.43	14.43	14.43	14.43	14.43	14.43	14.43

Source: Calculated from EPA (2010) and EIA (2025).

Figure A-1: Carbon Content for Samples of Pipeline-Quality Natural Gas Included in the Gas Technology Institute Database



¹⁶ R-squared represents the percentage of variation in the dependent variable (in this case carbon content) explained by variation in the independent variables.

Source: EIA (1994) Energy Information Administration, Emissions of Greenhouse Gases in the United States 1987-1992, U.S. Department of Energy, Washington, DC, November 1994, DOE/EIA 0573, Appendix A.

Natural gas suppliers may achieve the same overall energy content from a wide variety of methane, higher hydrocarbon, and non-hydrocarbon gas combinations. Thus, the plot reveals large variations in C content for a single Btu value. In fact, the variation in C content for a single Btu value may be nearly as great as the variation for the whole sample. As a result, while energy content has some predictive value, the specific energy content does not substantially improve the accuracy of an estimated C content coefficient beyond the ± 5.0 percent offered with the knowledge that it is of pipeline-quality.

The plot of C content also reveals other interesting anomalies. Samples with the lowest emissions coefficients tend to have energy contents of about 1,000 Btu per cubic foot. They are composed of almost pure CH₄. Samples with a greater proportion of NGLs (e.g., ethane, propane, and butane) tend to have energy contents greater than 1,000 Btu per cubic foot, along with higher emissions coefficients. Samples with a greater proportion of inert gases tend to have lower energy content, but they usually contain CO₂ as one of the inert gases and, consequently, also tend to have higher emission coefficients (see left side of Figure A-1).

For the full sample (n=6,743), the average C content of a cubic foot of gas was 14.48 MMT C/QBtu. Additionally, a regression analysis using the full sample produced a predicted C content of 14.49 MMT C/QBtu based on a heat content of 1,029 Btu/cf (the average heat content in the United States for the most recent year). However, these two values include an upward influence on the resulting carbon content that is caused by inclusion in the sample set of the samples that contain large amounts of inert carbon dioxide and those samples with more than 1,050 Btu per cubic foot that contain an unusually large amount of NGLs. Because typical gas consumed in the United States does not contain such a large amount of carbon dioxide or natural gas liquids, a C content of 14.43 MMT C/QBtu (see Table A-30), based on samples with less than 1.5 percent CO₂ and less than 1,050 Btu per cubic foot, better represents the pipeline-quality fuels typically consumed.

Furthermore, research was done on CO₂ emission factors for fuel gas used by upstream oil and gas producers in order to determine whether a different CO₂ emission factor for fuel gas used in offshore oil and gas production than the emission factor for the processed gas that enters the transmission, storage and distribution networks used in power and industrial plants and by other users is warranted. Research was done using the Greenhouse Gas Reporting Program (GHGRP) subpart C data on combustion (EPA 2024). Upstream oil and gas facilities were identified, and data was examined on facilities that utilized Tier 2 and Tier 3 estimation methods. The Tier 2 methods provided data on upstream natural gas High Heating Value (HHV) and the HHV used in this report, as discussed above, generally fits within the upper and lower quartiles of the Tier 2 data reported. The Tier 3 data provided information on a carbon emission factor for natural gas. While the amount of natural gas covered under the Tier 3 approach was small (less than 2 percent of upstream emissions) the calculated Tier 3 emission factors are within about 3 percent of the emission factors used in this report. Furthermore, the research highlighted the small contribution of upstream oil and gas natural gas CO₂ emissions compared to the total and the difficulty in determining quantities of natural gas used upstream. Therefore, it was determined that a different factor was not warranted and the same carbon factor is used for all natural gas consumption including upstream operations.

Petroleum

There are four critical determinants of the C content coefficient for a petroleum-based fuel:

- The density of the fuel (e.g., the weight in kilograms of one barrel of fuel);
- The fraction by mass of the product that consists of hydrocarbons, and the fraction of non-hydrocarbon impurities;
- The specific types of “families” of hydrocarbons that make up the hydrocarbon portion of the fuel; and
- The heat content of the fuel.

Equation A-4: C Content for a Petroleum-based Fuel

$$C_{\text{fuel}} = (D_{\text{fuel}} \times S_{\text{fuel}}) / E_{\text{fuel}}$$

where,

C_{fuel}	=	The C content coefficient of the fuel
D_{fuel}	=	The density of the fuel
S_{fuel}	=	The share of the fuel that is C
E_{fuel}	=	The heat content of the fuel

Most of the density, carbon share, or heat contents applied to calculate the carbon coefficients for petroleum products that are described in this sub-Annex and applied to this emissions *Inventory* were updated in 2010 for the 1990 through 2008 *Inventory* report. These changes have been made where necessary to increase the accuracy of the underlying data or to align the petroleum properties data used in this report with that developed for use in EPA's *Mandatory Reporting of Greenhouse Gases Rule* (EPA 2009b).

Petroleum products vary between 5.6 degrees API gravity¹⁷ (dense products such as asphalt and road oil) and 247 degrees (ethane). This is a range in density of 60 to 150 kilograms per barrel, or ± 50 percent. The variation in C content, however, is much smaller (± 5 to 7 percent) for products produced by standard distillation refining: ethane is 80 percent C by weight, while petroleum coke is 90 to 92 percent C. This tightly bound range of C contents can be explained by basic petroleum chemistry (see below). Additional refining can increase carbon contents. Calcined coke, for example, is formed by heat treating petroleum coke to about 1600 degrees Kelvin (calcining), to expel volatile materials and increase the percentage of elemental C. This product can contain as much as 97 to 99 percent carbon. Calcined coke is mainly used in the aluminum and steel industry to produce C anodes.

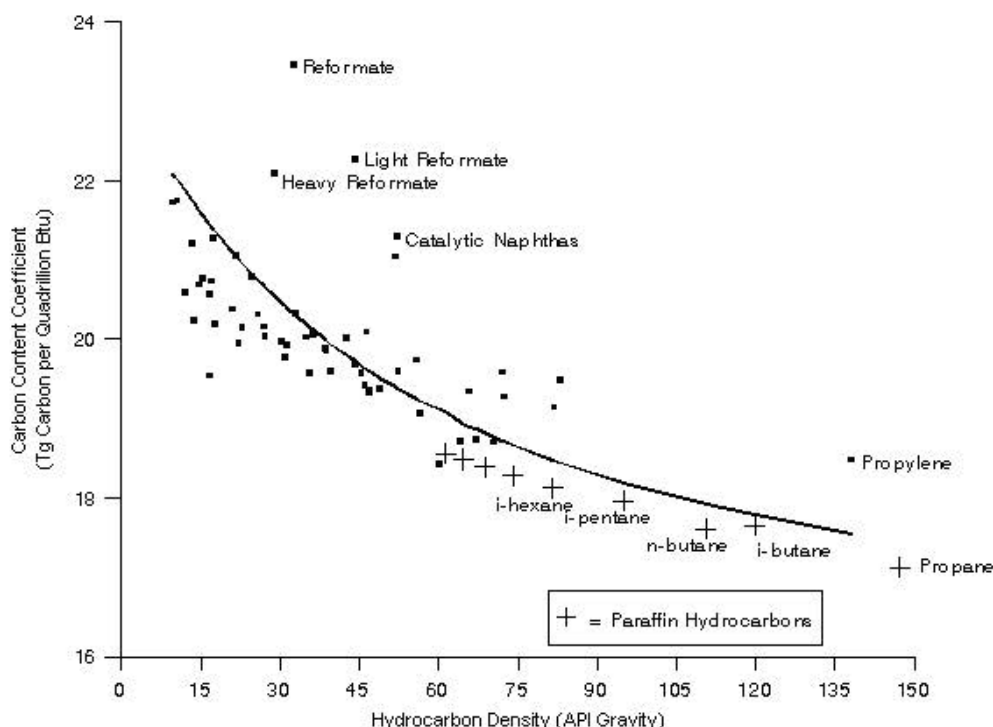
Petroleum Chemistry

Crude oil and petroleum products are typically mixtures of several hundred distinct compounds, predominantly hydrocarbons. All hydrocarbons contain hydrogen and C in various proportions. When crude oil is distilled into petroleum products, it is sorted into fractions by the boiling temperature of these hundreds of organic compounds. Boiling temperature is strongly correlated with the number of C atoms in each molecule. Petroleum products consisting of relatively simple molecules and few C atoms have low boiling temperatures, while larger molecules with more C atoms have higher boiling temperatures.

Products that boil off at higher temperatures are usually denser, which implies greater C content as well. Petroleum products with higher C contents, in general, have lower energy content per unit mass and higher energy content per unit volume than products with lower C contents. Empirical research led to the establishment of a set of quantitative relationships between density, energy content per unit weight and volume, and C and hydrogen content. Figure A-2 compares C content coefficients calculated on the basis of the derived formula with actual C content coefficients for a range of crude oils, fuel oils, petroleum products, and pure hydrocarbons. The actual fuel samples were drawn from the sources described below in the discussions of individual petroleum products.

¹⁷ API gravity is an arbitrary scale expressing the gravity or density of liquid petroleum products, as established by the American Petroleum Institute (API). The measuring scale is calibrated in terms of degrees API. The higher the API gravity, the lighter the compound. Light crude oils generally exceed 38 degrees API and heavy crude oils are all crude oils with an API gravity of 22 degrees or below. Intermediate crude oils fall in the range of 22 degrees to 38 degrees API gravity. API gravity can be calculated with the following formula: $\text{API Gravity} = (141.5 / \text{Specific Gravity}) - 131.5$. Specific gravity is the density of a material relative to that of water. At standard temperature and pressure, there are 62.36 pounds of water per cubic foot, or 8.337 pounds water per gallon.

Figure A-2: Estimated and Actual Relationships Between Petroleum Carbon Content Coefficients and Hydrocarbon Density



Source: Carbon content factors for paraffins are calculated based on the properties of hydrocarbons in V. Guthrie (ed.), *Petroleum Products Handbook* (New York: McGraw Hill, 1960) p. 33. Carbon content factors from other petroleum products are drawn from sources described below. Relationship between density and emission factors based on the relationship between density and energy content in U.S. Department of Commerce, National Bureau of Standards, *Thermal Properties of Petroleum Products*, Miscellaneous Publication, No. 97 (Washington, D.C., 1929), pp.16-21, and relationship between energy content and fuel composition in S. Ringen, J. Lanum, and F.P. Miknis, "Calculating Heating Values from the Elemental Composition of Fossil Fuels," *Fuel*, Vol. 58 (January 1979), p.69.

The derived empirical relationship between C content per unit heat and density is based on the types of hydrocarbons most frequently encountered. Petroleum fuels can vary from this relationship due to non-hydrocarbon impurities and variations in molecular structure among classes of hydrocarbons. In the absence of more exact information, this empirical relationship offers a good indication of C content.

Non-hydrocarbon Impurities

Most fuels contain a certain share of non-hydrocarbon material. This is also primarily true of crude oils and fuel oils. The most common impurity is sulfur, which typically accounts for between 0.5 and 4 percent of the mass of most crude oils, and can form an even higher percentage of heavy fuel oils. Some crude oils and fuel oils also contain appreciable quantities of oxygen and nitrogen, typically in the form of asphaltenes or various acids. The nitrogen and oxygen content of crude oils can range from near zero to a few percent by weight. Lighter petroleum products have much lower levels of impurities, because the refining process tends to concentrate all of the non-hydrocarbons in the residual oil fraction. Light products usually contain less than 0.5 percent non-hydrocarbons by mass. Thus, the C content of heavy fuel oils can often be several percent lower than that of lighter fuels, due entirely to the presence of non-hydrocarbons.

Variations in Hydrocarbon Classes

Hydrocarbons can be divided into five general categories, each with a distinctive relationship between density and C content and physical properties. Refiners tend to control the mix of hydrocarbon types in particular products in order to give petroleum products distinct properties. The main classes of hydrocarbons are described below.

Paraffins. Paraffins are the most common constituent of crude oil, usually comprising 60 percent by mass. Paraffins are straight-chain hydrocarbons with the general formula C_nH_{2n+2} . Paraffins include ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), and octane (C_8H_{18}). As the chemical formula suggests, the C content of the paraffins increases with their C number: ethane is 79.89 percent C by weight, octane 84.12 percent. As the size of paraffin molecules increases, the C content approaches the limiting value of 85.7 percent asymptotical (see Figure A-3).

Cycloparaffins. Cycloparaffins are similar to paraffins, except that the C molecules form ring structures rather than straight chains, and consequently require two fewer hydrogen molecules than paraffins. Cycloparaffins always have the general formula C_nH_{2n} and are 85.63 percent C by mass, regardless of molecular size.

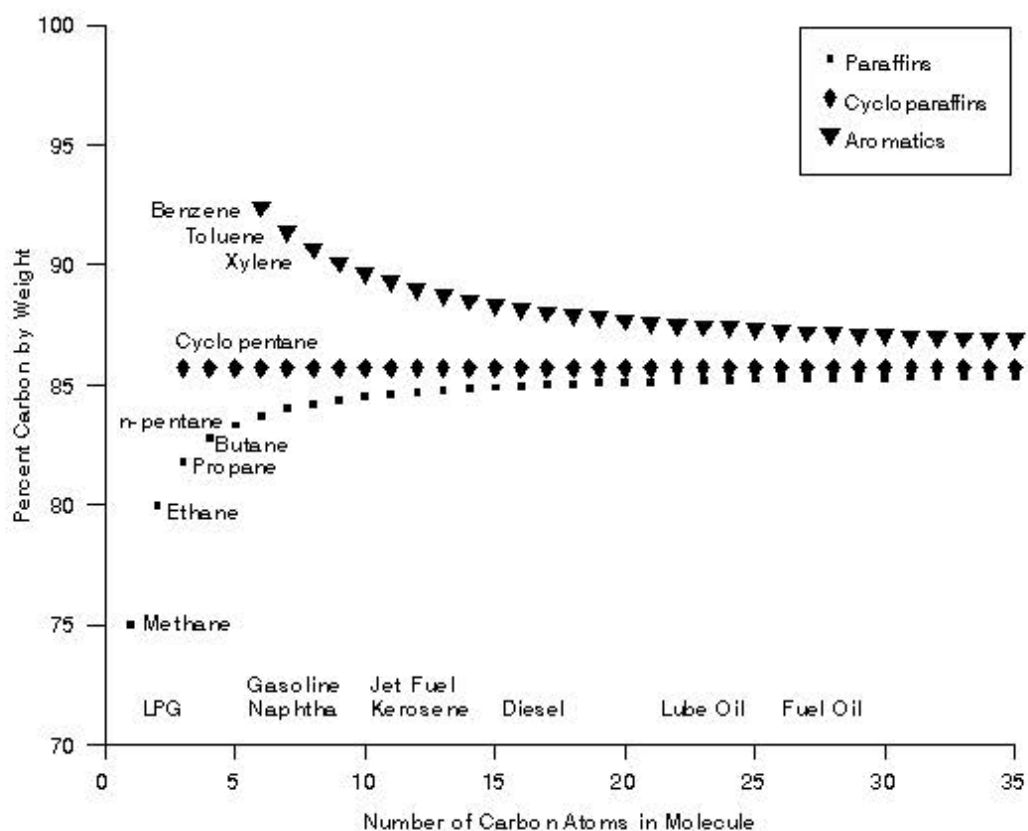
Olefins. Olefins are a very reactive and unstable form of paraffin: a straight chain with two carbon atoms double bonded together (thus are unsaturated) compared to the carbon atoms in a paraffin (which are saturated with hydrogen). They are never found in crude oil but are created in moderate quantities by the refining process. Gasoline, for example, may contain between 2 and 20 percent olefins. They also have the general formula C_nH_{2n} , and hence are also always 85.63 percent C by weight. Propylene (C_3H_6), a common intermediate petrochemical product, is an olefin.

Aromatics. Aromatics are very reactive hydrocarbons that are relatively uncommon in crude oil (10 percent or less). Light aromatics increase the octane level in gasoline, and consequently are deliberately created by catalytic reforming of heavy naphtha. Aromatics also take the form of ring structures with some double bonds between C atoms. The most common aromatics are benzene (C_6H_6), toluene (C_7H_8), and xylene (C_8H_{10}). The general formula for aromatics is C_nH_{2n-6} . Benzene is 92.26 percent C by mass, while xylene is 90.51 percent C by mass and toluene is 91.25 percent C by mass. Unlike the other hydrocarbon families, the C content of aromatics declines asymptotically toward 85.7 percent with increasing C number and density (see Figure A-3).

Polynuclear Aromatics. Polynuclear aromatics are large molecules with a multiple ring structure and few hydrogen atoms, such as naphthalene ($C_{10}H_8$ and 93.71 percent C by mass) and anthracene ($C_{14}H_{10}$ and 97.7 percent C). They are relatively rare but do appear in heavier petroleum products.

Figure A-3 illustrates the share of C by weight for each class of hydrocarbon. Hydrocarbon molecules containing 2 to 4 C atoms are all natural gas liquids; hydrocarbons with 5 to 10 C atoms are predominantly found in naphtha and gasoline; and hydrocarbon compounds with 12 to 20 C atoms comprise "middle distillates," which are used to make diesel fuel, kerosene and jet fuel. Larger molecules which can be vacuum distilled may be used as lubricants, waxes, and residual fuel oil or cracked and blended into the gasoline or distillate pools.

Figure A-3: Carbon Content of Pure Hydrocarbons as a Function of Carbon



Source: J.M. Hunt, *Petroleum Geochemistry and Geology* (San Francisco, CA, W.H. Freeman and Company, 1979), pp. 31-37.

If nothing is known about the composition of a particular petroleum product, assuming that it is 85.7 percent C by mass is not an unreasonable first approximation. Since denser products have higher C numbers, this guess would be most likely to be correct for crude oils and fuel oils. The C content of lighter products is more affected by the shares of paraffins and aromatics in the blend.

Energy Content of Petroleum Products

The exact energy content (gross heat of combustion) of petroleum products is not generally known. EIA estimates energy consumption in Btu on the basis of a set of industry-standard conversion factors. These conversion factors are generally accurate to within 3 to 5 percent.

Individual Petroleum Products

The United States maintains data on the consumption of more than twenty separate petroleum products and product categories. The C contents, heat contents, and density for each product are provided below in Table A-31. A description of the methods and data sources for estimating the key parameters for each individual petroleum product appears below.

Table A-31: 2023 Carbon Content Coefficients and Underlying Data for Petroleum Products

Fuel	Carbon Content (MMT C/QBtu)	Gross Heat of Combustion (MMBtu/Barrel)	Density (API Gravity)	Percent Carbon
Motor Gasoline ^a	19.27	(See a)	(See a)	(See a)
LPG (Propane)	17.15	3.841	155.3	81.80
HGL (Energy Use) ^b	17.77	(See b)	(See b)	(See b)
HGL (Non-Energy Use) ^b	16.81	(See b)	(See b)	(See b)
Jet Fuel	19.70	5.670	42.0	86.30
Distillate Fuel No. 1	19.98	5.822	35.3	86.40
Distillate Fuel No. 2	20.22	(See c)	(See c)	(See c)
Distillate Fuel No. 4	20.47	6.135	23.2	86.47
Residual Fuel No. 5	19.89	5.879	33.0	85.67
Residual Fuel No. 6	20.48	6.287	15.5	84.67
Asphalt and Road Oil	20.55	6.636	5.6	83.47
Lubricants	20.20	6.065	25.7	85.80
Naphtha (< 400 deg. F) ^c	18.55	5.248	62.4	84.11
Other Oil (>400 deg. F) ^c	20.17	5.825	35.8	87.30
Aviation Gasoline	18.86	5.048	69.0	85.00
Kerosene	19.96	5.670	35.3	86.40
Petroleum Coke	27.85	6.024	-	92.28
Special Naphtha	19.74	5.248	52.0	84.75
Petroleum Waxes	19.80	5.537	43.3	85.30
Still Gas	18.20	6.000	-	77.70
Crude Oil	20.31	5.800	31.2	85.49
Unfinished Oils	20.31	5.825	31.2	85.49
Miscellaneous Products	0.00	5.796	31.2	0.00
Natural Gasoline	18.24	4.620	81.3	83.70

^a Calculation of the carbon content coefficient for motor gasoline starting in 2009 uses separate higher heating values for conventional and reformulated gasoline of 5.222 and 5.150, respectively (EIA 2009a). Densities and carbon shares (percent carbon) are annually variable and separated by both fuel formulation and grade, see Motor Gasoline and Blending Components, below, for details.

^b HGL is a blend of multiple paraffinic hydrocarbons: ethane, propane, isobutane, and normal butane, and their associated olefins: ethylene, propylene, isobutylene, and butylene, each with their own heat content, density, and C content, see Table A-33.

^c Petrochemical feedstocks have been split into naphthas and other oils for this *Inventory* report. Parameters presented are for naphthas with a boiling temperature less than 400 degrees Fahrenheit. Other oils are petrochemical feedstocks with higher boiling points. They are assumed to have the same characteristics as distillate fuel oil no. 2.

Note: “-” Indicates no sample data available. For carbon content coefficients that are annually variable, 2023 values are shown.

Sources: EIA (1994); EIA (2009a); EPA (2020b); and EPA (2010).

Motor Gasoline and Motor Gasoline Blending Components

Motor gasoline is a complex mixture of relatively volatile hydrocarbons with or without small quantities of additives, blended to form a fuel suitable for use in spark-ignition engines.¹⁸ “Motor Gasoline” includes conventional gasoline; all types of oxygenated gasoline, including gasohol; and reformulated gasoline; but excludes aviation gasoline.

¹⁸ Motor gasoline, as defined in ASTM Specification D 4814 or Federal Specification VV-G-1690C, is characterized as having a boiling range of 122 degrees to 158 degrees Fahrenheit at the 10-percent recovery point to 365 degrees to 374 degrees Fahrenheit at the 90-percent recovery point.

Gasoline is the most widely used petroleum product in the United States, and its combustion accounts for 21.2 percent of all U.S. CO₂ emissions. EIA collects consumption data (i.e., “petroleum products supplied” to end-users) for several types of finished gasoline over the 1990 through 2023 time period: regular, mid-grade, and premium conventional gasoline (all years) and regular, mid-grade, and premium reformulated gasoline (November 1994 to 2023). Leaded and oxygenated gasoline are not separately included in the data used for this report.¹⁹

The American Society for Testing and Materials (ASTM) standards permit a broad range of densities for gasoline, ranging from 50 to 70 degrees API gravity, or 111.52 to 112.65 kilograms per barrel (EIA 1994), which implies a range of possible C and energy contents per barrel. The density of motor gasoline across grades and formulations for 1990-2008 is taken from the National Institute of Petroleum and Energy Research. Values from 2008 have been used as a proxy for 2009 through 2023.

The density of motor gasoline increased across all grades through 1994, partly as a result of the leaded gasoline phase-out. In order to maintain the “anti-knock” quality and octane ratings of gasoline in the absence of lead, the portion of aromatic hydrocarbons blended into gasoline through the refining process was increased. As discussed above, aromatic hydrocarbons have a lower ratio of hydrogen to C than other hydrocarbons typically found in gasoline, and therefore increase fuel density.

The trend in gasoline density was reversed beginning in 1996 with the development of fuel additives that raised oxygen content. In 1995, a requirement for reformulated gasoline in non-attainment areas implemented under the Clean Air Act Amendments further changed the composition of gasoline consumed in the United States. Through 2005, methyl tertiary butyl ether (MTBE), ethanol, ethyl tertiary butyl ether (ETBE), and tertiary amyl methyl ether (TAME) were added to reformulated and sometimes to conventional gasoline to boost its oxygen content, reduce its toxics impacts and increase its octane. The increased oxygen reduced the emissions of carbon monoxide and unburned hydrocarbons. These oxygen-rich blending components are also much lower in C than standard gasoline. The average gallon of reformulated gasoline consumed in 2005 contained over 10 percent MTBE and 0.6 percent TAME (by volume). The characteristics of reformulated fuel additives appear in Table A-32.

Table A-32: Characteristics of Major Reformulated Fuel Additives

Additive	Density (Degrees API)	Carbon Share (Percent)
MTBE	58.6	68.13
ETBE	58.5	70.53
TAME	51.2	70.53
DIPE	62.7	70.53
Ethanol (100%)	45.8	52.14

Source: EPA (2009b).

Since 2005, due to concerns about the potential environmental consequences of the use of MTBE in fuels, there has been a shift away from the addition of MTBE, TAME, ETBE, and DIPE and towards the use of ethanol as a fuel oxygenate.²⁰ Ethanol, also called ethyl alcohol, is an anhydrous alcohol with molecular formula C₂H₅OH. Ethanol has a lower C share than other oxygenates, approximately 52 percent compared to about 70 percent for MTBE and TAME. The density of ethanol was calculated by fitting density data at 10-degree intervals to a polynomial of order two and then using the fit to interpolate the value of the density at 15 degrees Celsius. A common fuel mixture of 10 percent denatured ethanol (denatured by 2 percent hydrocarbons) and 90 percent gasoline, known as E10, is widely used in the United States and does not require any modification to vehicle engines or fuel systems. The federal Renewable Fuel Standard (RFS) program requires a certain volume of renewable fuel, including ethanol, be blended into the national fuel supply.²¹ Ethanol blends up to E85 (85 percent ethanol, 15 percent gasoline) are in

¹⁹ Oxygenated gasoline volumes are included in the conventional gasoline data provided by EIA from 2007 onwards. Leaded gasoline was included in total gasoline by EIA until October 1993.

²⁰ The annual motor gasoline carbon contents that are applied for this *Inventory* do not include the carbon contributed by the ethanol contained in reformulated fuels. Ethanol is a biofuel, and net carbon fluxes from changes in biogenic carbon reservoirs in croplands are accounted for in the estimates for Land Use, Land-Use Change, and Forestry.

²¹ See <https://www.epa.gov/renewable-fuel-standard-program>.

use in the United States but can only be used in specially designed vehicles called flexible fuel vehicles (FFVs). Most ethanol fuel in the United States is produced using corn as feedstock,²² although production pathways utilizing agricultural waste, woody biomass and other resources are in development.

Methodology for Years 1990-1999

Step 1. Disaggregate U.S. gasoline consumption by grade and type

Separate monthly data for U.S. sales to end users of finished gasoline by product grade and season for both standard gasoline and reformulated gasoline were obtained from the EIA.

Step 2. Develop carbon content coefficients for each grade and type

Annual C content coefficients for each gasoline grade, type, and season are derived from four parameters for each constituent of the finished gasoline blend: the volumetric share of each constituent,²³ the density of the constituent, share of the constituent²⁴ that is C; and the energy content of a gallon of the relevant formulation of gasoline. The percent by mass of each constituent of each gasoline type was calculated using percent by volume data from the National Institute for Petroleum and Energy Research (NIPER) and the density of each constituent.

The ether additives listed in Table A-32 are accounted for in both reformulated fuels and conventional fuels, to the extent that they were present in the fuel. From 2006 onward, reformulated fuel mass percentages are calculated from their constituents, net of the share provided by ethanol. C content coefficients were then derived from the calculated percent by mass values by weighting the C share of each constituent by its contribution to the total mass of the finished motor gasoline product.

Step 3. Weight overall gasoline carbon content coefficient for consumption of each grade and type

The C content for each grade, type, and season of fuel is multiplied by the share of annual consumption represented by the grade and fuel type during the relevant time period. Individual coefficients are then summed and totaled to yield an overall C content coefficient for each year.

Methodology for Years 2000-Present

Step 1. Disaggregate U.S. gasoline consumption by grade and type

Separate monthly data for U.S. sales to end users of finished gasoline by product grade and season for both standard gasoline and reformulated gasoline were obtained from the EIA. The EIA publishes prime supplier sales volumes of motor gasoline by type (conventional, oxygenated, and reformulated) and by grade (regular, midgrade and premium) for each month from 1983 to present (EIA 2024b). Gasoline sold in May through August was assumed to be summer grade, gasoline sold in September was assumed to be half summer and half winter grade, and gasoline sold in other months was assumed to be winter grade. The amount of ethanol within each gasoline is removed as ethanol is treated separately in this *Inventory*.

Step 2. Develop carbon content coefficients for each grade and type

Fuel properties are gathered through the Alliance of North American Fuel Survey (NAFS) published by the Alliance of Automobile Manufacturers (AAM), an association which is now part of the Alliance for Automotive Innovation. This fuel survey includes measured properties of both regular and premium gasoline.

²² See <https://www.epa.gov/fuels-registration-reporting-and-compliance-help/public-data-renewable-fuel-standard>.

²³ Calculations account for the properties of the individual constituents of gasoline, including, as applicable to the fuel grade and type: aromatics (excluding benzene), olefins, benzene, saturates, MTBE, TAME, ETBE, DIPE and ethanol.

²⁴ Saturates are assumed to be octane and aromatics are assumed to be toluene.

The carbon content are calculated according to ASTM D3343, Standard Test Method for the Estimation of Hydrogen Content of Aviation Fuels, and ASTM D3338, Standard Test Method for the Net Heat of Combustion of Aviation Fuels, respectively using fuel properties inputs from the NAFS for each year and season. Historically, the carbon mass fraction of the hydrocarbon fraction of fuels calculated according to ASTM D3343 applies to hydrocarbon containing fuels only and is not applicable towards oxygenated fuel blends. However, recently EPA has proposed an amendment to 40 CFR §600.113-12, containing equations allowing for the estimation of base fuel blendstock properties using the bulk oxygenated fuel properties. This technique is applied in this *Inventory* for oxygenated gasoline calculations.

The fuels sampled in the NAFS by AAM are assumed to be representative of the seasonal fuels sold throughout the United States.

Data Sources

Data for the density of motor gasoline were derived from NIPER (1990 through 2009). Data on the characteristics of reformulated gasoline, including C share, were also taken from NIPER (1990 through 2009) and Alliance of North American Fuel Survey (NAFS) published by the Alliance of Automobile Manufacturers (AAM), an association which is now part of the Alliance for Automotive Innovation.

Standard heat contents for motor gasoline of 5.222 MMBtu per barrel conventional gasoline and 5.150 MMBtu per barrel reformulated gasoline²⁵ were adopted from EIA (2009a).

Uncertainty

For 1990 through 1999, the uncertainty underlying the C content coefficients for motor gasoline has three underlying sources: (1) the uncertainty in the averages published by NIPER, (2) uncertainty in the C shares assumed in the EPA's analysis to be representative of the constituent hydrocarbon classes within gasoline (aromatics, olefins and saturates), and (3) uncertainty in the heat contents applied. For 2000 through 2023, the uncertainty underlying the C content coefficients for motor gasoline has two sources: (1) the uncertainty in the fuel properties gathered through the Alliance of North American Fuel Survey (NAFS) to determine carbon content and (2) uncertainty in the heat contents applied.

For 1990 through 1999, a variable number of samples are used each year to determine the average percent by volume share of each hydrocarbon within each grade, season and formulation of gasoline that were obtained from NIPER through 1999. The total number of samples analyzed for each seasonal NIPER report varies from approximately 730 to over 1,800 samples over the period from 1990 through 2009. The number of samples analyzed that underlie the calculation of the average make-up of each seasonal formulation and grade varies from approximately 50 to over 400, with the greatest number of samples each season being of conventional, regular or premium gasoline. Further, not all sample data submitted to NIPER contains data for each of the properties, such that the number of samples underlying each constituent average value for each season, grade and formulation may be variable within the single gasoline type (e.g., of the 1,073 samples for which some data was obtained for gasoline sold in Winter 1995 through 1996, benzene content was provided for all samples, while olefin, aromatic and saturate content was provided for just 736 of those samples).

The distribution of sample origin collected for the NIPER report and the calculation of national averages are not reflective of sales volumes. The publication of simple, rather than sales-weighted averages to represent national average values increases the uncertainty in their application to the calculation of carbon content factors for the purposes of this *Inventory*. Further, data for each sample is submitted voluntarily, which may also affect their representativeness.

Additionally, because the simple average constituent shares are calculated based upon data that have been renormalized to account for the share of ethers and alcohols, total average volume shares may not equal 100 percent.

²⁵ The reformulated gasoline heat content is applied to both reformulated blends containing ethers and those containing ethanol.

The simple average for each hydrocarbon constituent is contained within a range of values that are as wide as -63.0/+74.5 percent of the mean across the Winter 2007 through 2008 and -51.3/+49.6 percent across the Summer 2008 samples of conventional, regular grade gasoline. However, these wide ranges exist for benzene, which generally accounts for only 1 percent, by volume, of each gallon. In contrast, saturates, the class of hydrocarbon that contribute the largest share, by volume, ranges only -6.5/+6.4 percent for the same set of winter samples and -8.8/+15.7 percent for the summer samples.

Secondly, for 1991 through 2000, EPA's calculation of C content factors for each gasoline type includes the following assumptions: for the purposes of assigning a carbon share to each compound in the blend, aromatic content (other than benzene) is assumed to be toluene and saturated hydrocarbons are assumed to be octane. All olefins have the same carbon share because they all have a molecular formula in the form C_nH_{2n} , so the C share applied to the olefin portion of the total gasoline blend does not increase the level of uncertainty in the calculation. These assumptions are based upon the use of octane and octane isomers as the primary saturates and toluene as the primary non-benzene aromatic in U.S. motor gasoline blends. The octane rating of a particular blend is based upon the equivalent iso-octane to heptane ratio, which is achieved through significant octane content relative to the other saturates. Aside from benzene, U.S. gasolines will include toluene as a major aromatic component, so toluene may be assumed a reasonable representative of total non-benzene aromatic content (EPA 2009a).

For each hydrocarbon category, the assumed C content lies within a range of possible values for all such hydrocarbons. Among saturated hydrocarbons, the C share of octane (84.12 percent) is at the high end of the range while ethane represents the low end of the range (79.89 percent C). Total saturates constitute from 40 to 95 percent by volume of a given gasoline blend. For aromatics, toluene (91.25 percent C) lies in the middle of the possible range. This range is bounded by cumene (89.94 percent C) and naphthalene (93.71 percent C). Total aromatics may make up between 3 and 50 percent by volume of any given gasoline blend. The range of these potential values contributes to the uncertainty surrounding the final calculated C factors.

However, as demonstrated above in Figure A-3, the amount of variation in C content of gasoline is restricted by the compounds in the fuel to ± 4 percent. Further, despite variation in sampling survey response, sample size and annually variable fuel formulation requirements, the observed variation in the annual weighted motor gasoline coefficients estimated for this *Inventory* is ± 0.4 percent over 1990 through 1999.

For 2000 through 2023, the exact number of samples to determine measured fuel carbon content of both regular and premium gasoline vary by year and location. Fuel samples are drawn from multiple retail locations in each of over 20 U.S. cities for each biannual survey which occur in January and July. The fuel carbon content for gasoline was determined separately for each city and season included for each year in the NAFS. These values were averaged by fuel Petroleum Administration for Defense Districts (PADDs) to assure accurate representations for each distribution area, but the number of samples used in the averages varies by fuel PADD. To determine annual national values for gasoline carbon content, a weighted average was performed using the sales volumes for each season and PADD as published by the EIA. Across the time-series, seasons, and gasoline types, the C share of gasoline ranges from 85.38 to 87.94 percent. The range of these C shares contributes to the uncertainty surrounding the final calculated C contents.

Additionally, for 2000 through 2023, it is assumed the midgrade C content for gasoline is an average of Regular and Premium gasoline, which may not be representative. Also, the method of calculation of the fuel properties of the hydrocarbon fraction of the fuel from blended fuel properties was developed for Tier 3 certification test fuels, and not commercial fuel blends as it is used for in this *Inventory*.

The third primary contributor to uncertainty across the entire time-series is the assumed heat content. The heat contents are industry standards established many years ago. The heat contents are standard conversion factors used by EIA to convert volumetric energy data to energy units. Because the heat contents of fuels change over time, without necessarily and directly altering their volume, the conversion of known volumetric data to energy units may introduce bias. Because gasoline is an oxygenated blend, the measured API gravity and the heating value calculated from ASTM D3338 cannot be used so the yearly heating value as published by EIA and previously reported API gravities are used for this purpose. A more precise approach to estimating emissions factors would be to calculate C content per unit of volume, rather than per unit of energy. Adopting this approach, however, makes it difficult to compare U.S. C content coefficients with those of other nations.

The changes in density of motor gasoline over the last decade suggest that the heat content of the fuels is also changing. However, that change within any season grade has been less than 1 percent over the decade. Of greater

concern is the use of a standardized heat content across grades that show a variation in density of ± 1.5 percent from the mean for conventional gasoline and ± 1.0 percent for reformulated fuels.

Jet Fuel

Jet fuel is a refined petroleum product used in jet aircraft engines. There are two classes of jet fuel used in the United States: “naphtha-based” jet fuels and “kerosene-based” jet fuels. In 1989, 13 percent of U.S. consumption was naphtha-based fuel, with the remainder kerosene-based jet fuel. In 1993, the U.S. Department of Defense began a conversion from naphtha-based JP-4 jet fuel to kerosene-based jet fuel, because of the possibility of increased demand for reformulated motor gasoline limiting refinery production of naphtha-based jet fuel. By 1996, naphtha-based jet fuel represented less than one-half of one percent of all jet fuel consumption. The C content coefficient for jet fuel used in this report prior to 1996 represents a consumption-weighted combination of the naphtha-based and kerosene-based coefficients. From 1996 to 2023, only the kerosene-based portion of total consumption is considered significant.

Methodology

Step 1. Estimate the carbon content for naphtha-based jet fuels

Because naphtha-based jet fuels are used on a limited basis in the United States, sample data on its characteristics are limited. The density of naphtha-based jet fuel (49 degrees) was estimated as the central point of the acceptable API gravity range published by ASTM. The heat content of the fuel was assumed to be 5.355 MMBtu per barrel based on EIA industry standards. The C fraction was derived from an estimated hydrogen content of 14.1 percent (Martel and Angello 1977), and an estimated content of sulfur and other non-hydrocarbons of 0.1 percent.

Step 2. Estimate the carbon content for kerosene-based jet fuels

The density of kerosene-based jet fuels was estimated at 42 degrees API and the carbon share at 86.3 percent. The density estimate was based on 38 fuel samples examined by NIPER. Carbon share was estimated on the basis of a hydrogen content of 13.6 percent found in fuel samples taken in 1959 and reported by Martel and Angello, and on an assumed sulfur content of 0.1 percent. The EIA’s standard heat content of 5.670 MMBtu per barrel was adopted for kerosene-based jet fuel.

Step 3. Weight the overall jet fuel carbon content coefficient for consumption of each type of fuel (1990-1995 only)

For years 1990 through 1995, the C content for each jet fuel type (naphtha-based, kerosene-based) is multiplied by the share of overall consumption of that fuel type, as reported by EIA (2009a). Individual coefficients are then summed and totaled to yield an overall C content coefficient. Only the kerosene-based C coefficient is reflected in the overall jet fuel coefficient for 1996 through 2023.

Data Sources

Data on the C content of naphtha-based jet fuel was taken from C.R. Martel and L.C. Angello (1977). Data on the density of naphtha-based jet fuel was taken from ASTM (1985). Standard heat contents for kerosene and naphtha-based jet fuels were adopted from EIA (2009a). Data on the C content of kerosene-based jet fuel is based on C.R. Martel and L.C. Angello (1977) and the density is derived from NIPER (1993).

Uncertainty

Variability in jet fuel is relatively small with the average C share of kerosene-based jet fuel varying by less than ± 1 percent and the density varying by ± 1 percent. This is because the ratio of fuel mass to useful energy must be tightly bounded to maximize safety and range. There is more uncertainty associated with the density and C share of naphtha-based jet fuel because sample data were unavailable and default values were used. This uncertainty has only a small impact on the overall uncertainty of the C content coefficient for jet fuels, however, because naphtha-based jet fuel represents a small and declining share of total jet fuel consumption in the United States and is treated as negligible when calculating C content factors for 1996 onward.

Distillate Fuel

Distillate fuel is a general classification for diesel fuels and fuel oils. Products known as No. 1, No. 2, and No. 4 diesel fuel are used in on-highway diesel engines, such as those in trucks and automobiles, as well as off-highway engines, such as those in railroad locomotives and agricultural machinery. No. 1, No. 2, and No. 4 fuel oils are also used for space heating and electric power generation.

Methodology

For this *Inventory*, separate C coefficients have been estimated for each of the three distillates, although the level of aggregation of U.S. energy statistics requires that a single coefficient is used to represent all three grades in inventory calculations. Distillate No. 2 is the representative grade applied to the distillate class for calculation purposes. Coefficients developed for No. 1 and No. 4 distillate are provided for informational purposes. The C share for distillate No. 1 and No. 4 is drawn from *Perry's Chemical Engineers' Handbook*, 8th Ed. (Green & Perry 2008). Each C share was combined with individual heat contents of 5.822 and 6.135 MMBtu per barrel, respectively for distillates No. 1 and No. 4, and densities of 35.3 and 23.2 degrees API to calculate C coefficients for each distillate type.

For 1990 to 1999, the C share for distillate No. 2 is drawn from *Perry's Chemical Engineers' Handbook*, 8th Ed. (Green & Perry 2008) and each share was combined with the heat content of 5.825 MMBtu per barrel and density of 35.8 degrees API to calculate C coefficients. For 2000 through 2023, the carbon content and net heating value of distillate No. 2, which is used in this *Inventory* for all distillate consumption, is calculated according to ASTM D3343, Standard Test Method for the Estimation of Hydrogen Content of Aviation Fuels, and ASTM D3338, Standard Test Method for the Net Heat of Combustion of Aviation Fuels, using fuel properties inputs from the Alliance of North American Fuel Survey (NAFS) data for each year and season. These methods use a correlation between the measured fuel distillation range, API gravity, and aromatic content to estimate the hydrogen content and net heating value.

Data Sources

For 2000 through 2023, fuel properties for distillate No. 2 were derived from diesel surveys taken by the Alliance of Automobile Manufacturers, an association which is now part of the Alliance for Automotive Innovation. Prime supplier sales volumes of diesel fuel for each month from 1983 to present are from EIA (2024b).

For previous years, the density of distillate fuel oil No. 2 is taken from *Perry's Chemical Engineer's Handbook*, 8th Ed. (Green & Perry, ed. 2008), Table 24-6. Heat contents are adopted from EIA (2025), and carbon shares for distillates No. 2 are from *Perry's Chemical Engineers' Handbook* (Green & Perry, ed. 2008), Table 24-6.

Uncertainty

Across the time-series, the primary source of uncertainty for the estimated C content of distillate fuel is the selection of No. 2 distillate as the typical distillate fuel oil or diesel fuel. No. 2 fuel oil is generally consumed for home heating. No. 1 distillate is generally less dense and if it is consumed in large portions for mobile sources, the application of the C content estimated for No. 2 for this report is likely to be too high when applied to both No. 1 and No. 2 distillates. The opposite is true of the application of a coefficient based upon the properties of No. 2 to the consumption of No. 4 distillate, which is of a significantly higher density and thus, has a higher C coefficient despite its lower C share. The overall effect on uncertainty from applying a single factor will depend on the relative annual consumption of each distillate.

For 1990 through 1999, the densities applied to the calculation of each carbon factor are an underlying a source of uncertainty. The factor applied to all distillates in the *Inventory* estimates (that for No. 2 oil) is based on a sample size of 144. The uncertainty associated with the assumed density of distillate fuels is predominately a result of the use of No. 2 to represent all distillate consumption. There is also a small amount of uncertainty in the No. 2 distillate density itself. This is due to the possible variation across seasonal diesel formulations and fuel grades and between stationary and transport applications within the No. 2 distillate classification. The range of the density of the samples of No. 2 diesel (regular grade, 15 ppm sulfur) is ± 2.5 percent from the mean, while the range in density across the small sample set of No. 1 diesel is -2.1 to $+1.6$ percent of the mean. Samples from AAM (2009) of Premium No. 2 diesel ($n=5$) and higher sulfur (500 ppm S) regular diesel ($n=2$), each have nominally higher

average densities (+1.3 percent and +0.6 percent, respectively) than do the low-sulfur regular diesel samples that underlie the density applied in this *Inventory*.

The use of the 144 AAM samples to define the density of No. 2 distillate (and those four samples used to define that of No. 1 distillate) may introduce additional uncertainty because the samples were collected from just one season of on-road fuel production (Winter 2008). Despite the limited sample frame, the average No. 2 density calculated from the samples is applied to the calculation of a uniform C coefficient applicable for all years of the *Inventory* and for all types of distillate consumption. The ASTM standards for each grade of diesel fuel oil do not include a required range in which the density must lie, and the density (as well as heat content and carbon share) may vary according to the additives in each seasonal blend and the sulfur content of each sub-grade.

However, previous studies also show relatively low variation in density across samples of No. 2 and across all distillates, supporting the application of a single No. 2 density to all U.S. distillate consumption. The average density calculated from samples analyzed by the EIA in 1994 (n=7) differs only very slightly from the value applied for the purposes of this *Inventory* (-0.12 percent for No. 2 distillate). Further, the difference between the mean density applied to this *Inventory* (No. 2 only) and that calculated from EIA samples of all distillates, regardless of grade, is also near zero (-0.06 percent, based on n=14, of distillates No. 1, No. 2 and No. 4 combined).

A C share of 87.30 percent is applied to No. 2 distillate, while No. 1 and No. 4 have C shares estimated at 86.40 and 86.47 percent, respectively. Again, the application of parameters specific to No. 2 to the consumption of all three distillates contributes to an increased level of uncertainty in the overall coefficient and emissions estimate and its broad application. For comparison, four No. 1 fuel oil samples obtained by EIA (1994) contained an average of 86.19 percent C, while seven samples No. 2 fuel oil from the same EIA analysis showed an average of 86.60 percent C. Additionally, three samples of No. 4 distillate indicate an average C share of 85.81 percent. The range of C share observed across the seven No. 2 samples is 86.1 to 87.5 percent, and across all samples (all three grades, n=14) the range is 85.3 to 87.5 percent C. There also exists an uncertainty of ± 1 percent in the share of C in No. 2 based on the limited sample size.

For 2000 through 2023, the exact number of samples to determine measured fuel carbon content of distillates vary by year and location. As is the same for motor gasoline, fuel samples are drawn from multiple retail locations in each of over 20 U.S. cities for each biannual survey which occur in January and July. The fuel carbon content for diesel fuel was determined separately for each city and season included for each year in the NAFS. Diesel national fuel averages for summer and winter are combined with sales volumes for each season to determine a national total. Across the time-series and seasons, the C share of diesel ranges from 86.68 to 87.07 percent. The range of these C shares contributes to the uncertainty surrounding the final calculated C contents.

Additionally, the two ASTM standard methods used for the calculation of carbon content and other properties, ASTM D3343 and D3338, were developed specifically for aviation fuels and not motor vehicle fuels. However, the EPA and other organizations regularly uses these methods for diesel fuel, and both are specified methods in Code of Federal Regulations (CFR) fuel economy calculations.

Residual Fuel

Residual fuel is a general classification for the heavier oils, known as No. 5 and No. 6 fuel oils, that remain after the distillate fuel oils and lighter hydrocarbons are distilled away in refinery operations. Residual fuel conforms to ASTM Specifications D 396 and D 975 and Federal Specification VV-F-815C. No. 5, a residual fuel oil of medium viscosity, is also known as Navy Special and is defined in Military Specification MIL-F-859E, including Amendment 2 (NATO Symbol F-770). It is used in steam-powered vessels in government service and inshore power plants. No. 6 fuel oil includes Bunker C fuel oil and is used for the production of electric power, space heating, vessel bunkering, and various industrial purposes.

In the United States, electric utilities purchase about one-third of the residual oil consumed. A somewhat larger share is used for vessel bunkering, and the balance is used in the commercial and industrial sectors. The residual oil (defined as No. 6 fuel oil) consumed by electric utilities has an energy content of 6.287 MMBtu per barrel (EIA 2008a) and an average sulfur content of 1 percent (EIA 2001). This implies a density of about 17 degrees API.

Methodology

Because U.S. energy consumption statistics are available only as an aggregate of No. 5 and No. 6 residual oil, a single coefficient must be used to represent the full residual fuel category. As in earlier editions of this report,

residual fuel oil has been defined as No. 6 fuel oil, due to the majority of residual consumed in the United States being No. 6. However, for this report, a separate coefficient for fuel oil No. 5 has also been developed for informational purposes. Densities of 33.0 and 15.5 degrees API were adopted when developing the C content coefficients for Nos. 5 and 6, respectively (Wauquier, J.-P., ed. 1995; Green & Perry, ed. 2008).

The estimated C share of fuel oil No. 5 is 85.67 percent, based on an average of 12 ultimate analyses of samples of fuel oil (EIA 1994). An average share of C in No. 6 residual oil of 84.67 percent by mass was used, based on Perry's, 8th Ed. (Green & Perry, ed. 2008).

Data Sources

Data on the C share and density of residual fuel oil No. 6 were obtained from Green & Perry, ed. (2008). Data on the C share of fuel oil No. 5 was adopted from EIA (1994), and the density of No. 5 was obtained from Wauquier, J.-P., ed. (1995). Heat contents for both No. 5 and No. 6 fuel oil are adopted from EPA (2009b).

Uncertainty

Beyond the application of a C factor based upon No. 6 oil to all residual oil consumption, the largest source of uncertainty in estimating the C content of residual fuel centers on the estimates of density. Fuel oils are likely to differ depending on the application of the fuel (i.e., power generation or as a marine vessel fuel). Slight differences between the density of residual fuel used by utilities and that used in mobile applications are likely attributable to non-sulfur impurities, which reduce the energy content of the fuel, but do not greatly affect the density of the product. Impurities of several percent are commonly observed in residual oil. The extent of the presence of impurities has a greater effect on the uncertainty of C share estimation than it does on density. This is because these impurities do provide some Btu content to the fuel, but they are absent of carbon. Fuel oils with significant sulfur, nitrogen and heavy metals contents would have a different total carbon share than a fuel oil that is closer to pure hydrocarbon. This contributes to the uncertainty of the estimation of an average C share and C coefficient for these varied fuels.

The 12 samples of residual oil (EIA 1994) cover a density range from 4.3 percent below to 8.2 percent above the mean density. The observed range of C share in these samples is -2.5 to +1.8 percent of the mean. Overall, the uncertainty associated with the C content of residual fuel is probably ± 1 percent.

Hydrocarbon Gas Liquids (HGL)

EIA identifies four categories of paraffinic hydrocarbons (i.e., ethane, propane, isobutane, and n-butane) and four categories of olefinic hydrocarbons (i.e., ethylene, propylene, isobutylene, and butylene) as HGL. Because each of these compounds is a pure paraffinic or olefinic hydrocarbon, their C shares are easily derived by taking into account the atomic weight of C (12.01) and the atomic weight of hydrogen (1.01). Thus, for example, the C share of propane, C₃H₈, is 81.71 percent. The densities and heat contents of the compounds are also well known, allowing C content coefficients to be calculated directly. Table A-33 summarizes the physical characteristic of HGL.

Table A-33: Physical Characteristics of Hydrocarbon Gas Liquids

Compound	Chemical Formula	Density (Barrels Per Metric Ton)	Carbon Content (Percent)	Energy Content (MMBtu/Barrel)	Carbon Content Coefficient (MMT C/QBtu)
Ethane	C ₂ H ₆	11.55	80	2.783	16.25
Propane	C ₃ H ₈	12.76	81.8	3.841	17.15
Isobutane	C ₄ H ₁₀	11.42	82.8	4.183	17.71
n-butane	C ₄ H ₁₀	10.98	82.3	4.353	17.66
Ethylene	C ₂ H ₄	11.07	85.71	2.436	17.99
Propylene	C ₃ H ₆	12.45	85.71	3.835	18.48
Isobutylene	C ₄ H ₈	10.68	85.71	4.355	18.78
Butylene	C ₄ H ₈	10.7	85.71	4.377	18.74

Source: Densities – CRC Handbook of Chemistry and Physics (2008/09) and EPA (2009c); Carbon Contents – derived from the atomic weights of the elements EPA (2013); Energy Contents – EIA (2025). All values are for the

compound in liquid form. The density and energy content of ethane are for refrigerated ethane (-89 degrees C). Values for n-butane are for pressurized butane (-25 degrees C).

Methodology

Step 1. Assign carbon content coefficients to each pure paraffinic compound

Based on their known physical characteristics, a C content coefficient is assigned to each compound contained in the U.S. energy statistics category, HGL.

Step 2. Weight individual HGL coefficients for share of fuel use consumption

A C content coefficient for HGL used as fuel is developed based on the consumption mix of the individual compounds reported in U.S. energy statistics.

Step 3. Weight individual HGL coefficients for share of non-fuel use consumption

The mix of HGL consumed for non-fuel use differs significantly from the mix of HGL that is combusted. EIA (2025) states that HGL consumption in the residential, commercial, and transportation sector is 100 percent propane, therefore a constant, non-weighted propane C content coefficient is applied to HGL (LPG – Propane) in these sectors. While the majority of HGL consumed for fuel use in the industrial sector is propane, ethane is the largest component of HGL used for non-fuel applications. C content coefficients for HGL used for fuel use and non-fuel applications are developed based on the consumption mix of the individual compounds reported in U.S. energy statistics.

Step 4. Weight the carbon content coefficients for fuel use and non-fuel use by their respective shares of consumption

The changing shares of HGL fuel use and non-fuel use consumption appear below in Table A-34.

Data Sources

Data on C share was derived via calculations based on atomic weights of each element of the four individual compounds densities are from the CRC Handbook of Chemistry and Physics, 89th Edition. The energy content of each HGL is from EIA (2025). HGL consumption was based on data obtained from EIA (2024a). Non-fuel use of HGL was obtained from EIA (2024a).

Uncertainty

Because HGL consists of pure paraffinic and olefinic compounds whose density, heat content, and C share are physical constants, there is limited uncertainty associated with the C content coefficient for this petroleum product. Any uncertainty is associated with the collection of data tabulating fuel- and non-fuel consumption in U.S. energy statistics. This uncertainty is likely less than ±3 percent.

Table A-34: Industrial Sector Consumption and Carbon Content Coefficients of Hydrocarbon Gas Liquids, 1990-2023

	1990	1995	2000	2005	2010	2016	2017	2018	2019	2020	2021	2022	2023
Energy Consumption (QBTU)													
Fuel Use	8.38	10.56	10.69	10.83	9.79	10.51	10.01	10.32	9.32	8.89	9.34	8.91	8.66
Ethane	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Propane	6.60	7.94	7.03	7.09	5.20	5.79	5.27	5.50	4.59	4.54	4.51	4.52	4.22
Butane	0.25	0.26	0.28	0.25	0.25	0.20	0.09	0.08	0.12	(0.03)	0.05	0.12	0.25
Isobutane	0.04	0.15	0.23	0.07	0.06	0.29	0.32	0.37	0.43	0.49	0.51	0.41	0.46
Ethylene	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Propylene	1.47	2.20	3.15	3.41	4.28	4.23	4.32	4.36	4.18	3.90	4.27	3.86	3.74
Butylene	0.01	0.01	0.01	0.01	0.01	(0.01)	0.01	0.02	+	(0.01)	(0.01)	(0.01)	(+)

Isobutylene	+	+	0.01	+	+	+	+	(+)	+	(+)	(+)	+	+
Non-Fuel Use	1.58	1.92	2.19	2.03	2.31	2.70	2.73	3.09	3.06	3.15	3.32	3.45	3.63
Ethane	0.51	0.63	0.78	0.67	0.89	1.15	1.26	1.50	1.56	1.75	1.84	2.05	2.19
Propane	0.55	0.64	0.65	0.72	0.81	0.85	0.80	0.89	0.77	0.75	0.74	0.71	0.66
Butane	0.14	0.15	0.16	0.14	0.14	0.11	0.05	0.05	0.07	(0.01)	0.03	0.07	0.14
Isobutane	0.02	0.09	0.13	0.04	0.03	0.17	0.18	0.21	0.24	0.28	0.29	0.23	0.26
Ethylene	+	+	+	+	0.01	+	+	+	+	+	+	+	+
Propylene	0.34	0.40	0.46	0.45	0.43	0.42	0.43	0.44	0.42	0.39	0.43	0.39	0.37
Butylene	0.01	0.01	0.01	0.01	0.01	(+)	+	0.01	+	(+)	(+)	(+)	(+)
Isobutylene	+	+	+	+	+	+	+	(+)	+	(+)	(+)	+	+
Carbon Content (MMT C/QBtu)													
Fuel Use	17.40	17.45	17.57	17.58	17.75	17.71	17.75	17.74	17.78	17.76	17.79	17.76	17.77
Non-Fuel Use	17.21	17.21	17.19	17.21	17.10	17.03	17.00	16.95	16.93	16.86	16.88	16.81	16.81

Notes: “+” indicates a value less than 0.01 QBtu. Parentheses indicate negative values. Totals may not sum due to independent rounding.

Sources: Fuel use of HGL based on data from EIA (2024a). Non-fuel use of HGL from (EIA 2024a). Volumes converted using the energy contents provided in Table A-33. C contents from EPA (2013).

Aviation Gasoline

Aviation gasoline is used in piston-powered airplane engines. It is a complex mixture of relatively volatile hydrocarbons with or without small quantities of additives, blended to form a fuel suitable for use in aviation reciprocating engines. Fuel specifications are provided in ASTM Specification D910 and Military Specification MIL-G-5572. Aviation gas is a relatively minor contributor to greenhouse gas emissions compared to other petroleum products, representing approximately 0.1 percent of all consumption.

The ASTM standards for boiling and freezing points in aviation gasoline effectively limit the aromatics content to a maximum of 25 percent (ASTM D910). Because weight is critical in the operation of an airplane, aviation gas must have as many Btu per pound (implying a lower density) as possible, given other requirements of piston engines such as high anti-knock quality.

Methodology

A C content coefficient for aviation gasoline was calculated on the basis of the EIA standard heat content of 5.048 MMBtu per barrel. This implies a density of approximately 69 degrees API gravity or 5.884 pounds per gallon, based on the relationship between heat content and density of petroleum liquids, as described in *Thermal Properties of Petroleum Products* (DOC 1929). To estimate the share of C in the fuel, it was assumed that aviation gasoline is 87.5 percent iso-octane, 9.0 percent toluene, and 3.5 percent xylene. The maximum allowable sulfur content in aviation gasoline is 0.05 percent, and the maximum allowable lead content is 0.1 percent. These amounts were judged negligible and excluded for the purposes of this analysis. This yielded a C share of 85.00 percent and a C content coefficient of 18.86 MMT C/QBtu.

Data Sources

Data sources include ASTM (1985). A standard heat content for aviation gas was adopted from EIA (2009a).

Uncertainty

The relationship used to calculate density from heat content has an accuracy of five percent at 1 atm. The uncertainty associated with the C content coefficient for aviation gasoline is larger than that for other liquid petroleum products examined because no ultimate analyses of samples are available. Given the requirements for safe operation of piston-powered aircraft the composition of aviation gas is well bounded, and the uncertainty of the C content coefficient is likely to be ± 5 percent.

Still Gas

Still gas, or refinery gas, is composed of light hydrocarbon gases that are released as petroleum is processed in a refinery. The composition of still gas is highly variable, depending primarily on the nature of the refining process and secondarily on the composition of the product being processed. Petroleum refineries produce still gas from

many different processes. Still gas can be used as a fuel or feedstock within the refinery, sold as a petrochemical feedstock, or purified and sold as pipeline-quality natural gas. For the purposes of this *Inventory*, the coefficient derived here is only applied to still gas that is consumed as a fuel. In general, still gas tends to include large amounts of free hydrogen and methane, as well as smaller amounts of heavier hydrocarbons. Because different refinery operations result in different gaseous by-products, it is difficult to determine what represents typical still gas.

Methodology

The properties of still gas used to calculate the carbon content are taken from the literature. The carbon share of still gas was calculated from its net calorific value and carbon content from IPCC (2006). This calculation yields a carbon share of 77.7 percent. The density of still gas was estimated to be 0.1405 metric tons per barrel based on its heat content (EIA 2008a) and the relationship between heat content and density that is described by the U.S. Department of Commerce, Bureau of Standards (DOC 1929).

Data Sources

The carbon share of still gas is calculated from data provided by IPCC (2006). Density is estimated at 0.1405 metric tons per barrel, approximately 28.3 degrees API, based on the heat content of 6.00 MMBtu/barrel of still gas from EIA (2009a).

Uncertainty

The EIA obtained data on four samples of still gas. Table A-35 below shows the composition of those samples.

Table A-35: Composition, Energy Content, and Carbon Content Coefficient for Four Samples of Still Gas

Sample	Hydrogen (%)	Methane (%)	Ethane (%)	Propane (%)	Btu Per Cubic Foot	Carbon Content (MMT C/QBtu)
One	12.7	28.1	17.1	11.9	1,388	17.51
Two	34.7	20.5	20.5	6.7	1,143	14.33
Three	72.0	12.8	10.3	3.8	672	10.23
Four	17.0	31.0	16.2	2.4	1,100	15.99

Source: EIA (2008b).

Because the composition of still gas is highly heterogeneous, the C content coefficient for this product is highly uncertain. Gas streams with a large, free-hydrogen content are likely to be used as refinery or chemical feedstocks. Therefore, the sample cited above with the very high H content of 72 percent (and the lowest calculated C content) is less likely to be representative of the still gas streams to which the calculated coefficient is applied. The C content coefficient used for this report is probably at the high end of the plausible range given that it is higher than the greatest sample-based C content in Table A-35.

Asphalt

Asphalt is used to pave roads. Because most of its C is retained in those roads, it is a small source of carbon dioxide emissions. It is derived from a class of hydrocarbons called “asphaltenes,” which are abundant in some crude oils but not in others. Asphaltenes have oxygen and nitrogen atoms bound into their molecular structure, so that they tend to have lower C contents than do other hydrocarbons.

Methodology

Ultimate analyses of twelve samples of asphalts showed an average C content of 83.47 percent. The EIA standard Btu content for asphalt of 6.636 MMBtu per barrel was assumed. The ASTM petroleum measurement tables show a density of 5.6 degrees API or 8.605 pounds per gallon for asphalt. Together, these variables generate C content coefficient of 20.55 MMT C/QBtu.

Data Sources

A standard heat content for asphalt was adopted from EIA (2009b). The density of asphalt was determined by the ASTM (1985). C share is adopted from analyses in EIA (2008b).

Uncertainty

The share of C in asphalt ranges from 79 to 88 percent by weight. Also present in the mixture are hydrogen and sulfur, with shares by weight ranging from seven to 13 percent for hydrogen, and from trace levels to eight percent for sulfur. Because C share and total heat content in asphalts do vary systematically, the overall C content coefficient is likely to be accurate to ± 5 percent.

Lubricants

Lubricants are substances used to reduce friction between bearing surfaces, or incorporated into processing materials used in the manufacture of other products, or used as carriers of other materials. Petroleum lubricants may be produced either from distillates or residues. Lubricants include all grades of lubricating oils, from spindle oil to cylinder oil to those used in greases. Lubricant consumption is dominated by motor oil for automobiles, but there is a large range of product compositions and end uses within this category.

Methodology

The ASTM Petroleum Measurement tables give the density of lubricants at 25.6 degrees API, or 0.1428 metric tons per barrel. Ultimate analysis of a single sample of motor oil yielded a C content of 85.80 percent. A standard heat content of 6.065 MMBtu per barrel was adopted from EIA. These factors produce a C content coefficient of 20.20 MMT C/QBtu.

Data Sources

A standard heat content was adopted from the EIA (2009b). The carbon content of lubricants is adopted from ultimate analysis of one sample of motor oil (EPA 2009a). The density of lubricating oils was determined by ASTM (1985).

Uncertainty

Uncertainty in the estimated C content coefficient for lubricants is driven by the large range of product compositions and end uses in this category combined with an inability to establish the shares of the various products captured under this category in U.S. energy statistics. Because lubricants may be produced from either the distillate or residual fractions during refineries, the possible C content coefficients range from 19.89 MMT C/QBtu to 21.48 MMT C/QBtu or an uncertainty band from -1.5 percent to $+1.4$ percent of the estimated value.

Petrochemical Feedstocks

U.S. energy statistics distinguish between two different kinds of petrochemical feedstocks: those with a boiling temperature below 400 degrees Fahrenheit, generally called “naphtha,” and those with a boiling temperature 401 degrees Fahrenheit and above, referred to as “other oils” for the purposes of *this Inventory*.

Methodology

The C content of these petrochemical feedstocks are estimated independently according to the following steps.

Step 1. Estimate the carbon content coefficient for naphtha

Because reformed naphtha is used to make motor gasoline (hydrogen is released to raise aromatics content and octane rating), “straight-run” naphtha is assumed to be used as a petrochemical feedstock. Ultimate analyses of five samples of naphtha were examined and showed an average C share of 84.11 percent. A density of 62.4 degrees API gravity was taken from the *Handbook of Petroleum Refining Processes*, 3rd ed. (Meyers 2004). The standard EIA heat content of 5.248 MMBtu per barrel is used to estimate a C content coefficient of 18.55 MMT C/QBtu.

Step 2. Estimate the carbon content coefficient for petrochemical feedstocks with a boiling temperature 400 degrees Fahrenheit and above (“other oils”)

The boiling temperature of this product places it into the “middle distillate” fraction in the refining process, and EIA estimates that these petrochemical feedstocks have the same heat content as distillate fuel No. 2. Thus, the C content coefficient of 20.17 MMT C/QBtu used for distillate fuel No. 2 is also adopted for this portion of the petrochemical feedstocks category.

Data Sources

Naphthas: Data on the C content was taken from Unzelman (1992). Density is from Meyers (2004). A standard heat content for naphthas was adopted from EIA (2009a). Other oils: See Distillate Fuel, Distillate No.2.

Uncertainty

Petrochemical feedstocks are not so much distinguished on the basis of chemical composition as on the identity of the purchaser, who are presumed to be a chemical company, or a petrochemical unit co-located on the refinery grounds. Naphthas are defined, for the purposes of U.S. energy statistics, as those naphtha products destined for use as a petrochemical feedstock. Because naphthas are also commonly used to produce motor gasoline, there exists a considerable degree of uncertainty about the exact composition of petrochemical feedstocks.

Different naphthas are distinguished by their density and by the share of paraffins, isoparaffins, olefins, naphthenes and aromatics contained in the oil. Naphtha from the same crude oil fraction may have vastly different properties depending on the source of the crude. Two different samples of Egyptian crude, for example, produced two straight run naphthas having naphthene and paraffin contents (percent volume) that differ by 18.1 and 17.5 percent, respectively (Matar and Hatch 2000).

Naphthas are typically used either as a petrochemical feedstock or a gasoline feedstock, with lighter paraffinic naphthas going to petrochemical production. Naphthas that are rich in aromatics and naphthenes tend to be reformed or blended into gasoline. Thus, the product category encompasses a range of possible fuel compositions, creating a range of possible C shares and densities. The uncertainty associated with the calculated C content of naphthas is primarily a function of the uncertainty that underlies the average carbon share calculation, which is based on a limited number of samples. Two additional samples cited by the EIA (1994) have a range of 83.80 to 84.42 percent C.

The uncertainty of the C content for other oils is based upon the assumption of distillate oil No. 2 as a product representative of the ill-defined classification of “other oils,” and from the calculation of the C content of No. 2 itself (see “Distillate Fuels,” above). While No. 2 distillate is used as a proxy for “other oils” for the purposes of this *Inventory’s* carbon coefficient, important differences exist between these two petroleum products, contributing some uncertainty to the cross-application. Other oils are defined herein as those “oils with a boiling range equal to or greater than 401 degrees F that are generally intended for use as a petrochemical feedstock and are not defined elsewhere.” For comparison, various material safety data sheets (MSDSs) published by producers of distillate No. 2 indicate a boiling range for this product of 320 to 700 degrees Fahrenheit. The relatively open definition of the classification “other oils” leaves room for potentially significant variation in the heating value, density and carbon share properties of each feedstock oil having a boiling point above 400 degrees Fahrenheit, creating a large band of uncertainty beyond that associated with the C factor for distillate No. 2.

Kerosene

A light petroleum distillate that is used in space heaters, cook stoves, and water heaters and is suitable for use as a light source when burned in wick-fed lamps, kerosene is drawn from the same petroleum fraction as jet fuel. Kerosene is generally comparable to No. 1 distillate oil.

Methodology

The average density and C share of kerosene are assumed to be the same as those for distillate No. 1 since the physical characteristics of the products are very similar. Thus, a density of 35.3 degrees API and average C share of 86.40 percent were applied to a standard heat content for distillate No. 1 of 5.825 MMBtu per barrel to yield a C content coefficient of 19.96 MMT C/QBtu.

Data Sources

A standard heat content for distillate No. 1 was adopted from EIA (2009a).

Uncertainty

Uncertainty in the estimated C content for kerosene is driven by the selection of distillate No. 1 as a proxy for kerosene. If kerosene is more like kerosene-based jet fuel, the true C content coefficient is likely to be some 1.3 percent lower. If kerosene is more aptly compared to No. 2 distillate oil, then the true C content coefficient is likely to be about 1.1 percent higher. While kerosene is a light petroleum distillate, like distillate No. 1, the two oil classes have some variation in their properties. For example, the boiling range of kerosene is 250 to 550 degrees Fahrenheit, whereas No. 1 oils typically boil over a range from 350 to 615 degrees Fahrenheit. The properties of individual kerosenes will vary with their use and particular crude origin, as well. Both kerosene and fuel oil No. 1 are primarily composed of hydrocarbons having 9 to 16 carbon atoms per molecule. However, kerosene is a straight-run No. 1 fuel oil, additional cracking processes and additives contribute to the range of possible fuels that make up the broader distillate No. 1 oil category.

Petroleum Coke

Petroleum coke is the solid residue by-product of the extensive processing of crude oil. It is a coal-like solid, usually has a C content greater than 90 percent, and is used as a boiler fuel and industrial raw material.

Methodology

Ultimate analyses of two samples of petroleum coke showed an average C share of 92.28 percent. The ASTM standard density of 9.543 pounds per gallon was adopted and the EIA standard energy content of 6.024 MMBtu per barrel assumed. Together, these factors produced an estimated C content coefficient of 27.85 MMT C/QBtu.

Data Sources

C content was derived from two samples from Martin, S.W. (1960). The density of petroleum coke was taken from the ASTM (1985). A standard heat content for petroleum coke was adopted from EIA (2009a).

Uncertainty

The uncertainty associated with the estimated C content coefficient of petroleum coke can be traced to two factors: the use of only two samples to establish C contents and a standard heat content which may be too low. Together, these uncertainties are likely to bias the C content coefficient upwards by as much as 6 percent.

Special Naphtha

Special naphtha is defined as a light petroleum product to be used for solvent applications, including commercial hexane and four classes of solvent: (1) Stoddard solvent, used in dry cleaning; (2) high flash point solvent, used as an industrial paint because of its slow evaporative characteristics; (3) odorless solvent, most often used for residential paints; and (4) high solvency mineral spirits, used for architectural finishes. These products differ in both density and C percentage, requiring the development of multiple coefficients.

Methodology

The method for estimating the C content coefficient of special naphtha includes three steps.

Step 1. Estimate the carbon content coefficient for hexane

Hexane is a pure paraffin containing 6 C atoms and 14 hydrogen atoms; thus, it is 83.63 percent C. Its density is 83.7 degrees API or 5.477 pounds per gallon and its derived C content coefficient is 21.40 MMT C/QBtu.

Step 2. Estimate the carbon contents of non-hexane special naphthas

The hydrocarbon compounds in special naphthas are assumed to be either paraffinic or aromatic (see discussion above). The portion of aromatics in odorless solvents is estimated at less than 1 percent, Stoddard and high flash point solvents contain 15 percent aromatics and high solvency mineral spirits contain 30 percent aromatics (Boldt

and Hall 1977). These assumptions, when combined with the relevant densities, yield the C content factors contained in Table A-36, below.

Table A-36: Characteristics of Non-hexane Special Naphthas

Special Naphtha	Aromatic Content (Percent)	Density (Degrees API)	Carbon Share (Percent Mass)	Carbon Content (MMT C/QBtu)
Odorless Solvent	1	55.0	84.51	19.41
Stoddard Solvent	15	47.9	84.44	20.11
High Flash Point	15	47.6	84.70	20.17
Mineral Spirits	30	43.6	85.83	20.99

Sources: EIA (2008b) and Boldt and Hall (1977).

Step 3. Develop weighted carbon content coefficient based on consumption of each special naphtha

EIA reports only a single consumption figure for special naphtha. The C contents of the five special naphthas are weighted according to the following formula: approximately 10 percent of all special naphtha consumed is hexane; the remaining 90 percent is assumed to be distributed evenly among the four other solvents. The resulting emissions coefficient for special naphthas is 19.74 MMT C/QBtu.

Data Sources

A standard heat content for special naphtha was adopted from EIA (2009a). Density and aromatic contents were adopted from Boldt and Hall (1977).

Uncertainty

The principal uncertainty associated with the estimated C content coefficient for special naphtha is the allocation of overall consumption across individual solvents. The overall uncertainty is bounded on the low end by the C content of odorless solvent and on the upper end by the C content of hexane. This implies an uncertainty band of – 1.7 percent to +8.4 percent.

Petroleum Waxes

The ASTM standards define petroleum wax as a product separated from petroleum that is solid or semi-solid at 77 degrees Fahrenheit (25 degrees Celsius). The two classes of petroleum wax are paraffin waxes and microcrystalline waxes. They differ in the number of C atoms and the type of hydrocarbon compounds. Microcrystalline waxes have longer C chains and more variation in their chemical bonds than paraffin waxes.

Methodology

The method for estimating the C content coefficient for petroleum waxes includes three steps.

Step 1. Estimate the carbon content of paraffin waxes

For the purposes of this analysis, paraffin waxes are assumed to be composed of 100 percent paraffinic compounds with a chain of 25 C atoms. The resulting C share for paraffinic wax is 85.23 percent and the density is estimated at 45 degrees API or 6.684 pounds per gallon.

Step 2. Estimate the carbon content of microcrystalline waxes

Microcrystalline waxes are assumed to consist of 50 percent paraffinic and 50 percent cycloparaffinic compounds with a chain of 40 C atoms, yielding a C share of 85.56 percent. The density of microcrystalline waxes is estimated at 36.7 degrees API, based on a sample of 10 microcrystalline waxes found in the *Petroleum Products Handbook* (Martin, S.W. 1960).

Step 3. Develop a carbon content coefficient for petroleum waxes by weighting the density and carbon content of paraffinic and microcrystalline waxes

A weighted average density and C content was calculated for petroleum waxes, assuming that wax consumption is 80 percent paraffin wax and 20 percent microcrystalline wax. The weighted average C content is 85.30 percent, and the weighted average density is 6.75 pounds per gallon. EIA's standard heat content for waxes is 5.537 MMBtu per barrel. These inputs yield a C content coefficient for petroleum waxes of 19.80 MMT C/QBtu.

Data Sources

Density of paraffin wax was taken from ASTM (1985). Density of microcrystalline waxes was derived from 10 samples found in Guthrie (1960). A standard heat content for petroleum waxes was adopted from EIA (2009a).

Uncertainty

Although there is considerable qualitative uncertainty associated with the allocation of petroleum waxes and microcrystalline waxes, the quantitative variation in the C contents for all waxes is limited to ± 1 percent because of the nearly uniform relationship between C and other elements in petroleum waxes broadly defined.

Crude Oil, Unfinished Oils, and Miscellaneous Products

U.S. energy statistics include several categories of petroleum products designed to ensure that reported refinery accounts "balance" and cover any "loopholes" in the taxonomy of petroleum products. These categories include crude oil, unfinished oils, and miscellaneous products. Crude oil is rarely consumed directly, miscellaneous products account for less than one percent of oil consumption, and unfinished oils are a balancing item that may show negative consumption. For C accounting purposes, it was assumed that all unfinished oils have the same C content as crude oil. The miscellaneous products category reported by EIA includes miscellaneous products that are not reported elsewhere in the EIA data set. According to EIA recovered sulfur compounds from petroleum and natural gas processing, and potentially carbon black feedstock could be reported in this category. Recovered sulfur has no carbon content and would not be reported in the *Inventory*. Based on this information, the miscellaneous products category reported by EIA was assumed to be mostly petroleum refinery sulfur compounds that do not contain carbon (EIA 2019). Therefore, the carbon content for miscellaneous products was assumed to be zero across the time series.

Methodology

EIA reports on the average density and sulfur content of U.S. crude oil purchased by refineries. To develop a method of estimating C content based on this information, results of ultimate analyses of 182 crude oil samples were collected. Within the sample set, C content ranged from 82 to 88 percent C, but almost all samples fell between 84 percent and 86 percent C. The density and sulfur content of the crude oil data were regressed on the C content, producing the following equation:

Equation A-5: C Content of Crude Oil

$$\text{Percent C} = 76.99 + (10.19 \times \text{Specific Gravity}) + (-0.76 \times \text{Sulfur Content})$$

Absent the term representing sulfur content, the equation had an R-squared of only 0.35.²⁶ When C content was adjusted to exclude sulfur, the R-squared value rose to 0.65. While sulfur is the most important non-hydrocarbon impurity, nitrogen and oxygen can also be significant, but they do not seem to be correlated with either density or sulfur content. Restating these results, density accounts for about 35 percent of the variation in C content, impurities account for about 30 percent of the variation, and the remaining 35 percent is accounted for by other factors, including (presumably) the degree to which aromatics and polynuclear aromatics are present in the crude oil. Applying this equation to the 2008 crude oil quality data (30.21 degrees API and 1.47 percent sulfur) produces

²⁶ R-squared represents the percentage of variation in the dependent variable (in this case carbon content) explained by variation in the independent variables.

an estimated C content of 84.79 percent. Applying the density and C content to the EIA standard energy content for crude oil of 5.800 MMBtu per barrel produced an emissions coefficient of 20.31 MMT C/QBtu.

Data Sources

Carbon content was derived from 182 crude oil samples, including 150 samples from U.S. National Research Council (1927). A standard heat content for crude oil was adopted from EIA (2009a).

Uncertainty

The uncertainty of the estimated C content for crude oil centers on the 35 percent of variation that cannot be explained by density and sulfur content. This variation is likely to alter the C content coefficient by ± 3 percent. Since unfinished oils and miscellaneous products are impossible to define, the uncertainty of applying a crude oil C content is likely to be bounded by the range of petroleum products described in this chapter at ± 10 percent.

Chronology and Explanation of Changes in Individual Carbon Content Coefficients of Fossil Fuels

The following section describes changes to carbon content coefficients of fossil fuels, organized by the calendar year in which the update was implemented. Additional information on which *Inventory* year these changes appear is provided within each section.

Coal

Original 1994 Analysis

A set of 5,426 coal samples from the EIA coal analysis file were used to develop C content estimates. The results from that sample set appear below in Table A-37. The EIA Coal Analysis File was originally developed by the U.S. Bureau of Mines and contained over 60,000 coal samples obtained through numerous coal seams throughout the United States. Many of the samples were collected starting in the 1940s and 1950s through the 1980s and analyzed in U.S. government laboratories. The coefficients developed in 1994 were in use for the 1990 through 2000 *Inventory* and are provided in Table A-37.

Table A-37: Carbon Content Coefficients for Coal by Consuming Sector and Coal Rank, 1990 – 2000 (MMT C/QBtu)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Consuming Sector											
Electric Power	25.68	25.69	25.69	26.71	25.72	25.74	25.74	25.76	25.76	25.76	25.76
Industrial Coking	25.51	25.51	25.51	25.51	25.52	25.53	25.55	25.56	25.56	25.56	25.56
Other Industrial	25.58	25.59	25.62	25.61	25.63	25.63	25.61	25.63	25.63	25.63	25.63
Residential/Commercial	25.92	26.00	26.13	25.97	25.95	26.00	25.92	26.00	26.00	26.00	26.00
Coal Rank											
Anthracite	28.13	28.13	28.13	28.13	28.13	28.13	28.13	28.13	28.13	28.13	28.13
Bituminous	25.37	25.37	25.37	25.37	25.37	25.37	25.37	25.37	25.37	25.37	25.37
Sub-bituminous	26.24	26.24	26.24	26.24	26.24	26.24	26.24	26.24	26.24	26.24	26.24
Lignite	26.62	26.62	26.62	26.62	26.62	26.62	26.62	26.62	26.62	26.62	26.62

Sources: Emission factors by consuming sector from B.D. Hong and E.R. Slatnick, "Carbon Dioxide Emission Factors for Coal," U.S. EIA, *Quarterly Coal Report*, January-March 1994 (Washington, DC, 1994); and emission factors by rank from Science Applications International Corporation, *Analysis of the Relationship Between Heat and Carbon Content of U.S. Fuels: Final Task Report*, Prepared for the U.S. EIA, Office of Coal, Nuclear, Electric and Alternative Fuels (Washington, DC 1992).

Subsequent Updates

In 2002 a database compiled by the U.S. Geological Survey (USGS), CoalQual 2.0 (1998), was adopted to update the analysis. The updated sample set included 6,588 coal samples collected by the USGS and its state affiliates between 1973 and 1989. The decision to switch to the sample data contained in the USGS CoalQual database

from the EIA database was made because the samples contained in the USGS database were collected and analyzed more recently than those obtained by EIA from the Bureau of Mines. The updated methodology first appeared in the 1990-2004 *Inventory*. The methodology employed for these estimates has remained unchanged since 2002,²⁷ however, the underlying coal data sample set has been updated over the years to integrate new data sets as they became available.

In 2010 sample data from the Energy Institute at Pennsylvania State University (504 samples) were added to the 6,588 USGS samples to create a new database of 7,092 samples. The new coefficients developed in the 2010 update were first implemented for the 1990 through 2008 *Inventory*.

In 2019 sample data from the Montana Bureau of Mines & Geology (908 samples), the Illinois State Geological Survey Coal Quality Database (460 samples), and the Indiana Geological Survey Coal Quality Database (745 samples) were used to calculate updated carbon contents by rank for Montana, Illinois, and Indiana. Combining revised carbon contents for these three states with the carbon contents for all other states calculated from the USGS and Pennsylvania State University samples yielded updated national average carbon contents by coal rank and end-use sector. The new coefficients developed in the 2019 update were first implemented for the 1990 through 2017 *Inventory*.

In 2023, carbon content coefficients for industrial coking coal were updated to be annually variable to align with the variability of other sectors and coal ranks. The new coefficients developed were first implemented for the 1990 through 2019 *Inventory*. See Table A-20 for the carbon content coefficients values used in this *Inventory*.

Natural Gas

Original 1994 Analysis

Prior to the 1990 through 2008 *Inventory*, descriptive statistics were used to stratify 6,743 samples of pipeline quality natural gas by heat content and then to determine the average C content of natural gas at the national average heat content (EIA 1994). The same coefficient was applied to all pipeline natural gas consumption for all years, because U.S. energy statistics showed a range of national average heat contents of pipeline gas of only 1,025 to 1,031 Btu per cubic foot (1 percent) from 1990 through 1994. A separate factor was developed in the same manner for all flared gas. Previously, a weighted national average C content was calculated using the average C contents for each sub-sample of gas that conformed with an individual state's typical cubic foot of natural gas since there is regional variation in energy content. The result was a weighted national average of 14.47 MMT C/QBtu.

2010 and 2019 Updates

A revised analytical methodology introduced in 2010 underlies the natural gas C coefficients used in this report. This methodology was first implemented in the 1990 through 2008 *Inventory*. The revised analysis conducted in 2010 used the same set of samples, but utilized a regression equation, as described above, of sample-based heat content and carbon content data in order to calculate annually variable national average C content coefficients based on annual national average heat contents for pipeline natural gas and for flare gas. In addition, the revised analysis calculated an average C content from all samples with less than 1.5 percent CO₂ and less than 1,050 Btu/cf (samples most closely approximating the makeup of pipeline quality natural gas).

In 2019, this analysis was updated again to calculate annually variable national average C content coefficients for years 2009 through 2017 in the time series using heat contents published in EIA (2019). The resulting average was 14.43 MMT C/QBtu, which is slightly less than the previous weighted national average of 14.47 MMT C/QBtu. The 2019 update was first implemented in the 1990 through 2017 *Inventory*. The average C contents from the 1994 calculations are presented in Table A-38 below for comparison.

²⁷ In 2009, the analysis of the USGS Coal Qual data was updated to make a technical correction that affected the value for lignite and those sectors which consume lignite. The updated coefficients resulting from this correction were first implemented for the 1990 through 2007 *Inventory*.

Table A-38: Carbon Content of Pipeline-Quality Natural Gas by Energy Content (MMT C/QBtu)

Sample	Average Carbon Content
GRI Full Sample	14.51
Greater than 1,000 Btu	14.47
1,025 to 1,035 Btu	14.45
975 to 1,000 Btu	14.73
1,000 to 1,025 Btu	14.43
1,025 to 1,050 Btu	14.47
1,050 to 1,075 Btu	14.58
1,075 to 1,100 Btu	14.65
Greater than 1,100 Btu	14.92
Weighted National Average	14.47

Source: EIA (1994).

Petroleum Products

2010 Update

All of the petroleum product C coefficients except that for Aviation Gasoline Blending Components were updated in 2010 for the 1990 through 2008 *Inventory* and held constant through the current *Inventory*. EPA updated these factors to better align the fuel properties data that underlie the *Inventory* factors with those published in EPA's *Mandatory Reporting of Greenhouse Gases Rule* (EPA 2009b), Suppliers of Petroleum Products (MM) and Stationary Combustion (C) subparts. The coefficients that were applied in previous reports are provided in Table A-42 below. Specifically, each of the coefficients used in this report have been calculated from updated density and C share data, largely adopted from analyses undertaken for the Greenhouse Gas Reporting Rule (EPA 2009b). In some cases, the heat content applied to the conversion to a carbon-per-unit-energy basis was also updated. Additionally, the category Misc. Products (U.S. Territories), which is based upon the coefficients calculated for crude oil, was allowed to vary annually with the crude oil coefficient. The petrochemical feedstock category was eliminated because the constituent products—naphthas and other oils—are estimated independently. Further, although the level of aggregation of U.S. energy statistics currently limits the application of coefficients for residual and distillate fuels to these two generic classifications, individual coefficients for the five major types of fuel oil (Nos. 1, 2, 4, 5 and 6) were estimated and are presented in Table A-36 above. Each of the C coefficients applied in previous *Inventories* are provided below for comparison (Table A-39).

Table A-39: 2008 Carbon Content Coefficients and Underlying Data for Petroleum Products

Fuel	Carbon Content (MMT C/QBtu)	Gross Heat of Combustion (MMBtu/Barrel)	Density (API Gravity)	Percent Carbon
Motor Gasoline	19.27	5.220	59.1	86.60
LPG (Propane)	17.15	3.841	155.3	81.80
HGL (Energy Use) ^a	17.47	(See b)	(See b)	(See b)
HGL (Non-Energy Use) ^a	16.85	(See b)	(See b)	(See b)
Jet Fuel	19.33	5.670	42.0	86.30
Distillate Fuel	19.95	5.825	35.5	86.34
Residual Fuel	21.49	6.287	11.0	85.68
Asphalt and Road Oil	20.62	6.636	5.6	83.47
Lubricants	20.24	6.065	25.6	85.80
Petrochemical Feedstocks	19.37	5.248 ^c	67.1 ^c	84.11 ^c
Aviation Gas	18.87	5.048	69.0	85.00
Kerosene	19.72	5.670	41.4	86.01
Petroleum Coke	27.85	6.024	-	92.28
Special Naphtha	19.86	5.248	51.2	84.76
Petroleum Waxes	19.81	5.537	43.3	85.29
Still Gas	17.51	6.000	-	-
Crude Oil	20.33	5.800	30.5	85.49
Unfinished Oils	20.33	5.825	30.5	85.49
Miscellaneous Products ^d	0.00	0.00	30.5	85.49
Pentanes Plus ^e	18.24	4.620	81.7	83.70
Natural Gasoline ^e	18.24	4.620	81.7	83.70

“-” Indicates no sample data available.

^a HGL is a blend of multiple paraffinic and olefinic hydrocarbons: ethane, propane, isobutane, and normal butane, each with their own heat content, density and C content, see Table A-33.

^b Heat, density, and percent carbon values are provided separately for ethane, and isobutene, butane, ethylene, isobutylene, and butylene.

^c Parameters presented are for naphthas with a boiling temperature less than 400 degrees Fahrenheit. Petrochemical feedstocks with higher boiling points are assumed to have the same characteristics as distillate fuel.

^d The miscellaneous products category reported by EIA is assumed to be mostly petroleum refinery sulfur compounds that do not contain carbon (EIA 2019).

^e Removed for current analysis since not considered final product.

Sources: EIA (1994), EIA (2008a), EPA (2009c), EPA (2020b), ICF (2020).

Additional revisions to the *Inventory*’s C coefficients since 1990 are detailed below.

Jet Fuel

1995 Update

Between 1994 and 1995, the C content coefficient for kerosene-based jet fuel was revised downward from 19.71 MMT C/QBtu to 19.33 MMT C/QBtu. This downward revision was the result of a shift in the sample set used from one collected between 1959 and 1972 and reported on by Martel and Angello in 1977 to one collected by Boeing in 1989 and published by Hadaller and Momeny in 1990. The downward revision was a result of a decrease in density, as well as slightly lower C shares than in the earlier samples. However, the assumed heat content is unchanged because it is based on an EIA standard and probably yields a downward bias in the revised C content coefficient. The coefficient revised in 1995 was first implemented in the 1990 through 2007 *Inventory*.

2010 Update

The coefficient was revised again for the 1990 through 2008 *Inventory*, returning to Martel and Angello and NIPER as the source of the carbon share and density data, respectively, for kerosene-based fuels. This change was made in order to align the coefficients used for this report with the values used in EPA’s *Mandatory Reporting of*

Greenhouse Gases Rule (EPA 2009b). The return to the use of the Martel and Angello and NIPER coefficients was deemed more appropriate for the Rule as it was considered a more conservative coefficient given the uncertainty and variability in coefficients across the types of jet fuel in use in the United States.

Hydrocarbon Gas Liquids (HGL)

Summary of Previous Updates

The C content coefficient of HGL is updated annually to reflect changes in the consumption mix of the underlying compounds: ethane; propane; isobutane; normal butane; ethylene; propylene; isobutylene; and butylene. According to EIA, LPG is a subset of HGL, which include the paraffinic compounds: ethane; propane; isobutane; and normal butane. In 1994, EIA included pentanes plus—assumed to have the characteristics of hexane—in the mix of compounds broadly described as LPG. In 1995, EIA removed pentanes plus from this fuel category. Because pentanes plus is relatively rich in C per unit of energy, its removal from the consumption mix lowered the C content coefficient for LPG from 17.26 MMT C/QBtu to 16.99 MMT C/QBtu. In 1998, EIA began separating LPG consumption into two categories: energy use and non-fuel use and providing individual coefficients for each. Because LPG for fuel use typically contains higher proportions of propane than LPG for non-fuel use, the C content coefficient for fuel use was 1.8 to 2.5 percent higher than the coefficient for non-fuel use in previous inventories (see Table A-39).

However, in 2010 the assumptions that underlie the selection of density and heat content data for each pure LPG compound were updated, leading to a significant revision of the assumed properties of ethane. In 2010, the physical characteristics of ethane, which constitutes over 90 percent of LPG consumption for non-fuel uses, were updated to reflect ethane that is in (refrigerated) liquid form. Previously, the share of ethane was included using the density and energy content of gaseous ethane. Table A-40, below, compares the values applied for each of the compounds under the two sets of coefficient calculations, those used in the 1990 through 2007 *Inventory* and those used in the 1990 through 2008 *Inventory* to the 1990 through 2018 *Inventory*. The C share of each pure compound was also updated by using more precise values for each compound’s molecular weight.

Due in large part to the revised assumptions for ethane, the weighted C content for non-fuel use was now higher than that of the weighted coefficient for fuel use, which is dominated by the consumption of more dense propane. Under the revised assumptions, each annual weighted coefficient for non-fuel LPG consumption is 1.2 to 1.7 percent higher each year than is that for LPGs consumed for fuel (energy) uses.

Table A-40: Physical Characteristics of Liquefied Petroleum Gases

Compound	Chemical Formula	1990-2007	2010 Update	1990-2007	2010 Update	1990-2007	2010 Update
		Density (bbl / MT)	Density (bbl / MT)	Energy Content (MMBtu/bbl)	Energy Content (MMBtu/bbl)	C Content Coefficient (MMT C/QBtu)	C Content Coefficient (MMT C/QBtu)
Ethane	C ₂ H ₆	16.88	11.55	2.916	3.082	16.25	17.16
Propane	C ₃ H ₈	12.44	12.76	3.824	3.836	17.20	16.76
Isobutane	C ₄ H ₁₀	11.20	11.42	4.162	3.974	17.75	17.77
n-butane	C ₄ H ₁₀	10.79	10.98	4.328	4.326	17.72	17.75

Sources: Updated: Densities – CRC Handbook of Chemistry and Physics, 89th Ed. (2008/09); Energy Contents – EPA (2009b). All values are for the compound in liquid form. The density and energy content of ethane are for refrigerated ethane (-89 degrees C). Values for n-butane are for pressurized butane (-25 degrees C). Values in previous editions of this *Inventory*: Gurthrie (1960).

2023 Updates

In 2023, the coefficients were revised again. This update was made in order to align the coefficients used for this report with the updated heat content values used in EIA’s energy data statistics (EIA 2025; EIA 2024a). EIA states, “LPG is a subset of HGL, which include the paraffinic compounds: ethane; propane; isobutane; and normal butane,” therefore the *Inventory* revised the fuel type classification of LPG to HGL to indicate this fuel types includes both paraffinic and olefinic compounds. Furthermore, EIA (2024) states that HGL consumption in the residential, commercial, and transportation sectors is 100 percent propane. Therefore, a constant, non-weighted propane C content coefficient is applied to HGL consumption in these sectors and is referred to as “LPG – Propane” throughout the *Inventory*.

The mix of HGL consumed for non-fuel use differs significantly from the mix of HGL that is combusted. C content coefficients for HGL used for fuel use and non-fuel applications were developed based on the consumption mix of the individual compounds reported in U.S. energy statistics (EIA 2024a) for industrial fuel use and industrial non-fuel use across the *Inventory* time series. The C content of each HGL was obtained from EPA (2013) and applied to the fuel use and non-fuel use consumption of each compound. The carbon content coefficient for industrial fuel use and industrial non-fuel use HGL was then calculated through a weighted average that accounts for the consumption proportion for each paraffinic and olefinic compound and their associated C contents (ICF 2020).

Distillate Fuel

2023 Updates

The carbon content of diesel fuel is calculated according to ASTM D3343,²⁸ *Standard Test Method for the Estimation of Hydrogen Content of Aviation Fuels* using fuel properties inputs from the NAFS for each year and season. This method uses a correlation between the measured fuel distillation range, API gravity, and aromatic content to estimate the hydrogen content (Browning 2020).²⁹

Motor Gasoline

Summary of Previous Updates

The C content coefficient for motor gasoline varies annually based on the density of and proportion of additives in a representative sample of motor gasoline examined each year. However, in 1997 EIA began incorporating the effects of the introduction of reformulated gasoline into its estimate of C content coefficients for motor gasoline. This change resulted in a downward step function in C content coefficients for gasoline of approximately 0.3 percent beginning in the 1990 through 1995 *Inventory*. In 2005 through 2006 reformulated fuels containing ethers began to be phased out nationally. Ethanol was added to gasoline blends as a replacement oxygenate, leading to another shift in gasoline density (see Table A-31), in the list and proportion of constituents that form the blend and in the blended C share based on those constituents.

²⁸ ASTM International, ASTM D3343-16, *Standard Test Method for Estimation of Hydrogen Content of Aviation Fuels*, <https://www.astm.org/Standards/D3343.htm>.

²⁹ As equations are based on assuming hydrocarbon containing fuels only, C % is 100 - H %.

Table A-41: Carbon Content Coefficients for Petroleum Products, 1990-2007 (MMT C/QBtu)

Fuel Type	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Petroleum														
Asphalt and Road Oil	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62	20.62
Aviation Gasoline	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87
Distillate Fuel Oil	20.17	20.17	20.17	20.17	20.17	20.17	20.39	20.36	20.36	20.37	20.39	20.37	20.33	20.25
Jet Fuel ^a	19.40	19.34	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70
Kerosene	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72	19.72
LPG (energy use) ^a	17.21	17.20	17.20	17.18	17.23	17.25	17.20	17.21	17.20	17.21	17.20	17.19	17.19	17.18
LPG (non-energy use) ^a	16.83	16.87	16.86	16.88	16.88	16.84	16.81	16.83	16.82	16.84	16.81	16.81	16.78	16.76
Lubricants	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24	20.24
Motor Gasoline ^a	19.42	19.36	19.35	19.36	19.37	19.32	19.47	19.34	19.36	19.61	19.43	19.32	19.47	19.57
Residual Fuel	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49	21.49
Other Petroleum														
AvGas Blend Components	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87	18.87
MoGas Blend Components ^a	19.42	19.36	19.35	19.36	19.37	19.32	19.33	19.34	19.38	19.36	19.38	19.36	19.45	19.56
Crude Oil ^a	20.15	20.21	20.23	20.22	20.22	20.17	20.22	20.27	20.28	20.25	20.31	20.31	20.28	20.28
Misc. Products ^a	20.16	20.23	20.25	20.24	20.24	20.19	20.23	20.29	20.30	20.28	20.33	20.33	20.33	20.33
Misc. Products (Terr.)	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
Naphtha (<401 deg. F)	18.14	18.14	18.14	18.14	18.14	18.14	18.14	18.14	18.14	18.14	18.14	18.14	18.14	18.14
Other Oil (>401 deg. F)	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95	19.95
Pentanes Plus	18.24	18.24	18.24	18.24	18.24	18.24	18.24	18.24	18.24	18.24	18.24	18.24	18.24	18.24
Petrochemical Feed.	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37	19.37
Petroleum Coke	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85	27.85
Still Gas	17.51	17.51	17.51	17.51	17.51	17.51	17.51	17.51	17.51	17.51	17.51	17.51	17.51	17.51
Special Naphtha	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86	19.86
Unfinished Oils ^a	20.15	20.21	20.23	20.22	20.22	20.17	20.22	20.27	20.28	20.25	20.31	20.31	20.28	20.28
Waxes	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81
Other Wax and Misc.	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81	19.81

^aC contents vary annually based on changes in fuel composition.

2023 Updates

The annual C content of gasoline over the time series of the *Inventory* was determined using a combination of two data sources (Browning 2020). The first is the measured properties of both regular and premium gasoline from the Alliance of North American Fuel Survey (NAFS). The second is the prime supplier sales volumes of motor gasoline by type and grade from the EIA.

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2.3. Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels

Carbon (C) storage associated with the non-energy use of fossil fuels was calculated by multiplying each fuel's potential emissions (i.e., each fuel's total C content) by a fuel-specific storage factor, as listed in Table A-42. The remaining C—i.e., that which is not stored—is emitted. This sub-annex explains the methods and data sources employed in developing the storage factors for (1) petrochemical feedstocks (industrial other coal, natural gas for non-fertilizer uses, hydrocarbon gas liquids (HGL), naphthas, other oils, still gas, special naphtha), (2) asphalt and road oil, (3) lubricants, and (4) waxes. The storage factors³⁰ for the remaining other (industrial coking coal, petroleum coke, distillate fuel oil, and other petroleum) non-energy fuel uses are either based on values recommended for use by IPCC (2006), or when these were not available, assumptions based on the potential fate of C in the respective non-energy use (NEU) products.

Table A-42: Fuel Types and Percent of C Stored for Non-Energy Uses

Sector/Fuel Type	Storage Factor (%)
Industry	
Industrial Coking Coal ^a	10%
Industrial Other Coal ^b	66%
Natural Gas to Chemical Plants ^b	66%
Asphalt & Road Oil	100%
HGL ^b	66%
Lubricants	9%
Natural Gasoline ^b	66%
Naphtha (<401 deg. F) ^b	66%
Other Oil (>401 deg. F) ^b	66%
Still Gas ^b	66%
Petroleum Coke ^c	30%
Special Naphtha ^b	66%
Distillate Fuel Oil	50%
Waxes	58%
Miscellaneous Products ^d	0%
Transportation	
Lubricants	9%
U.S. Territories	
Lubricants	9%
Other Petroleum (Misc. Prod.)	10%

^a Includes processes for which specific coking coal consumption and emission factor data are not available. Consumption of coking coal for production of iron and steel is covered in the Industrial Processes and Product Use chapter.

^b The storage factor listed is the value for 2023. As described in this annex, the factor varies over time.

^c Assumes petroleum coke consumption is for pigments. Consumption of petroleum coke for production of primary aluminum anodes, electric arc furnace anodes, titanium dioxide, ammonia, urea, and ferroalloys is covered in the Industrial Processes and Product Use chapter.

^d The miscellaneous products category reported by EIA is assumed to be mostly petroleum refinery sulfur compounds that do not contain carbon (EIA 2019).

The following sections describe the non-energy uses in greater detail, outlining the methods employed and data used in estimating each storage factor. Several of the fuel types tracked by EIA are used in organic chemical synthesis and in other manufacturing processes and are referred to collectively as “petrochemical feedstocks.” Because the methods and data used to analyze them overlap, they are handled as a group and are discussed first. Discussions of the storage factors for asphalt and road oil, lubricants, waxes, and other products follow.

³⁰ Throughout this section, references to “storage factors” represent the proportion of carbon stored.

Petrochemical Feedstocks

Petrochemical feedstocks—industrial other coal, natural gas for non-fertilizer uses,³¹ HGL, natural gasoline (formerly referred to as pentanes plus), naphthas, other oils, still gas, special naphtha—are used in the manufacture of a wide variety of man-made chemicals and products. Plastics, rubber, synthetic fibers, solvents, paints, fertilizers, pharmaceuticals, and food additives are just a few of the derivatives of these fuel types. Chemically speaking, these fuels are diverse, ranging from simple natural gas (i.e., predominantly CH₄) to heavier, more complex naphthas and other oils.³²

After adjustments for (1) use in industrial processes and (2) net exports, these eight fuel categories constituted approximately 259.9 MMT CO₂ Eq., or 75 percent, of the 348.0 MMT CO₂ Eq. of non-energy fuel consumption in 2023. For 2023, the storage factor for the eight fuel categories was 66 percent. In other words, of the net consumption, 66 percent was destined for long-term storage in products—including products subsequently combusted for waste disposal—while the remaining 34 percent was emitted to the atmosphere directly as CO₂ (e.g., through combustion of industrial by-products) or indirectly as CO₂ precursors (e.g., through evaporative product use). The indirect emissions include a variety of organic gases such as volatile organic compounds (VOCs) and carbon monoxide (CO), which eventually oxidize into CO₂ in the atmosphere. The derivation of the storage factor is described in the following sections.

Methodology and Data Sources

The petrochemical feedstocks storage factor is equal to the ratio of C stored in the final products to total C content for the non-energy fossil fuel feedstocks used in industrial processes, after adjusting for net exports of feedstocks. One aggregate storage factor was calculated to represent all eight fuel feedstock types. The feedstocks were grouped because of the overlap of their derivative products. Due to the many reaction pathways involved in producing petrochemical products (or wastes), it becomes extraordinarily complex to link individual products (or wastes) to their parent fuel feedstocks.

Import and export data for feedstocks were obtained from the Energy Information Administration (EIA) for the major categories of petrochemical feedstocks. EIA's *Petroleum Supply Annual* publication tracks imports and exports of petrochemical feedstocks, including HGL,³³ and naphthas (i.e., most of the large volume primary chemicals produced by petroleum refineries). These imports and exports are already factored into the U.S. fuel consumption statistics. However, EIA does not track imports and exports of chemical intermediates and products produced by the chemical industry (e.g., xylenes, vinyl chloride), which are derived from the primary chemicals produced by the refineries. These products represent very large flows of C derived from fossil fuels (i.e., fossil C), so estimates of net flows not already considered in EIA's dataset were developed for the entire time series from 1990 to 2023.

The approach to estimate imports and exports involves three steps, listed here and then described in more detail below:

- Step 1.* Identify commodities derived from petrochemical feedstocks and calculate net import/export for each.
- Step 2.* Estimate the C content for each commodity.

³¹ Natural gas used as a petrochemical feedstock includes use in production of methanol. The storage factor developed for petrochemical feedstocks includes emissions from the use of products. Therefore, it is assumed that emissions from the combustion of methanol used in biodiesel are captured here and not reported as part of biodiesel combustion emissions.

³² Naphthas are compounds distilled from petroleum containing 4 to 12 carbon atoms per molecule and having a boiling point less than 401 degrees Fahrenheit. "Other oils" are distillates containing 12 to 25 carbon atoms per molecule and having a boiling point greater than 401 degrees Fahrenheit.

³³ HGL (formerly referred to as liquefied petroleum gas, or LPG) are hydrocarbons that occur as gases at atmospheric pressure and as liquids under higher pressures. HGLs include paraffins, such as ethane, propane, butanes, and pentanes plus, and HGLs include olefins, such as ethylene, propylene, and butylene. Adjustments were made in the current *Inventory* report to HGL activity data, carbon content coefficients, and heat contents HGL.

Step 3. Sum the net C imports/exports across all commodities.

Step 1 relies heavily on information provided by the National Petrochemical and Refiners Association (NPRA) and U.S. Bureau of the Census (BoC) trade statistics published by the U.S. International Trade Commission (USITC). NPRA provided a spreadsheet of the ten-digit BoC Harmonized Tariff Schedule (HTS) Commodity Codes used to compile import-export data for periodic reports issued to NPRA's membership on trade issues. Additional feedstock commodities were identified by HTS code in the BoC data system and included in the net import/export analysis.

One of the difficulties in analyzing trade data is that a large portion of the outputs from the refining industry are fuels and fuel components, and it was difficult to segregate these from the outputs used for non-energy uses. The NPRA-supplied codes identify fuels and fuel components, thus providing a sound basis for isolating net imports/exports of petrochemical feedstocks. Although MTBE and related ether imports are included in the published NPRA data, these commodities are not included in the total net imports/exports calculated here, because it is assumed that they are fuel additives and do not contribute to domestic petrochemical feedstocks. Net exports of MTBE and related ethers are also not included in the totals, as these commodities are considered to be refinery products that are already accounted for in the EIA data. Imports and exports of commodities for which production and consumption data are provided by EIA (e.g., butane, ethylene, and liquefied petroleum gases) are also not included in the totals, to avoid double-counting.

Another difficulty is that one must be careful to assure that there is not double-counting of imports and exports in the data set. Other parts of the mass balance (described later) provide information on C flows, in some cases based on production data and in other cases based on consumption data. Production data relates only to production within the country; consumption data incorporates information on imports and exports as well as production. Because many commodities are emissive in their use, but not necessarily their production, consumption data is appropriately used in calculations for emissive fates. For purposes of developing an overall mass balance on U.S. non-energy uses of C, for those materials that are non-emissive (e.g., plastics), production data is most applicable. And for purposes of adjusting the mass balance to incorporate C flows associated with imports and exports, it was necessary to carefully review whether or not the mass balance already incorporated cross-boundary flows (through the use of consumption data), and to adjust the import/export balance accordingly.

The BoC trade statistics are publicly available³⁴ and cover a complete time series from 1990 to 2023. These statistics include information on imports and exports of thousands of commodities. After collecting information on annual flows of the more than 100 commodities identified by NPRA, Step 2 involves calculating the C content for each commodity from its chemical formula. In cases where the imports and exports were expressed in units of volume, rather than mass, they were converted to mass based on the commodities' densities.

Step 3 involves summing the net C imports/exports across all commodities. The results of this step are shown in Table A-43. As shown in the table, the United States has been a net exporter of chemical intermediates and products throughout the 1990 to 2023 period.

Table A-43: Net Exports of Petrochemical Feedstocks, 1990–2023 (MMT CO₂ Eq.)

	1990	2005	2010	2019	2020	2021	2022	2023
Net Exports	12.0	6.3	7.0	20.1	21.0	20.9	23.2	21.1

After adjusting for imports and exports, the C budget is adjusted for the quantity of C that is used in the Industrial Processes and Product Use sector of the *Inventory*. Fossil fuels used for non-energy purposes in industrial processes—and for which C emissions and storage have been characterized through mass balance calculations and/or emission factors that directly link the non-energy use fossil fuel raw material and the industrial process product—are not included in the non-energy use sector. These industrial processes (and their non-energy use fossil fuel raw materials) include iron and steel (coal coke), primary aluminum (petroleum coke), titanium oxide (petroleum coke), ferroalloys (petroleum coke), carbon black (petroleum coke and other oils), silicon carbide (petroleum coke), and ammonia and urea (petroleum coke and natural gas).

³⁴ See the U.S. International Trade Commission (USITC) Trade Dataweb at <http://dataweb.usitc.gov/>.

For each year of the *Inventory*, the total C content of non-energy uses was calculated by starting with the EIA estimate of non-energy use, and reducing it by the adjustment factor for net exports (see Table A-43) and non-energy use reported in the Industrial Processes and Product Use (IPPU) sector to yield net domestic fuel consumption for non-energy. The balance was apportioned to either stored C or emissive C, based on a storage factor.

The overall storage factor for the feedstocks was determined by developing a mass balance on the C in feedstocks, and characterizing products, uses, and environmental releases as resulting in either storage or emissions. The total C in the system was estimated by multiplying net domestic consumption for non-energy by the C content of each of the feedstocks (i.e., industrial other coal, natural gas for non-fertilizer uses, HGL, naphthas, other oils, still gas, special naphtha). Carbon content values for the fuel feedstocks are discussed in the Estimating Emissions from Fossil Fuel Combustion and Estimating the Carbon Content from Fossil Fuel Combustion Annexes.

Next, C pools and releases in a variety of industrial releases, energy recovery processes, and products were characterized. The C fate categories are plastics, energy recovery, synthetic rubber, synthetic fibers, organic solvents, C black, detergents and personal cleansers, industrial non-methane volatile organic compound (NMVOC) emissions, hazardous waste incineration, industrial toxic chemical (i.e., TRI) releases, pesticides, food additives, antifreeze and deicers (glycols), and silicones.³⁵

The C in each product or waste produced was categorized as either stored or emitted. The aggregate storage factor is the C-weighted average of storage across fuel types. As discussed later in the section on uncertainty, the sum of stored C and emitted C (i.e., the outputs of the system) exceeded total C consumption (i.e., the inputs to the system) for some years in the time series. To address this mass imbalance, the storage factor was calculated as C storage divided by total C outputs (rather than C storage divided by C inputs).

Note that the system boundaries for the storage factor do not encompass the entire life-cycle of fossil-based C consumed in the United States insofar as emissions of CO₂ from waste combustion are accounted for separately in the *Inventory* and are discussed in the Incineration of Waste section of the Energy chapter.

The following sections provide details on the calculation steps, assumptions, and data sources employed in estimating and classifying the C in each product and waste shown in Table A-44. Summing the C stored and dividing it by total C outputs yields the overall storage factor, as shown in the following equation for 2023:

Equation A-6: NEU Storage Factor Estimate for 2023

$$\begin{aligned} \text{Overall Storage Factor} &= \text{C Stored} / (\text{C Stored} + \text{C Emitted} + \text{C Unaccounted for}) \\ &= 171.6 \text{ MMT CO}_2 \text{ Eq.} / (171.6 + 62.5 + 25.8) \text{ MMT CO}_2 \text{ Eq.} = 66\% \end{aligned}$$

Table A-44: C Stored and Emitted by Products from Feedstocks in 2023 (MMT CO₂ Eq.)

Product/Waste Type	C Stored (MMT CO ₂ Eq.)	C Emitted (MMT CO ₂ Eq.)
		Eq.)
Industrial Releases	0.1	6.1
TRI Releases	0.1	1.0
Industrial VOCs	NA	4.0
Non-combustion CO	NA	0.4
Hazardous Waste Incineration	NA	0.7
Energy Recovery	NA	44.4
Products	171.5	12.0
Plastics	150.9	NA
Synthetic Rubber	12.8	NA
Antifreeze and Deicers	NA	1.1
Abraded Tire Rubber	NA	0.3

³⁵ For the most part, the releases covered by the U.S. Toxic Release Inventory (TRI) represent air emissions or water discharges associated with production facilities. Similarly, VOC emissions are generally associated with production facilities. These emissions could have been accounted for as part of the Waste chapter, but because they are not necessarily associated with waste management, they were included here. Toxic releases are not a “product” category, but they are referred to as such for ease of discussion.

Food Additives	NA	1.1
Silicones	0.5	NA
Synthetic Fiber	7.0	NA
Pesticides	0.2	0.3
Soaps, Shampoos, Detergents	NA	4.1
Solvent VOCs	NA	5.2
Total	171.6	62.5

NA (Not Applicable)

Note: Totals may not sum due to independent rounding.

The C unaccounted for is the difference between the C accounted for (discussed below) and the total C in the Total U.S. Petrochemical consumption, which are the potential carbon emissions from all energy consumption in Non-Energy Use.

The three categories of C accounted for in the table are industrial releases, energy recovery, and products. Each is discussed below.

Industrial Releases

Industrial releases include toxic chemicals reported through the Toxics Release *Inventory* (TRI), industrial emissions of volatile organic compounds (VOCs), CO emissions (other than those related to fuel combustion), and emissions from hazardous waste incineration.

TRI Releases

Fossil-derived C is found in many toxic substances released by industrial facilities. The TRI, maintained by EPA, tracks these releases by chemical and environmental release medium (i.e., land, air, or water) on a biennial basis (EPA 2000b). By examining the C contents and receiving media for the top 35 toxic chemicals released, which account for 90 percent of the total mass of chemicals, the quantity of C stored and emitted in the form of toxic releases can be estimated.

The TRI specifies releases by chemical, so C contents were assigned to each chemical based on molecular formula. The TRI also classifies releases by disposal location as either off-site or on-site. The on-site releases are further subdivided into air emissions, surface water discharges, underground injection, and releases to land; the latter is further broken down to disposal in a RCRA Subtitle C (i.e., hazardous waste) landfill or to “Other On-Site Land Disposal.”³⁶ The C released in each disposal location is provided in Table A-45.

Each on-site classification was assigned a storage factor. A 100 percent storage factor was applied to disposition of C to underground injection and to disposal to RCRA-permitted landfills, while the other disposition categories were assumed to result in an ultimate fate of emission as CO₂ (i.e., a storage factor of zero was applied to these categories). The release allocation is not reported for off-site releases; therefore, the approach was to develop a C-weighted average storage factor for the on-site C and apply it to the off-site releases.

For the remaining 10 percent of the TRI releases, the weights of all chemicals were added and an average C content value, based upon the top 35 chemicals’ C contents, was applied. The storage and emission allocation for the remaining 10 percent of the TRI releases was carried out in the same fashion as for the 35 major chemicals.

Data on TRI releases for the full 1990 through 2023 time series were not readily available. Since this category is small (less than 1 MMT C emitted and stored), the 1998 value was applied for the entire time series.

³⁶ Only the top nine chemicals had their land releases separated into RCRA Landfills and Other Land Disposal. For the remaining chemicals, it was assumed that the ratio of disposal in these two categories was equal to the carbon-weighted average of the land disposal fate of the top nine chemicals (i.e., 8 percent attributed to RCRA Landfills and 92 percent in the “Other” category).

Table A-45: 1998 TRI Releases by Disposal Location (kt CO₂ Eq.)

Disposal Location	Carbon Stored (kt CO₂ Eq.)	Carbon Emitted (kt CO₂ Eq.)
Air Emissions	NA	924
Surface Water Discharges	NA	6.7
Underground Injection	89.4	NA
RCRA Subtitle C Landfill Disposal	1.4	NA
Other On-Site Land Releases	NA	15.9
Off-site Releases	6.4	36
Total	97.2	982.6

NA (Not Applicable)

Note: Totals may not sum due to independent rounding.

Volatile Organic Compound Emissions from Industrial Processes and Solvent Evaporation Emissions

Data on annual non-methane volatile organic compound (NMVOC) emissions were obtained (EPA 2024b) and disaggregated based on EPA (2003), which has been published on the National Emission *Inventory* (NEI) Air Pollutant Emission Trends web site. The 1990 through 2023 Trends data include information on NMVOC emissions by end-use category; some of these fall into the heading of “industrial releases” in Table A-44 above, and others are related to “product use;” for ease of discussion, both are covered here. The end-use categories that represent “Industrial NMVOC Emissions” include some chemical and allied products, certain petroleum related industries, and other industrial processes. NMVOC emissions from solvent utilization (product use) were considered to be a result of non-energy use of petrochemical feedstocks. These categories were used to distinguish non-energy uses from energy uses; other categories where VOCs could be emitted due to combustion of fossil fuels were excluded to avoid double counting.

Because solvent evaporation and industrial NMVOC emission data are provided in tons of total NMVOCs, assumptions were made concerning the average C content of the NMVOCs for each category of emissions. The assumptions for calculating the C fraction of industrial and solvent utilization emissions were made separately and differ significantly. For industrial NMVOC emissions, a C content of 85 percent was assumed. This value was chosen to reflect the C content of an average volatile organic compound based on the list of the most abundant NMVOCs provided in the Trends Report. The list contains only pure hydrocarbons, including saturated alkanes (C contents ranging from 80 to 85 percent based upon C number), alkenes (C contents approximately 85 percent), and some aromatics (C contents approximately 90 percent, depending upon substitution).

An EPA solvent evaporation emissions dataset (Tooly 2001) was used to estimate the C content of solvent emissions. The dataset identifies solvent emissions by compound or compound category for six different solvent end-use categories: degreasing, graphic arts, dry cleaning, surface coating, other industrial processes, and non-industrial processes. The percent C of each compound identified in the dataset was calculated based on the molecular formula of the individual compound (e.g., the C content of methylene chloride is 14 percent; the C content of toluene is 91 percent). For solvent emissions that are identified in the EPA dataset only by chemical category (e.g., butanediol derivatives) a single individual compound was selected to represent each category, and the C content of the category was estimated based on the C content of the representative compound. The overall C content of the solvent evaporation emissions for 1998, estimated to be 56 percent, is assumed to be constant across the entire time series.

The results of the industrial and solvent NMVOC emissions analysis are provided in Table A-46 for 1990 through 2023. Industrial NMVOC emissions in 2023 were 4.0 MMT CO₂ Eq. and solvent evaporation emissions in 2023 were 5.2 MMT CO₂ Eq.

Table A-46: Industrial and Solvent NMVOC Emissions

	1990	1995	2000	2005	2019	2020	2021	2022	2023
Industrial NMVOCs^a									
NMVOCs ('000 Short Tons)	1,279	1,358	802	1,380	1,287	1,295	1,405	1,399	1,399
Carbon Content (%)	85%	85%	85%	85%	85%	85%	85%	85%	85%
Carbon Emitted (MMT CO ₂ Eq.)	3.8	3.8	2.3	3.9	3.6	3.7	4.0	4.0	4.0
Solvent Evaporation^b									
Solvents ('000 Short Tons)	5,755	6,189	4,836	2,969	2,567	2,761	2,906	2,777	2,777
Carbon Content (%)	56%	56%	56%	56%	56%	56%	56%	56%	56%
Carbon Emitted (MMT CO ₂ Eq.)	10.8	11.6	9.1	5.6	4.8	5.2	5.4	5.2	5.2

^a Includes emissions from chemical and allied products, petroleum and related industries, and other industrial processes categories.

^b Includes solvent usage and solvent evaporation emissions from degreasing, graphic arts, dry cleaning, surface coating, other industrial processes, and non-industrial processes.

Non-Combustion Carbon Monoxide Emissions

Carbon monoxide (CO) emissions data were also obtained from the EIS NIR mapping data (EPA 2024b) and disaggregated based on EPA (2003). There are three categories of CO emissions in the report that are classified as process-related emissions not related to fuel combustion. These include chemical and allied products manufacturing, metals processing, and other industrial processes. Some of these CO emissions are accounted for in the Industrial Processes and Product Use section of this report and are therefore not accounted for in this section. These include total C emissions from the primary aluminum, titanium dioxide, iron and steel, and ferroalloys production processes. The total C (CO and CO₂) emissions from oil and gas production, petroleum refining, and asphalt manufacturing are also accounted for elsewhere in this *Inventory*. Biogenic emissions (e.g., pulp and paper process emissions) are accounted for in the Land Use, Land-Use Change and Forestry chapter and excluded from calculation of CO emissions in this section. Those CO emissions that are not accounted for elsewhere are considered to be by-products of non-fuel use of feedstocks and are thus included in the calculation of the petrochemical feedstocks storage factor. Table A-47 lists the CO emissions that remain after taking into account the exclusions listed above.

Table A-47: Non-Combustion Carbon Monoxide Emissions

	1990	199	2000	2005	2019	2020	2021	2022	2023
CO Emissions ('000 Short Tons)	489	481	623	501	323	300	311	315	315
Carbon Emitted (MMT CO ₂ Eq.)	0.7	0.7	0.9	0.7	0.5	0.4	0.4	0.4	0.4

Note: Includes emissions from chemical and allied products, petroleum and related industries, metals processing, and other industrial processes categories.

Hazardous Waste Incineration

Hazardous wastes are defined by the EPA under the Resource Conservation and Recovery Act (RCRA).³⁷ Industrial wastes, such as rejected products, spent reagents, reaction by-products, and sludges from wastewater or air pollution control, are federally regulated as hazardous wastes if they are found to be ignitable, corrosive, reactive, or toxic according to standardized tests or studies conducted by EPA.

Hazardous wastes must be treated prior to disposal according to the federal regulations established under the authority of RCRA. Combustion is one of the most common techniques for hazardous waste treatment, particularly for those wastes that are primarily organic in composition or contain primarily organic contaminants.

³⁷ [42 U.S.C. §6924, SDWA §3004]

Generally speaking, combustion devices fall into two categories: incinerators that burn waste solely for the purpose of waste management, and boilers and industrial furnaces (BIFs) that burn waste in part to recover energy from the waste. More than half of the hazardous waste combusted in the United States is burned in BIFs; because these processes are included in the energy recovery calculations described below, they are not included as part of hazardous waste incineration.

EPA's Office of Solid Waste requires biennial reporting of hazardous waste management activities, and these reports provide estimates of the amount of hazardous waste burned for incineration or energy recovery. EPA stores this information in its Resource Conservation and Recovery Act (RCRA) Information system (EPA 2013a), formerly reported in its Biennial Reporting System (BRS) database (EPA 2000a, 2009, 2015a, 2016a, 2018, 2021b, 2024c). Combusted hazardous wastes are identified based on EPA-defined management system types M041 through M049 (incineration). Combusted quantities are grouped into four representative waste form categories based on the form codes reported in the BRS: aqueous liquids, organic liquids and sludges, organic solids, and inorganic solids. To relate hazardous waste quantities to C emissions, "fuel equivalent" factors were derived for hazardous waste by assuming that the hazardous wastes are simple mixtures of a common fuel, water, and noncombustible ash. For liquids and sludges, crude oil is used as the fuel equivalent and coal is used to represent solids.

Fuel equivalent factors were multiplied by the tons of waste incinerated to obtain the tons of fuel equivalent. Multiplying the tons of fuel equivalent by the C content factors (discussed in the Estimating the Carbon Content from Fossil Fuel Combustion Annex) yields tons of C emitted. Implied C content is calculated by dividing the tons of C emitted by the associated tons of waste incinerated.

Waste quantity data for hazardous wastes were obtained from EPA's RCRA Information/BRS database for reporting years 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, 2007, 2009, 2011, 2013, 2015, 2017, 2019, 2021, and 2023 (EPA 2000a, 2009, 2013a, 2015a, 2016a, 2018, 2021b, 2024c). Combusted waste quantities were obtained from Form GM (Generation and Management) for wastes burned on site and Form WR (Wastes Received) for waste received from off-site for combustion. For each of the waste types, assumptions were developed on average waste composition (see Table A-48). Regulations require incinerators to achieve at least 99.99 percent destruction of organics; this formed the basis for assuming the fraction of C oxidized. Emissions from hazardous waste incineration in 2023 were 0.7 MMT CO₂ Eq. Table A-49 lists the CO₂ emissions from hazardous waste incineration.

Table A-48: Assumed Composition of Combusted Hazardous Waste by Weight (Percent)

Waste Type	Water (%)	Noncombustibles (%)	Fuel Equivalent (%)
Aqueous Waste	90	5	5
Organic Liquids and Sludges	40	20	40
Organic Solids	20	40	40
Inorganic Solids	20	70	10

Table A-49: CO₂ Emitted from Hazardous Waste Incineration (MMT CO₂ Eq.)

	1990	1995	2000	2005	2019	2020	2021	2022	2023
CO ₂ Emissions	1.1	1.7	1.4	1.5	0.9	0.9	0.8	0.8	0.7

Energy Recovery

The amount of feedstocks combusted for energy recovery was estimated from data included in EIA's Manufacturers Energy Consumption Survey (MECS) for 1991, 1994, 1998, 2002, 2006, 2010, 2014, and 2018 (EIA 1994; 1997; 2001; 2005; 2010; 2013b; 2017; 2021). Some fraction of the fossil C exiting refineries and designated for use for feedstock purposes actually ends up being combusted for energy recovery (despite the designation of feedstocks as a "non-energy" use) because the chemical reactions in which fuel feedstocks are used are not 100 percent efficient. These chemical reactions may generate unreacted raw material feedstocks or generate by-products that have a high energy content. The chemical industry and many downstream industries are energy-intensive and often have boilers or other energy recovery units on-site, and thus these unreacted feedstocks or by-products are often combusted for energy recovery. Also, as noted above in the section on hazardous waste incineration, regulations provide a strong incentive—and in some cases require—burning of organic wastes generated from chemical production processes.

Information available from the MECS include data on the consumption for energy recovery of “other” fuels in the petroleum and coal products, chemicals, primary metals, nonmetallic minerals, and other manufacturing sectors. These “other” fuels include refinery still gas; waste gas; waste oils, tars, and related materials; petroleum coke, coke oven and blast furnace gases; scrap tires; liquor or black liquor; woodchips and bark; and other uncharacterized fuels. Fuel use of petroleum coke is included separately in the fuel use data provided annually by EIA, and energy recovery of coke oven gas and blast furnace gas (i.e., by-products of the iron and steel production process) is addressed in the Iron and Steel production section in the Industrial Processes and Product Use chapter. Consumption of refinery still gas in the refinery sector is also included separately in the fuel use data from EIA. The combustion of scrap tires in cement kilns, lime kilns, and electric arc furnaces is accounted for in the Waste Incineration chapter; data from the U.S. Tire Manufacturers Association (USTMA 2012) were used to subtract out energy recovery from scrap tires in these industries. Consumption of net steam, assumed to be generated from fossil fuel combustion, is also included separately in the fuel use data from EIA. Therefore, these categories of “other” fuels are addressed elsewhere in the *Inventory* and not considered as part of the petrochemical feedstocks energy recovery analysis. Liquor or black liquor and woodchips and bark are assumed to be biogenic fuels, in accordance with IPCC (2006), and therefore are not included in the *Inventory*. The remaining categories of fuels, including waste gas; waste oils, tars, and related materials; and other uncharacterized fuels are assumed to be petrochemical feedstocks burned for energy recovery (see Table A-50). The conversion factors listed in Annex 2.1 were used to convert the Btu values for each fuel feedstock to MMT CO₂. Petrochemical feedstocks combusted for energy recovery corresponded to 42.5 MMT CO₂ Eq. in 1991, 35.1 MMT CO₂ Eq. in 1994, 58.0 MMT CO₂ Eq. in 1998, 70.6 MMT CO₂ Eq. in 2002, 74.7 MMT CO₂ Eq. in 2006, 41.3 MMT CO₂ Eq. in 2010, 45.6 MMT CO₂ Eq. in 2014, and 44.4 MT CO₂ Eq in 2018. Values for petrochemical feedstocks burned for energy recovery for years between 1991 and 1994, between 1994 and 1998, between 1998 and 2002, between 2002 and 2006, between 2007 and 2010, between 2011 and 2013, and between 2015 and 2017 have been estimated by linear interpolation. The value for 1990 is assumed to be the same as the value for 1991, and the values from 2019 to 2023 are assumed to be the same as the value for 2018 (Table A-51).

Table A-50: Summary of 2018 MECS Data for Other Fuels Used in Manufacturing/Energy Recovery (Trillion Btu)

Subsector and Industry	NAICS CODE	Waste Gas ^a	Waste Oils/Tars ^b	Refinery Still Gas ^c	Net Steam ^d	Other Fuels ^e
Printing and Related Support	323	0	0	0	0	0
Petroleum and Coal Products	324	0	2	1,394	191	76
Chemicals	325	402	6	0	310	116
Plastics and Rubber Products	326	0	0	0	0	0
Nonmetallic Mineral Products	327		9	0	0	18
Primary Metals	331	3		0	10	3
Fabricated Metal Products	332	0		0	0	2
Machinery	333			0	0	1
Computer and Electronic Products	334	0	0	0	0	0
Electrical Equip., Appliances, Components	335	0	0	0	0	0
Transportation Equipment	336	1	0	0	1	5
Furniture and Related Products	337	0		0	0	5
Miscellaneous	339	0	0	0	0	1
Total (Trillion Btu)		406	17	1,394	511	227
Average C Content (MMT/QBtu)		18.14	20.62	17.51	0	19.37
Fraction Oxidized		1	1	1	0	1
Total C (MMT)		7.36	0.35	24.41	0.00	4.40
Total C (MMT) (ex. still gas from refining)		7.36	0.35	0.00	0.00	4.40

NA (Not Applicable)

^a C content: Waste Gas is assumed to be same as naphtha <401 deg. F.

^b C content: Waste Oils/Tars is assumed to be same as asphalt/road oil.

^c Refinery "still gas" fuel consumption is reported elsewhere in the *Inventory* and is excluded from the total C content estimate.

^d Net steam fuel consumption is reported elsewhere in the *Inventory* and is excluded from the total C content estimate.

^e C content: "Other" is assumed to be the same as petrochemical feedstocks.

Table A-51: Carbon Emitted from Fuels Burned for Energy Recovery (MMT CO₂ Eq.)

	1990	1995	2000	2005	2019	2020	2021	2022	2023
C Emissions	42.5	40.8	64.3	73.7	44.4	44.4	44.4	44.4	44.4

Products

More C is found in products than in industrial releases or energy recovery. The principal types of products are plastics; synthetic rubber; synthetic fiber; C black; pesticides; soaps, detergents, and cleansers; food additives; antifreeze and deicers (glycols); silicones; and solvents. Solvent evaporation was discussed previously along with industrial releases of NMVOCs; the other product types are discussed below.

Plastics

Data on annual production of plastics through 2005 were taken from the American Plastics Council (APC), as published in *Chemical & Engineering News* and on the APC and Society of Plastics Industry (SPI) websites, and through direct communication with the APC (APC 2000, 2001, 2003 through 2006; SPI 2000; Eldredge-Roebuck 2000). Data for 2006 through 2023 were taken directly or derived from the American Chemistry Council (ACC 2007 through 2024a supplemented by Vallianos 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023, 2024). In 2009, the American Chemistry Council consolidated the resin categories for which it reports plastics production. Production numbers in the original categories were provided via personal correspondence for 2009, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, and 2023 (Vallianos 2011; 2012; 2013; 2014; 2015; 2016; 2017; 2018; 2019; 2020; 2021; 2022; 2023; 2024). Production figures for the consolidated resin categories in 2010 were linearly interpolated from 2009 and 2011 data. Production was organized by resin type (see Table A-52) and by year.

Several of the resin categories included production from Canada and/or Mexico, in addition to the U.S. values for part of the time series. The production data for the affected resins and years were corrected using an economic adjustment factor, based on the percent of North American production value in this industry sector accounted for by the United States (Chemistry Industry Association of Canada 2024; Bank of Canada 2024). A C content was then assigned for each resin. These C contents were based on molecular formulae and are listed in Table A-53 and Table A-54. In cases where the resin type is generic, referring to a group of chemicals and not a single polymer (e.g., phenolic resins, other styrenic resins), a representative compound was chosen. For other resins, a weighted C content of 75 percent was assumed (i.e., it was assumed that these resins had the same content as those for which a representative compound could be assigned).

There were no emissive uses of plastics identified, so 100 percent of the C was considered stored in products. As noted in the chapter, an estimate of emissions related to the combustion of these plastics in the municipal solid waste stream can be found in the Incineration of Waste section of the Energy chapter; those emissions are not incorporated in the mass balance for feedstocks (described in this annex) to avoid double-counting.

Table A-52: 2023 Plastic Resin Production (MMT dry weight) and C Stored (MMT CO₂ Eq.)

Resin Type	2023 Production ^a (MMT dry weight)	Carbon Stored (MMT CO ₂ Eq.)
Epoxy	0.2	0.6
Polyester	0.7	1.7
Urea	1.2	1.5
Melamine	0.1	0.1
Phenolic	1.6	4.6
Low-Density Polyethylene (LDPE)	3.8	11.8
Linear Low-Density Polyethylene (LLDPE)	10.8	33.8
High Density Polyethylene (HDPE)	10.2	32.2
Polypropylene (PP)	6.9	21.7
Acrylonitrile-butadiene-styrene (ABS)	1.3	3.9

Other Styrenics ^b	0.5	1.6
Polystyrene (PS)	1.3	4.6
Nylon	0.5	1.1
Polyvinyl chloride (PVC) ^c	6.5	9.2
Thermoplastic Polyester	3.1	7.0
All Other (including Polyester (unsaturated))	5.6	15.7
Total	54.2	150.9

^a Production estimates provided by the American Chemistry Council include Canadian production for Urea, Melamine, Phenolic, LDPE, LLDPE, HDPE, PP, ABS, SAN, Other Styrenics, PS, Nylon, PVC, and Thermoplastic Polyester, and Mexican production for PP, ABS, SAN, Other Styrenics, Nylon, and Thermoplastic Polyester. Values have been adjusted to account just for U.S. production.

^b Includes Styrene-acrylonitrile (SAN).

^c Includes copolymers.

Note: Totals may not sum due to independent rounding.

Table A-53: Assigned C Contents of Plastic Resins (% by weight)

Resin Type	C Content	Source of C Content Assumption
Epoxy	76%	Typical epoxy resin made from epichlorhydrin and bisphenol A
Polyester (Unsaturated)	63%	Poly (ethylene terephthalate) (PET)
Urea	34%	50% carbamal, 50% N-(hydroxymethyl) urea *
Melamine	29%	Trimethylol melamine *
Phenolic	77%	Phenol
Low-Density Polyethylene (LDPE)	86%	Polyethylene
Linear Low-Density Polyethylene (LLDPE)	86%	Polyethylene
High Density Polyethylene (HDPE)	86%	Polyethylene
Polypropylene (PP)	86%	Polypropylene
Acrylonitrile-Butadiene-Styrene (ABS)	85%	50% styrene, 25% acrylonitrile, 25% butadiene
Styrene-Acrylonitrile (SAN)	80%	50% styrene, 50% acrylonitrile
Other Styrenics	92%	Polystyrene
Polystyrene (PS)	92%	Polystyrene
Nylon	65%	Average of nylon resins (see Table C-14)
Polyvinyl Chloride (PVC)	38%	Polyvinyl chloride
Thermoplastic Polyester	63%	Polyethylene terephthalate
All Other	76%	Weighted average of other resin production

^a Does not include alcoholic hydrogens.

Table A-54: Major Nylon Resins and their C Contents (% by weight)

Resin	C Content
Nylon 6	64%
Nylon 6,6	64%
Nylon 4	52%
Nylon 6,10	68%
Nylon 6,11	69%
Nylon 6,12	70%
Nylon 11	72%

Synthetic Rubber

Data on synthetic rubber in tires were derived from data on the scrap tire market and the composition of scrap tires from the U.S. Tire Manufacturers Association (USTMA). The market information is presented in the report *2023 End-of-Life Tire Management Report* (USMTA 2024), while the tire composition information is from the “Scrap Tires, Facts and Figures” section of the organization’s website (USTMA 2012). Data on synthetic rubber in other products (durable goods, nondurable goods, and containers and packaging) were obtained from EPA’s *Municipal Solid Waste in the United States* reports (1996 through 2003a, 2005, 2007b, 2008, 2009a, 2011a, 2013b, 2014, 2016b,

2019) and detailed unpublished backup data for some years not shown in the *Characterization of Municipal Solid Waste in the United States* reports (Schneider 2007). The abraded rubber from scrap passenger tires was assumed to be 2.5 pounds per scrap tire, while the abraded rubber from scrap commercial tires was assumed to be 10 pounds per scrap tire. Data on abraded rubber weight were obtained by calculating the average weight difference between new and scrap tires (USTMA 2024). Import and export data were obtained from the published by the U.S. International Trade Commission (U.S. International Trade Commission 1990 through 2024).

A C content for synthetic rubber (90 percent for tire synthetic rubber and 85 percent for non-tire synthetic rubber) was assigned based on the weighted average of C contents (based on molecular formula) by elastomer type consumed in 1998, 2001, and 2002 (see Table A-55). The 1998 consumption data were obtained from the International Institute of Synthetic Rubber Producers (IISRP) press release *Synthetic Rubber Use Growth to Continue Through 2004, Says IISRP and RMA* (IISRP 2000). The 2001 and 2002 consumption data were obtained from the IISRP press release, *IISRP Forecasts Moderate Growth in North America to 2007* (IISRP 2003).

The rubber in tires that is abraded during use (the difference between new tire and scrap tire rubber weight) was considered to be 100 percent emitted. Other than abraded rubber, there were no emissive uses of scrap tire and non-tire rubber identified, so 100 percent of the non-abraded amount was assumed stored. Emissions related to the combustion of rubber in scrap tires and consumer goods can be found in the Incineration of Waste section of the Energy chapter.

Table A-55: 2002 Rubber Consumption (kt) and C Content (%)

Elastomer Type	2002 Consumption (kt) ^a	C Content
SBR Solid	768	91%
Polybutadiene	583	89%
Ethylene Propylene	301	86%
Polychloroprene	54	59%
NBR Solid	84	77%
Polyisoprene	58	88%
Others	367	88%
Weighted Average	NA	90%
Total	2,215	NA

NA (Not Applicable)

^a Includes consumption in Canada.

Note: Totals may not sum due to independent rounding.

Synthetic Fibers

Annual synthetic fiber production data were obtained from the ACC, as published in the *Guide to the Business of Chemistry* (ACC 2024b), and the Fiber Economics Bureau, as published in *Chemical & Engineering News* (FEB 2001, 2003, 2005, 2007, 2009, 2010, 2011, 2012, 2013). For acrylic fiber, the most recent data available were for 2012, so it was assumed that the 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, and 2023 consumption was equal to that of 2012. For polyester, nylon, and olefin, the most recent data were for 2023. These data are organized by year and fiber type. For each fiber, a C content was assigned based on molecular formula (see Table A-56). For polyester, the C content for poly (ethylene terephthalate) (PET) was used as a representative compound. For nylon, the average C content of nylon 6 and nylon 6.6 was used, since these are the most widely produced nylon fibers. Cellulosic fibers, such as acetate and rayon, have been omitted from the synthetic fibers' C accounting displayed here because much of their C is of biogenic origin and carbon fluxes from biogenic compounds are accounted for in the Land Use, Land-Use Change and Forestry chapter. These fibers account for only 4 percent of overall fiber production by weight.

There were no emissive uses of fibers identified, so 100 percent of the C was considered stored. Note that emissions related to the combustion of textiles in municipal solid waste are accounted for under the Incineration of Waste section of the Energy chapter.

Table A-56: 2023 Fiber Production (MMT), C Content (%), and C Stored (MMT CO₂ Eq.)

Fiber Type	Production (MMT)	C Content	C Stored (MMT CO ₂ Eq.)
Polyester	1.1	63%	2.5
Nylon	0.5	64%	1.1
Olefin	1.1	86%	3.4
Acrylic	0.0	68%	0.1
Total	2.7	NA	7.0

+ Does not exceed 0.05 MMT.

NA (Not Applicable)

Note: Totals may not sum due to independent rounding.

Pesticides

Pesticide consumption data were obtained from the 1994/1995, 1996/1997, 1998/1999, 2000/2001, 2006/2007, and 2008-2012 *Pesticides Industry Sales and Usage Market Estimates* (EPA 1998, 1999, 2002, 2004, 2011b, 2017) reports. The most recent data available were for 2012, so it was assumed that the 2013 through 2023 consumption was equal to that of 2012. Active ingredient compound names and consumption weights were available for the top 25 agriculturally-used pesticides and top 10 pesticides used in the home and garden and the industry/commercial/government categories. The report provides a range of consumption for each active ingredient; the midpoint was used to represent actual consumption. Each of these compounds was assigned a C content value based on molecular formula. If the compound contained aromatic rings substituted with chlorine or other halogens, then the compound was considered persistent and the C in the compound was assumed to be stored. All other pesticides were assumed to release their C to the atmosphere. Over one-third of 2012 total pesticide active ingredient consumption was not specified by chemical type in the *Sales and Usage* report (EPA 2017). This unspecified portion of the active ingredient consumption was treated as a single chemical and assigned a C content and a storage factor based on the weighted average of the known chemicals' values.

Table A-57: Active Ingredient Consumption in Pesticides (Million lbs.) and C Emitted and Stored (MMT CO₂ Eq.) in 2012

Pesticide Use ^a	Active Ingredient (Million lbs.)	C Emitted (MMT CO ₂ Eq.)	C Stored (MMT CO ₂ Eq.)
Agricultural Uses	606.0	0.2	0.1
Non-Agricultural Uses	58.0	+	+
Home & Garden	39.5	+	+
Industry/Gov't/Commercial	28.0	+	+
Other	342.0	0.1	0.1
Total	1,006.0	0.3	0.2

+ Does not exceed 0.05 MMT CO₂ Eq.

^a 2012 estimates (EPA 2017).

Note: Totals may not sum due to independent rounding.

Soaps, Shampoos, and Detergents

Cleansers—soaps, shampoos, and detergents³⁴are among the major consumer products that may contain fossil C. All of the C in cleansers was assumed to be fossil-derived, and, as cleansers eventually biodegrade, all of the C was assumed to be emitted. The first step in estimating C flows was to characterize the “ingredients” in a sample of cleansers. For this analysis, cleansers were limited to the following personal household cleaning products: bar soap, shampoo, laundry detergent (liquid and granular), dishwasher detergent, and dishwashing liquid. Data on the annual consumption of household personal cleansers were obtained from the U.S. Census Bureau 1992, 1997, 2002, 2007, 2012, and 2017 Economic Census (U.S. Bureau of the Census 1994, 1999, 2004, 2009, 2014, 2021). Production values, given in terms of the value of shipments, for 1990 and 1991 were assumed to be the same as the 1992 value; consumption was interpolated between 1992 and 1997, 1997 and 2002, 2002 and 2007, 2007 and 2012; 2012 and 2017; production for 2018 through 2023 was assumed to equal the 2017 value. Cleanser production values were adjusted by import and export data to develop U.S. consumption estimates.

Chemical formulae were used to determine C contents (as percentages) of the ingredients in the cleansers. Each product's overall C content was then derived from the composition and contents of its ingredients. From these values the mean C content for cleansers was calculated to be 21.9 percent.

The Census Bureau presents consumption data in terms of quantity (in units of million gallons or million pounds) and/or terms of value (thousands of dollars) for eight specific categories, such as “household liquid laundry detergents, heavy duty” and “household dry alkaline automatic dishwashing detergents.” Additionally, the report provides dollar values for the total consumption of “soaps, detergents, etc.—dry” and “soaps, detergents, etc.—liquid.” The categories for which both quantity and value data are available are a subset of total production. Those categories that presented both quantity and value data were used to derive pounds per dollar and gallons per dollar conversion rates, and they were extrapolated (based on the Census Bureau estimate of total value) to estimate the total quantity of dry and liquid³⁸ cleanser categories, respectively.

Next, the total tonnage of cleansers was calculated (wet and dry combined) for 1997. Multiplying the mean C content (21.9 percent) by this value yielded an estimate of 4.6 MMT CO₂ Eq. in cleansers for 1997. For all subsequent years, it was assumed that the ratio of value of shipments to total carbon content remained constant. For 1998 through 2023, value of shipments was adjusted to 1997 dollars using the producer price index for soap and other detergent manufacturing (Bureau of Labor Statistics 2024). The ratio of value of shipments to carbon content was then applied to arrive at total carbon content of cleansers. Estimates are shown in Table A-58.

Table A-58: C Emitted from Utilization of Soaps, Shampoos, and Detergents (MMT CO₂ Eq.)

	1990	1995	2000	2005	2019	2020	2021	2022	2023
C Emissions	3.6	4.2	4.5	6.9	5.4	5.5	5.4	4.5	4.1

Antifreeze and Deicers

Glycol compounds, including ethylene glycol, propylene glycol, diethylene glycol, and triethylene glycol, are used as antifreeze in motor vehicles, deicing fluids for commercial aircraft, and other similar uses. These glycol compounds are assumed to ultimately enter wastewater treatment plants where they are degraded by the wastewater treatment process to CO₂ or to otherwise biodegrade to CO₂. Glycols are water soluble and degrade rapidly in the environment (Howard 1993).

Annual production data for each glycol compound used as antifreeze and deicers were obtained from the *Guide to the Business of Chemistry* (ACC 2024b) and the EPA Chemical Data Access Tool (CDAT) (EPA 2014). Import and export data were used to adjust annual production data to annual consumption data. The percentage of the annual consumption of each glycol compound used for antifreeze and deicing applications was estimated from Chemical Profiles data published from the Innovation Group website and from similar data published in the Chemical Market Reporter, which became ICIS Chemical Business in 2005.³⁹ Production data for propylene glycol, diethylene glycol, and triethylene glycol are no longer reported in the Guide to the Business of Chemistry, so data from ICIS Chemical Business on total demand was used with import and export data to estimate production of these chemicals. ICIS last reported total demand for propylene glycol and diethylene glycol in 2006, and triethylene glycol demand in 2007. EPA reported total U.S. production of propylene glycol, diethylene glycol, and triethylene glycol in 2012 in the CDAT (EPA 2014). Total demand for these compounds for 2012 was calculated from the 2012 production data using import and export data. Demand for propylene glycol and diethylene glycol was interpolated for years between 2006 and 2012, and demand for triethylene glycol was interpolated for years between 2007 and 2012, using the calculated 2012 total demand values for each compound and the most recently reported total demand data from ICIS. Values for 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, and 2023 for these compounds were assumed to be the same as the 2012 values.

The glycol compounds consumed in antifreeze and deicing applications is assumed to be 100 percent emitted as CO₂. Emissions of CO₂ from utilization of antifreeze and deicers are summarized in Table A-59.

³⁸ A density of 1.05 g/mL—slightly denser than water—was assumed for liquid cleansers.

³⁹ See <http://www.icis.com/home/default.aspx>.

Table A-59: C Emitted from Utilization of Antifreeze and Deicers (MMT CO₂ Eq.)

	1990	1995	2000	2005	2019	2020	2021	2022	2023
C Emissions	1.2	1.4	1.5	1.2	1.0	0.9	0.9	1.0	1.1

Food Additives

Petrochemical feedstocks are used to manufacture synthetic food additives, including preservatives, flavoring agents, and processing agents. These compounds include glycerin, propylene glycol, benzoic acid, and other compounds. These compounds are incorporated into food products and are assumed to ultimately enter wastewater treatment plants where they are degraded by the wastewater treatment processes to CO₂ or to otherwise biodegrade to CO₂. Certain food additives, e.g., glycerin, are manufactured both from petrochemical feedstocks and from biogenic feedstocks. Food additives that are derived from biogenic feedstocks are accounted for in the Land Use, Land-Use Change and Forestry chapter.

Annual production data for food additive compounds were obtained from the *Guide to the Business of Chemistry* (ACC 2024b). Historical values for adipic acid, acetic acid, and maleic anhydride were adjusted according to the most recent data in the 2024 *Guide to the Business of Chemistry*. Import and export data were used to adjust annual production data to annual consumption data. The percentage of the annual consumption of food additive compounds was estimated from Chemical Profiles data published on by the Innovation Group and from similar data published in the Chemical Market Reporter, which became ICIS Chemical Business in 2005.⁴⁰ Production data for several food additive compounds are no longer reported in the *Guide to the Business of Chemistry*, so data from ICIS Chemical Business on total demand was used with import and export data to estimate production of these chemicals.

ICIS last reported total demand for glycerin and benzoic acid in 2007, and demand for propionic acid in 2008. Total demand for dipropylene glycol was last reported by ICIS in 2004. ICIS last reported cresylic acid demand in 1999. EPA reported total U.S. production of these compounds in 2012 in the CDAT (EPA 2014). Total demand for these compounds for 2012 was calculated from the 2012 production data using import and export data. Demand for each of these compounds was interpolated for years between the most recently reported total demand data from ICIS and 2012, using the calculated 2012 total demand values for each compound. Values for 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, and 2023 for these compounds were assumed to be the same as the 2012 values.

The consumption of synthetic food additives is assumed to be 100 percent emitted as CO₂. Emissions of CO₂ from utilization of synthetic food additives are summarized in Table A-60.

Table A-60: C Emitted from Utilization of Food Additives (MMT CO₂ Eq.)

Year	1990	1995	2000	2005	2019	2020	2021	2022	2023
C Emissions	0.6	0.7	0.7	0.8	1.1	1.1	1.1	1.1	1.1

Silicones

Silicone compounds (e.g., polymethyl siloxane) are used as sealants and in manufactured products. Silicone compounds are manufactured from petrochemical feedstocks including methyl chloride. It is assumed that petrochemical feedstocks used to manufacture silicones are incorporated into the silicone products and not emitted as CO₂ in the manufacturing process. It is also assumed that the C contained in the silicone products is stored, and not emitted as CO₂.

Import and export data were used to adjust annual production data to annual consumption data. The percentage of the annual consumption of each silicone manufacturing compound was estimated from Chemical Profiles data published on The Innovation Group website and from similar data published in the Chemical Market Reporter, which became ICIS Chemical Business in 2005.⁴¹ ICIS last reported production of methyl chloride in 2007. EPA

⁴⁰ See <http://www.icis.com/home/default.aspx>.

⁴¹ See <http://www.icis.com/home/default.aspx>.

reported total U.S. production of methyl chloride in 2012 in the CDAT (EPA 2014). Total consumption of methyl chloride for 2012 was calculated from the 2012 production data using import and export data. Production of methyl chloride was interpolated for years between 2007 and 2012, using the calculated 2012 total production value for methyl chloride and the most recently reported total production data from ICIS. The production values for 2013, 2014, 2015, 2016, 2017, 2018 2019, 2020, 2021, 2022, and 2023 were assumed to be the same as the 2012 value.

The consumption of silicone manufacturing compounds is assumed to be 100 percent stored, and not emitted as CO₂. Storage of silicone manufacturing compounds is summarized in Table A-61.

Table A-61: C Stored in Silicone Products (MMT CO₂ Eq.)

Year	1990	1995	2000	2005	2019	2020	2021	2022	2023
C Storage	0.3	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5

Uncertainty

A Tier 2 Monte Carlo analysis was performed using @RISK software to determine the level of uncertainty surrounding the estimates of the feedstocks C storage factor and the quantity of C emitted from feedstocks in 2023. The Tier 2 analysis was performed to allow the specification of probability density functions for key variables, within a computational structure that mirrors the calculation of the *Inventory* estimate. Statistical analyses or expert judgments of uncertainty were not available directly from the information sources for the activity variables; thus, uncertainty estimates were determined using assumptions based on source category knowledge. Uncertainty estimates for production data (the majority of the variables) were assumed to exhibit a normal distribution with a relative error of ±20 percent in the underlying EIA estimates, plus an additional ±15 percent to account for uncertainty in the assignment of imports and exports. An additional 10 percent (for a total of ±45 percent) was applied to the production of other oils (>401 degrees Fahrenheit) to reflect the additional uncertainty in the assignment of part of the production quantity to industrial processes. A relatively narrow uniform distribution ±1 percent to ±15 percent, depending on the fuel type, was applied to each C coefficient.

The Monte Carlo analysis produced a storage factor distribution with a standard deviation of 7 percent and the 95 percent confidence interval of 52 percent and 74 percent. This compares to the calculated *Inventory* estimate of 66 percent. The analysis produced a C emission distribution with a standard deviation of 29.3 MMT CO₂ Eq. and 95 percent confidence limits of 51.7 and 156.0 MMT CO₂ Eq. This compares with a calculated *Inventory* estimate of 88.3MMT CO₂ Eq.

The apparently tight confidence limits for the storage factor and C storage probably understate uncertainty, as a result of the way this initial analysis was structured. As discussed above, the storage factor for feedstocks is based on an analysis of six fates that result in long-term storage (e.g., plastics production), and eleven that result in emissions (e.g., volatile organic compound emissions). Rather than modeling the total uncertainty around all 17 of these fate processes, the current analysis addresses only the storage fates, and assumes that all C that is not stored is emitted. As the production statistics that drive the storage factors are relatively well-characterized, this approach yields a result that is probably biased toward understating uncertainty.

As far as specific sources of uncertainty, there are several cross-cutting factors that pervade the characterization of C flows for feedstocks. The aggregate storage factor for petrochemical feedstocks (industrial other coal, natural gas for non-fertilizer uses, HGL, naphthas, other oils, still gas, special naphtha) is based on assuming that the ultimate fates of all of these fuel types—in terms of storage and emissions—are similar. In addition, there are uncertainties associated with the simplifying assumptions made for each end use category C estimate. Generally, the estimate for a product is subject to one or more of the following uncertainties:

- The value used for estimating the C content has been assumed or assigned based upon a representative compound.
- The split between C storage and emission has been assumed based on an examination of the environmental fate of the products in each end use category.
- Environmental fates leading to emissions are assumed to operate rapidly, i.e., emissions are assumed to occur within one year of when the fossil C enters the non-energy mass balance. Some of the pathways

that lead to emissions as CO₂ may actually take place on a time-scale of several years or decades. By attributing the emissions to the year in which the C enters the mass balance (i.e., the year in which it leaves refineries as a non-energy fuel use and thus starts being tracked by EIA), this approach has the effect of “front-end loading” the emission profile.

Another cross-cutting source of uncertainty is that for several sources the amount of C stored or emitted was calculated based on data for only a single year. This specific year may not be representative of storage for the entire *Inventory* period. Sources of uncertainty associated with specific elements of the analysis are discussed below.

Import and export data for petrochemical feedstocks were obtained from EIA, the National Petroleum Refiners Association, and the BoC for the major categories of petrochemical feedstocks (EIA 2001; NPRA 2001; and U.S. Bureau of the Census 2017). The complexity of the organic chemical industry, with multiple feedstocks, intermediates, and subtle differences in nomenclature, makes it difficult to ensure that the adjustments to the EIA data for imports and exports is accurate and the approach used here may underestimate or overestimate net exports of C.

Oxidation factors have been applied to non-energy uses of petrochemical feedstocks in the same manner as for energy uses. However, for those fuels where IPCC storage factors are used, this “oxidation factor” may be inherent in the storage factor applied when calculating emissions from non-energy consumption, which would result in a double-counting of the unoxidized C. Oxidation factors are small corrections, on the order of 1 percent, and therefore application of oxidation factors to non-energy uses may result in a slight underestimation of C emissions from non-energy uses.

The major uncertainty in using the TRI data is the possibility of double counting emissions that are already accounted for in the NMVOC data (see above) and in the storage and emission assumptions used. The approach for predicting environmental fate simplifies some complex processes, and the balance between storage and emissions is very sensitive to the assumptions on fate. Extrapolating from known to unknown characteristics also introduces uncertainty. The two extrapolations with the greatest uncertainty are: (1) that the release media and fate of the off-site releases were assumed to be the same as for on-site releases, and (2) that the C content of the least frequent 10 percent of TRI releases was assumed to be the same as for the chemicals comprising 90 percent of the releases. However, the contribution of these chemicals to the overall estimate is small. The off-site releases only account for 3 percent of the total releases, by weight, and, by definition, the less frequent compounds only account for 10 percent of the total releases.

The principal sources of uncertainty in estimating CO₂ emissions from solvent evaporation and industrial NMVOC emissions are in the estimates of (a) total emissions and (b) their C content. Solvent evaporation and industrial NMVOC emissions reported by EPA are based on a number of data sources and emission factors and may underestimate or overestimate emissions. The C content for solvent evaporation emissions is calculated directly from the specific solvent compounds identified by EPA as being emitted and is thought to have relatively low uncertainty. The C content for industrial emissions has more uncertainty, however, as it is calculated from the average C content of an average volatile organic compound based on the list of the most abundant measured NMVOCs provided in EPA (2002a).

Uncertainty in the hazardous waste combustion analysis is introduced by the assumptions about the composition of combusted hazardous wastes, including the characterization that hazardous wastes are similar to mixtures of water, noncombustibles, and fuel equivalent materials. Another limitation is the assumption that all of the C that enters hazardous waste combustion is emitted—some small fraction is likely to be sequestered in combustion ash—but given that the destruction and removal efficiency for hazardous organics is required to meet or exceed 99.99 percent, this is a very minor source of uncertainty. C emission estimates from hazardous waste should be considered central value estimates that are likely to be accurate to within ±50 percent.

The amount of feedstocks combusted for energy recovery was estimated from data included in the *Manufacturers Energy Consumption Surveys* (MECS) for 1991, 1994, 1998, 2002, 2006, 2010, 2014, and 2018 (EIA 1994, 1997, 2001, 2005, 2010, 2013b, 2017, 2021). MECS is a comprehensive survey that is conducted every four years and intended to represent U.S. industry as a whole, but because EIA does not receive data from all manufacturers (i.e., it is a sample rather than a census), EIA must extrapolate from the sample. Also, the “other” fuels are identified in the MECS data in broad categories, including refinery still gas; waste gas; waste oils, tars, and related materials;

petroleum coke, coke oven and blast furnace gases; and other uncharacterized fuels. Moreover, the industries using these “other” fuels are also identified only in broad categories, including the petroleum and coal products, chemicals, primary metals, nonmetallic minerals, and other manufacturing sectors. The “other” fuel consumption data are reported in BTUs (energy units) and there is uncertainty concerning the selection of a specific conversion factor for each broad “other” fuel category to convert energy units to mass units. Taken as a whole, the estimate of energy recovery emissions probably introduces more uncertainty than any other element of the non-energy analysis.

Uncertainty in the C storage estimate for plastics arises primarily from four factors. First, production of some plastic resins is not tracked directly and must be estimated based on other market data. Second, the raw data on production for several resins include Canadian and/or Mexican production and may overestimate the amount of plastic produced from U.S. fuel feedstocks; this analysis includes adjustments to “back out” the Canadian and Mexican values, but these adjustments are approximate. Third, the assumed C content values are estimates for representative compounds, and thus do not account for the many formulations of resins available. This uncertainty is greater for resin categories that are generic (e.g., phenolics, other styrenics, nylon) than for resins with more specific formulations (e.g., polypropylene, polyethylene). Fourth, the assumption that all of the C contained in plastics is stored ignores certain end uses (e.g., adhesives and coatings) where the resin may be released to the atmosphere; however, these end-uses are likely to be small relative to use in plastics.

The quantity of C stored in synthetic rubber only accounts for the C stored in scrap tire synthetic rubber. The value does not take into account the rubber stored in other durable goods, clothing, footwear, and other non-durable goods, or containers and packaging. This adds uncertainty to the total mass balance of C stored. There are also uncertainties as to the assignment of C content values; however, they are much smaller than in the case of plastics. There are probably fewer variations in rubber formulations than in plastics, and the range of potential C content values is much narrower. Lastly, assuming that all of the C contained in rubber is stored ignores the possibility of volatilization or degradation during product lifetimes. However, the proportion of the total C that is released to the atmosphere during use is probably negligible.

A small degree of uncertainty arises from the assignment of C content values in textiles; however, the magnitude of this uncertainty is less than that for plastics or rubber. Although there is considerable variation in final textile products, the stock fiber formulations are standardized and proscribed explicitly by the Federal Trade Commission.

For pesticides, the largest source of uncertainty involves the assumption that an active ingredient’s C is either zero percent stored or 100 percent stored. This split is a generalization of chemical behavior, based upon active-ingredient molecular structure, and not on compound-specific environmental data. The mechanism by which a compound is bound or released from soils is very complicated and can be affected by many variables, including the type of crop, temperature, application method, and harvesting practice. Another smaller source of uncertainty arises from the C content values applied to the unaccounted for portion of active ingredient. C contents vary widely among pesticides, from 7 to 77 percent, and the remaining pesticides may have a chemical make-up that is very different from the 49 pesticides that have been examined. Additionally, pesticide consumption data were only available for 1987, 1993, 1995, 1997, 1999, 2001, 2007, 2009, and 2012; the majority of the time series data were interpolated or held constant at the latest (2012) value. Another source of uncertainty is that only the “active” ingredients of pesticides are considered in the calculations; the “inactive” ingredients may also be derived from petrochemical feedstocks.

It is important to note that development of this uncertainty analysis is a multi-year process. The current feedstocks analysis examines NEU fuels that end in storage fates. Thus, only C stored in pesticides, plastics, synthetic fibers, synthetic rubbers, silicones, and TRI releases to underground injection and Subtitle C landfills is accounted for in the uncertainty estimate above. In the future this analysis will be expanded to include the uncertainty surrounding emitted fates in addition to the storage fates. Estimates of variable uncertainty will also be refined where possible to include fewer assumptions. With these major changes in future Inventories, the uncertainty estimate is expected to change, and likely increase. An increase in the uncertainty estimate in the coming years will not indicate that the *Inventory* calculations have become less certain, but rather that the methods for estimating uncertainty have become more comprehensive; thus, potential future changes in the results of this analysis will reflect a change in the uncertainty analysis, not a change in the *Inventory* quality.

Asphalt and Road Oil

Asphalt is one of the principal non-energy uses of fossil fuels. The term “asphalt” generally refers to a mixture of asphalt cement and a rock material aggregate, a volatile petroleum distillate, or water. For the purposes of this analysis, “asphalt” is used interchangeably with asphalt cement, a residue of crude oil. Though minor amounts of C are emitted during production, asphalt has an overall C storage factor of almost 100 percent, as discussed below.

Paving is the primary application of asphalt cement, comprising 86 percent of production. The three types of asphalt paving produced in the United States are hot mix asphalt (HMA), cut-backs, and emulsified asphalt. HMA, which makes up 90 percent of total asphalt paving (EPA 2001), contains asphalt cement mixed with an aggregate of rock materials. Cut-back asphalt is composed of asphalt cement thinned with a volatile petroleum distillate (e.g., naphtha). Emulsified asphalt contains only asphalt cement and water. Roofing products are the other significant end use of asphalt cement, accounting for approximately 14 percent of U.S. production (Kelly 2000). No data were available on the fate of C in asphalt roofing; it was assumed that it has the same fate as C in asphalt paving applications.

Methodology and Data Sources

A C storage factor was calculated for each type of asphalt paving. The fraction of C emitted by each asphalt type was multiplied by consumption data for asphalt paving (EPA 2001) to estimate a weighted average C storage factor for asphalt as a whole.

The fraction of C emitted by HMA was determined by first calculating the organic emissions (volatile organic compounds [VOCs], carbon monoxide [CO], polycyclic aromatic hydrocarbons [PAHs], hazardous air pollutants [HAPs], and phenol) from HMA paving, using emission factors reported in EPA (2001) and total HMA production.⁴² The next step was to estimate the C content of the organic emissions. This calculation was based on the C content of CO and phenol, and an assumption of 85 percent C content for PAHs and HAPs. The C content of asphalt paving is a function of (1) the proportion of asphalt cement in asphalt paving, assumed to be 8 percent asphalt cement content based on EPA (2001), and (2) the proportion of C in asphalt cement. For the latter factor, all paving types were characterized as having a mass fraction of 85 percent C in asphalt cement, based on the assumption that asphalt is primarily composed of saturated paraffinic hydrocarbons. By combining these estimates, the result is that over 99.5 percent of the C in asphalt cement was retained (i.e., stored), and less than 0.5 percent was emitted.

Cut-back asphalt is produced in three forms: rapid, medium, and slow cure. The production processes for all three forms emit C primarily from the volatile petroleum distillate used in the process as a diluent to thin the asphalt cement so that it can be applied more readily (EPA 2001).

A mass balance on C losses from asphalt was constructed by first estimating the amount of carbon emitted as VOCs. Values for medium cure asphalt are used to represent all cut-back asphalt. The average weight of distillates used in medium cure cut-back asphalt (35 percent) is multiplied by the loss rate (as emissions of VOCs) of 70 percent from the *Emissions Inventory Guidebook* to arrive at an estimate that 25 percent of the diluent is emitted (Environment Canada 2006). Next, the fraction of C in the asphalt/ diluent mix that is emitted was estimated, assuming 85 percent C content; this yields an overall storage factor of 93.5 percent for cut-back asphalt.

One caveat associated with this calculation is that it is possible that the carbon flows for asphalt and diluent (volatile petroleum distillate) are accounted for separately in the EIA statistics on fossil fuel flows, and thus the mass balance calculation may need to re-map the system boundaries to correctly account for carbon flows. EPA plans to re-evaluate this calculation in the future.

It was assumed that there was no loss of C from emulsified asphalt (i.e., the storage factor is 100 percent) based on personal communication with an expert from Akzo Nobel Coatings, Inc. (James 2000).

Data on asphalt and road oil consumption and C content factors were supplied by EIA. Hot mix asphalt production and emissions factors, and the asphalt cement content of HMA were obtained from *Hot Mix Asphalt Plants*

⁴² The emission factors are expressed as a function of asphalt paving tonnage (i.e., including the rock aggregate as well as the asphalt cement).

Emissions Assessment Report from EPA's AP-42 (EPA 2001) publication. The consumption data for cut-back and emulsified asphalts were taken from a Moulthrop, et al. study used as guidance for estimating air pollutant emissions from paving processes (EIIP 2001). "Asphalt Paving Operation" AP-42 (EPA 2001) provided the emissions source information used in the calculation of the C storage factor for cut-back asphalt. The storage factor for emulsified asphalt was provided by Alan James of Akzo Nobel Coatings, Inc. (James 2000).

Uncertainty

A Tier 2 Monte Carlo analysis was performed using @RISK software to determine the level of uncertainty surrounding the estimates of the asphalt C storage factor and the quantity of C stored in asphalt in 2023. The Tier 2 analysis was performed to allow the specification of probability density functions for key variables, within a computational structure that mirrors the calculation of the *Inventory* estimate. Statistical analyses or expert judgments of uncertainty were not available directly from the information sources for the activity variables; thus, uncertainty estimates were determined using assumptions based on source category knowledge. Uncertainty estimates for asphalt production were assumed to be ± 20 percent, while the asphalt property variables were assumed to have narrower distributions. A narrow uniform distribution, with maximum 5 percent uncertainty (± 5 percent) around the mean, was applied to the C content coefficient.

The Monte Carlo analysis produced a tight distribution of storage factor values, with the 95 percent confidence interval of 99.1 percent and 99.8 percent. This compares to the storage factor value used in the *Inventory* of 99.6 percent. The analysis produced a C emission distribution with a standard deviation of 0.1 and 95 percent confidence limits of 0.1 MMT CO₂ Eq. and 0.6 MMT CO₂ Eq. This compares to an *Inventory* calculated estimate of 0.3 MMT CO₂ Eq.

The principal source of uncertainty is that the available data are from short-term studies of emissions associated with the production and application of asphalt. As a practical matter, the cement in asphalt deteriorates over time, contributing to the need for periodic re-paving. Whether this deterioration is due to physical erosion of the cement and continued storage of C in a refractory form or physicochemical degradation and eventual release of CO₂ is uncertain. Long-term studies may reveal higher lifetime emissions rates associated with degradation.

Many of the values used in the analysis are also uncertain and are based on estimates and professional judgment. For example, the asphalt cement input for hot mix asphalt was based on expert advice indicating that the range is variable—from about 3 to 5 percent—with actual content based on climate and geographical factors (Connolly 2000). Over this range, the effect on the calculated C storage factor is minimal (on the order of 0.1 percent). Similarly, changes in the assumed C content of asphalt cement would have only a minor effect.

The consumption figures for cut-back and emulsified asphalts are based on information reported for 1994. More recent trends indicate a decrease in cut-back use due to high VOC emission levels and a related increase in emulsified asphalt use as a substitute. This change in trend would indicate an overestimate of emissions from asphalt.

Future improvements to this uncertainty analysis, and to the overall estimation of a storage factor for asphalt, include characterizing the long-term fate of asphalt.

Lubricants

Lubricants are used in industrial and transportation applications. They can be subdivided into oils and greases, which differ in terms of physical characteristics (e.g., viscosity), commercial applications, and environmental fate. According to EIA (2025), the C content from U.S. production of lubricants in 2023 was approximately 3.7 MMT C. Based on apportioning oils and greases to various environmental fates, and characterizing those fates as resulting in either long-term storage or emissions, the overall C storage factor was estimated to be 9.2 percent; thus, emissions in 2023 were about 3.4 MMT C, or 12.4 MMT CO₂ Eq.

Methodology and Data Sources

For each lubricant category, a storage factor was derived by identifying disposal fates and applying assumptions as to the disposition of the C for each practice. An overall lubricant C storage factor was calculated by taking a production-weighted average of the oil and grease storage factors.

Oils

Regulation of used oil in the United States has changed dramatically over the past 20 years.⁴³ The effect of these regulations and policies has been to restrict landfilling and dumping, and to encourage collection of used oil. The economics of the petroleum industry have generally not favored re-refining—instead, most of the used oil that has been collected has been combusted.

Table A-62 provides an estimated allocation of the fates of lubricant oils (Rinehart 2000), along with an estimate of the proportion of C stored in each fate. The ultimate fate of the majority of oils (about 84 percent) is combustion, either during initial use or after collection as used oil. Combustion results in 99 percent oxidation to CO₂ (EIIP 1999), with correspondingly little long-term storage of C in the form of ash. Dumping onto the ground or into storm sewers, primarily by “do-it-yourselfers” who change their own oil, is another fate that results in conversion to CO₂ given that the releases are generally small and most of the oil is biodegraded (based on the observation that land farming—application to soil—is one of the most frequently used methods for degrading refinery wastes). In the landfill environment, which tends to be anaerobic within municipal landfills, it is assumed that 90 percent of the oil persists in an undegraded form, based on analogy with the persistence of petroleum in native petroleum-bearing strata, which is also anaerobic. Re-refining adds a recycling loop to the fate of oil. Re-refined oil was assumed to have a storage factor equal to the weighted average for the other fates (i.e., after re-refining, the oil would have the same probability of combustion, landfilling, or dumping as virgin oil), that is, it was assumed that about 97 percent of the C in re-refined oil is ultimately oxidized. Because of the dominance of fates that result in eventual release as CO₂, only about 3 percent of the C in oil lubricants goes into long-term storage.

Table A-62: Commercial and Environmental Fate of Oil Lubricants (Percent)

Fate of Oil	Portion of Total Oil	C Stored
Combusted During Use	20%	0.2%
Not Combusted During Use	80%	2.7%
Combusted as Used Oil ^a	64%	0.6%
Dumped on the ground or in storm sewers	6%	NA
Landfilled	2%	1.8%
Re-refined into lube oil base stock and other products	8%	0.2%
Weighted Average	NA	2.9%

NA (Not Applicable)

^aFor example, in boilers or space heaters.

Greases

Table A-63 provides analogous estimates for lubricant greases. Unlike oils, grease is generally not combusted during use, and combustion for energy recovery and re-refining is thought to be negligible. Although little is known about the fate of waste grease, it was assumed that 90 percent of the non-combusted portion is landfilled, and the remainder is dumped onto the ground or storm sewers. Because much of the waste grease will be in containers that render it relatively inaccessible to biodegradation, and because greases contain longer chain paraffins, which are more persistent than oils, it was assumed that 77 percent and 5 percent of the C in landfilled and dumped grease, respectively, would be stored. The overall storage factor is 82 percent for grease.

⁴³ For example, the U.S. EPA “RCRA (Resource Conservation and Recovery Act) On-line” web site (<http://www.epa.gov/rcraonline/>) has over 50 entries on used oil regulation and policy for 1994 through 2000.

Table A-63: Commercial and Environmental Fate of Grease Lubricants (Percent)

Fate of Grease	Portion of Total Grease	C Stored
Combusted During Use	5%	0.1%
Not Combusted During Use	95%	81.7%
Landfilled	90%	77.0%
Dumped on the ground or in storm sewers	10%	4.8%
Weighted Average	NA	81.8%

Having derived separate storage factors for oil and grease, the last step was to estimate the weighted average for lubricants as a whole. No data were found apportioning the mass of lubricants into these two categories, but the U.S. Census Bureau does maintain records of the value of production of lubricating oils and lubricating greases. These were retrieved from the relevant industry series summaries from the 1997 *Economic Census* (U.S. Bureau of the Census 1999). Assuming that the mass of lubricants can be allocated according to the proportion of value of production (92 percent oil, 8 percent grease), applying these weights to the storage factors for oils and greases (3 percent and 82 percent) yields an overall storage factor of 9.2 percent.

Uncertainty

A Tier 2 Monte Carlo analysis was performed using @RISK software to determine the level of uncertainty surrounding the estimates of the lubricants weighted average C storage factor and the quantity of C emitted from lubricants in 2023. The Tier 2 analysis was performed to allow the specification of probability density functions for key variables, within a computational structure that mirrors the calculation of the *Inventory* estimate. Statistical analyses or expert judgments of uncertainty were not available directly from the information sources for the activity variables; thus, uncertainty estimates were determined using assumptions based on source category knowledge. Uncertainty estimates for oil and grease variables were assumed to have a moderate variance, in triangular or uniform distribution. Uncertainty estimates for lubricants production were assumed to be rather high (± 20 percent). A narrow uniform distribution, with 6 percent uncertainty (± 6 percent) around the mean, was applied to the lubricant C content coefficient.

The Monte Carlo analysis produced a storage factor distribution with the 95 percent confidence interval of 3.8 percent and 17.5 percent. This compares to the calculated *Inventory* estimate of 9.2 percent. The analysis produced a C emission distribution approximating a normal curve with a standard deviation of 1.1 and 95 percent confidence limits of 10.3 MMT CO₂ Eq. and 14.4 MMT CO₂ Eq. This compares to an inventory-calculated estimate of 12.4 MMT CO₂ Eq.

The principal sources of uncertainty for the disposition of lubricants are the estimates of the commercial use, post-use, and environmental fate of lubricants, which, as noted above, are largely based on assumptions and judgment. There is no comprehensive system to track used oil and greases, which makes it difficult to develop a verifiable estimate of the commercial fates of oil and grease. The environmental fate estimates for percent of C stored are less uncertain, but also introduce uncertainty in the estimate.

The assumption that the mass of oil and grease can be divided according to their value also introduces uncertainty. Given the large difference between the storage factors for oil and grease, changes in their share of total lubricant production have a large effect on the weighted storage factor.

Future improvements to the analysis of uncertainty surrounding the lubricants C storage factor and C stored include further refinement of the uncertainty estimates for the individual activity variables.

Waxes

Waxes are organic substances that are solid at ambient temperature, but whose viscosity decreases as temperature increases. Most commercial waxes are produced from petroleum refining, though “mineral” waxes derived from animals, plants, and lignite (coal) are also used. An analysis of wax end uses in the United States, and the fate of C in these uses, suggests that about 42 percent of C in waxes is emitted, and 58 percent is stored.

Methodology and Data Sources

The National Petroleum Refiners Association (NPRA) considers the exact amount of wax consumed each year by end use to be proprietary (Maguire 2004). In general, about thirty percent of the wax consumed each year is used in

packaging materials, though this percentage has declined in recent years. The next highest wax end use, and fastest growing end use, is candles, followed by construction materials and firelogs. Table A-64 categorizes some of the wax end uses, which the NPRA generally classifies into cosmetics, plastics, tires and rubber, hot melt (adhesives), chemically modified wax substances, and other miscellaneous wax uses (NPRA 2002).

Table A-64: Emissive and Non-emissive (Storage) Fates of Waxes: Uses by Fate and Percent of Total Mass

Use	Emissive	Non-emissive
Packaging	6%	24%
Non-packaging	36%	34%
Candles	18%	2%
Construction Materials	4%	14%
Firelogs	7%	+
Cosmetics	1%	2%
Plastics	1%	2%
Tires/Rubber	1%	1%
Hot Melts	1%	1%
Chemically Modified	+	1%
Other	2%	9%
Total	42%	58%

+ Does not exceed 0.5 percent.

Note: Totals may not sum due to independent rounding.

A C storage factor for each wax end use was estimated and then summed across all end uses to provide an overall C storage factor for wax. Because no specific data on C contents of wax used in each end use were available, all wax products are assumed to have the same C content.

Table A-65 categorizes wax end uses identified by the NPRA and lists the estimated C storage factor of each end use.

Table A-65: Wax End-Uses by Fate, Percent of Total Mass, Percent C Stored, and Percent of Total C Mass Stored

Use	Percent of Total Wax Mass	Percent of C Stored	Percent of Total C Mass Stored
Packaging	30%	79%	24%
Non-Packaging			
Candles	20%	10%	2%
Construction Materials	18%	79%	14%
Firelogs	7%	1%	+
Cosmetics	3%	79%	2%
Plastics	3%	79%	2%
Tires/Rubber	3%	47%	1%
Hot Melts	3%	50%	1%
Chemically Modified	1%	79%	1%
Other	12%	79%	9%
Total	100%	NA	58%

+ Does not exceed 0.5 percent.

NA (Not Applicable)

Notes: Totals may not sum due to independent rounding. Estimates of percent stored are based on ICF professional judgment. Source mass percentages: NPRA (2002).

Emissive wax end-uses include candles, firelogs (synthetic fireplace logs), hotmelts (adhesives), matches, and explosives. At about 20 percent, candles consume the greatest portion of wax among emissive end uses. As candles combust during use, they release emissions to the atmosphere. For the purposes of the *Inventory*, it is assumed that 90 percent of C contained in candles is emitted as CO₂. In firelogs, petroleum wax is used as a binder and as a fuel, and is combusted during product use, likely resulting in the emission of nearly all C contained

in the product. Similarly, C contained in hotmelts is assumed to be emitted as CO₂ as heat is applied to these products during use. It is estimated that 50 percent of the C contained in hot melts is stored. Together, candles, firelogs, and hotmelts constitute approximately 30 percent of annual wax production (NPRA 2002).

All of the wax utilized in the production of packaging, cosmetics, plastics, tires and rubber, and other products is assumed to remain in the product (i.e., it is assumed that there are no emissions of CO₂ from wax during the production of the product). Wax is used in many different packaging materials including wrappers, cartons, papers, paperboard, and corrugated products (NPRA 2002). Davie (1993) and Davie et al. (1995) suggest that wax coatings in packaging products degrade rapidly in an aerobic environment, producing CO₂; however, because packaging products ultimately enter landfills typically having an anaerobic environment, most of the C from this end use is assumed to be stored in the landfill.

In construction materials, petroleum wax is used as a water repellent on wood-based composite boards, such as particle board (IGI 2002). Wax used for this end-use should follow the life-cycle of the harvested wood used in product, which is classified into one of 21 categories, evaluated by life-cycle, and ultimately assumed to either be disposed of in landfills or be combusted (EPA 2003).

The fate of wax used for packaging, in construction materials, and for most remaining end uses is ultimately to enter the municipal solid waste (MSW) stream, where it is either combusted or sent to landfill for disposal. Most of the C contained in these wax products will be stored. It is assumed that approximately 21 percent of the C contained in these products will be emitted through combustion or at landfill. With the exception of tires and rubber, these end-uses are assigned a C storage factor of 79 percent.

Waxes used in tires and rubber follow the life cycle of the tire and rubber products. Used tires are ultimately recycled, landfilled, or combusted. The life-cycle of tires is addressed elsewhere in this annex as part of the discussion of rubber products derived from petrochemical feedstocks. For the purposes of the estimation of the C storage factor for waxes, wax contained in tires and rubber products is assigned a C storage factor of 47 percent.

Uncertainty

A Tier 2 Monte Carlo analysis was performed using @RISK software to determine the level of uncertainty surrounding the estimates of the wax C storage factor and the quantity of C emitted from wax in 2023. A Tier 2 analysis was performed to allow the specification of probability density functions for key variables, within a computational structure that mirrors the calculation of the *Inventory* estimate. Statistical analyses or expert judgments of uncertainty were not available directly from the information sources for the activity variables; thus, uncertainty estimates were determined using assumptions based on source category knowledge. Uncertainty estimates for wax variables were assumed to have a moderate variance, in normal, uniform, or triangular distribution; uniform distributions were applied to total consumption of waxes and the C content coefficients.

The Monte Carlo analysis produced a storage factor distribution, whose 95 percent confidence interval values fell within the range of 47.4 percent and 67.5 percent. This compares to the calculated *Inventory* estimate of 57.8 percent. The analysis produced an emission distribution with the 95 percent confidence interval values of 0.2 MMT CO₂ Eq. and 0.6 MMT CO₂ Eq. This compares with a calculated *Inventory* estimate of 0.3 MMT CO₂ Eq., which falls within the range of 95 percent confidence limits established by this quantitative uncertainty analysis. Uncertainty associated with the wax storage factor is considerable due to several assumptions pertaining to wax imports/exports, consumption, and fates.

Miscellaneous Products

Miscellaneous products are defined by the U.S. Energy Information Administration as: “all finished [petroleum] products not classified elsewhere, e.g., petrolatum; lube refining by-products (e.g., aromatic extracts and tars); absorption oils; ram-jet fuel; petroleum rocket fuel; synthetic natural gas feedstocks; and specialty oils.”

Methodology and Data Sources

The “miscellaneous products” category reported by EIA includes miscellaneous products that are not reported elsewhere in the EIA data set. The EIA does not have firm data concerning the amounts of various products that are being reported in the “miscellaneous products” category; however, EIA has indicated that recovered sulfur compounds from petroleum and natural gas processing, and potentially also carbon black feedstock could be reported in this category. Recovered sulfur has no carbon content and would not be reported in the NEU

calculation or elsewhere in the *Inventory*. Based on this information, the miscellaneous products category reported by EIA was assumed to be mostly petroleum refinery sulfur compounds that do not contain carbon (EIA 2019). Therefore, the carbon content for miscellaneous products was updated to be zero across the time series in the previous *Inventory*. This resulted in recalculating historical emissions from 1990 through 2018.

Other Non-Energy Uses

The remaining fuel types use storage factors that are not based on U.S.-specific analysis. For industrial coking coal and distillate fuel oil, storage factors were taken from Marland and Rotty (1984). These factors are 0.1 and 0.5, respectively.

IPCC does not provide guidance on storage factors for the remaining fuel types (petroleum coke and other petroleum), and assumptions were made based on the potential fate of C in the respective NEUs. Specifically, the storage factor for petroleum coke is 0.3, based on information from Huurman (2006) indicating that petroleum coke is used in the Netherlands for production of pigments, with 30 percent being stored long-term. Carbon dioxide emissions from carbide production are implicitly accounted for in the storage factor calculation for the non-energy use of petroleum coke. The “other petroleum” category is reported by U.S. Territories and accounts mostly for the same products as miscellaneous products, but probably also includes some asphalt, known to be non-emissive. The exact amount of asphalt or any of the other miscellaneous products is confidential business information, but based on judgment, the storage factor for this category was estimated at 0.1.

For all these fuel types, the overall methodology simply involves multiplying C content by a storage factor, yielding an estimate of the mass of C stored. To provide a complete analysis of uncertainty for the entire NEU subcategory, the uncertainty around the estimate of “other” NEUs was characterized, as discussed below.

Uncertainty

A Tier 2 Monte Carlo analysis was performed using @RISK software to determine the level of uncertainty surrounding the weighted average of the remaining fuels’ C storage factors and the total quantity of C emitted from these other fuels in 2023. A Tier 2 analysis was performed to allow the specification of probability density functions for key variables, within a computational structure that mirrors the calculation of the *Inventory* estimate. Statistical analyses or expert judgments of uncertainty were not available directly from the information sources for some of the activity variables; thus, uncertainty estimates were determined using assumptions based on source category knowledge. A uniform distribution was applied to coking coal consumption, while the remaining consumption inputs were assumed to be normally distributed. The C content coefficients were assumed to have a uniform distribution; the greatest uncertainty range of 10 percent (± 10 percent) around the *Inventory* value, was applied to coking coal. C coefficients for distillate fuel oil ranged from 18.5 to 21.1 MMT C/QBtu. The fuel-specific storage factors were assigned wide triangular distributions indicating greater uncertainty.

The Monte Carlo analysis produced a storage factor distribution with 95 percent confidence limits of 7.4 percent and 82.7 percent. This compares to the *Inventory* calculation of weighted average (across the various fuels) storage factor of about 12.6 percent. The analysis produced an emission distribution, with the 95 percent confidence limit of 1.1 MMT CO₂ Eq. and 6.7 MMT CO₂ Eq. This compares with the *Inventory* estimate of 5.7 MMT CO₂ Eq., which falls closer to the upper boundary of the 95 percent confidence limit. The uncertainty analysis results are driven primarily by the very broad uncertainty inputs for the storage factors.

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ANNEX 3 Methodological Descriptions for Additional Source or Sink Categories

3.1. Methodology for Estimating Emissions of CH₄, N₂O, and Indirect Greenhouse Gases from Stationary Combustion

Estimates of CH₄ and N₂O Emissions

Methane (CH₄) and nitrous oxide (N₂O) emissions from stationary combustion were estimated using methods from the Intergovernmental Panel on Climate Change (IPCC). Estimates were obtained by multiplying emission factors—by sector and fuel type—by fossil fuel and wood consumption data. This “top-down” methodology is characterized by two basic steps, described below. Data are presented in Table A-66 through Table A-68.

Step 1: Determine Energy Consumption by Sector and Fuel Type

Energy consumption from stationary combustion activities was grouped by sector: industrial, commercial, residential, electric power, and U.S. Territories. For CH₄ and N₂O emissions from industrial, commercial, residential, and U.S. Territories, estimates were based upon consumption of coal, gas, oil, and wood. Energy consumption and wood consumption data for the United States were obtained from the Energy Information Administration’s (EIA) *Monthly Energy Review* (EIA 2025). Because the United States does not include U.S. Territories in its national energy statistics, fuel consumption data for U.S. Territories were collected from EIA’s International Energy Statistics database (EIA 2024) and Jacobs (2010).⁴⁴ Fuel consumption for the industrial sector was adjusted to subtract out construction and agricultural use, which is reported under mobile sources.⁴⁵ Construction and agricultural fuel use was obtained from EPA (2022b) and the Federal Highway Administration (FHWA) (1996 through 2024). The energy consumption data by sector were then adjusted from higher to lower heating values by multiplying by 0.90 for natural gas and wood and by 0.95 for coal and petroleum fuel. This is a simplified convention used by the International Energy Agency (IEA). Table A-66 provides annual energy consumption data for the years 1990 through 2023.

In this *Inventory*, the energy consumption estimation methodology for the electric power sector used a Tier 2 methodology as fuel consumption by technology-type for the electric power sector was estimated based on the Acid Rain Program Dataset (EPA 2024a). Total fuel consumption in the electric power sector from EIA (2025) was apportioned to each combustion technology type and fuel combination using a ratio of fuel consumption by technology type derived from EPA (2024a) data. The combustion technology and fuel use data by facility obtained from EPA (2024a) were only available from 1996 to 2023, so the consumption estimates from 1990 to 1995 were estimated by applying the 1996 consumption ratio by combustion technology type from EPA (2024a) to the total EIA (2025) consumption for each year from 1990 to 1995.

⁴⁴ U.S. Territories data also include combustion from mobile activities because data to allocate U.S. Territories’ energy use were unavailable. For this reason, CH₄ and N₂O emissions from combustion by U.S. Territories are only included in the stationary combustion totals.

⁴⁵ Though emissions from construction and farm use occur due to both stationary and mobile sources, detailed data was not available to determine the magnitude from each. Currently, these emissions are assumed to be predominantly from mobile sources.

Step 2: Determine the Amount of CH₄ and N₂O Emitted

Activity data for industrial, commercial, residential, and U.S. Territories and fuel type for each of these sectors were then multiplied by default Tier 1 emission factors to obtain emission estimates. Emission factors for the residential, commercial, and industrial sectors were taken from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). These N₂O emission factors by fuel type (equivalent across sectors) were also assumed for U.S. Territories. The CH₄ emission factors by fuel type for U.S. Territories were estimated based on the emission factor for the primary sector in which each fuel was combusted. Table A-67 provides emission factors used for each sector and fuel type. For the electric power sector, emissions were estimated by multiplying fossil fuel and wood consumption by technology- and fuel-specific Tier 2 IPCC emission factors shown in Table A-68. Emission factors were taken from U.S. EPA publications on emissions rates for combustion sources, and EPA's Compilation of Air Pollutant Emission Factors, AP-42 (EPA 1997) for combined cycle natural gas units. The EPA factors were in large part used in the *2006 IPCC Guidelines* as the factors presented.

Estimates of NO_x, CO, and NMVOC Emissions

Emissions estimates for NO_x, CO, and NMVOCs were obtained from data published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site (EPA 2024b) and disaggregated based on EPA (2003).

For indirect greenhouse gases, the major source categories included coal, fuel oil, natural gas, wood, other fuels (i.e., bagasse, liquefied petroleum gases, coke, coke oven gas, and others), and stationary internal combustion, which includes emissions from internal combustion engines not used in transportation. EPA periodically estimates emissions of NO_x, CO, and NMVOCs by sector and fuel type using a “bottom-up” estimating procedure. In other words, the emissions were calculated either for individual sources (e.g., industrial boilers) or for many sources combined, using basic activity data (e.g., fuel consumption or deliveries) as indicators of emissions. The national activity data used to calculate the individual categories were obtained from various sources. Depending upon the category, these activity data may include fuel consumption or deliveries of fuel, tons of refuse burned, raw material processed, etc. Activity data were used in conjunction with emission factors that relate the quantity of emissions to the activity.

The basic calculation procedure for most source categories presented in EPA (2003) and EPA (2024b) is represented by the following equation:

Equation A-7: NO_x, CO, and NMVOC Emissions Estimates

$$E_{p,s} = A_s \times EF_{p,s} \times (1 - C_{p,s}/100)$$

where,

E	=	Emissions
p	=	Pollutant
s	=	Source category
A	=	Activity level
EF	=	Emission factor
C	=	Percent control efficiency

EPA currently derives the overall emission control efficiency of a category from a variety of sources, including published reports, the 1985 National Acid Precipitation and Assessment Program (NAPAP) emissions inventory, and other EPA databases. The U.S. approach for estimating emissions of NO_x, CO, and NMVOCs from stationary combustion as described above is similar to the methodology recommended by IPCC.

Table A-66: Fuel Consumption by Stationary Combustion for Calculating CH₄ and N₂O Emissions (Tbtu)

Fuel/End-Use Sector	1990	1995	2000	2005	2010	2016	2017	2018	2019	2020	2021	2022	2023
Coal	19,637	20,912	23,088	22,966	20,731	14,269	13,770	13,161	11,132	9,121	10,404	9,748	8,133
Residential	31	17	11	8	0	0	0	0	0	0	0	0	0
Commercial	124	117	92	97	70	24	21	19	17	15	15	14	12
Industrial	1,668	1,557	1,362	1,246	993	662	615	569	517	449	450	450	381
Electric Power	17,807	19,216	21,618	21,582	19,633	13,547	13,110	12,546	10,559	8,625	9,908	9,252	7,713
U.S. Territories ^a	5	5	5	33	35	35	25	28	39	33	31	32	28
Petroleum	6,388	5,847	6,640	6,632	4,958	4,207	3,932	4,123	4,078	3,581	3,644	3,996	3,756
Residential	1,376	1,259	1,425	1,366	1,100	805	774	955	995	864	875	929	876
Commercial	1,022	724	767	761	695	839	815	741	815	780	799	934	860
Industrial	2,925	2,713	2,687	2,852	2,342	2,135	1,980	2,055	1,984	1,685	1,710	1,840	1,745
Electric Power	797	860	1,269	1,003	412	159	71	93	42	24	22	48	30
U.S. Territories ^a	268	290	491	649	408	270	292	278	241	228	238	245	245
Natural Gas	17,229	19,315	20,900	20,921	22,897	26,566	26,111	28,952	29,967	29,352	29,329	30,857	31,051
Residential	4,487	4,954	5,105	4,946	4,878	4,506	4,563	5,174	5,208	4,846	4,889	5,140	4,677
Commercial	2,680	3,096	3,252	3,073	3,165	3,224	3,273	3,638	3,647	3,279	3,409	3,635	3,455
Industrial	7,687	8,701	8,637	7,315	7,670	8,770	8,847	9,325	9,482	9,284	9,473	9,629	9,728
Electric Power	2,376	2,564	3,894	5,562	7,157	10,003	9,381	10,752	11,559	11,894	11,484	12,403	13,107
U.S. Territories ^a	0	0	13	24	28	64	48	62	71	50	74	51	85
Wood	2,216	2,370	2,262	2,137	2,217	2,216	2,175	2,252	2,227	1,960	1,979	2,002	1,931
Residential	580	520	420	430	541	445	430	525	546	345	344	422	450
Commercial	66	72	71	70	72	74	74	74	74	73	73	73	72
Industrial	1,442	1,652	1,636	1,452	1,409	1,474	1,442	1,432	1,407	1,356	1,366	1,309	1,235
Electric Power	129	125	134	185	196	224	229	221	201	185	197	198	174
U.S. Territories	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE

NE (Not Estimated)

^a U.S. Territories coal is assumed to be primarily consumed in the electric power sector, natural gas in the industrial sector, and petroleum in the transportation sector.

Note: Totals may not sum due to independent rounding.

Table A-67: CH₄ and N₂O Emission Factors by Fuel Type and Sector (g/GJ)^a

Fuel/End-Use Sector	CH ₄	N ₂ O
Coal		
Residential	300	1.5
Commercial	10	1.5
Industrial	10	1.5
U.S. Territories	1	1.5
Petroleum		
Residential	10	0.6
Commercial	10	0.6
Industrial	3	0.6
U.S. Territories	5	0.6
Natural Gas		
Residential	5	0.1
Commercial	5	0.1
Industrial	1	0.1
U.S. Territories	1	0.1
Wood		
Residential	300	4.0
Commercial	300	4.0
Industrial	30	4.0
U.S. Territories	NA	NA

NA (Not Applicable)

^aGJ (Gigajoule) = 10⁹ joules. One joule = 9.486×10⁻⁴ Btu.**Table A-68: CH₄ and N₂O Emission Factors by Technology Type and Fuel Type for the Electric Power Sector (g/GJ)^a**

Technology	Configuration	CH ₄	N ₂ O
Liquid Fuels			
Residual Fuel Oil/Shale Oil Boilers	Normal Firing	0.8	0.3
	Tangential Firing	0.8	0.3
Gas/Diesel Oil Boilers	Normal Firing	0.9	0.4
	Tangential Firing	0.9	0.4
Large Diesel Oil Engines >600 hp (447kW)		4.0	NA
Solid Fuels			
Pulverized Bituminous Combination Boilers	Dry Bottom, wall fired	0.7	5.8
	Dry Bottom, tangentially fired	0.7	1.4
	Wet bottom	0.9	1.4
Bituminous Spreader Stoker Boilers	With and without re-injection	1.0	0.7
Bituminous Fluidized Bed Combustor	Circulating Bed	1.0	61
	Bubbling Bed	1.0	61
Bituminous Cyclone Furnace		0.2	0.6
Lignite Atmospheric Fluidized Bed		NA	71
Natural Gas			
Boilers		1.0	0.3
Gas-Fired Gas Turbines >3MW		3.7	1.3
Large Dual-Fuel Engines		258	NA
Combined Cycle		3.7	1.3
Peat			
Peat Fluidized Bed Combustion	Circulating Bed	3.0	7.0
	Bubbling Bed	3.0	3.0
Biomass			

Wood/Wood Waste Boilers	11.0	7.0
Wood Recovery Boilers	1.0	1.0

NA (Not Applicable)

^aIbid.

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3.2. Methodology for Estimating Emissions of CH₄, N₂O, and Indirect Greenhouse Gases from Mobile Combustion and Methodology for and Supplemental Information on Transportation-Related Greenhouse Gas Emissions

Estimating CO₂ Emissions by Transportation Mode

Transportation-related CO₂ emissions, as presented in the CO₂ Emissions from Fossil Fuel Combustion section of the Energy chapter, were calculated using the methodology described in Annex 2.1. This section provides additional information on the data sources and approach used for each transportation fuel type. As noted in Annex 2.1, CO₂ emissions estimates for the transportation sector were calculated directly for on-road diesel fuel and motor gasoline based on data sources for individual modes of transportation (considered a bottom-up approach). For most other fuel and energy types (aviation gasoline, residual fuel oil, natural gas, liquefied petroleum gas [LPG], and electricity), CO₂ emissions were calculated based on transportation sector-wide fuel consumption estimates from the Energy Information Administration (EIA 2024b and EIA 2024c) and apportioned to individual modes (considered a “top down” approach). Carbon dioxide emissions from commercial jet fuel use are obtained directly from the Federal Aviation Administration (FAA 2024) for the years 1990 through 2022.⁴⁶

Based on interagency discussions between the Environmental Protection Agency (EPA), EIA, and the Federal Highway Administration (FHWA) beginning in 2005, it was agreed that use of “bottom up” data would be more accurate for diesel fuel and motor gasoline consumption in the transportation sector, based on the availability of reliable data sources. A “bottom up” diesel calculation was first implemented in the 1990 through 2005 *Inventory*, and a bottom-up gasoline calculation was introduced in the 1990 through 2006 *Inventory* for the calculation of emissions from on-road vehicles. On-road fuel consumption data from FHWA Table MF-21 were used to determine total on-road use of motor gasoline and diesel fuel. (FHWA 1996 through 2024). Ratios developed from EPA’s Motor Vehicle Emission Simulator (MOVES) output are then used to apportion FHWA fuel consumption data to vehicle type and fuel type.

A primary challenge to switching from a top-down approach to a bottom-up approach for the transportation sector relates to potential incompatibilities with national energy statistics. From a multi-sector national standpoint, EIA develops the most accurate estimate of total motor gasoline and diesel fuel supplied and consumed in the United States. EIA then allocates this total fuel consumption to each major end-use sector (residential, commercial, industrial and transportation) using data from EIA Monthly Energy Review for 1990-2023 for distillate fuel oil and FHWA for motor gasoline. However, the “bottom-up” approach used for the on-road and non-road fuel consumption estimate, as described above, is the most representative of the transportation sector’s share of the EIA total consumption. Therefore, for years in which there was a disparity between EIA’s fuel allocation estimate for the transportation sector and the “bottom-up” estimate, adjustments were made to other end-use sector fuel allocations (residential, commercial, and industrial) for the consumption of all sectors combined to equal the “top-down” EIA value.

In the case of motor gasoline, estimates of fuel use by recreational boats come from the nonroad component of EPA’s MOVES5 model (EPA 2024a), and these estimates, along with those from other sectors (e.g., commercial sector, industrial sector), were adjusted for years in which the bottom-up on-road motor gasoline consumption estimate exceeded the EIA estimate for total gasoline consumption of all sectors. Similarly, to ensure consistency with EIA’s total diesel estimate for all sectors, the diesel consumption totals for the residential, commercial, and industrial sectors were adjusted proportionately.

⁴⁶ For the Public Review Inventory, estimates for 2023 are proxied based on 2022 data.

Estimates of diesel fuel consumption from rail were taken from: the Association of American Railroads (AAR 2008 through 2024) for Class I railroads, the American Public Transportation Association (APTA 2007 through 2024 and APTA 2006), FTA(2024) for years 2021 to 2023, and Gaffney (2007) for commuter rail, the Upper Great Plains Transportation Institute (Benson 2002 through 2004), Whorton (2006 through 2014), and Railinc (2014 through 2024) for Class II and III railroads, and the U.S. Department of Energy’s *Transportation Energy Data Book* (DOE 1993 through 2022) for passenger rail. Class II and III railroad diesel consumption is estimated by applying the historical average fuel usage per carload factor to yearly carloads. Estimates of diesel fuel consumption from ships and boats were taken from EIA’s *Fuel Oil and Kerosene Sales* (1991 through 2022). Data for 2021, 2022 and 2023 diesel fuel consumption for ships and boats was proxied.

As noted above, for fuels other than motor gasoline and diesel, EIA’s transportation sector total was apportioned to specific transportation sources. For jet fuel, estimates come from: FAA (2024) for domestic and international commercial aircraft, and DLA Energy (2023) for domestic and international military aircraft. Military fuel consumption was proxied for 2023. General aviation jet fuel consumption is calculated as the difference between total jet fuel consumption as reported by EIA and the total consumption from commercial and military jet fuel consumption. Commercial jet fuel CO₂ estimates are obtained directly from the Federal Aviation Administration (FAA 2024), while CO₂ emissions from domestic military and general aviation jet fuel consumption is determined using a top-down approach. Domestic commercial jet fuel CO₂ from FAA is subtracted from total domestic jet fuel CO₂ emissions, and this remaining value is apportioned among domestic military and domestic general aviation based on their relative proportion of energy consumption. Estimates for biofuels, including ethanol and biodiesel, were discussed separately in Section 3.2 Carbon Emitted from Non-Energy Uses of Fossil Fuels under the methodology for Estimating CO₂ from Fossil Combustion, and in Section 3.10 Wood Biomass and Ethanol Consumption, and were not apportioned to specific transportation sources. Consumption estimates for biofuels were calculated based on data from the Energy Information Administration (EIA 2024b).

Table A-69 displays estimated fuel consumption by fuel and vehicle type. Table A-70 displays estimated energy consumption by fuel and vehicle type. The values in both tables correspond to the figures used to calculate CO₂ emissions from transportation. Except as noted above, they are estimated based on EIA transportation sector energy estimates by fuel type, with activity data used to apportion fuel consumption to the various modes of transport. The motor gasoline and diesel fuel consumption volumes published by EIA and FHWA include ethanol blended with gasoline and biodiesel blended with diesel. Biofuels blended with conventional fuels were subtracted from these consumption totals in order to be consistent with IPCC methodological guidance and national inventory report standards, for which net carbon fluxes in biogenic carbon reservoirs in croplands are accounted for in the estimates for the Land Use, Land-Use Change, and Forestry chapter, not in Energy chapter totals. Ethanol fuel volumes were removed from motor gasoline consumption estimates for years 1990 through 2022. Biodiesel fuel volumes were removed from diesel fuel consumption volumes for years 2001 through 2023, as there was negligible use of biodiesel as a diesel blending component prior to 2001. The subtraction or removal of biofuels blended into motor gasoline and diesel were conducted following the methodology outlined in Step 2 (“Remove Biofuels from Petroleum”) of the EIA’s *Monthly Energy Review* (MER) Section 12 notes.

To remove the volume of biodiesel blended into diesel fuel, the 2009 to 2023 biodiesel and renewable diesel fuel consumption estimates from EIA (2024b) were subtracted from the transportation sector’s total diesel fuel consumption volume (for both the “top-down” EIA and “bottom-up” FHWA estimates). To remove the ethanol blended into motor gasoline, ethanol energy consumption data sourced from MER *Table 10.2b - Renewable Energy Consumption: Industrial and Transportation Sectors* (EIA 2024b) were subtracted from the total EIA and FHWA transportation motor gasoline energy consumption estimates. Total ethanol and biodiesel consumption estimates are in Table A-71.⁴⁷

⁴⁷ Note that the refinery and blender net volume inputs of renewable diesel fuel sourced from EIA’s Petroleum Supply Annual (PSA) differs from the biodiesel volume presented in Table A-71. The PSA data is representative of the amount of biodiesel that refineries and blenders added to diesel fuel to make low level biodiesel blends. This is the appropriate value to subtract from total diesel fuel volume, as it represents the amount of biofuel blended into diesel to create low-level biodiesel blends. The biodiesel consumption value presented in Table A-69 is representative of the total biodiesel consumed and includes biodiesel components in all types of fuel formulations, from low level (<5%) to high level (6–20%, 100%) blends of biodiesel. This value is sourced from MER Table 10.4 and is calculated as biodiesel production plus biodiesel net imports minus biodiesel stock exchange.

Table A-69: Fuel Consumption by Fuel and Vehicle Type (million gallons unless otherwise specified)

Fuel/Vehicle Type	1990	2000	2010 ^a	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Motor Gasoline^{b,c}	107,651	125,232	119,829	116,810	116,960	121,472	120,631	123,482	123,079	124,886	123,709	106,645	117,104	115,484	117,896
Passenger Cars	69,913	62,228	52,321	42,708	43,575	44,791	43,765	44,032	42,583	41,971	40,853	33,896	35,755	33,765	33,421
Light-Duty Trucks	30,500	56,674	62,665	69,408	68,650	71,728	71,877	74,155	74,971	77,096	76,872	67,222	75,003	75,043	77,675
Motorcycles	367	460	691	771	744	758	733	776	766	782	766	689	784	930	974
Buses	576	366	167	199	218	253	268	295	353	395	412	349	403	446	469
Medium- and Heavy-Duty Trucks	4,691	3,899	2,672	2,481	2,554	2,744	2,791	3,018	3,196	3,424	3,585	3,362	3,950	4,073	4,127
Recreational Boats ^d	1,604	1,606	1,315	1,243	1,220	1,196	1,197	1,205	1,211	1,218	1,220	1,126	1,209	1,227	1,231
Distillate Fuel Oil (Diesel Fuel)^{b,c}	25,631	39,241	41,311	41,470	41,785	43,203	44,377	44,012	45,337	46,347	46,096	43,520	46,752	46,371	45,843
Passenger Cars	964	564	257	235	250	271	287	270	254	241	240	193	195	186	172
Light-Duty Trucks	799	1,902	2,708	3,166	2,983	3,023	3,138	3,134	3,125	3,087	3,116	2,570	2,708	2,715	2,676
Buses	760	1,483	1,402	1,577	1,585	1,714	1,776	1,762	1,835	1,948	1,968	1,584	1,743	1,894	1,875
Medium- and Heavy-Duty Trucks	18,722	29,545	32,089	31,579	32,014	33,191	33,783	34,011	35,245	36,141	36,268	35,139	37,919	37,370	37,080
Recreational Boats	267	270	263	252	246	245	256	262	269	276	279	256	275	288	284
Ships and Non-Recreational Boats	658	1,372	809	830	841	719	1,278	1,060	975	908	725	742	756	755	746
Rail ^e	3,461	4,106	3,783	3,831	3,866	4,041	3,858	3,514	3,635	3,746	3,501	3,036	3,157	3,163	3,009
Jet Fuel^f	19,168	19,992	15,529	14,698	15,082	15,210	16,155	17,021	17,609	17,667	18,489	12,372	15,656	16,906	18,353
Commercial Aircraft	11,569	14,672	11,931	11,932	12,031	12,131	12,534	12,674	13,475	13,650	14,397	9,613	12,527	13,654	13,654
General Aviation Aircraft	3,940	3,107	2,287	1,629	2,005	1,751	2,327	3,152	2,952	2,880	2,950	1,659	1,966	2,105	3,599
Military Aircraft	3,660	2,213	1,311	1,137	1,046	1,327	1,294	1,194	1,181	1,138	1,141	1,100	1,163	1,147	1,099
Aviation Gasoline^f	374	302	225	209	186	181	176	170	174	186	195	168	179	186	176
General Aviation Aircraft	374	302	225	209	186	181	176	170	174	186	195	168	179	186	176
Residual Fuel Oil^{f,g}	2,006	2,963	1,818	1,410	1,345	517	378	1,152	1,465	1,246	1,289	651	2,155	2,037	1,478
Ships and Non-Recreational Boats	2,006	2,963	1,818	1,410	1,345	517	378	1,152	1,465	1,246	1,289	651	2,155	2,037	1,478
Natural Gas^f (trillion cubic feet)	0.7	0.7	0.7	0.8	0.9	0.7	0.7	0.7	0.8	0.9	1.1	1.1	1.2	1.3	1.3
Passenger Cars	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+

Fuel/Vehicle Type	1990	2000	2010 ^a	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Medium- and Heavy-Duty Trucks	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Buses	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Pipelines	0.7	0.7	0.7	0.8	0.9	0.7	0.7	0.7	0.8	0.9	1.1	1.1	1.2	1.3	1.3
LPG^f	251	130	50	49	67	83	109	129	136	138	137	95	107	122	122
Passenger Cars	1	0.3	+	+	+	+	+	+	+	0	0	+	+	+	+
Light-Duty Trucks	25	9	2	1	1	2	2	1	2	8	8	6	7	10	12
Medium- and Heavy-Duty Trucks	225	84	21	19	26	27	31	34	31	119	116	80	87	94	90
Buses	+	37	27	30	40	54	77	94	103	11	12	9	12	17	20
Electricity^{h,i}	4,751	5,382	7,735	7,482	7,965	8,310	8,433	8,569	8,928	9,778	10,405	9,339	10,116	11,893	14,178
Passenger Cars	+	+	+	+	+	0	5	26	54	102	145	185	484	960	1,850
Light-Duty Trucks	+	+	1	127	303	511	743	1,011	1,310	1,969	2,585	2,563	3,253	4,288	5,417
Buses	+	+	22	35	37	42	49	36	41	42	43	44	45	46	47
Rail	4,751	5,382	7,712	7,320	7,625	7,758	7,637	7,497	7,523	7,665	7,632	6,548	6,334	6,599	6,864

+ Does not exceed 0.05 units (trillion cubic feet, million kilowatt-hours, or million gallons, as specified).

^a Fuel is allocated to vehicle classes using MOVES5 ratios of fuel in each vehicle class to total fuel.

^b Figures do not include ethanol blended in motor gasoline or biodiesel blended into distillate fuel oil. Net carbon fluxes associated with ethanol are accounted for in the Land Use, Land-Use Change and Forestry chapter. This table is calculated with the heat content for gasoline without ethanol (from Table A.1 in the EIA Monthly Energy Review) rather than the annually variable quantity-weighted heat content for gasoline with ethanol, which varies by year.

^c Gasoline and diesel highway vehicle fuel consumption estimates are based on data from FHWA Highway Statistics Table MF-21, MF-27, and ratios developed from MOVES5 to apportion FHWA fuel consumption data to vehicle type and fuel type. Estimates for 2023 are proxied based FHWA traffic volume trends data.

^d Fluctuations in recreational boat gasoline estimates reflect the use of this category to reconcile bottom-up values with EIA total gasoline estimates.

^e Class II and Class III diesel consumption data for 2014-2023 is estimated by applying the historical average fuel usage per carload factor to the annual number of carloads.

^f Estimated based on EIA transportation sector energy estimates by fuel type, with bottom-up activity data used for apportionment to modes. Transportation sector natural gas and LPG consumption are based on data from EIA (2024c). In previous *Inventory* years, data from DOE TEDB was used to estimate each vehicle class's share of the total natural gas and LPG consumption. Since TEDB does not include estimates for natural gas use by medium and heavy-duty trucks or LPG use by passenger cars, EIA Alternative Fuel Vehicle Data (Browning 2022b) is now used to determine each vehicle class's share of the total natural gas and LPG consumption.

^g Fluctuations in reported fuel consumption may reflect data collection problems.

^h Million kilowatt-hours

ⁱ Electricity consumption by passenger cars, light-duty trucks (SUVs), and buses is based on plug-in electric vehicle sales data and engine efficiencies, as outlined in Browning (2022b).

Note: Totals may not sum due to independent rounding.

Table A-70: Energy Consumption by Fuel and Vehicle Type (TBtu)

Fuel/Vehicle Type	1990	2000	2010 ^a	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Motor Gasoline^{a,b}	13,464	15,663	14,899	14,523	14,542	15,103	14,999	15,353	15,303	15,528	15,381	13,260	14,560	14,358	14,658
Passenger Cars	8,744	7,783	6,505	5,310	5,418	5,569	5,441	5,475	5,294	5,218	5,079	4,214	4,445	4,198	4,155
Light-Duty Trucks	3,815	7,088	7,791	8,630	8,535	8,918	8,937	9,220	9,321	9,586	9,558	8,358	9,325	9,330	9,658
Motorcycles	46	57	86	96	92	94	91	97	95	97	95	86	98	116	121
Buses	72	46	21	25	27	32	33	37	44	49	51	43	50	55	58
Medium- and Heavy-Duty Trucks	587	488	332	308	318	341	347	375	397	426	446	418	491	506	513
Recreational Boats ^c	201	201	163	155	152	149	149	150	151	151	152	140	150	153	153
Distillate Fuel Oil (Diesel Fuel)^{a,b}	3,555	5,442	5,729	5,751	5,795	5,992	6,155	6,104	6,288	6,428	6,393	6,036	6,484	6,431	6,358
Passenger Cars	134	78	36	33	35	38	40	37	35	33	33	27	27	26	24
Light-Duty Trucks	111	264	376	439	414	419	435	435	433	428	432	356	376	377	371
Buses	105	206	194	219	220	238	246	244	255	270	273	220	242	263	260
Medium- and Heavy-Duty Trucks	2,597	4,098	4,450	4,380	4,440	4,603	4,685	4,717	4,888	5,012	5,030	4,873	5,259	5,183	5,143
Recreational Boats	37	37	36	35	34	34	36	36	37	38	39	35	38	40	39
Ships and Non-Recreational Boats	91	190	112	115	117	100	177	147	135	126	101	103	105	105	104
Rail ^d	480	569	525	531	536	560	535	487	504	520	486	421	438	439	417
Jet Fuel^e	2,588	2,699	2,096	1,984	2,036	2,053	2,181	2,298	2,377	2,385	2,496	1,670	2,114	2,282	2,478
Commercial Aircraft	1,562	1,981	1,611	1,611	1,624	1,638	1,692	1,711	1,819	1,843	1,944	1,298	1,691	1,843	1,843
General Aviation Aircraft	532	419	309	220	271	236	314	426	399	389	398	224	265	284	486
Military Aircraft	494	299	177	154	141	179	175	161	159	154	154	149	157	155	148
Aviation Gasoline	45	36	27	25	22	22	21	20	21	22	23	20	22	22	21
General Aviation Aircraft	45	36	27	25	22	22	21	20	21	22	23	20	22	22	21
Residual Fuel Oil^{e,f}	300	443	272	211	201	77	57	172	219	186	193	97	323	305	221
Ships and Non-Recreational Boats	300	443	272	211	201	77	57	172	219	186	193	97	323	305	221
Natural Gas^e	679	672	719	780	887	760	745	757	799	962	1,114	1,111	1,232	1,367	1,356
Passenger Cars	+	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	+	+	+	+

Fuel/Vehicle Type	1990	2000	2010 ^a	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Light-Duty Trucks	+	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.2	0.2
Medium- and Heavy-Duty Trucks	+	0.2	0.7	0.9	1.0	1.1	1.1	1.4	1.4	1.5	1.5	1.6	1.7	1.8	1.8
Buses	+	3	4	4	4	4	5	5	5	6	5	5	4	5	6
Pipelines	679	668	714	775	882	754	739	750	791	955	1,107	1,105	1,226	1,360	1,348
LPG^e	23	12	5	5	6	8	10	12	12	13	12	9	10	11	11
Passenger Cars	0.1	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Light-Duty Trucks	2	1	0	+	0	0	0	0	0	1	1	1	1	1	1
Medium- and Heavy-Duty Trucks	21	8	2	2	2	2	3	3	3	11	11	7	8	9	8
Buses	+	3.4	2	3	4	5	7	9	9	1	1	1	1	2	2
Electricity^g	16	18	26	26	27	28	29	29	30	33	36	32	35	41	48
Passenger Cars	+	+	+	+	+	+	+	0.1	0.2	0.3	0.5	0.6	1.7	3.3	6.3
Light-Duty Trucks	+	+	+	0.4	1.0	1.7	2.5	3.4	4.5	6.7	8.8	8.7	11.1	14.6	18.5
Buses	+	+	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2
Rail	16	18	26	25	26	26	26	26	26	26	26	22	22	23	23
Total	20,670	24,986	23,774	23,305	23,518	24,043	24,195	24,746	25,049	25,557	25,648	22,235	24,778	24,818	25,152

Note: Totals may not sum due to independent rounding.

Table A-71: Transportation Sector Biofuel Consumption by Fuel Type (million gallons)

Fuel Type	1990	2000	2010	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Ethanol	699	1,556	11,833	11,997	12,154	12,758	12,793	13,261	13,401	13,573	13,589	11,744	13,015	12,943	13,197
Biodiesel	NA	NA	260	899	1,429	1,417	1,494	2,085	1,985	1,904	1,813	1,873	1,709	1,608	1,615

Estimates of CH₄ and N₂O Emissions

Mobile source emissions of greenhouse gases other than CO₂ are reported by transport mode (e.g., road, rail, aviation, and waterborne), vehicle type, and fuel type. Emissions estimates of CH₄ and N₂O were derived using a methodology like that outlined in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006).

Activity data were obtained from several U.S. government agencies and other publications. Depending on the category, basic activity data included fuel consumption and vehicle miles traveled (VMT). These estimates were then multiplied by emission factors, expressed as grams per unit of fuel consumed or per vehicle mile.

Methodology for On-Road Gasoline and Diesel Vehicles

Step 1: Determine Vehicle Miles Traveled by Vehicle Type, Fuel Type, and Model Year

Total VMT were obtained from the FHWA's *Highway Statistics* (FHWA 1996 through 2024). As these vehicle categories are not fuel specific, VMT for each vehicle type was disaggregated by fuel type (gasoline, diesel) to ensure that the appropriate emission factors were applied. VMT from *Highway Statistics* Table VM-1 (FHWA 1996 through 2024) was allocated to fuel types (gasoline, diesel, other) using EPA's MOVES5 model ratios of VMT per vehicle class to total VMT. This corrects historical inconsistencies in vehicle type definitions in FHWA data⁴⁸ (Browning 2022a). VMT for alternative fuel vehicles (AFVs) was calculated separately, and the methodology is explained in the following section on AFVs. Estimates of VMT from AFVs were then subtracted from the appropriate total VMT estimates to develop the final VMT estimates by vehicle/fuel type category.⁴⁹ The resulting national VMT estimates for gasoline and diesel on-road vehicles are presented in Table A-72 and Table A-73, respectively.

Total VMT for each on-road category (i.e., gasoline passenger cars, light-duty gasoline trucks, heavy-duty gasoline vehicles, diesel passenger cars, light-duty diesel trucks, medium- and heavy-duty diesel trucks, heavy-duty diesel buses, and motorcycles) were distributed across 30 model years shown for 2023 in Table A-74.

This distribution was derived by weighting the appropriate age distribution of the U.S. vehicle fleet according to vehicle registrations by the average annual age-specific vehicle mileage accumulation of U.S. vehicles. Age distribution values were obtained from EPA's MOBILE6 model for all years before 1999 (EPA 2000) and EPA's MOVES5 model for years 1999 forward (EPA 2024).⁵⁰ Age-specific vehicle mileage accumulations were also obtained from EPA's MOVES5 model (EPA 2024).⁵¹

Step 2: Allocate VMT Data to Control Technology Type

VMT by vehicle type for each model year was distributed across various control technologies as shown Table A-80 through Table A-83. The categories "EPA Tier 0" and "EPA Tier 1" were used instead of the early three-way catalyst and advanced three-way catalyst categories, respectively, as defined in the *Revised 1996 IPCC Guidelines*. EPA Tier 0, EPA Tier 1, EPA Tier 2, and EPA Tier 3 refer to U.S. emission regulations and California Air Resources Board (CARB) LEV, CARB LEVII, and CARB LEVII refer to California emissions regulations, rather than control technologies; however, each does correspond to particular combinations of control technologies and engine design. EPA Tier 2 and Tier 3 and its predecessors EPA Tier 1 and Tier 0 as well as CARB LEV, LEVII, and LEVIII apply to vehicles equipped with three-way catalysts. The introduction of "early three-way catalysts," and "advanced

⁴⁸ VMT is allocated to vehicle classes using MOVES5 ratios of VMT in each vehicle class to total VMT.

⁴⁹ In *Inventories* through 2002, gasoline-electric hybrid vehicles were part of an "alternative fuel and advanced technology" category. However, vehicles are now separated into gasoline, diesel, or alternative fuel categories, and gas-electric hybrids are now within the gasoline vehicle category.

⁵⁰ Age distributions were held constant for the period 1990 to 1998 and reflect a 25-year vehicle age span. EPA (2022) provides a variable age distribution and 31-year vehicle age span beginning in year 1999.

⁵¹ The updated vehicle distribution and mileage accumulation rates by vintage obtained from the MOVES5 model resulted in a decrease in emissions due to more miles driven by newer light-duty gasoline vehicles.

three-way catalysts,” as described in the *Revised 1996 IPCC Guidelines*, roughly correspond to the introduction of EPA Tier 0 and EPA Tier 1 regulations (EPA 1998).⁵² EPA Tier 2 regulations affect vehicles produced starting in 2004 and are responsible for a noticeable decrease in N₂O emissions compared to EPA Tier 1 emissions technology (EPA 1999). EPA Tier 3 regulations affect vehicles produced starting in 2017 and are fully phased in by 2025. CARB LEVII regulations affect California vehicles produced starting in 2004 while ARB LEVIII affect California vehicles produced starting in 2015.

EPA estimated emission control technology assignments for light- and heavy-duty conventional fuel vehicles for model years 1972 (when regulations began to take effect) through 1995 in EPA (1998). Assignments for 1996 and 1997 were estimated given the fact that EPA Tier 1 standards for light-duty vehicles were fully phased in by 1996. Assignments for 1998 through 2022 were determined using confidential engine family sales data submitted to EPA (EPA 2023b). Vehicle classes and emission standard tiers to which each engine family was certified were taken from annual certification test results and data (EPA 2023a). This information was used to determine the fraction of sales of each class of vehicle that met EPA Tier 0, EPA Tier 1, EPA Tier 2, EPA Tier 3 and CARB LEV, CARB LEVII, and CARB LEVIII standards. Tier 2 began initial phase-in by 2004. EPA Tier 3 began initial phase-in by 2017 and CARB LEV III standards began initial phase-in by 2015.

Step 3: Determine CH₄ and N₂O Emission Factors by Vehicle, Fuel, and Control Technology Type

Methane and N₂O emission factors (in grams of CH₄ and N₂O per mile) for gasoline and diesel on-road vehicles utilizing EPA Tier 2, EPA Tier 3, and CARB LEV, LEVII, and LEVIII technologies were developed by Browning (2019). Motorcycle emission factors were updated for advanced technology motorcycles (Browning 2020). These emission factors were calculated based upon annual certification data submitted to EPA by vehicle manufacturers. Emission factors for earlier standards and technologies were developed by ICF (2004) based on EPA, CARB, and Environment and Climate Change Canada laboratory test results of different vehicle and control technology types. The EPA, CARB and Environment and Climate Change Canada tests were designed following the Federal Test Procedure (FTP). The procedure covers three separate driving segments since vehicles emit varying amounts of GHGs depending on the driving segment. These driving segments are: (1) a transient driving cycle that includes cold start and running emissions, (2) a cycle that represents running emissions only, and (3) a transient driving cycle that includes hot start and running emissions. For each test run, a bag was affixed to the tailpipe of the vehicle and the exhaust was collected; the content of this bag was later analyzed to determine quantities of gases present. The emission characteristics of driving Segment 2 was used to define running emissions. Running emissions were subtracted from the total FTP emissions to determine start emissions. These were recombined based upon MOBILE 6.2’s ratio of start to running emissions for each vehicle class to approximate average driving characteristics.

Step 4: Determine the Amount of CH₄ and N₂O Emitted by Vehicle, Fuel, and Control Technology Type

Emissions of CH₄ and N₂O were calculated by multiplying total VMT by vehicle, fuel, and control technology type by the emission factors developed in Step 3.

Methodology for Alternative Fuel Vehicles (AFVs)

Step 1: Determine Vehicle Miles Traveled by Vehicle and Fuel Type

VMT for alternative fuel and advanced technology vehicles were calculated from “Updated Methodology for Estimating CH₄ and N₂O Emissions from Highway Vehicle Alternative Fuel Vehicles” (Browning 2017) and modified with “Updated Methodology for Estimating CH₄ and N₂O Emissions from Highway Vehicle Alternative Fuel Vehicles” (Browning 2022b). Alternative fuels include compressed natural gas (CNG), liquid natural gas (LNG), liquefied petroleum gas (LPG), ethanol, methanol, biodiesel, hydrogen, and electricity. Most of the vehicles that use these fuels run on an internal combustion engine (ICE) powered by the alternative fuel, although many of the vehicles can

⁵² For further description, see the “Definitions of Emission Control Technologies and Standards” section below.

run on either the alternative fuel or gasoline (or diesel), or some combination.⁵³ Except for electric vehicles and plug-in hybrid vehicles, the alternative fuel vehicle VMT were calculated using the Energy Information Administration (EIA) Alternative Fuel Vehicle Data (2023a). The EIA data provides vehicle counts and fuel use for fleet vehicles used by electricity providers, federal agencies, natural gas providers, propane providers, state agencies and transit agencies, for calendar years 2003 through 2017. For 1992 to 2002, EIA data tables were used to estimate fuel consumption and vehicle counts by vehicle type. These tables include total vehicle fuel use and vehicle counts by fuel and calendar year for the United States over the period 1992 through 2010. Breakdowns by vehicle type for 1992 through 2002 (both fuel consumed and vehicle counts) were assumed to be at the same ratio as for 2003 where data existed. For 1990 and 1991, fuel consumed by alternative fuel and vehicle type were extrapolated based on a regression analysis using the best curve fit based upon R^2 using the nearest five years of data. Fuel consumption for vehicles from 2018 onward was determined using the same ratio of annual AFV VMT to annual conventional vehicle VMT, as was calculated for 2017 using EIA data and GREET 2023 Energy Efficiency Ratios.

For 2018 to 2023, counts of electric, plug-in electric and fuel cell vehicles were determined from confidential sales data while electric and fuel cell heavy-duty bus counts were determined from Smart Cities Dive (2022). A regression analysis of vehicle counts was used for other fuels for the 2018 to 2023 period. Annual VMT for those vehicles are assumed to be less than the annual VMT of conventional fueled vehicles of the same class.

Counts of electric vehicles (EVs) and plug-in hybrid-electric vehicles (PHEVs) were taken from data compiled by Hybridcars.com from 2010 to 2018 (Hybridcars.com 2019). For 2019 through 2023, EV and PHEV sales were taken from Wards Intelligence U.S. Light Vehicle Sales Report (Wards Intelligence 2023). EVs were divided into cars and trucks using vehicle type information from fueleconomy.gov publications (EPA 2010-2023). Fuel use per vehicle for personal EVs and PHEVs were calculated from fuel economies listed in the fueleconomy.gov publications multiplied by the average light duty car and truck mileage accumulation rates determined from MOVES5. PHEV VMT was divided into gasoline and electric VMT using the Society of Automotive Engineers Utility Factor Standard J2841 (SAE 2010).

Because AFVs run on different fuel types, their fuel use characteristics are not directly comparable. Accordingly, fuel economy for each vehicle type is expressed in gasoline equivalent terms, i.e., how much gasoline contains the equivalent amount of energy as the alternative fuel. Energy economy ratios (the ratio of the gasoline equivalent fuel economy of a given technology to that of conventional gasoline or diesel vehicles) were taken from the Argonne National Laboratory's GREET2022 model (ANL 2022). These ratios were used to estimate fuel economy in miles per gasoline gallon equivalent for each alternative fuel and vehicle type. Energy use per fuel type was then divided among the various weight categories and vehicle technologies that use that fuel. Total VMT per vehicle type for each calendar year was then determined by dividing the energy usage by the fuel economy. For AFVs capable of running on both/either traditional or alternative fuels, the VMT given reflects only those miles driven that were powered by the alternative fuel, as explained in Browning (2017). VMT estimates for AFVs by vehicle category (passenger car, light-duty truck, medium-duty and heavy-duty vehicles) are shown in Table A-73, while more detailed estimates of VMT by control technology are shown Table A-74.

Step 2: Determine CH₄ and N₂O Emission Factors by Vehicle and Alternative Fuel Type

Methane and N₂O emission factors for alternative fuel vehicles (AFVs) were calculated using Argonne National Laboratory's GREET model (ANL 2023). These emission factors are shown in Table A-85 and Table A-86.

⁵³ Fuel types used in combination depend on the vehicle class. For light-duty vehicles, gasoline is generally blended with ethanol and diesel is blended with biodiesel; dual-fuel vehicles can run on gasoline or an alternative fuel – either natural gas or LPG – but not at the same time, while flex-fuel vehicles are designed to run on E85 (85 percent ethanol) or gasoline, or any mixture of the two in between. Heavy-duty vehicles are more likely to run on diesel fuel, natural gas, or LPG.

Step 3: Determine the Amount of CH₄ and N₂O Emitted by Vehicle and Fuel Type

Emissions of CH₄ and N₂O were calculated by multiplying total VMT for each vehicle and fuel type (Step 1) by the appropriate emission factors (Step 2).

Methodology for Non-Road Mobile Sources

Methane and N₂O emissions from non-road mobile sources were estimated by applying emission factors to the amount of fuel consumed by mode and vehicle type.

Activity data for non-road vehicles include annual fuel consumption statistics by transportation mode and fuel type, as shown in Table A-79. Consumption data for ships and boats (i.e., vessel bunkering) were obtained from DHS (2008) and EIA (1991 through 2022) for distillate fuel, and DHS (2008) and EIA (2024b) for residual fuel; marine transport fuel consumption data for U.S. Territories (EIA 2017) were added to domestic consumption, and this total was reduced by the amount of fuel used for international bunkers.⁵⁴ Fuel consumption data and emissions for ships and non-recreational boats are not further disaggregated by vessel type or vocation. Gasoline consumption by recreational boats was obtained from the nonroad component of EPA's MOVES5 model (EPA 2024). Annual diesel consumption for Class I rail was obtained from the Association of American Railroads (AAR 2008 through 2024), diesel consumption from commuter rail was obtained from APTA (2007 through 2024) and Gaffney (2007), and consumption by Class II and III rail was provided by Benson (2002 through 2004) and Whorton (2006 through 2014).⁵⁵ It is estimated that an average of 41 gallons of diesel consumption per Class II and III carload originated from 2000-2009 based on carload data reported from AAR (2008 through 2023) and fuel consumption data provided by Whorton, D. (2006 through 2014). Class II and Class III diesel consumption for 2014-2022 is estimated by multiplying this average historical fuel usage per carload factor by the number of shortline carloads originated each year (RailInc 2014 through 2024). Diesel consumption by commuter and intercity rail was obtained from DOE (1993 through 2022). Data for 2021-2023 was obtained from the National Transit Database "Fuel and Energy" table (FTA 2023). Diesel consumption for Intercity Rail for 2019 through 2023 was obtained from the Bureau of Transportation Statistics "Amtrak Fuel Consumption and Travel Data" table. Data on the consumption of jet fuel and aviation gasoline in aircraft were obtained from EIA (2024a) and FAA (2023), as described in Annex 2.1: Methodology for Estimating Emissions of CO₂ from Fossil Fuel Combustion and were reduced by the amount allocated to international bunker fuels (DLA 2023 and FAA 2023). Pipeline fuel consumption was obtained from EIA (2024c) (note: pipelines are a transportation source but are stationary, not mobile sources). Data on fuel consumption by non-transportation mobile sources were obtained from the Nonroad component of EPA's MOVES5 model (EPA 2024) for gasoline and diesel powered equipment, and from FHWA (1996 through 2024) for gasoline consumption by off-road trucks used in the agriculture, industrial, commercial, and construction sectors.⁵⁶ Specifically, this *Inventory* uses FHWA's Agriculture, Construction, and Commercial/Industrial MF-24 fuel volumes along with the MOVES-Nonroad model gasoline volumes to estimate non-road mobile source CH₄ and N₂O emissions for these categories. For agriculture, the MF-24 gasoline volume is used directly because it includes both off-road trucks and equipment. For construction and commercial/industrial gasoline estimates, the 2014 and older MF-24 volumes represented off-road trucks only; therefore, the MOVES-Nonroad gasoline volumes for construction and commercial/industrial are added to the respective categories in the *Inventory*. Beginning in 2015, this addition is no longer necessary since the FHWA updated its method for estimating on-road and non-road

⁵⁴ See International Bunker Fuels section of the Energy chapter.

⁵⁵ Diesel consumption from Class II and Class III railroad were unavailable for 2014-2023. Diesel consumption data for 2014-2023 is estimated by applying the historical average fuel usage per carload factor to the annual number of carloads.

⁵⁶ "Non-transportation mobile sources" are defined as any vehicle or equipment not used on the traditional road system, but excluding aircraft, rail and watercraft. This category includes snowmobiles, golf carts, riding lawn mowers, agricultural equipment, and trucks used for off-road purposes, among others. This category is similar to the IPCC's "Off-road" category (1 A 3 e ii) described in Chapter 3: Mobile Combustion *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, in Table 3.1.1.

gasoline consumption. Among the method updates, FHWA now incorporates MOVES-Nonroad equipment gasoline volumes in the construction and commercial/industrial categories.

Since the nonroad component of EPA's MOVES5 model does not account for the COVID-19 pandemic and associated restrictions, fuel consumption for non-transportation mobile sources for 2021 were developed by adjusting 2019 and 2020 consumption. Sector specific adjustments were applied to the 2019 consumption for agricultural equipment (-1.6 percent) and airport equipment (-38 percent) to estimate 2020 volumes. An adjustment factor for agricultural equipment was derived using employment data from the Bureau of Labor and Statistics (BLS 2022). An adjustment factor for airport equipment was derived based on the decline in commercial aviation fuel consumption. For all other nonroad equipment sectors, a 7.7 percent reduction factor was applied to 2019 values to estimate 2020. This is based on the reduction in transportation diesel consumption from 2019 to 2020 (EIA 2023b). In a similar fashion, trends in all these variables between 2020 and 2021 were used to estimate 2021 values.

Emissions of CH₄ and N₂O from non-road mobile sources were calculated using the updated 2006 IPCC Tier 3 guidance and estimates of activity from EPA's MOVES5 model. CH₄ and N₂O emission factors were calculated from engine certification data by engine and fuel type and weighted by activity estimates calculated by MOVES5 to determine overall emission factors in grams per kg of fuel consumed by fuel type (Browning 2020).

Estimates of NO_x, CO, and NMVOC Emissions

The emission estimates of NO_x, CO, and NMVOCs from mobile combustion (transportation) were obtained from EPA's National Emission *Inventory* (NEI) Air Pollutant Emission Trends web site (EPA 2024c). This EPA report provides emission estimates for these gases by fuel type using a procedure whereby emissions were calculated using basic activity data, such as amount of fuel delivered or miles traveled, as indicators of emissions. Emissions for heavy-duty diesel trucks and heavy-duty diesel buses were calculated by distributing the total heavy-duty diesel vehicle emissions in the ratio of VMT for each individual category.

Table A-72: Vehicle Miles Traveled for Gasoline On-Road Vehicles (billion miles)

Year	Passenger Cars ^b	Light-Duty Trucks ^b	Heavy-Duty Vehicles ^{a,b}	Motorcycles ^b
1990	1,474.4	409.3	46.6	11.4
1991	1,457.4	448.3	46.2	11.5
1992	1,470.4	498.7	46.9	11.8
1993	1,464.4	545.2	46.9	12.0
1994	1,464.3	596.4	47.1	12.3
1995	1,464.5	650.4	47.4	12.5
1996	1,461.3	706.0	47.5	12.8
1997	1,463.4	767.3	47.9	13.1
1998	1,459.5	829.1	48.0	13.4
1999	1,447.8	889.6	48.0	13.6
2000	1,455.7	939.5	44.8	12.2
2001	1,459.9	977.1	43.4	11.1
2002	1,472.0	1,020.4	42.9	11.2
2003	1,465.5	1,051.3	43.0	11.4
2004	1,470.9	1,116.8	40.6	15.0
2005	1,459.6	1,153.6	37.9	13.8
2006	1,432.8	1,182.6	40.3	19.2
2007	1,427.5	1,200.3	37.3	21.4
2008	1,401.4	1,168.9	38.2	20.8
2009	1,396.4	1,178.3	35.7	20.8
2010	1,390.6	1,200.4	32.5	18.5

2011	1,320.7	1,271.2	29.7	18.6
2012	1,194.8	1,406.9	30.0	21.4
2013	1,217.3	1,399.2	29.8	20.4
2014	1,217.3	1,431.3	30.4	20.0
2015	1,225.6	1,489.4	30.7	19.7
2016	1,233.8	1,549.3	31.9	20.5
2017	1,211.1	1,598.8	33.6	20.2
2018	1,183.5	1,644.0	35.0	20.2
2019	1,168.5	1,684.4	36.4	19.8
2020	991.1	1,518.8	34.2	18.1
2021	1,023.7	1,679.3	39.2	19.9
2022	997.5	1,743.7	41.2	24.0
2023	985.4	1,808.2	41.7	24.8

^a Heavy-Duty Vehicles includes Medium-Duty Trucks, Heavy-Duty Trucks, and Buses.

^b VMT is allocated to vehicle classes using MOVES5 ratios.

Notes: In 2015, EIA changed its methods for estimating AFV fuel consumption. These methodological changes included how vehicle counts are estimated, moving from estimates based on modeling to one that is based on survey data. EIA now publishes data about fuel use and number of vehicles for only four types of AFV fleets: federal government, state government, transit agencies, and fuel providers. These changes were first incorporated in the 1990 through 2014 *Inventory* and apply to the 1990 through 2023 time period. This resulted in large reductions in AFV VMT, thus leading to a shift in VMT to conventional on-road vehicle classes. Gasoline and diesel highway vehicle mileage are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2024). VMT estimates are allocated to vehicle type using EPA's MOVES5 model ratios of VMT per vehicle class to total VMT. VMT for 2023 is proxied based on FHWA's Traffic Volume Trends data.

Source: Derived from FHWA (1996 through 2024), DOE (1990 through 2022), Browning (2022a), Browning (2018a), and Browning (2017).

Table A-73: Vehicle Miles Traveled for Diesel On-Road Vehicles (billion miles)

Year	Passenger Cars ^b	Light-Duty Trucks ^b	Heavy-Duty Trucks ^{a,b}	Heavy-Duty Buses ^b
1990	40.7	18.7	136.7	6.0
1991	39.0	20.3	142.5	6.5
1992	37.9	22.4	151.6	7.1
1993	36.3	24.3	159.0	7.6
1994	34.8	26.4	167.6	8.3
1995	33.2	28.6	176.7	8.9
1996	31.4	30.9	185.8	9.5
1997	29.7	33.4	196.2	10.3
1998	27.7	35.9	206.3	11.0
1999	25.5	38.4	215.9	11.7
2000	23.2	39.8	219.0	11.9
2001	21.6	41.9	230.7	10.6
2002	19.5	43.4	233.9	11.1
2003	17.6	44.6	244.4	11.2
2004	16.1	47.9	244.6	11.4
2005	14.6	49.5	247.5	11.2
2006	13.2	51.7	259.9	12.0
2007	11.7	51.4	266.0	12.5
2008	10.5	48.5	271.8	12.8

2009	9.9	47.5	251.8	12.4
2010	9.5	45.9	253.6	11.9
2011	8.7	47.8	233.9	11.9
2012	7.7	52.2	235.3	12.7
2013	8.2	49.2	238.4	12.9
2014	8.7	49.2	241.8	13.5
2015	9.1	51.3	241.6	13.6
2016	8.5	52.9	244.8	13.5
2017	7.9	53.5	253.5	14.0
2018	7.4	53.7	259.6	14.6
2019	7.0	53.0	254.2	14.1
2020	5.7	45.2	254.1	11.2
2021	5.9	49.1	280.7	12.5
2022	5.7	50.3	283.2	13.7
2023	5.2	49.8	282.1	13.5

^a Heavy-Duty Trucks includes Medium-Duty Trucks and Heavy-Duty Trucks.

^b VMT is allocated to vehicle classes using MOVES5 ratios.

Notes: Gasoline and diesel highway vehicle mileage are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2024). VMT estimates were then allocated using EPA's MOVES5 model ratios of VMT per vehicle class to total VMT. VMT for 2023 is proxied based on FHWA's Traffic Volume Trends data.

Sources: Derived from FHWA (1996 through 2024), DOE (1993 through 2022), and Browning (2017), Browning (2018a), Browning (2022a).

Table A-74: Vehicle Miles Traveled for Alternative Fuel On-Road Vehicles (billion miles)

Year	Passenger Cars	Light-Duty Trucks	Heavy-Duty Trucks ^a	Buses
1990	0.0	0.1	0.4	0.0
1991	0.0	0.1	0.4	0.0
1992	0.0	0.1	0.4	0.0
1993	0.0	0.1	0.4	0.0
1994	0.0	0.1	0.4	0.0
1995	0.0	0.1	0.4	0.1
1996	0.0	0.1	0.4	0.1
1997	0.0	0.1	0.4	0.1
1998	0.0	0.1	0.5	0.1
1999	0.0	0.1	0.5	0.2
2000	0.1	0.2	0.6	0.2
2001	0.1	0.2	0.6	0.2
2002	0.2	0.3	0.7	0.2
2003	0.1	0.6	0.7	0.3
2004	0.1	0.7	0.7	0.3
2005	0.1	0.6	1.1	0.3
2006	0.2	0.6	2.0	0.4
2007	0.2	0.5	2.5	0.4
2008	0.2	1.3	2.2	0.4
2009	0.2	1.5	2.3	0.4
2010	0.2	2.1	2.0	0.4
2011	0.5	1.9	5.5	0.6
2012	0.8	2.1	5.5	0.6
2013	1.5	2.9	8.5	0.8
2014	2.1	2.7	8.5	0.9
2015	2.9	2.5	9.1	0.9
2016	3.8	2.7	12.7	1.2
2017	4.6	2.8	12.3	1.2
2018	6.8	3.1	12.4	1.6
2019	9.0	3.4	11.9	1.6
2020	9.0	4.1	12.1	1.4
2021	11.3	6.8	11.7	1.4
2022	14.7	10.6	11.5	1.6
2023	19.3	19.5	14.0	1.9

^a Heavy-Duty Trucks includes medium-duty trucks and heavy-duty trucks.

Sources: Derived from Browning (2017), Browning (2018a), Browning (2022b), and EIA (2023c).

Notes: In 2017, estimates of alternative fuel vehicle mileage for the last ten years were revised to reflect updates made to EIA data on alternative fuel use and vehicle counts. These changes were incorporated into this year's *Inventory* and apply to the 2005 to 2023 time period.

Table A-75: Detailed Vehicle Miles Traveled for Alternative Fuel On-Road Vehicles (Million Miles)

Vehicle Type/Year	1990	2000	2010	2015	2016	2017	2018	2019	2020	2021	2022	2023
Light-Duty Cars	3.4	82.6	246.4	2,874.0	3,757.2	4,646.1	6,817.1	9,037.2	9,003.1	11,302.8	14,705.1	19,283.1
Methanol-Flex Fuel ICE	+	+	+	+	+	+	+	+	+	+	+	+
Ethanol-Flex Fuel ICE	+	17.0	104.4	102.4	115.1	79.9	79.0	74.2	61.6	61.2	58.1	54.9
CNG ICE	+	4.5	9.2	10.0	11.6	10.7	10.9	10.5	9.0	9.3	9.1	9.0
CNG Bi-fuel	+	14.6	6.8	1.6	1.3	1.4	0.9	0.6	0.2	+	+	+
LPG ICE	1.0	1.0	+	0.1	0.2	0.2	0.2	0.1	+	+	+	+
LPG Bi-fuel	2.4	2.4	1.0	0.1	0.1	+	+	+	+	+	+	+
Biodiesel (BD100)	+	1.6	59.0	339.3	432.1	372.6	329.4	315.7	246.3	232.2	208.2	257.6
NEVs	+	40.8	63.4	155.1	111.4	128.7	135.4	144.2	148.7	153.1	157.6	170.7
Electric Vehicle	+	0.7	0.7	1,354.7	1,827.9	2,373.9	4,020.1	5,925.2	6,119.7	8,077.3	11,339.4	15,661.0
SI PHEV - Electricity	+	+	1.9	910.1	1,251.7	1,655.5	2,205.6	2,515.5	2,369.2	2,698.9	2,845.2	3,023.2
Fuel Cell Hydrogen	+	+	+	0.7	6.0	23.1	35.6	51.2	48.4	70.9	87.4	106.6
Light-Duty Trucks	66.4	152.8	2,067.5	2,461.7	2,708.3	2,835.5	3,086.5	3,405.3	4,125.6	6,835.1	10,567.1	19,503.8
Ethanol-Flex Fuel ICE	+	17.9	111.1	195.1	247.9	369.0	400.7	420.2	379.3	432.9	484.1	540.0
CNG ICE	+	4.3	7.3	4.0	3.5	4.8	3.4	2.9	2.0	1.7	1.2	0.7
CNG Bi-fuel	+	36.2	17.4	18.2	23.4	21.4	21.5	21.4	18.2	19.7	20.9	22.2
LPG ICE	19.2	21.1	8.5	4.9	4.9	5.0	5.3	5.4	4.8	5.3	5.8	6.3
LPG Bi-fuel	47.2	51.9	21.7	8.1	6.1	7.3	8.2	8.2	7.0	7.6	8.1	8.7
LNG	+	0.1	+	+	+	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Biodiesel (BD100)	+	17.2	1,899.2	2,201.2	2,196.0	1,962.3	1,859.1	1,868.3	2,100.6	2,399.1	2,562.1	3,472.3
Electric Vehicle	+	4.0	2.3	21.9	183.2	360.4	581.4	776.8	1,220.6	2,952.9	5,610.2	12,096.9
SI PHEV - Electricity	+	+	+	7.5	42.1	96.0	197.6	290.9	381.4	1,000.1	1,855.4	3,335.4
Fuel Cell Hydrogen	+	+	+	0.7	1.3	9.2	9.3	11.1	11.6	15.7	19.0	21.1
Medium-Duty Trucks	176.0	175.1	473.2	2,623.3	3,743.1	3,596.8	3,498.4	3,412.5	3,514.1	3,423.9	3,328.0	4,112.5
CNG ICE	+	0.7	5.5	11.2	13.3	14.0	14.1	15.8	16.2	17.7	18.5	18.8
CNG Bi-fuel	+	6.9	6.2	11.1	12.1	13.3	13.8	15.4	15.7	17.1	17.7	18.1
LPG ICE	142.6	128.9	27.9	18.2	15.8	14.3	11.3	9.6	7.1	5.1	2.9	0.8
LPG Bi-fuel	33.5	31.5	13.1	19.8	24.9	24.4	25.9	28.6	29.2	31.6	32.7	33.2

LNG	+	+	+	0.2	0.2	0.4	0.3	0.4	0.4	0.5	0.5	0.6
Biodiesel (BD100)	+	7.2	420.5	2,562.8	3,676.7	3,530.6	3,433.0	3,342.7	3,445.4	3,351.9	3,255.6	4,041.1
Heavy-Duty Trucks	201.1	201.0	1,115.2	5,510.3	7,751.0	7,532.8	7,247.8	6,892.3	7,233.5	6,886.5	6,573.1	7,992.0
Neat Methanol ICE	100.6	110.3	1,030.0	5,450.2	7,681.4	7,461.2	7,179.2	6,830.1	7,175.1	6,829.4	6,520.0	7,941.7
Neat Ethanol ICE	+	+	+	+	+	+	+	+	+	+	+	+
CNG ICE	+	+	+	1.1	4.0	9.6	8.0	6.3	3.6	1.7	1.0	0.5
LPG ICE	+	0.8	13.1	19.9	28.9	29.3	32.3	33.2	35.8	39.7	40.8	42.6
LPG Bi-fuel	94.5	84.3	58.5	30.2	28.2	24.6	20.5	15.9	12.5	9.3	5.5	2.0
LNG	6.1	5.4	10.1	5.3	5.3	5.2	5.1	4.6	4.5	4.4	4.1	3.9
Biodiesel (BD100)	+	+	3.6	3.6	3.1	2.9	2.7	2.3	2.1	1.9	1.6	1.3
Buses	31.5	209.2	379.7	923.5	1,187.9	1,175.1	1,640.5	1,620.2	1,385.4	1,432.4	1,610.9	1,862.5
Neat Methanol ICE	15.7	104.6	189.8	461.9	594.1	587.8	820.6	810.6	693.2	717.3	807.4	934.1
Neat Ethanol ICE	3.6	+	+	+	+	+	+	+	+	+	+	+
CNG ICE	+	+	+	2.8	2.6	1.9	199.8	201.4	173.1	196.5	219.1	221.0
LPG ICE	+	79.7	130.6	160.1	173.8	185.3	4.6	4.8	4.2	4.8	5.5	5.5
LNG	12.1	10.8	6.7	2.8	4.8	3.6	2.2	1.4	0.6	+	+	+
Biodiesel (BD100)	+	11.5	6.6	4.1	3.8	2.8	195.2	187.6	158.9	153.7	161.1	193.6
Electric	+	1.2	43.5	289.4	402.5	386.2	381.2	366.5	310.4	300.2	314.6	378.1
Fuel Cell Hydrogen	+	1.3	2.4	2.3	6.2	7.6	36.9	48.0	45.0	59.9	103.3	130.1
Total VMT	478.5	820.7	4,281.9	14,392.7	19,147.5	19,786.3	22,290.3	24,367.5	25,261.8	29,880.6	36,784.1	52,753.9

+ Does not exceed 0.05 million vehicle miles traveled.

Sources: Derived from Browning (2017), Browning (2018a), Browning (2022b), and EIA (2024a).

Notes: Throughout the rest of this *Inventory*, medium-duty trucks are grouped with heavy-duty trucks; they are reported separately here because these two categories may run on a slightly different range of fuel types. In 2017, estimates of alternative fuel vehicle mileage for the last ten years were revised to reflect updates made to EIA data on alternative fuel use and vehicle counts. These changes were incorporated into this year's *Inventory* and apply to the 2005 to 2023 time period. Totals may not sum due to independent rounding.

Table A-76: Age Distribution by Vehicle/Fuel Type for On-Road Vehicles^a 2023

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC	Hddb
0	3.8%	6.3%	6.3%	0.0%	4.9%	5.5%	5.9%	4.5%
1	2.7%	5.6%	8.4%	0.0%	5.1%	6.9%	5.7%	3.2%
2	3.0%	6.1%	6.1%	0.0%	5.3%	4.7%	6.3%	4.1%
3	3.6%	5.7%	6.1%	0.0%	3.7%	6.4%	4.4%	4.8%
4	4.5%	6.7%	6.0%	0.1%	5.5%	6.1%	4.2%	5.7%
5	4.9%	6.2%	3.9%	0.8%	5.8%	4.5%	4.0%	5.6%
6	5.8%	6.1%	5.4%	1.0%	5.7%	4.5%	3.9%	5.6%
7	5.9%	5.4%	5.0%	1.0%	6.1%	5.3%	4.0%	5.7%
8	6.4%	5.2%	4.7%	12.6%	6.3%	4.8%	3.7%	5.3%
9	6.1%	4.4%	2.9%	15.6%	3.8%	3.3%	3.6%	4.7%
10	6.3%	3.9%	2.9%	16.3%	2.7%	3.1%	3.2%	3.9%
11	5.5%	3.3%	3.4%	13.3%	3.2%	3.6%	3.0%	3.9%
12	4.1%	3.3%	2.7%	9.3%	2.9%	2.5%	2.1%	4.0%
13	4.1%	2.6%	1.3%	8.3%	1.3%	1.4%	1.7%	4.2%
14	3.5%	1.9%	1.7%	5.2%	1.2%	1.9%	3.6%	3.5%
15	4.2%	3.1%	2.9%	0.5%	3.6%	3.0%	4.3%	3.3%
16	4.3%	3.2%	2.3%	0.4%	3.3%	4.5%	5.5%	3.1%
17	3.6%	2.9%	3.0%	4.7%	4.8%	4.1%	5.3%	3.0%
18	3.2%	2.8%	2.4%	3.0%	3.8%	3.5%	4.8%	2.2%
19	2.6%	2.8%	2.1%	1.7%	4.1%	2.4%	3.7%	2.3%
20	2.4%	2.3%	1.8%	1.9%	3.3%	2.2%	3.9%	2.1%
21	1.9%	2.0%	1.8%	1.7%	2.6%	1.9%	2.9%	2.2%
22	1.6%	1.7%	2.1%	1.0%	2.6%	2.4%	2.4%	2.1%
23	1.4%	1.5%	2.1%	0.8%	1.7%	2.8%	1.9%	2.0%
24	1.0%	1.2%	3.5%	0.4%	1.8%	2.1%	1.4%	2.0%
25	0.8%	0.9%	1.7%	0.3%	0.5%	1.3%	1.1%	1.7%
26	0.7%	0.9%	1.9%	0.1%	1.5%	1.3%	0.9%	1.4%
27	0.5%	0.6%	1.4%	0.1%	0.9%	1.2%	0.8%	1.2%
28	0.5%	0.6%	1.9%	0.1%	0.9%	1.3%	0.6%	1.1%
29	0.4%	0.5%	1.1%	0.0%	0.6%	1.0%	0.5%	0.9%
30	0.3%	0.4%	1.0%	0.0%	0.6%	0.8%	0.5%	0.8%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

^aThe following abbreviations correspond to vehicle types: LDGV (light-duty gasoline vehicles), LDGT (light-duty gasoline trucks), HDGV (heavy-duty gasoline vehicles), LDDV (light-duty diesel vehicles), LDDT (light-duty diesel trucks), HDDV (heavy-duty diesel vehicles), MC (motorcycles) and Hddb (heavy-duty diesel buses).

Note: This year's *Inventory* includes updated vehicle population data based on the MOVES5 Model. Totals may not sum due to independent rounding.

Source: EPA (2024).

Table A-77: Annual Average Vehicle Mileage Accumulation per Vehicles^a (miles) 2023

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC ^b	Hddb
0	14,772	15,489	20,214	-	15,489	48,058	10,667	24,835
1	14,268	15,005	21,328	-	15,005	41,681	5,696	20,403
2	13,790	14,453	20,475	-	14,454	41,910	4,309	21,398
3	13,339	14,007	20,595	-	14,007	46,215	3,563	21,189
4	12,912	13,588	19,763	12,912	13,588	43,137	3,083	21,657
5	12,507	13,181	17,357	12,507	13,181	39,625	2,741	19,892
6	12,124	12,786	17,878	12,124	12,786	37,453	2,485	18,863

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC ^b	Hddb
7	11,761	12,406	16,229	11,761	12,406	41,175	2,283	20,080
8	11,416	12,037	15,041	11,416	12,037	36,594	2,112	18,985
9	11,089	11,676	13,551	11,089	11,676	34,644	1,973	18,545
10	10,776	11,329	12,600	10,776	11,329	32,404	1,856	17,782
11	10,478	10,986	11,881	10,478	10,986	26,364	1,749	16,471
12	10,192	10,657	10,608	10,192	10,657	20,730	1,664	15,338
13	9,918	10,333	9,412	9,918	10,333	23,075	1,579	15,843
14	9,653	10,014	8,148	9,653	10,014	20,853	1,504	16,521
15	9,397	9,703	6,838	9,397	9,703	11,897	1,440	15,867
16	9,148	9,399	5,561	9,148	9,399	15,459	1,387	15,526
17	8,904	9,101	5,377	8,904	9,101	11,728	1,333	15,719
18	8,663	8,810	4,907	8,664	8,810	11,172	1,280	13,445
19	8,425	8,527	4,651	8,425	8,527	9,425	1,237	12,761
20	8,188	8,250	4,448	8,188	8,250	8,948	1,195	14,504
21	7,951	7,978	4,149	7,951	7,978	7,294	1,163	13,296
22	7,712	7,713	3,769	7,712	7,713	7,652	1,131	12,653
23	7,469	7,453	3,463	7,469	7,453	8,422	1,067	13,093
24	7,223	7,195	3,050	7,223	7,195	7,845	1,003	13,338
25	6,968	6,941	2,942	6,968	6,941	7,370	939	13,171
26	6,707	6,697	2,600	6,707	6,697	5,454	864	12,119
27	6,437	6,458	2,474	6,437	6,458	5,334	800	12,165
28	6,156	6,222	2,114	6,156	6,222	4,085	757	11,757
29	5,863	5,991	2,094	5,863	5,991	3,428	704	12,688
30	2,616	4,611	1,034	1,526	4,395	1,041	266	10,732

^aThe following abbreviations correspond to vehicle types: LDGV (light-duty gasoline vehicles), LDGT (light-duty gasoline trucks), HDGV (heavy-duty gasoline vehicles), LDDV (light-duty diesel vehicles), LDDT (light-duty diesel trucks), HDDV (heavy-duty diesel vehicles), MC (motorcycles) and Hddb (heavy-duty diesel buses).

^bBecause of a lack of data, all motorcycles over 12 years old are considered to have the same emissions and travel characteristics, and therefore are presented in aggregate.

Source: EPA (2024).

Table A-78: VMT Distribution by Vehicle Age and Vehicle/Fuel Type,^a 2023

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC	Hddb
0	5.29%	8.39%	9.78%	0.00%	6.80%	9.40%	23.60%	19.39%
1	3.64%	7.17%	13.86%	0.00%	6.80%	10.17%	12.01%	7.39%
2	3.88%	7.48%	9.64%	0.00%	6.81%	7.00%	10.18%	7.09%
3	4.51%	6.85%	9.74%	0.00%	4.56%	10.52%	5.89%	6.88%
4	5.43%	7.76%	9.20%	0.09%	6.63%	9.30%	4.79%	7.03%
5	5.69%	7.02%	5.17%	1.00%	6.83%	6.31%	4.10%	6.10%
6	6.53%	6.62%	7.50%	1.20%	6.50%	6.01%	3.62%	5.52%
7	6.51%	5.74%	6.28%	1.12%	6.73%	7.71%	3.37%	5.17%
8	6.84%	5.34%	5.45%	13.93%	6.72%	6.28%	2.94%	4.47%
9	6.30%	4.40%	3.05%	16.72%	3.91%	4.09%	2.63%	3.74%
10	6.35%	3.73%	2.77%	17.02%	2.76%	3.52%	2.23%	2.92%
11	5.41%	3.10%	3.14%	13.48%	3.16%	3.40%	1.97%	2.70%
12	3.93%	3.01%	2.24%	9.14%	2.76%	1.83%	1.33%	2.67%
13	3.79%	2.29%	0.94%	7.93%	1.17%	1.11%	1.01%	2.65%
14	3.17%	1.63%	1.04%	4.87%	1.09%	1.38%	2.02%	2.11%
15	3.66%	2.59%	1.55%	0.49%	3.08%	1.26%	2.32%	1.87%
16	3.64%	2.54%	0.96%	0.33%	2.72%	2.46%	2.82%	1.69%
17	2.99%	2.27%	1.24%	4.08%	3.90%	1.69%	2.64%	1.58%

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC	Hddb
18	2.57%	2.12%	0.92%	2.48%	2.94%	1.39%	2.27%	1.11%
19	2.04%	2.01%	0.75%	1.35%	3.13%	0.80%	1.72%	1.15%
20	1.80%	1.63%	0.63%	1.47%	2.40%	0.69%	1.72%	0.99%
21	1.41%	1.37%	0.58%	1.28%	1.83%	0.48%	1.28%	1.00%
22	1.11%	1.12%	0.61%	0.73%	1.76%	0.65%	1.00%	0.95%
23	0.98%	0.95%	0.56%	0.59%	1.10%	0.82%	0.76%	0.85%
24	0.70%	0.77%	0.83%	0.26%	1.18%	0.59%	0.54%	0.79%
25	0.54%	0.56%	0.39%	0.23%	0.28%	0.35%	0.37%	0.64%
26	0.42%	0.51%	0.39%	0.07%	0.87%	0.25%	0.28%	0.48%
27	0.30%	0.33%	0.26%	0.07%	0.54%	0.22%	0.23%	0.39%
28	0.28%	0.32%	0.30%	0.05%	0.48%	0.19%	0.18%	0.34%
29	0.20%	0.26%	0.17%	0.01%	0.34%	0.12%	0.14%	0.24%
30	0.08%	0.14%	0.08%	0.01%	0.22%	0.03%	0.05%	0.09%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

^aThe following abbreviations correspond to vehicle types: LDGV (light-duty gasoline vehicles), LDGT (light-duty gasoline trucks), HDGV (heavy-duty gasoline vehicles), LDDV (light-duty diesel vehicles), LDDT (light-duty diesel trucks), HDDV (heavy-duty diesel vehicles), MC (motorcycles) and Hddb (heavy-duty diesel buses).

Notes: Estimated by weighting data in Table A-77. This year's *Inventory* includes updated vehicle population data based on the MOVES5 model that affects this distribution. Totals may not sum due to independent rounding.

Table A-79: Fuel Consumption for Non-Road Sources by Fuel Type (million gallons unless otherwise noted)

Vehicle Type/Year	1990	2000	2010	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Aircraft^a	19,542	20,294	15,754	14,907	15,268	15,390	16,331	17,191	17,783	17,854	18,683	12,540	15,835	17,092	18,529
Aviation Gasoline	374	302	225	209	186	181	176	170	174	186	195	168	179	186	176
Jet Fuel	19,168	19,992	15,529	14,698	15,082	15,210	16,155	17,021	17,609	17,667	18,489	12,372	15,656	16,906	18,353
Commercial Aviation ^b	11,569	14,672	11,931	11,932	12,031	12,131	12,534	12,674	13,475	13,650	14,397	9,613	12,527	13,654	13,654
Ships and Boats	4,826	6,544	4,693	4,239	4,175	3,191	3,652	4,235	4,469	4,190	4,053	3,312	4,945	4,871	4,336
Diesel	1,156	1,882	1,361	1,389	1,414	1,284	1,881	1,680	1,593	1,525	1,342	1,342	1,377	1,401	1,421
Gasoline	1,611	1,636	1,446	1,372	1,349	1,323	1,325	1,335	1,344	1,352	1,355	1,251	1,345	1,366	1,370
Residual	2,060	3,027	1,886	1,477	1,413	584	445	1,219	1,532	1,313	1,356	719	2,222	2,104	1,545
Construction/Mining Equipment^c															
Diesel	4,317	5,181	5,727	5,533	5,447	5,313	5,200	5,483	5,978	6,262	6,464	5,966	6,414	6,782	6,829
Gasoline	472	357	678	651	1,100	710	367	375	375	385	387	389	363	290	290
CNG (million cubic feet)	5,082	6,032	6,219	5,957	5,802	5,598	5,430	5,629	6,018	6,204	6,321	5,834	6,272	6,477	6,499
LPG	22	27	26	24	24	23	22	23	25	26	27	25	27	28	28
Agricultural Equipment^d															
Diesel	3,514	3,278	3,942	3,932	3,900	3,925	3,862	3,760	3,728	3,732	3,742	3,682	3,741	3,689	3,689
Gasoline	813	652	692	875	655	644	159	168	168	160	129	135	147	148	148
CNG (million cubic feet)	1,758	1,678	1,647	1,611	1,588	1,590	1,561	1,517	1,503	1,502	1,507	1,483	1,506	1,485	1,487
LPG	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rail	3,461	4,106	3,807	3,921	4,025	4,201	4,020	3,715	3,832	3,936	3,696	3,225	3,354	3,394	3,325
Diesel	3,461	4,106	3,807	3,921	4,025	4,201	4,020	3,715	3,832	3,936	3,696	3,225	3,354	3,394	3,325
Other^e															
Diesel	2,095	2,047	2,450	2,639	2,725	2,811	2,832	2,851	2,919	3,027	3,110	2,849	3,071	3,348	3,442
Gasoline	4,371	4,673	5,525	5,189	5,201	5,281	5,083	5,137	5,178	5,238	5,287	5,041	5,268	5,515	5,539
CNG (million cubic feet)	20,894	25,035	29,891	35,085	37,436	39,705	38,069	37,709	38,674	40,390	41,474	38,280	41,151	44,451	45,699
LPG	1,412	2,191	2,165	2,181	2,213	2,248	2,279	2,316	2,408	2,526	2,616	2,415	2,596	2,891	3,003
Total (gallons)	44,845	49,351	45,459	44,092	44,734	43,737	43,808	45,254	46,864	47,335	48,195	39,579	45,762	48,047	49,158
Total (million cubic feet)	27,735	32,745	37,757	42,653	44,826	46,893	45,060	44,854	46,194	48,097	49,301	45,597	48,929	52,413	53,684

Table A-80: Emissions Control Technology Assignments for Gasoline Passenger Cars (Percent of VMT)

Model Years	Non-catalyst	Oxidation	EPA Tier 0	EPA Tier 1	CARB LEV	CARB LEV 2	EPA Tier 2	CARB LEV 3	EPA Tier 3
1973-1975	100%	-	-	-	-	-	-	-	-
1976	20%	80%	-	-	-	-	-	-	-
1977-1978	15%	85%	-	-	-	-	-	-	-
1979-1980	10%	90%	-	-	-	-	-	-	-
1981	-	15%	85%	-	-	-	-	-	-
1982	-	14%	86%	-	-	-	-	-	-
1983	-	12%	88%	-	-	-	-	-	-
1984-1993	-	-	100%	-	-	-	-	-	-
1994	-	-	80%	20%	-	-	-	-	-
1995	-	-	60%	40%	-	-	-	-	-
1996	-	-	40%	54%	6%	-	-	-	-
1997	-	-	20%	68%	12%	-	-	-	-
1998	-	-	<1%	82%	18%	-	-	-	-
1999	-	-	<1%	67%	33%	-	-	-	-
2000	-	-	-	44%	56%	-	-	-	-
2001	-	-	-	3%	97%	-	-	-	-
2002	-	-	-	1%	99%	-	-	-	-
2003	-	-	-	<1%	85%	2%	12%	-	-
2004	-	-	-	<1%	24%	16%	60%	-	-
2005	-	-	-	-	13%	27%	60%	-	-
2006	-	-	-	-	18%	35%	47%	-	-
2007	-	-	-	-	4%	43%	53%	-	-
2008	-	-	-	-	2%	42%	56%	-	-
2009	-	-	-	-	<1%	43%	57%	-	-
2010	-	-	-	-	-	44%	56%	-	-
2011	-	-	-	-	-	42%	58%	-	-
2012	-	-	-	-	-	41%	59%	-	-
2013	-	-	-	-	-	40%	60%	-	-
2014	-	-	-	-	-	37%	62%	1%	-
2015	-	-	-	-	-	33%	56%	11%	<1%
2016	-	-	-	-	-	25%	50%	18%	6%
2017	-	-	-	-	-	14%	0%	29%	56%
2018	-	-	-	-	-	7%	0%	42%	52%
2019	-	-	-	-	-	3%	0%	44%	53%
2020	-	-	-	-	-	0%	0%	50%	50%
2021	-	-	-	-	-	2%	0%	48%	50%
2022	-	-	-	-	-	1%	0%	49%	50%
2023	-	-	-	-	-	1%		49%	50%

- (Not Applicable)

Note: Detailed descriptions of emissions control technologies are provided in the following section of this Annex. In 2016, historical confidential vehicle sales data was re-evaluated to determine the engine technology assignments. First, several light-duty trucks were re-characterized as heavy-duty vehicles based upon gross vehicle weight rating (GVWR) and confidential sales data. Second, which emission standards each vehicle type was assumed to have met were re-examined using confidential sales data. Also, in previous *Inventories*, non-plug-in hybrid electric vehicles (HEVs) were considered alternative fueled vehicles and therefore were not included in the engine technology breakouts. For this *Inventory*, HEVs are now classified as gasoline vehicles across the entire time series.

Sources: EPA (1998), EPA (2024a), and EPA (2024b).

Table A-81: Emissions Control Technology Assignments for Gasoline Light-Duty Trucks (Percent of VMT)^a

Model Years	Non-catalyst	Oxidation	EPA Tier 0	EPA Tier 1	CARB LEV ^b	CARB LEV 2	EPA Tier 2	CARB LEV 3	EPA Tier 3
1973-1975	100%	-	-	-	-	-	-	-	-
1976	30%	70%	-	-	-	-	-	-	-
1977	20%	80%	-	-	-	-	-	-	-
1978-1979	25%	75%	-	-	-	-	-	-	-
1980	20%	80%	-	-	-	-	-	-	-
1981	-	95%	5%	-	-	-	-	-	-
1982	-	90%	10%	-	-	-	-	-	-
1983	-	80%	20%	-	-	-	-	-	-
1984	-	70%	30%	-	-	-	-	-	-
1985	-	60%	40%	-	-	-	-	-	-
1986	-	50%	50%	-	-	-	-	-	-
1987-1993	-	5%	95%	-	-	-	-	-	-
1994	-	-	60%	40%	-	-	-	-	-
1995	-	-	20%	80%	-	-	-	-	-
1996	-	-	-	100%	-	-	-	-	-
1997	-	-	-	100%	-	-	-	-	-
1998	-	-	-	87%	13%	-	-	-	-
1999	-	-	-	61%	39%	-	-	-	-
2000	-	-	-	63%	37%	-	-	-	-
2001	-	-	-	24%	76%	-	-	-	-
2002	-	-	-	31%	69%	-	-	-	-
2003	-	-	-	25%	69%	-	6%	-	-
2004	-	-	-	1%	26%	8%	65%	-	-
2005	-	-	-	-	17%	17%	66%	-	-
2006	-	-	-	-	24%	22%	54%	-	-
2007	-	-	-	-	14%	25%	61%	-	-
2008	-	-	-	-	<1%	34%	66%	-	-
2009	-	-	-	-	-	34%	66%	-	-
2010	-	-	-	-	-	30%	70%	-	-
2011	-	-	-	-	-	27%	73%	-	-
2012	-	-	-	-	-	24%	76%	-	-
2013	-	-	-	-	-	31%	69%	-	-
2014	-	-	-	-	-	26%	73%	1%	-
2015	-	-	-	-	-	22%	72%	6%	-
2016	-	-	-	-	-	20%	62%	16%	2%
2017	-	-	-	-	-	9%	14%	28%	48%
2018	-	-	-	-	-	7%	-	38%	55%
2019	-	-	-	-	-	3%	-	44%	53%
2020	-	-	-	-	-	-	-	50%	50%
2021	-	-	-	-	-	-	-	50%	50%
2022	-	-	-	-	-	-	-	50%	50%
2023	-	-	-	-	-	0%	-	49%	50%

- (Not Applicable)

^a Detailed descriptions of emissions control technologies are provided in the following section of this Annex.

^b The proportion of LEVs as a whole has decreased since 2001, as carmakers have been able to achieve greater emission reductions with certain types of LEVs, such as ULEVs. Because ULEVs emit about half the emissions of LEVs, a carmaker can reduce the total number of LEVs they need to build to meet a specified emission average for all of their vehicles in a given model year.

Notes: In 2016, historical confidential vehicle sales data was re-evaluated to determine the engine technology assignments. First several light-duty trucks were re-characterized as heavy-duty vehicles based upon gross vehicle weight rating (GVWR) and confidential sales data. Second, which emission standards each vehicle type was assumed to have met were re-examined using confidential sales data. Also, in previous *Inventories*, non-plug-in hybrid electric vehicles (HEVs) were considered alternative fueled vehicles and therefore were not included in the engine technology breakouts. For this *Inventory*, HEVs are now classified as gasoline vehicles across the entire time series.

Sources: EPA (1998), EPA (2023a), and EPA (2024b).

Table A-82: Emissions Control Technology Assignments for Gasoline Heavy-Duty Vehicles (Percent of VMT)^a

Model Years	Uncontrolled	Non-catalyst	Oxidation	EPA Tier 0	EPA Tier 1	CARB LEV ^b	CARB LEV 2	EPA Tier 2	CARB LEV 3	EPA Tier 3
≤1980	100%	-	-	-	-	-	-	-	-	-
1981-1984	95%	-	5%	-	-	-	-	-	-	-
1985-1986	-	95%	5%	-	-	-	-	-	-	-
1987	-	70%	15%	15%	-	-	-	-	-	-
1988-1989	-	60%	25%	15%	-	-	-	-	-	-
1990-1995	-	45%	30%	25%	-	-	-	-	-	-
1996	-	-	25%	10%	65%	-	-	-	-	-
1997	-	-	10%	5%	85%	-	-	-	-	-
1998	-	-	-	-	100%	-	-	-	-	-
1999	-	-	-	-	98%	2%	-	-	-	-
2000	-	-	-	-	93%	7%	-	-	-	-
2001	-	-	-	-	78%	22%	-	-	-	-
2002	-	-	-	-	94%	6%	-	-	-	-
2003	-	-	-	-	85%	14%	-	1%	-	-
2004	-	-	-	-	-	33%	-	67%	-	-
2005	-	-	-	-	-	15%	-	85%	-	-
2006	-	-	-	-	-	50%	-	50%	-	-
2007	-	-	-	-	-	-	27%	73%	-	-
2008	-	-	-	-	-	-	46%	54%	-	-
2009	-	-	-	-	-	-	45%	55%	-	-
2010	-	-	-	-	-	-	24%	76%	-	-
2011	-	-	-	-	-	-	7%	93%	-	-
2012	-	-	-	-	-	-	17%	83%	-	-
2013	-	-	-	-	-	-	17%	83%	-	-
2014	-	-	-	-	-	-	19%	81%	-	-
2015	-	-	-	-	-	-	31%	64%	5%	-
2016	-	-	-	-	-	-	24%	10%	21%	44%
2017	-	-	-	-	-	-	8%	8%	39%	45%
2018	-	-	-	-	-	-	13%	-	35%	52%
2019	-	-	-	-	-	-	10%	-	40%	50%
2020	-	-	-	-	-	-	-	-	50%	50%
2021	-	-	-	-	-	-	-	-	50%	50%
2022	-	-	-	-	-	-	-	-	50%	50%
2023	-	-	-	-	-	-	-	-	45%	55%

- (Not Applicable)

^a Detailed descriptions of emissions control technologies are provided in the following section of this Annex.

^b The proportion of LEVs as a whole has decreased since 2000, as carmakers have been able to achieve greater emission reductions with certain types of LEVs, such as ULEVs. Because ULEVs emit about half the emissions of LEVs, a manufacturer can reduce the total number of LEVs they need to build to meet a specified emission average for all of their vehicles in a given model year.

Notes: In 2016, historical confidential vehicle sales data was re-evaluated to determine the engine technology assignments. First several light-duty trucks were re-characterized as heavy-duty vehicles based upon gross vehicle weight rating (GVWR) and confidential sales data. Second, which emission standards each vehicle type was assumed to have met were re-examined using confidential sales data. Also, in previous *Inventories*, non-plug-in hybrid electric vehicles (HEVs) were considered alternative fueled vehicles and therefore were not included in the engine technology breakouts. For this *Inventory*, HEVs are now classified as gasoline vehicles across the entire time series.

Sources: EPA (1998), EPA (2023a), and EPA (2024b).

Table A-83: Emissions Control Technology Assignments for Diesel On-Road Vehicles and Motorcycles

Vehicle Type/Control Technology	Model Years
Diesel Passenger Cars and Light-Duty Trucks	
Uncontrolled	1960–1982
Moderate Control	1983–1995
Advanced Control	1996–2006
Aftertreatment	2007–2023
Diesel Medium- and Heavy-Duty Trucks and Buses	
Uncontrolled	1960–1989
Moderate Control	1990–2003
Advanced Control	2004–2006
Aftertreatment	2007–2023
Motorcycles	
Uncontrolled	1960–1995
Non-Catalyst Controls	1996–2005
Advanced	2006–2023

Note: Detailed descriptions of emissions control technologies are provided in the following section of this Annex.

Source: EPA (1998) and Browning (2005).

Table A-84: Emission Factors for CH₄ and N₂O for On-Road Vehicles

Vehicle Type/Control Technology	N ₂ O (g/mi)	CH ₄ (g/mi)
Gasoline Passenger Cars		
EPA Tier 3	0.0015	0.0055
ARB LEV III	0.0012	0.0045
EPA Tier 2	0.0048	0.0072
ARB LEV II	0.0043	0.0070
ARB LEV	0.0205	0.0100
EPA Tier 1 ^a	0.0429	0.0271
EPA Tier 0 ^a	0.0647	0.0704
Oxidation Catalyst	0.0504	0.1355
Non-Catalyst Control	0.0197	0.1696
Uncontrolled	0.0197	0.1780
Gasoline Light-Duty Trucks		
EPA Tier 3	0.0012	0.0092
ARB LEV III	0.0012	0.0065
EPA Tier 2	0.0025	0.0100
ARB LEV II	0.0057	0.0084
ARB LEV	0.0223	0.0148
EPA Tier 1 ^a	0.0871	0.0452
EPA Tier 0 ^a	0.1056	0.0776

Oxidation Catalyst	0.0639	0.1516
Non-Catalyst Control	0.0218	0.1908
Uncontrolled	0.0220	0.2024
Gasoline Heavy-Duty Vehicles		
EPA Tier 3	0.0063	0.0252
ARB LEV III	0.0136	0.0411
EPA Tier 2	0.0015	0.0297
ARB LEV II	0.0049	0.0391
ARB LEV	0.0466	0.0300
EPA Tier 1 ^a	0.1750	0.0655
EPA Tier 0 ^a	0.2135	0.2630
Oxidation Catalyst	0.1317	0.2356
Non-Catalyst Control	0.0473	0.4181
Uncontrolled	0.0497	0.4604
Diesel Passenger Cars		
Aftertreatment	0.0192	0.0302
Advanced	0.0010	0.0005
Moderate	0.0010	0.0005
Uncontrolled	0.0012	0.0006
Diesel Light-Duty Trucks		
Aftertreatment	0.0214	0.0290
Advanced	0.0014	0.0009
Moderate	0.0014	0.0009
Uncontrolled	0.0017	0.0011
Diesel Medium- and Heavy-Duty Trucks and Buses		
Aftertreatment	0.0431	0.0095
Advanced	0.0048	0.0051
Moderate	0.0048	0.0051
Uncontrolled	0.0048	0.0051
Motorcycles		
Advanced	0.0179	0.0661
Non-Catalyst Control	0.0069	0.0672
Uncontrolled	0.0087	0.0899

^aThe categories “EPA Tier 0” and “EPA Tier 1” were substituted for the early three-way catalyst and advanced three-way catalyst categories, respectively, as defined in the 2006 IPCC Guidelines. Detailed descriptions of emissions control technologies are provided at the end of this Annex.

Source: ICF (2006 and 2017), Browning (2022a).

Table A-85: Emission Factors for N₂O for Alternative Fuel Vehicles (g/mi)

	1990	2000	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Light-Duty Cars														
Methanol-Flex Fuel ICE	0.040	0.027	0.006	0.006	0.006	0.006	0.005	0.005	0.005	0.004	0.004	0.004	0.004	0.004
Ethanol-Flex Fuel ICE	0.040	0.027	0.006	0.006	0.006	0.006	0.005	0.005	0.005	0.004	0.004	0.004	0.004	0.004
CNG ICE	0.024	0.022	0.006	0.006	0.006	0.006	0.005	0.005	0.005	0.004	0.004	0.004	0.004	0.004
CNG Bi-fuel	0.024	0.022	0.006	0.006	0.006	0.006	0.005	0.005	0.005	0.004	0.004	0.004	0.004	0.004
LPG ICE	0.024	0.022	0.006	0.006	0.006	0.006	0.005	0.005	0.005	0.004	0.004	0.004	0.004	0.004
LPG Bi-fuel	0.024	0.022	0.006	0.006	0.006	0.006	0.005	0.005	0.005	0.004	0.004	0.004	0.004	0.004
Biodiesel (BD100)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Light-Duty Trucks														
Ethanol-Flex Fuel ICE	0.077	0.056	0.007	0.007	0.007	0.007	0.007	0.006	0.006	0.005	0.005	0.005	0.005	0.005
CNG ICE	0.046	0.045	0.007	0.007	0.007	0.007	0.007	0.006	0.006	0.005	0.005	0.005	0.005	0.005
CNG Bi-fuel	0.046	0.045	0.007	0.007	0.007	0.007	0.007	0.006	0.006	0.005	0.005	0.005	0.005	0.005
LPG ICE	0.046	0.045	0.007	0.007	0.007	0.007	0.007	0.006	0.006	0.005	0.005	0.005	0.005	0.005
LPG Bi-fuel	0.046	0.045	0.007	0.007	0.007	0.007	0.007	0.006	0.006	0.005	0.005	0.005	0.005	0.005
LNG	0.046	0.045	0.007	0.007	0.007	0.007	0.007	0.006	0.006	0.005	0.005	0.005	0.005	0.005
Biodiesel (BD100)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Medium-Duty Trucks														
CNG ICE	0.127	0.127	0.106	0.108	0.109	0.110	0.088	0.067	0.045	0.023	0.001	0.001	0.001	0.001
CNG Bi-fuel	0.127	0.127	0.106	0.108	0.109	0.110	0.088	0.067	0.045	0.023	0.001	0.001	0.001	0.001
LPG ICE	0.127	0.127	0.106	0.108	0.109	0.110	0.092	0.073	0.055	0.037	0.018	0.018	0.018	0.018
LPG Bi-fuel	0.127	0.127	0.106	0.108	0.109	0.110	0.092	0.073	0.055	0.037	0.018	0.018	0.018	0.018
LNG	0.127	0.127	0.106	0.108	0.109	0.110	0.088	0.067	0.045	0.023	0.001	0.001	0.001	0.001
Biodiesel (BD100)	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Heavy-Duty Trucks														
Neat Methanol ICE	0.128	0.128	0.121	0.124	0.127	0.130	0.110	0.089	0.069	0.048	0.028	0.027	0.026	0.026
Neat Ethanol ICE	0.128	0.128	0.121	0.124	0.127	0.130	0.110	0.089	0.069	0.048	0.028	0.027	0.026	0.026
CNG ICE	0.077	0.077	0.109	0.108	0.108	0.108	0.086	0.065	0.043	0.022	0.000	0.000	0.000	0.000
LPG ICE	0.077	0.077	0.109	0.108	0.108	0.108	0.090	0.073	0.055	0.038	0.020	0.017	0.014	0.012
LPG Bi-fuel	0.077	0.077	0.109	0.108	0.108	0.108	0.087	0.067	0.047	0.027	0.007	0.006	0.006	0.006
LNG	0.077	0.077	0.109	0.108	0.108	0.108	0.086	0.065	0.043	0.022	0.000	0.000	0.000	0.000
Biodiesel (BD100)	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Buses														
Neat Methanol ICE	0.198	0.198	0.141	0.139	0.137	0.136	0.114	0.093	0.072	0.051	0.029	0.029	0.029	0.028

	1990	2000	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Neat Ethanol ICE	0.198	0.198	0.141	0.139	0.137	0.136	0.114	0.093	0.072	0.051	0.029	0.029	0.029	0.028
CNG ICE	0.119	0.119	0.084	0.083	0.082	0.081	0.065	0.049	0.033	0.017	0.001	0.001	0.001	0.001
LPG ICE	0.119	0.119	0.084	0.083	0.082	0.081	0.070	0.059	0.048	0.036	0.025	0.022	0.018	0.015
LNG	0.119	0.119	0.084	0.083	0.082	0.081	0.065	0.049	0.033	0.017	0.001	0.001	0.001	0.001
Biodiesel (BD100)	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003

Note: When driven in all-electric mode, plug-in electric vehicles have zero tailpipe emissions. Therefore, emissions factors for battery electric vehicles (BEVs) and the electric portion of plug-in hybrid electric vehicles (PHEVs) are not included in this table.

Source: Developed by ICF (Browning 2022b) using ANL (2022).

Table A-86: Emission Factors for CH₄ for Alternative Fuel Vehicles (g/mi)

	1990	2000	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Light-Duty Cars														
Methanol-Flex Fuel ICE	0.126	0.083	0.020	0.018	0.017	0.016	0.016	0.015	0.015	0.015	0.015	0.013	0.012	0.011
Ethanol-Flex Fuel ICE	0.126	0.083	0.020	0.018	0.017	0.016	0.016	0.015	0.015	0.015	0.015	0.013	0.012	0.011
CNG ICE	1.793	1.103	0.198	0.185	0.171	0.158	0.156	0.153	0.151	0.149	0.146	0.133	0.120	0.106
CNG Bi-fuel	1.793	1.103	0.198	0.185	0.171	0.158	0.156	0.153	0.151	0.149	0.146	0.133	0.120	0.106
LPG ICE	0.179	0.110	0.020	0.018	0.017	0.016	0.016	0.015	0.015	0.015	0.015	0.013	0.012	0.011
LPG Bi-fuel	0.179	0.110	0.020	0.018	0.017	0.016	0.016	0.015	0.015	0.015	0.015	0.013	0.012	0.011
Biodiesel (BD100)	-	-	0.012	0.018	0.024	0.030	0.019	0.030	0.030	0.030	0.030	0.030	0.030	0.030
Light-Duty Trucks														
Ethanol-Flex Fuel ICE	0.184	0.118	0.021	0.019	0.018	0.016	0.016	0.016	0.016	0.016	0.016	0.014	0.013	0.012
CNG ICE	2.632	1.580	0.211	0.195	0.179	0.164	0.162	0.161	0.160	0.159	0.158	0.144	0.130	0.116
CNG Bi-fuel	2.632	1.580	0.211	0.195	0.179	0.164	0.162	0.161	0.160	0.159	0.158	0.144	0.130	0.116
LPG ICE	0.263	0.158	0.021	0.019	0.018	0.016	0.016	0.016	0.016	0.016	0.016	0.014	0.013	0.012
LPG Bi-fuel	0.263	0.158	0.021	0.019	0.018	0.016	0.016	0.016	0.016	0.016	0.016	0.014	0.013	0.012
LNG	2.632	1.580	0.211	0.195	0.179	0.164	0.162	0.161	0.160	0.159	0.158	0.144	0.130	0.116
Biodiesel (BD100)	-	-	0.012	0.017	0.023	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029
Medium-Duty Trucks														
CNG ICE	6.800	6.800	5.697	5.762	5.827	5.893	5.052	4.212	3.372	2.532	1.691	1.675	1.658	1.641
CNG Bi-fuel	6.800	6.800	5.697	5.762	5.827	5.893	5.052	4.212	3.372	2.532	1.691	1.675	1.658	1.641
LPG ICE	0.680	0.680	0.570	0.576	0.583	0.589	0.473	0.357	0.241	0.125	0.009	0.009	0.009	0.009

	1990	2000	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
LPG Bi-fuel	0.680	0.680	0.570	0.576	0.583	0.589	0.473	0.357	0.241	0.125	0.009	0.009	0.009	0.009
LNG	6.800	6.800	5.697	5.762	5.827	5.893	5.052	4.212	3.372	2.532	1.691	1.675	1.658	1.641
Biodiesel (BD100)	0.287	0.009-	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009
Heavy-Duty Trucks														
Neat Methanol ICE	0.287	0.287	0.271	0.278	0.285	0.292	0.249	0.205	0.162	0.118	0.075	0.073	0.072	0.070
Neat Ethanol ICE	0.287	0.287	0.271	0.278	0.285	0.292	0.249	0.205	0.162	0.118	0.075	0.073	0.072	0.070
CNG ICE	4.100	4.100	5.827	5.805	5.783	5.761	4.785	3.808	2.832	1.855	0.879	0.879	0.879	0.879
LPG ICE	0.410	0.410	0.583	0.581	0.578	0.576	0.462	0.347	0.232	0.119	0.003	0.003	0.003	0.002
LPG Bi-fuel	0.410	0.410	0.583	0.581	0.578	0.576	0.462	0.347	0.232	0.119	0.003	0.003	0.003	0.002
LNG	4.100	4.100	5.827	5.805	5.783	5.761	4.785	3.808	2.832	1.855	0.879	0.879	0.879	0.879
Biodiesel (BD100)	-	-	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009
Buses														
Neat Methanol ICE	1.316	1.316	0.937	0.926	0.915	0.904	0.762	0.620	0.478	0.337	0.195	0.193	0.190	0.188
Neat Ethanol ICE	1.316	1.316	0.937	0.926	0.915	0.904	0.762	0.620	0.478	0.337	0.195	0.193	0.190	0.188
CNG ICE	18.800	18.800	13.389	13.229	13.068	12.908	10.801	8.694	6.588	4.481	2.734	2.348	2.321	2.295
LPG ICE	1.880	1.880	1.339	1.323	1.307	1.291	1.034	0.778	0.522	0.265	0.009	0.008	0.006	0.005
LNG	18.800	18.800	13.389	13.229	13.068	12.908	10.801	8.694	6.588	4.481	2.374	2.348	2.321	2.295
Biodiesel (BD100)	-	-	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009

Note: When driven in all-electric mode, plug-in electric vehicles have zero tailpipe emissions. Therefore, emissions factors for battery electric vehicles (BEVs) and the electric portion of plug-in hybrid electric vehicles (PHEVs) are not included in this table.

Source: Developed by ICF (Browning 2022b) using ANL (2022).

Table A-87: Emission Factors for N₂O Emissions from Non-Road Mobile Combustion (g/kg fuel)

	1990	2000	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Ships and Boats														
Residual Fuel Oil	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088
Gasoline														
2 Stroke	0.021	0.021	0.025	0.026	0.026	0.026	0.027	0.027	0.027	0.027	0.027	0.028	0.028	0.028
4 Stroke	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.003	0.003	0.003	0.003	0.003
Distillate Fuel Oil	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054
Rail														
Diesel	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080
Aircraft														
Jet Fuel	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100
Aviation Gasoline	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040

	1990	2000	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Agricultural Equipment^a														
Gasoline-Equipment														
2 Stroke	0.103	0.118	0.170	0.170	0.170	0.170	0.170	0.170	0.170	0.170	0.170	0.170	0.170	0.169
4 Stroke	0.355	0.365	0.415	0.417	0.420	0.422	0.423	0.425	0.427	0.429	0.431	0.433	0.433	0.431
Gasoline-Off-road Trucks	0.355	0.365	0.415	0.417	0.420	0.422	0.423	0.425	0.427	0.429	0.431	0.433	0.430	0.430
Diesel-Equipment	0.336	0.336	0.336	0.336	0.336	0.336	0.336	0.336	0.336	0.336	0.336	0.336	0.336	0.335
Diesel-Off-Road Trucks	0.174	0.174	0.174	0.174	0.174	0.174	0.174	0.174	0.174	0.174	0.174	0.174	0.174	0.175
CNG	0.061	0.061	0.075	0.075	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076
LPG	0.389	0.389	0.444	0.446	0.449	0.451	0.452	0.454	0.456	0.458	0.460	0.462	0.462	0.460
Construction/Mining Equipment^b														
Gasoline-Equipment														
2 Stroke	0.028	0.030	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042
4 Stroke	0.408	0.450	0.521	0.523	0.524	0.525	0.526	0.527	0.527	0.528	0.528	0.528	0.528	0.530
Gasoline-Off-road Trucks	0.41	0.45	0.52	0.52	0.52	0.52	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53
Diesel-Equipment	0.295	0.295	0.295	0.295	0.295	0.295	0.295	0.295	0.295	0.295	0.295	0.295	0.295	0.296
Diesel-Off-Road Trucks	0.174	0.174	0.174	0.174	0.174	0.174	0.174	0.174	0.174	0.174	0.174	0.174	0.174	0.175
CNG	0.367	0.367	0.398	0.402	0.405	0.409	0.416	0.424	0.431	0.437	0.442	0.445	0.445	0.446
LPG	0.197	0.197	0.229	0.231	0.233	0.235	0.237	0.239	0.240	0.242	0.243	0.243	0.243	0.244
Lawn and Garden Equipment														
Gasoline-Residential														
2 Stroke	0.107	0.120	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.174
4 Stroke	0.519	0.578	0.690	0.692	0.693	0.694	0.695	0.695	0.695	0.696	0.696	0.696	0.696	0.701
Gasoline-Commercial														
2 Stroke	0.071	0.079	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.111
4 Stroke	0.409	0.476	0.532	0.533	0.534	0.534	0.534	0.535	0.535	0.535	0.535	0.535	0.535	0.539
Diesel-Residential	0.167	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.154
Diesel-Commercial	0.167	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.154
LPG	0.245	0.245	0.300	0.302	0.303	0.304	0.305	0.306	0.306	0.306	0.306	0.306	0.306	0.308
Airport Equipment														
Gasoline														
4 Stroke	0.299	0.316	0.378	0.380	0.381	0.382	0.382	0.383	0.383	0.383	0.383	0.383	0.383	0.400
Diesel	0.364	0.364	0.364	0.364	0.364	0.364	0.364	0.364	0.364	0.364	0.364	0.364	0.364	0.380
LPG	0.346	0.346	0.424	0.427	0.429	0.430	0.431	0.431	0.432	0.432	0.432	0.432	0.432	0.451
Industrial/Commercial Equipment														
Gasoline														

	1990	2000	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
2 Stroke	0.107	0.123	0.177	0.178	0.178	0.178	0.178	0.178	0.178	0.178	0.178	0.178	0.178	0.182
4 Stroke	0.425	0.473	0.548	0.550	0.551	0.552	0.553	0.553	0.552	0.551	0.551	0.550	0.550	0.563
Diesel	0.183	0.180	0.190	0.191	0.192	0.190	0.190	0.189	0.189	0.189	0.189	0.189	0.189	0.195
CNG	0.034	0.031	0.043	0.044	0.044	0.044	0.043	0.043	0.043	0.043	0.043	0.042	0.042	0.043
LPG	0.250	0.250	0.303	0.305	0.307	0.308	0.309	0.310	0.311	0.311	0.311	0.312	0.312	0.324
Logging Equipment														
Gasoline														
2 Stroke	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4 Stroke	0.579	0.604	0.688	0.699	0.709	0.719	0.725	0.730	0.733	0.735	0.736	0.737	0.737	0.733
Diesel	0.398	0.398	0.398	0.398	0.398	0.398	0.398	0.398	0.398	0.398	0.398	0.398	0.398	0.395
Railroad Equipment														
Gasoline														
4 Stroke	0.498	0.555	0.646	0.647	0.648	0.649	0.649	0.650	0.650	0.650	0.650	0.650	0.650	0.665
Diesel	0.297	0.297	0.297	0.297	0.297	0.297	0.297	0.297	0.297	0.297	0.297	0.297	0.297	0.304
LPG	0.005	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004
Recreational Equipment														
Gasoline														
2 Stroke	0.034	0.034	0.036	0.036	0.037	0.037	0.037	0.038	0.038	0.039	0.039	0.039	0.039	0.039
4 Stroke	0.487	0.503	0.535	0.536	0.536	0.536	0.536	0.536	0.536	0.537	0.537	0.531	0.531	0.535
Diesel	0.207	0.207	0.207	0.207	0.207	0.207	0.207	0.207	0.207	0.207	0.207	0.207	0.207	0.208
LPG	0.255	0.255	0.275	0.277	0.279	0.281	0.284	0.286	0.288	0.290	0.293	0.295	0.295	0.297

- Not applicable

^a Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

^b Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

Source: IPCC (2006) and Browning, L (2018b), EPA (2024).

Table A-88: Emission Factors for CH₄ Emissions from Non-Road Mobile Combustion (g/kg fuel)

	1990	2000	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Ships and Boats													
Residual Fuel Oil	0.309	0.309	0.309	0.309	0.309	0.309	0.309	0.309	0.309	0.309	0.309	0.309	0.309
Gasoline													
2 Stroke	1.255	1.270	1.536	1.557	1.578	1.597	1.615	1.629	1.642	1.652	1.661	1.672	1.672
4 Stroke	0.717	0.725	0.773	0.777	0.783	0.788	0.793	0.797	0.801	0.805	0.808	0.813	0.813
Distillate Fuel Oil	2.008	2.008	2.008	2.008	2.008	2.008	2.008	2.008	2.008	2.008	2.008	2.039	2.039
Rail													

	1990	2000	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Diesel	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250
Aircraft													
Jet Fuel ^a	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Aviation Gasoline	2.640	2.640	2.640	2.640	2.640	2.640	2.640	2.640	2.640	2.640	2.640	2.640	2.640
Agricultural Equipment^b													
Gasoline-Equipment													
2 Stroke	1.500	1.720	2.480	2.480	2.480	2.480	2.480	2.480	2.480	2.480	2.480	2.471	2.471
4 Stroke	0.570	0.586	0.670	0.674	0.677	0.679	0.682	0.686	0.689	0.692	0.695	0.692	0.692
Gasoline-Off-road Trucks	0.570	0.586	0.670	0.674	0.677	0.679	0.682	0.686	0.689	0.692	0.695	0.692	0.692
Diesel-Equipment	0.397	0.397	0.397	0.397	0.397	0.397	0.397	0.397	0.397	0.397	0.397	0.396	0.396
Diesel-Off-Road Trucks	0.286	0.286	0.286	0.286	0.286	0.286	0.286	0.286	0.286	0.286	0.286	0.287	0.287
CNG	1.391	1.391	1.719	1.726	1.731	1.734	1.736	1.736	1.736	1.736	1.736	1.730	1.730
LPG	0.135	0.135	0.155	0.156	0.157	0.157	0.158	0.158	0.159	0.160	0.160	0.160	0.160
Construction/Mining Equipment^c													
Gasoline-Equipment													
2 Stroke	1.868	1.997	2.858	2.858	2.858	2.858	2.858	2.858	2.858	2.858	2.858	2.866	2.866
4 Stroke	0.789	0.871	1.011	1.013	1.015	1.017	1.019	1.020	1.021	1.022	1.022	1.025	1.025
Gasoline-Off-road Trucks	0.789	0.871	1.011	1.013	1.015	1.017	1.019	1.020	1.021	1.022	1.022	1.025	1.025
Diesel-Equipment	0.317	0.317	0.316	0.316	0.316	0.316	0.317	0.317	0.317	0.317	0.317	0.318	0.318
Diesel-Off-Road Trucks	0.286	0.286	0.286	0.286	0.286	0.286	0.286	0.286	0.286	0.286	0.286	0.287	0.287
CNG	1.322	1.322	1.447	1.459	1.473	1.499	1.529	1.554	1.574	1.595	1.605	1.609	1.609
LPG	0.233	0.233	0.273	0.276	0.278	0.280	0.283	0.285	0.286	0.287	0.288	0.289	0.289
Lawn and Garden Equipment													
Gasoline-Residential													
2 Stroke	1.489	1.666	2.381	2.381	2.382	2.382	2.382	2.382	2.383	2.383	2.384	2.403	2.403
4 Stroke	0.803	0.894	1.070	1.072	1.073	1.074	1.075	1.075	1.075	1.076	1.076	1.084	1.084
Gasoline-Commercial													
2 Stroke	1.685	1.859	2.609	2.609	2.609	2.609	2.610	2.610	2.610	2.611	2.611	2.631	2.631
4 Stroke	0.821	0.956	1.071	1.072	1.072	1.073	1.073	1.073	1.073	1.073	1.074	1.082	1.082
Diesel-Residential	0.236	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.209	0.209
Diesel-Commercial	0.236	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.209	0.209
LPG	0.137	0.137	0.169	0.170	0.171	0.171	0.171	0.171	0.171	0.171	0.171	0.179	0.179
Airport Equipment													
Gasoline													
4 Stroke	0.287	0.303	0.364	0.365	0.366	0.366	0.366	0.367	0.367	0.367	0.367	0.383	0.383
Diesel	0.593	0.593	0.593	0.593	0.593	0.593	0.593	0.593	0.593	0.593	0.593	0.619	0.619

	1990	2000	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
LPG	0.137	0.137	0.169	0.170	0.171	0.171	0.171	0.171	0.171	0.171	0.171	0.179	0.179
Industrial/Commercial Equipment													
Gasoline													
2 Stroke	1.541	1.774	2.550	2.551	2.552	2.553	2.553	2.554	2.554	2.554	2.555	2.617	2.617
4 Stroke	0.758	0.837	0.984	0.987	0.987	0.987	0.987	0.986	0.985	0.984	0.983	1.006	1.006
Diesel	0.120	0.106	0.140	0.143	0.141	0.139	0.135	0.134	0.133	0.133	0.132	0.135	0.135
CNG	2.334	2.420	2.837	2.832	2.854	2.867	2.877	2.885	2.892	2.897	2.904	2.986	2.986
LPG	0.174	0.174	0.212	0.213	0.214	0.215	0.215	0.216	0.216	0.216	0.216	0.225	0.225
Logging Equipment													
Gasoline													
2 Stroke	2.289	2.423	3.468	3.468	3.468	3.468	3.468	3.468	3.468	3.468	3.468	3.446	3.446
4 Stroke	0.914	0.950	1.114	1.127	1.137	1.143	1.149	1.153	1.157	1.159	1.161	1.153	1.153
Diesel	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.152	0.152
Railroad Equipment													
Gasoline													
4 Stroke	0.897	0.990	1.155	1.157	1.158	1.158	1.159	1.160	1.160	1.160	1.160	1.190	1.19
Diesel	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.130	0.13
LPG	0.784	0.787	0.919	0.927	0.936	0.943	0.956	0.962	0.966	0.970	0.973	1.000	1.00
Recreational Equipment													
Gasoline													
2 Stroke	5.170	5.252	5.781	5.862	5.944	6.024	6.100	6.176	6.244	6.310	3.510	3.534	3.534
4 Stroke	0.935	0.965	1.029	1.030	1.030	1.030	1.031	1.031	1.031	1.032	0.975	0.982	0.982
Diesel	0.228	0.228	0.228	0.228	0.228	0.228	0.228	0.228	0.228	0.228	0.228	0.230	0.230
LPG	0.182	0.182	0.198	0.200	0.201	0.203	0.204	0.206	0.208	0.209	0.211	0.213	0.213

Definitions of Emission Control Technologies and Standards

The N₂O and CH₄ emission factors used depend on the emission standards in place and the corresponding level of control technology for each vehicle type. Table A-80 through Table A-83 show the years in which these technologies or standards were in place and the penetration level for each vehicle type. These categories are defined below and were compiled from EPA (1998, 1999) and IPCC/UNEP/OECD/IEA (1997).

Uncontrolled

Vehicles manufactured prior to the implementation of pollution control technologies are designated as uncontrolled. Gasoline passenger cars and light-duty trucks (pre-1973), gasoline heavy-duty vehicles (pre-1984), diesel vehicles (pre-1983), and motorcycles (pre-1996) are assumed to have no control technologies in place.

Gasoline Emission Controls

Below are the control technologies and emissions standards applicable to gasoline vehicles.

Non-catalyst

These emission controls were common in gasoline passenger cars and light-duty gasoline trucks during model years (1973-1974) but phased out thereafter, in heavy-duty gasoline vehicles beginning in the mid-1980s, and in motorcycles from 1996 to 2005. This technology reduces hydrocarbon (HC) and carbon monoxide (CO) emissions through adjustments to ignition timing and air-fuel ratio, air injection into the exhaust manifold, and exhaust gas recirculation (EGR) valves, which also helps meet vehicle NO_x standards.

Oxidation Catalyst

This control technology designation represents the introduction of the catalytic converter, which was the most common technology in gasoline passenger cars and light-duty gasoline trucks made from 1975 to 1980 (cars) and 1975 to 1985 (trucks). This technology was also used in some heavy-duty gasoline vehicles between 1982 and 1997. The two-way catalytic converter oxidizes HC and CO, significantly reducing emissions over 80 percent beyond non-catalyst-system capacity. One reason unleaded gasoline was introduced in 1975 was due to the fact that oxidation catalysts cannot function properly with leaded gasoline.

Advanced Control

Motorcycles built after 2005 are assumed to have advanced emission control systems to better capture emissions from motorcycles. This can include fuel injection, closed loop control, and three-way catalysts.

EPA Tier 0

This emission standard from the Clean Air Act was met through the implementation of early "three-way" catalysts, a technology used in gasoline passenger cars and light-duty gasoline trucks beginning in the early 1980s which remained common until 1994. This more sophisticated emission control system improves the efficiency of the catalyst by converting CO and HC to CO₂ and H₂O, reducing NO_x to nitrogen and oxygen, and using an on-board diagnostic computer and oxygen sensor. In addition, this type of catalyst includes a fuel metering system (carburetor or fuel injection) with electronic "trim" (also known as a "closed-loop system"). New cars with three-way catalysts met the Clean Air Act's amended standards (enacted in 1977) of reducing HC to 0.41 g/mile by 1980, CO to 3.4 g/mile by 1981 and NO_x to 1.0 g/mile by 1981.

EPA Tier 1

This emission standard created through the 1990 amendments to the Clean Air Act limited passenger car NO_x emissions to 0.4 g/mi, and HC emissions to 0.25 g/mi. These bounds amounted to a 60 and 40 percent reduction respectively from the EPA Tier 0 standard set in 1981. For light-duty trucks, this standard set emissions at 0.4 to 1.1 g/mi for NO_x, and 0.25 to 0.39 g/mi for HCs, depending on the weight of the truck. Emission reductions were met through the use of more advanced emission control systems applied to light-duty gasoline vehicles beginning in

1994. These advanced emission control systems included advanced three-way catalysts, electronically controlled fuel injection and ignition timing, EGR, and air injection.

EPA Tier 2

This emission standard was specified in the 1990 amendments to the Clean Air Act, limiting passenger car NO_x emissions to 0.07 g/mi on average and aligning emissions standards for passenger cars and light-duty trucks. Manufacturers can meet this average emission level by producing vehicles in eleven emission “Bins,” the three highest of which expired in 2006. These emission standards represent a 77 to 95 percent reduction in emissions from the EPA Tier 1 standard set in 1994. Emission reductions were met via more advanced emission control systems and lower sulfur fuels and applied to vehicles beginning in 2004. These advanced emission control systems include improved combustion, advanced three-way catalysts, electronically controlled fuel injection and ignition timing, EGR, and air injection.

EPA Tier 3

These standards begin in 2017 and will fully phase-in by 2025, although some Tier 3-compliant vehicles were produced prior to 2017. This emission standard reduces both tailpipe and evaporative emissions from passenger cars, light-duty trucks, medium-duty passenger vehicles, and some heavy-duty vehicles. It is combined with a gasoline sulfur standard that will enable more stringent vehicle emissions standards and will make emissions control systems more effective.

CARB Low Emission Vehicles (LEV)

This emission standard requires a much higher emission control level than the Tier 1 standard. Applied to light-duty gasoline passenger cars and trucks beginning in small numbers in the mid-1990s, LEV includes multi-port fuel injection with adaptive learning, an advanced computer diagnostics systems and advanced and close coupled catalysts with secondary air injection. LEVs as defined here include transitional low-emission vehicles (TLEVs), low emission vehicles, ultra-low emission vehicles (ULEVs). In this analysis, all categories of LEVs are treated the same given there are limited CH₄ or N₂O emission factor data for LEVs to distinguish among the different types of vehicles. Zero emission vehicles (ZEVs) are incorporated into the alternative fuel and advanced technology vehicle assessments.

CARB LEVII

This emission standard builds upon ARB’s LEV emission standards. They represent a significant strengthening of the emission standards and require light trucks under 8500 lbs. gross vehicle weight to meet passenger car standards. It also introduces a super ultra-low vehicle (SULEV) emission standard. The LEVII standards decreased emission requirements for LEV and ULEV vehicles as well as increasing the useful life of the vehicle to 150,000. These standards began with 2004 vehicles. In this analysis, all categories of LEVIIs are treated the same given there are limited CH₄ or N₂O emission factor data for LEVIIs to distinguish among the different types of vehicles. Zero emission vehicles (ZEVs) are incorporated into the alternative fuel and advanced technology vehicle assessments.

CARB LEVIII

These standards begin in 2015 and are fully phased in by 2025, although some LEVIII-compliant vehicles were produced prior to 2017. LEVIII set new vehicle emissions standards and lowered the sulfur content of gasoline, considering the vehicle and its fuel as an integrated system. These new tailpipe standards apply to all light-duty vehicles, medium duty, and some heavy-duty vehicles. Zero emission vehicles (ZEVs) are incorporated into the alternative fuel and advanced technology vehicle assessments.

Diesel Emission Controls

Below are the three levels of emissions control for diesel vehicles.

Moderate control

Improved injection timing technology and combustion system design for light- and heavy-duty diesel vehicles (in place in model years 1983 to 1995) are considered moderate control technologies. These controls were implemented to meet emission standards for diesel trucks and buses adopted by the EPA in 1985 to be met in 1991 and 1994.

Advanced control

EGR and modern electronic control of the fuel injection system are designated as advanced control technologies. These technologies provide diesel vehicles with the level of emission control necessary to comply with standards in place from 1996 through 2006.

Aftertreatment

Use of diesel particulate filters (DPFs), oxidation catalysts and NO_x absorbers or selective catalytic reduction (SCR) systems are designated as aftertreatment control. These technologies provide diesel vehicles with a level of emission control necessary to comply with standards in place from 2007 on.

Supplemental Information on Greenhouse Gas Emissions from Transportation and Other Mobile Sources

This section of this Annex includes supplemental information on the contribution of transportation and other mobile sources to U.S. greenhouse gas emissions. In the main body of the *Inventory* report, emission estimates are presented by greenhouse gas, with separate discussions of the methodologies used to estimate CO₂, N₂O, CH₄, and HFC emissions. The purpose of this sub-annex, within the Annex that details the calculation methods and data used for non-CO₂ calculations, is to consolidate all transportation estimates presented throughout the report.

This section of this Annex reports total greenhouse gas emissions from transportation and other (non-transportation) mobile sources in CO₂ equivalents, with information on the contribution by greenhouse gas and by mode, vehicle type, and fuel type. Additional analyses were conducted to develop estimates of CO₂ from non-transportation mobile sources (e.g., agricultural equipment, construction/mining equipment, recreational vehicles), and to provide more detailed breakdowns of emissions by source.

Estimation of CO₂ from Non-Transportation Mobile Sources

The estimates of N₂O and CH₄ from fuel combustion presented in the Energy chapter of the *Inventory* include both transportation sources and other mobile sources. Other mobile sources include construction/mining equipment, agricultural equipment, vehicles used off-road, and other sources that have utility associated with their movement but do not have a primary purpose of transporting people or goods (e.g., snowmobiles, riding lawnmowers, etc.). Estimates of CO₂ from non-transportation mobile sources, based on EIA fuel consumption estimates, are included in the industrial and commercial sectors of the *Inventory*. In order to provide comparable information on transportation and mobile sources, Table A-89 provides estimates of CO₂ from these other mobile sources, developed from the Nonroad component of EPA's MOVES5 model and FHWA's Highway Statistics. These other mobile source estimates were developed using the same fuel consumption data utilized in developing the N₂O and CH₄ estimates (see Table A-79). Note that the method used to estimate fuel consumption volumes for CO₂ emissions from non-transportation mobile sources for the supplemental information presented in Table A-89, Table A-91, and Table A-92 differs from the method used to estimate fuel consumption volumes for CO₂ in the industrial and commercial sectors in this *Inventory*, which include CO₂ emissions from all non-transportation mobile sources (see Section 3.1 for a discussion of that methodology).

Estimation of HFC Emissions from Transportation Sources

In addition to CO₂, N₂O and CH₄ emissions, transportation sources also result in emissions of HFCs. HFCs are emitted to the atmosphere during equipment manufacture and operation (because of component failure, leaks, and purges), as well as at servicing and disposal events. There are three categories of transportation-related HFC emissions: Mobile air-conditioning represents the emissions from air conditioning units in passenger cars, light-

duty trucks, and heavy-duty vehicles; Comfort Cooling represents the emissions from air conditioning units in passenger trains and buses; and Refrigerated Transport represents the emissions from units used to cool freight during transportation Table A-90 below presents these HFC emissions. Table A-91 presents all transportation and mobile source greenhouse gas emissions, including HFC emissions.

Table A-89: CO₂ Emissions from Non-Transportation Mobile Sources (MMT CO₂ Eq.)^a

Fuel Type/ Vehicle Type	1990	2000	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Agricultural Equipment ^a	43.4	39.9	48.0	45.8	45.9	41.1	40.2	39.8	39.8	39.7	39.1	39.8	39.3	39.3
Construction/Mining Equipment ^b	48.9	57.4	62.9	65.9	61.1	57.0	60.0	65.1	68.2	70.3	65.1	69.5	72.7	73.2
Other Sources ^c	69.6	76.3	85.9	87.0	88.8	87.4	88.3	89.9	92.3	94.1	88.0	93.4	100.2	102.1
Total	161.9	173.6	196.8	198.7	195.9	185.6	188.4	194.8	200.3	204.1	192.2	202.8	212.2	214.6

Table A-90: HFC Emissions from Transportation Sources (MMT CO₂ Eq.)

Vehicle Type	1990	2000	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Mobile AC	+	50.2	47.9	42.4	39.4	36.8	33.6	30.2	28.2	26.2	24.2	22.4	20.4	18.4
Passenger Cars	+	25.5	18.7	15.7	14.4	13.3	12.0	10.4	9.4	8.4	7.6	7.0	6.6	5.7
Light-Duty Trucks	+	23.3	26.6	24.1	22.4	20.9	19.2	17.5	16.4	15.4	14.2	13.0	11.4	10.4
Heavy-Duty Vehicles	+	1.5	2.7	2.6	2.6	2.6	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.3
Comfort Cooling for Trains and Buses	+	0.1	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5
School and Tour Buses	+	0.1	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Transit Buses	+	+	+	+	+	+	+	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Rail	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Refrigerated Transport	+	0.8	3.9	4.4	4.9	5.4	5.9	6.4	6.9	7.4	7.9	8.4	8.8	9.0
Medium- and Heavy-Duty Trucks	+	0.4	2.0	2.3	2.5	2.6	2.8	3.0	3.2	3.4	3.6	3.8	3.9	3.9
Rail	+	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Ships and Boats	+	0.3	1.7	2.0	2.3	2.6	2.9	3.2	3.6	3.9	4.2	4.5	4.8	5.1
Total	+	51.1	52.3	47.3	44.7	42.6	39.9	37.0	35.5	34.0	32.5	31.2	29.6	27.9

+ Does not exceed 0.05 MMT CO₂ Eq.

Note: Totals may not sum due to independent rounding.

Contribution of Transportation and Mobile Sources to Greenhouse Gas Emissions, by Mode/Vehicle Type/Fuel Type

Table A-91 presents estimates of greenhouse gas emissions from an expanded analysis including all transportation and additional mobile sources, as well as emissions from electricity generation by the consuming category, in CO₂ equivalents. In total, transportation and non-transportation mobile sources emitted 2,049.1 MMT CO₂ Eq. in 2023, an increase of 21 percent from 1990.⁵⁷ Transportation sources account for 1,827.5 MMT CO₂ Eq.

⁵⁷ Recommended Best Practice for Quantifying Speciated Organic Gas Emissions from Aircraft Equipped with Turbofan, Turbojet and Turboprop Engines,” EPA-420-R-09-901, May 27, 2009 (see <https://www.epa.gov/regulations-emissions-vehicles-and-engines/organic-gas-speciation-profile-aircraft>).

while non-transportation mobile sources account for 221.7 MMT CO₂ Eq. These estimates include HFC emissions for mobile AC, comfort cooling for trains and buses, and refrigerated transport. These estimates were generated using the estimates of CO₂ emissions from transportation sources reported in Section 3.1 CO₂ Emissions from Fossil Fuel Combustion, and CH₄ emissions and N₂O emissions reported in the Mobile Combustion section of the Energy chapter; information on HFCs from mobile air conditioners, comfort cooling for trains and buses, and refrigerated transportation from the Substitution of Ozone Depleting Substances section of the IPPU chapter; and estimates of CO₂ emitted from non-transportation mobile sources reported in Table A-89 above.

Although all emissions reported here are based on estimates reported throughout this *Inventory*, some additional calculations were performed to provide a detailed breakdown of emissions by mode and vehicle category. In the case of N₂O and CH₄, additional calculations were performed to develop emission estimates by type of aircraft and type of heavy-duty vehicle (i.e., medium- and heavy-duty trucks or buses) to match the level of detail for CO₂ emissions. N₂O estimates for both jet fuel and aviation gasoline, and CH₄ estimates for aviation gasoline were developed for individual aircraft types by multiplying the emissions estimates for each fuel type (jet fuel and aviation gasoline) by the portion of fuel used by each aircraft type (from FAA 2024 and DLA 2022). Emissions of CH₄ from jet fuels are no longer considered to be emitted from aircraft gas turbine engines burning jet fuel A at higher power settings. This update applies to the entire time series.⁵⁸ Recent research indicates that modern aircraft jet engines are typically net consumers of methane (Santoni et al. 2011). Methane is emitted at low power and idle operation, but at higher power modes aircraft engines consume methane. Over the range of engine operating modes, aircraft engines are net consumers of methane on average. Based on this data, CH₄ emission factors for jet aircraft were reported as zero to reflect the latest emissions testing data.

Similarly, N₂O and CH₄ estimates were developed for medium- and heavy-duty trucks by multiplying the emission estimates for heavy-duty vehicles for each fuel type (gasoline, diesel) from the Mobile Combustion section in the Energy chapter, by the portion of fuel used by each vehicle type (from DOE 1993 through 2022). Carbon dioxide emissions from non-transportation mobile sources are calculated using data from the Nonroad component of EPA's MOVES5 model (EPA 2024). Otherwise, the table and figure are drawn directly from emission estimates presented elsewhere in the *Inventory*, and are dependent on the methodologies presented in Annex 2.1 (for CO₂), Chapter 4, and Annex 3.10 (for HFCs), and earlier in this Annex (for CH₄ and N₂O).

Transportation sources include on-road vehicles, aircraft, boats and ships, rail, and pipelines (note: pipelines are a transportation source but are stationary, not mobile, emissions sources). In addition, transportation-related greenhouse gas emissions also include HFC released from mobile air-conditioners and refrigerated transport, and the release of CO₂ from lubricants (such as motor oil) used in transportation. Together, transportation sources were responsible for 1,827.5 MMT CO₂ Eq. in 2023.

On-road vehicles were responsible for about 73 percent of all transportation and non-transportation mobile greenhouse gas emissions in 2023. Although light-duty vehicles make up the largest component of on-road vehicle greenhouse gas emissions, medium- and heavy-duty trucks have been the primary sources of growth in on-road vehicle emissions. Greenhouse gas emissions from passenger cars decreased 54 percent between 1990 and 2023. Greenhouse gas emissions from light-duty trucks increased by 151 percent between 1990 and 2023. Overall, between 1990 and 2023, greenhouse gas emissions from passenger cars and light-duty trucks together increased by 8.5 percent. Greenhouse gas emissions from medium- and heavy-duty trucks increased 81 percent between 1990 and 2023, reflecting the increased volume of total freight movement and an increasing share of freight transported by trucks.

Greenhouse gas emissions from aircraft decreased 4 percent between 1990 and 2023. Emissions from military aircraft decreased 66 percent between 1990 and 2023. Commercial aircraft emissions increased 27 percent between 1990 and 2007, dropped 2 percent from 2007 to 2019, dropped another 33 percent from 2019 to 2020,

⁵⁸ VMT is allocated to vehicle classes using MOVES5 ratios of VMT in each vehicle class to total VMT.

followed by an increase of 42 percent from 2020 to 2023. Overall, this represents a change of approximately 18 percent between 1990 and 2023.

Non-transportation mobile sources, such as construction/mining equipment, agricultural equipment, and industrial/commercial equipment, emitted approximately 221.7 MMT CO₂ Eq. in 2023. Together, these sources emitted more greenhouse gases than ships and boats, and rail combined. Emissions from non-transportation mobile sources increased, growing approximately 34 percent between 1990 and 2023. Methane and N₂O emissions from these sources are included in the “Mobile Combustion” section and CO₂ emissions are included in the relevant economic sectors.

Contribution of Transportation and Mobile Sources to Greenhouse Gas Emissions, by Gas

Table A-92 presents estimates of greenhouse gas emissions from transportation and other mobile sources broken down by greenhouse gas. As this table shows, CO₂ accounts for most transportation greenhouse gas emissions (approximately 98 percent in 2023). Emissions of CO₂ from transportation and mobile sources increased by 357 MMT CO₂ Eq. between 1990 and 2023. In contrast, the combined emissions of CH₄ and N₂O decreased by 26.2 MMT CO₂ Eq. over the same period, due largely to the introduction of emission control technologies designed to reduce criteria pollutant emissions.⁵⁹ HFC emissions from mobile air-conditioners and refrigerated transport increased from virtually no emissions in 1990 to 27.9 MMT CO₂ Eq. in 2023 as these chemicals were phased in as substitutes for ozone depleting substances. It should be noted, however, that the ozone depleting substances that HFCs replaced are also powerful greenhouse gases but are not included in national greenhouse gas inventories per national inventory reporting standards.

Greenhouse Gas Emissions from Freight and Passenger Transportation

Table A-93 and Table A-94 present greenhouse gas estimates from transportation, broken down into the passenger and freight categories. Passenger modes include light-duty vehicles, buses, passenger rail, aircraft (general aviation and commercial aircraft), recreational boats, and mobile air conditioners, and are illustrated in Table A-93. Freight modes include medium- and heavy-duty trucks, freight rail, refrigerated transport, waterborne freight vessels, pipelines, and commercial aircraft and are illustrated in Table A-94. Commercial aircraft do carry some freight, in addition to passengers, and emissions have been split between passenger and freight transportation. The amount of commercial aircraft emissions allocated to the passenger and freight categories was calculated using BTS data on freight shipped by commercial aircraft, and the total number of passengers enplaned (DOT 1991 through 2025). Each passenger was considered to weigh an average of 150 pounds, with a luggage weight of 50 pounds. The total freight weight and total passenger weight carried were used to determine percent shares which were used to split the total commercial aircraft emission estimates. The remaining transportation and mobile emissions were from sources not considered to be either freight or passenger modes (e.g., construction/mining and agricultural equipment, lubricants).

The estimates in these tables are derived from the estimates presented in Table A-91. In addition, estimates of fuel consumption from DOE (1993 through 2022) were used to allocate rail emissions between passenger and freight categories.

In 2023, passenger transportation modes emitted 1,232.0 MMT CO₂ Eq., while freight transportation modes emitted 575.1 MMT CO₂ Eq. Between 1990 and 2023, the percentage growth of greenhouse gas emissions from freight sources was 62 percent. Emissions from passenger sources increased by 10 percent from 1990 to 2023. This difference in growth is due largely to the rapid increase in emissions associated with medium- and heavy-duty trucks.

⁵⁹ The decline in CFC emissions is not captured in the official transportation estimates.

Table A-91: Total U.S. Greenhouse Gas Emissions from Transportation and Mobile Sources (MMT CO₂ Eq.)

Mode / Vehicle Type / Fuel Type	1990	2000	2010	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	% of total	% Change 1990 - 2023
Transportation Total^a	1,523.9	1,910.0	1,801.9	1,752.5	1,787.3	1,795.6	1,830.7	1,848.2	1,878.2	1,878.5	1,628.8	1,809.5	1,808.6	1,827.5	90%	19%
On-Road Vehicles	1,201.4	1,550.9	1,510.0	1,462.1	1,510.9	1,507.5	1,531.0	1,537.1	1,559.6	1,548.0	1,373.2	1,495.1	1,474.6	1,490.1	73%	24%
Passenger Cars	658.7	610.6	501.8	407.9	416.4	405.6	406.0	391.2	383.9	372.7	309.6	325.4	307.3	303.3	15%	-54%
Gasoline ^b	648.8	579.2	474.2	389.7	399.2	389.3	391.2	378.2	372.0	361.7	300.0	316.2	298.4	295.1	14%	-55%
Diesel ^b	9.9	5.9	2.6	2.6	2.8	3.0	2.8	2.6	2.5	2.5	2.0	2.0	1.9	1.8	0%	-82%
AFVs ^c	+	+	+	+	+	+	+	+	+	0.1	0.1	0.2	0.4	0.7	0%	13782%
HFCs from Mobile AC	-	25.5	25.0	15.7	14.4	13.3	12.0	10.4	9.4	8.4	7.6	7.0	6.6	5.7	0%	NA
Light-Duty Trucks	289.7	571.4	624.8	669.3	693.7	693.8	711.7	717.0	733.3	729.8	636.9	705.8	704.5	726.2	35%	151%
Gasoline ^b	281.3	528.3	565.8	614.2	639.8	640.1	659.7	666.6	684.0	681.0	595.1	663.4	663.3	686.0	33%	144%
Diesel ^b	8.2	19.7	27.9	30.8	31.2	32.4	32.4	32.3	32.0	32.3	26.6	28.1	28.2	27.8	1%	239%
AFVs ^c	0.1	0.1	+	0.2	0.3	0.4	0.5	0.6	0.9	1.1	1.0	1.3	1.7	2.0	0%	1283%
HFCs from Mobile AC	-	23.3	31.0	24.1	22.4	20.9	19.2	17.5	16.4	15.4	14.2	13.0	11.4	10.4	1%	NA
Medium- and Heavy-Duty Trucks	236.6	345.5	360.4	359.2	373.3	379.9	384.4	398.8	411.1	414.0	400.3	434.6	430.2	427.6	21%	81%
Gasoline ^b	43.0	36.4	24.4	22.9	24.5	24.9	26.8	28.4	30.3	31.7	29.7	34.9	35.9	36.4	2%	-15%
Diesel ^b	192.2	306.7	331.4	330.9	343.2	349.4	351.8	364.5	374.2	375.5	363.9	392.9	387.3	384.4	19%	100%
AFVs ^c	1.3	0.5	0.2	0.4	0.4	0.5	0.6	0.5	0.9	0.9	0.6	0.7	0.7	0.7	0%	-47%
HFCs from Refrigerated Transport and Mobile AC ^e	-	1.9	4.4	4.9	5.1	5.2	5.3	5.4	5.6	5.8	6.1	6.3	6.3	6.1	0.0	NA
Buses	13.1	19.3	16.8	19.2	21.0	21.9	22.1	23.4	24.5	24.8	20.2	22.3	24.4	24.4	1%	86%
Gasoline ^b	5.3	3.4	1.5	2.0	2.3	2.4	2.6	3.1	3.5	3.6	3.1	3.6	3.9	4.1	0%	-22%
Diesel ^b	7.8	15.4	14.5	16.4	17.7	18.4	18.2	19.0	20.2	20.4	16.4	18.1	19.6	19.4	1%	149%
AFVs ^c	+	0.4	0.4	0.5	0.6	0.8	0.9	0.9	0.5	0.4	0.3	0.3	0.4	0.5	0%	5287%
HFCs from Comfort Cooling	-	0.1	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0%	NA
Motorcycles	3.3	4.2	6.2	6.7	6.8	6.6	6.9	6.9	7.0	6.8	6.2	7.0	8.3	8.7	0%	159%
Gasoline ^b	3.3	4.2	6.2	6.7	6.8	6.6	6.9	6.9	7.0	6.8	6.2	7.0	8.3	8.7	0%	159%
Aircraft	188.8	199.1	154.6	149.8	151.0	160.3	168.8	174.6	175.3	183.4	123.0	155.4	167.8	181.9	9%	-4%
General Aviation Aircraft	42.0	35.3	26.3	23.3	20.5	26.5	34.8	32.9	32.4	33.3	19.2	22.8	24.5	39.5	2%	-6%
Jet Fuel ^f	38.8	32.7	24.4	21.7	19.0	25.0	33.3	31.5	30.8	31.7	17.8	21.3	22.9	38.0	2%	-2%
Aviation Gasoline	3.2	2.6	1.9	1.6	1.5	1.5	1.5	1.5	1.6	1.7	1.4	1.5	1.6	1.5	0%	-53%
Commercial Aircraft	110.8	140.5	114.2	115.2	116.1	120.0	121.4	129.0	130.7	137.8	92.0	120.0	130.8	130.8	6%	18%
Jet Fuel ^f	110.8	140.5	114.2	115.2	116.1	120.0	121.4	129.0	130.7	137.8	92.0	120.0	130.8	130.8	6%	18%

Military Aircraft	36.0	23.3	14.0	11.3	14.4	13.9	12.6	12.6	12.2	12.3	11.8	12.6	12.5	11.6	1%	-68%
Jet Fuel ^f	36.0	23.3	14.0	11.3	14.4	13.9	12.6	12.6	12.2	12.3	11.8	12.6	12.5	11.6	1%	-68%
Ships and Boats^d	47.0	65.9	45.0	39.7	29.1	33.8	40.7	43.8	41.1	40.0	32.2	50.7	49.9	43.8	2%	-7%
Gasoline	14.4	14.5	11.8	10.9	10.7	10.7	10.7	10.8	10.9	10.9	10.0	10.8	11.0	11.0	1%	-24%
Distillate Fuel	9.8	17.4	11.3	11.5	10.2	16.2	14.0	13.1	12.5	10.6	10.6	10.9	11.0	10.9	1%	12%
Residual Fuel ^e	22.8	33.6	20.7	15.3	5.9	4.3	13.1	16.6	14.2	14.6	7.4	24.5	23.1	16.8	1%	-26%
HFCs from Refrigerated Transport ^e	+	0.3	1.2	2.0	2.3	2.6	2.9	3.2	3.6	3.9	4.2	4.5	4.8	5.1	0%	NA
Rail	39.0	46.6	44.0	44.4	46.2	44.0	40.2	41.3	42.5	39.7	34.2	35.5	35.6	33.8	2%	-13%
Distillate Fuel ^f	35.8	42.9	39.3	40.1	41.9	40.0	36.5	37.7	38.9	36.3	31.5	32.8	32.8	31.2	2%	-13%
Electricity	3.1	3.5	4.5	4.1	4.1	3.8	3.5	3.4	3.4	3.2	2.5	2.5	2.5	2.5	0%	-19%
Other Emissions from Rail Electricity Use ^g	0.1	+	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0%	9%
HFCs from Comfort Cooling	-	+	+	+	+	+	+	+	+	+	+	+	+	+	0%	NA
HFCs from Refrigerated Transport ^e	-	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	+	0%	NA
Pipelines^h	36.0	35.5	37.9	46.8	39.9	39.1	39.7	41.9	50.5	58.5	58.5	64.9	72.0	71.3	3%	98%
Natural Gas	36.0	35.5	37.9	46.8	39.9	39.1	39.7	41.9	50.5	58.5	58.5	64.9	72.0	71.3	3%	98%
Other Transportation	11.8	12.1	10.4	9.6	10.0	11.0	10.4	9.6	9.2	8.8	7.8	8.0	8.7	6.6	0%	-45%
Lubricants	11.8	12.1	10.4	9.6	10.0	11.0	10.4	9.6	9.2	8.8	7.8	8.0	8.7	6.6	0%	-45%
Non-Transportation Mobileⁱ																
Total	166.9	179.1	205.3	205.6	202.8	192.0	194.9	201.4	207.0	210.9	198.7	209.5	2192	221.7	11%	34%
Agricultural Equipment^{k,j}	44.7	41.1	48.1	47.3	47.4	42.4	41.4	41.1	41.1	40.9	40.3	41.0	40.5	40.5	2%	-9%
Gasoline	7.5	6.0	6.2	5.8	5.7	1.4	1.5	1.5	1.4	1.1	1.2	1.3	1.3	1.3	0%	-82%
Diesel	37.2	35.0	41.8	41.4	41.6	40.9	39.8	39.5	39.6	39.7	39.0	39.6	39.1	39.1	2%	6%
CNG	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0%	-14%
LPG	+	+	+	+	+	+	+	+	+	+	+	+	+	+	0%	-10%
Construction/Mining Equipment^k	50.2	58.9	67.1	67.8	62.9	58.6	61.6	66.9	70.0	72.2	66.9	71.4	74.6	75.1	4%	51%
Gasoline	4.4	3.3	6.1	9.9	6.4	3.3	3.4	3.4	3.5	3.5	3.5	3.3	2.6	2.6	0%	-40%
Diesel	45.4	55.1	60.5	57.5	56.1	54.8	57.8	63.0	66.0	68.2	62.9	67.6	71.5	72.4	4%	59%
CNG	0.3	0.3	0.4	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.3	0.4	0.4	0.4	0%	31%
LPG	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.2	0.2	0.2	0%	27%
Other Equipment^{k,l}	71.9	79.1	90.1	90.5	92.4	90.9	91.8	93.5	96.0	97.9	91.6	97.0	104.1	106.1	5%	48%
Gasoline	40.5	43.2	50.0	46.8	47.5	45.6	46.1	46.5	47.1	47.5	45.3	47.2	49.4	49.6	2%	23%

Diesel	21.9	21.6	25.7	28.5	29.4	29.6	29.8	30.5	31.7	32.5	29.8	32.1	35.0	36.0	2%	65%
CNG	1.2	1.4	1.7	2.1	2.2	2.2	2.1	2.2	2.3	2.4	2.2	2.3	2.5	2.6	0%	123%
LPG	8.3	12.9	12.8	13.1	13.3	13.5	13.7	14.3	15.0	15.5	14.3	15.4	17.1	17.8	1%	116%
Transportation and Non-Transportation Mobile Total^l	1,690.8	2,089.0	2,007.2	1,958.3	1,990.2	1,987.8	2,025.6	2,049.6	2,085.2	2,089.4	1,827.6	2,019.0	2,027.9	2,049.3	100%	21%

+ Does not exceed 0.05 MMT CO₂ Eq.

NA (Not Applicable), as there were no HFC emissions allocated to the transport sector in 1990, and thus a growth rate cannot be calculated.

^a Not including emissions from international bunker fuels.

^b Gasoline and diesel highway vehicle fuel consumption estimates used to develop CO₂ estimates in this *Inventory* are based on data from FHWA Highway Statistics Table MF-21, MF-27 and ratios developed from MOVES5 to apportion FHWA fuel consumption data to vehicle type and fuel type. MOVES5 ratios of fuel use by vehicle class to total fuel use are used to allocate fuel consumption between each on-road vehicle class. For mobile CH₄ and N₂O emissions estimates, gasoline and diesel highway vehicle mileage estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2024). Total VMT estimates are allocated to vehicle type using EPA's MOVES5 model ratios of VMT per vehicle class to total VMT.

^c In 2017, estimates of alternative fuel vehicle mileage for the last ten years were revised to reflect updates made to EIA data on alternative fuel use and vehicle counts. These changes were incorporated into this year's *Inventory* and apply to the 2003 to 2017 time period. For 2017 and later, estimates were made using available data (Browning 2022b).

^d Fluctuations in emission estimates reflect data collection problems. Note that CH₄ and N₂O from U.S. Territories are included in this value, but not CO₂ emissions from U.S. Territories, which are estimated separately in the section on U.S. Territories.

^e Domestic residual fuel for ships and boats is estimated by taking the total amount of residual fuel and subtracting out an estimate of international bunker fuel use.

^f Class II and Class III diesel consumption data for 2014 to 2023 is not available. Diesel consumption data for 2014 to 2023 is estimated by applying the historical average fuel usage per carload factor to the annual number of carloads.

^g Other emissions from electricity generation are a result of waste incineration (as the majority of municipal solid waste is combusted in "trash-to-steam" electricity generation plants), electrical transmission and distribution, and a portion of other process uses of carbonates (from pollution control equipment installed in electricity generation plants).

^h Includes only CO₂ from natural gas used to power natural gas pipelines; does not include emissions from electricity use or non-CO₂ gases.

ⁱ Note that the method used to estimate CO₂ emissions from non-transportation mobile sources in this supplementary information table differs from the method used to estimate CO₂ in the industrial and commercial sectors in the *Inventory*, which include CO₂ emissions from all non-transportation mobile sources (see Section 3.1 for the methodology for estimating CO₂ emissions from fossil fuel combustion in this *Inventory*).

^j Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

^k Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

^l "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

Notes: Increases to CH₄ and N₂O emissions from mobile combustion relative to previous *Inventories* are largely due to updates made to the Motor Vehicle Emissions Simulator (MOVES5) model that is used to estimate on-road gasoline vehicle distribution and mileage across the time series, as well as non-transportation mobile fuel consumption. See Section 3.1 CH₄ and N₂O from Mobile Combustion for more detail. This year's *Inventory* uses the Nonroad component of MOVES5 for years 1999 through 2023. In 2016, historical confidential vehicle sales data were re-evaluated to determine the engine technology assignments. First, several light-duty trucks were re-characterized as heavy-duty vehicles based upon gross vehicle weight rating (GVWR) and confidential sales data. Second, the emission standards each vehicle type was assumed to have met were re-examined using confidential sales data. Also, in previous *Inventories*, non-plug-in hybrid electric vehicles (HEVs) were

considered alternative fueled vehicles and therefore not included in the engine technology breakouts. For this *Inventory*, HEVs are classified as gasoline vehicles across the entire time series. Totals may not sum due to independent rounding.

Table A-92: Transportation and Mobile Source Emissions by Gas (MMT CO₂ Eq.)

															Percent Change 1990- 2023
Year	1990	2000	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	
CO ₂ ^a	1,645.7	1,981.3	1,869.2	1,881.5	1,917.7	1,919.0	1,960.7	1,988.7	2,026.9	2,033.8	1,776.5	1,968.3	1,979.0	2,002.6	22%
N ₂ O	37.8	49.8	27.4	25.8	24.3	22.7	21.8	20.8	19.7	18.7	16.0	16.8	16.5	16.2	-57%
CH ₄	7.2	6.7	3.5	3.4	3.2	3.2	3.1	3.0	2.9	2.8	2.5	2.5	2.6	2.5	-65%
HFC	+	51.1	52.3	47.3	44.7	42.6	39.9	37.0	35.5	34.0	32.5	31.2	29.6	27.9	NA
Total ^b	1,690.7	2,089.0	1,952.4	1,958.0	1,989.9	1,987.5	2,025.5	2,049.6	2,085.1	2,089.3	1,827.5	2,018.8	2,027.7	2,049.2	21%

+ Does not exceed 0.05 MMT CO₂ Eq.

NA (Not Applicable), as there were no HFC emissions allocated to the transport sector in 1990, and thus a growth rate cannot be calculated.

^aThe method used to estimate CO₂ emissions from non-transportation mobile sources in this supplementary information table differs from the method used to estimate CO₂ in the industrial and commercial sectors in the *Inventory*, which include CO₂ emissions from all non-transportation mobile sources (see Section 3.1 for the methodology for estimating CO₂ emissions from fossil fuel combustion in this *Inventory*).

^bTotal excludes other emissions from electricity generation and CH₄ and N₂O emissions from electric rail.

Notes: Gasoline and diesel highway vehicle fuel consumption estimates used to develop CO₂ estimates in this *Inventory* are based on data from FHWA Highway Statistics Table MF-21, MF-27 and ratios developed from MOVES5 to apportion FHWA fuel consumption data to vehicle type and fuel type. For mobile CH₄ and N₂O emissions estimates, gasoline and diesel highway vehicle miles travelled estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2024). VMT estimates are allocated to vehicle type using ratios of VMT per vehicle type to total VMT, derived from EPA's MOVES5 model.

In 2016, historical confidential vehicle sales data was re-evaluated to determine the engine technology assignments. First several light-duty trucks were re-characterized as heavy-duty vehicles based upon gross vehicle weight rating (GVWR) and confidential sales data. Second, the emission standards each vehicle type was assumed to have met were re-examined using confidential sales data. Also, in previous *Inventories*, non-plug-in hybrid electric vehicles (HEVs) were considered alternative fueled vehicles and therefore not included in the engine technology breakouts. For this *Inventory*, HEVs are classified as gasoline vehicles across the entire time series. Totals may not sum due to independent rounding.

Figure A-4: Domestic Greenhouse Gas Emissions by Mode and Vehicle Type, 1990 to 2023

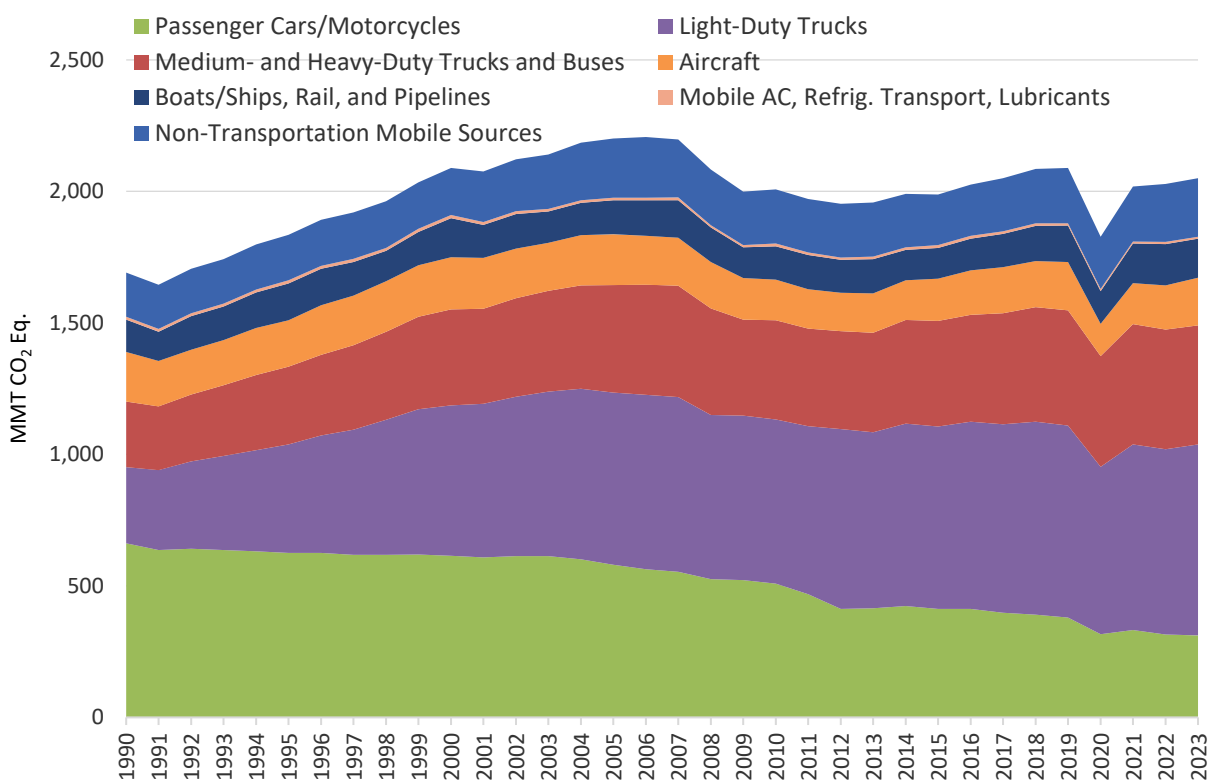


Table A-93: Greenhouse Gas Emissions from Passenger Transportation (MMT CO₂ Eq.)

Vehicle Type	1990	2000	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	% Change 90-23
On-Road															
Vehicles^{a,b}	964.8	1,205.5	1,114.8	1,103.1	1,137.9	1,127.9	1,146.8	1,138.5	1,148.7	1,134.2	972.9	1,060.5	1,044.5	1,062.6	10%
Passenger Cars	658.7	610.6	405.2	407.9	416.4	405.6	406.0	391.2	383.9	372.7	309.6	325.4	307.3	303.3	-54%
Light-Duty Trucks	289.7	571.4	683.7	669.3	693.7	693.8	711.7	717.0	733.3	729.8	636.9	705.8	704.5	726.2	151%
Buses	13.1	19.4	18.9	19.3	21.0	21.9	22.1	23.4	24.5	24.8	20.2	22.3	24.3	24.4	86%
Motorcycles	3.3	4.2	6.9	6.7	6.8	6.6	6.9	6.9	7.0	6.8	6.2	7.0	8.3	8.7	162%
Aircraft	133.6	151.5	118.1	122.6	120.4	130.0	139.3	143.6	144.4	151.8	83.4	118.6	134.0	152.1	14%
General Aviation	42.0	35.3	19.6	23.3	20.5	26.5	34.8	32.9	32.4	33.3	19.2	22.8	24.5	39.5	-6%
Commercial Aircraft	91.6	116.1	98.5	99.4	99.9	103.5	104.6	110.6	112.0	118.5	64.2	95.8	109.5	112.6	23%
Recreational															
Boats	17.2	17.3	13.7	13.4	13.2	13.3	13.4	13.6	13.7	13.8	12.7	13.6	13.9	13.9	-19%
Passenger Rail	4.4	5.2	5.5	5.8	5.7	5.4	5.2	5.1	4.5	4.2	3.6	3.6	3.7	3.4	-23%
Total	1,119.9	1,379.5	1,252.1	1,245.0	1,277.2	1,276.5	1,304.8	1,300.8	1,311.3	1,304.0	1,072.6	1,196.3	1,196.1	1,232.0	10%

Note: Totals may not sum due to independent rounding.

Table A-94: Greenhouse Gas Emissions from Domestic Freight Transportation (MMT CO₂ Eq.)

By Mode	1990	2000	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	% Change 90-23
Trucking ^{a,b}	236.6	344.0	350.9	356.6	370.6	377.3	381.7	396.2	408.5	411.4	397.9	432.2	427.8	425.3	80%
Freight Rail	34.5	41.3	38.3	38.6	40.5	38.5	34.9	36.2	37.9	35.4	30.5	31.8	31.8	30.5	-12%
Ships and Non-Recreational Boats	29.8	48.5	26.6	26.3	15.9	20.5	27.3	30.3	27.4	26.3	19.5	37.0	36.0	29.9	0%
Pipelines ^c	36.0	35.5	41.1	46.8	39.9	39.1	39.7	41.9	50.5	58.5	58.5	64.9	72.0	71.3	98%
Commercial Aircraft	19.2	24.3	15.7	15.9	16.2	16.5	16.8	18.4	18.7	19.3	27.8	24.2	21.2	18.2	-5%
Total	356.0	493.7	472.6	484.1	483.1	491.9	500.4	522.9	543.0	551.0	534.2	590.1	588.9	575.1	62%

^a The current *Inventory* includes updated vehicle population data based on the MOVES5 Model.

^b Gasoline and diesel highway vehicle fuel consumption estimates used to develop CO₂ estimates in this *Inventory* are based on data from FHWA Highway Statistics Table MF-21, MF-27 and ratios developed from MOVES5 to apportion FHWA fuel consumption data to vehicle type and fuel type. For mobile CH₄ and N₂O emissions estimates, gasoline and diesel highway vehicle mileage estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2024) and

MOVES5 model ratios of VMT per vehicle class to total VMT.

^c Pipelines reflect CO₂ emissions from natural gas-powered pipelines transporting natural gas.

Notes: Data from DOE (1993 through 2022) were used to disaggregate emissions from rail and buses. Emissions from HFCs have been included in these estimates. This year's *Inventory* uses the Nonroad component of MOVES5 for years 1999 through 2023. In 2017, estimates of alternative fuel vehicle mileage for the last ten years were revised to reflect updates made to EIA data on alternative fuel use and vehicle counts. These changes apply to the 2003 to 2017 time period. For 2017 and later, estimates were made using available data (Browning 2022b).

In 2016, historical confidential vehicle sales data were re-evaluated to determine the engine technology assignments. First, several light-duty trucks were re-characterized as heavy-duty vehicles based upon gross vehicle weight rating (GVWR) and confidential sales data. Second, the emission standards each vehicle type was assumed to have met were re-examined using confidential sales data. Also, in previous *Inventories*, non-plug-in hybrid electric vehicles (HEVs) were considered alternative fueled vehicles and therefore not included in the engine technology breakouts. For this *Inventory*, HEVs are classified as gasoline vehicles across the entire time series. Totals may not sum due to independent rounding.

Motor Vehicle Emission Simulator (MOVES)

As noted in the preceding methodology discussion, EPA's Motor Vehicle Emission Simulator (MOVES) is used to derive some of the activity data that are used as inputs to the calculation of greenhouse gas emissions in this *Inventory*. The model is not used to directly estimate greenhouse gas emissions. With respect to estimating CO₂ emissions from the transportation sector, MOVES is used to estimate fuel use by recreational boats and ratios developed from MOVES output are used to apportion FHWA fuel consumption data to vehicle type and fuel type. For non-CO₂ greenhouse gas emissions, MOVES is used to generate the age distribution and age-specific vehicle mileage accumulations for the U.S. vehicle fleet. Additionally, the Nonroad component of MOVES is used to estimate fuel consumption for gasoline- and diesel-powered equipment, and CH₄ and N₂O emission factors for nonroad mobile sources are calculated from engine certification data and weighted by activity estimates calculated by MOVES. Finally, the Supplemental Information on Greenhouse Gas Emissions from Transportation and Other Mobile Sources section of this Annex provides estimates of CO₂ from non-transportation mobile sources, developed from the Nonroad component of MOVES.

The Motor Vehicle Emission Simulator (EPA 2024) is EPA's state-of-the-science emission modeling system that estimates emissions for mobile sources at the national, county, and project level for criteria air pollutants, greenhouse gases, and air toxics. It is a bottom-up emissions model that is designed to estimate emissions from separate physical emission processes depending on the source. MOVES models "fleet average" emissions, rather than emissions from individual vehicles or nonroad equipment types, and MOVES adjusts emission rates to represent real-world conditions. The model covers onroad vehicles such as cars, trucks and buses, and nonroad equipment such as construction and lawn and garden equipment; it does not estimate emissions from aircraft, locomotives, and commercial marine vessels. MOVES accounts for the phase-in of federal emissions standards, vehicle and equipment activity, fuels, temperatures, humidity, and emission control activities such as inspection and maintenance programs for calendar years 1990 and 1999 through 2060. Emissions from onroad and nonroad sources can be modeled at the national or county scale using either model defaults or user-supplied inputs. Emissions from onroad sources can also be modeled at a more detailed "project" scale if the user supplies detailed inputs describing project parameters. The current *Inventory* uses output from MOVES5, which is the latest official version of MOVES. Previous versions of the model include MOVES4, MOVES3, MOVES2014 and MOVES2010.

MOVES is used by EPA to estimate emission impacts of mobile source regulations and policies, and to generate mobile sector information for national inventories of air pollutants such as the National Emissions Inventory and the Air Toxics Screening Assessment. U.S. state and local agencies use MOVES to develop emissions inventories for a variety of regulatory purposes, including the development of state implementation plans, transportation conformity determinations, general conformity evaluations, and analyses required under the National Environmental Policy Act. Others, including academics and interest groups, may also use MOVES to model the effects of policy choices and various mobile source scenarios.

The way MOVES calculates emissions varies depending on the processes and pollutants being modeled, and the vehicle or equipment type. MOVES includes the following emissions processes: running exhaust, start exhaust, hoteling (extended idle exhaust and auxiliary power exhaust), crankcase (running, start, and extended idle), brake wear, evaporative permeation, evaporative fuel vapor venting, evaporative fuel leaks, and refueling displacement vapor and spillage loss.

Running emissions are the archetypal mobile source emissions—exhaust emissions from a running vehicle. Running operation is defined as operation of internal-combustion engines after the engine and emission control systems have stabilized at operating temperature, i.e., "hot-stabilized" operation. The model uses vehicle population information to sort the vehicle population into source bins defined by vehicle source type, fuel type (gas, diesel, etc.), regulatory class, model year and age. Regulatory classes define vehicles with similar emission standards, such as heavy heavy-duty regulatory classes, which may occur in vehicles classified in several different source types, such as long-haul combination, short-haul single-unit and refuse trucks. For each source bin, the model uses vehicle characteristics and activity data (VMT, speed, idle fractions and driving cycles) to estimate the source hours in each running operating mode. The running operating modes are defined by the vehicle's instantaneous vehicle speed, acceleration, and estimated vehicle power. Each source bin and operating mode is

associated with an emission rate, and these are multiplied by source hours, adjusted as needed, and summed to estimate the total running emissions. Depending on the vehicle characteristics, MOVES may adjust the running emissions to account for local fuel parameters, air conditioning effects, humidity, inspection and maintenance programs, and fuel economy adjustments.

Onroad “start” emissions are the instantaneous exhaust emissions occur at the engine start (e.g., due to the fuel rich conditions in the cylinder to initiate combustion) as well as the additional running exhaust emissions that occur because the engine and emission control systems have not yet stabilized at the running operating temperature. Operationally, start emissions are defined as the difference in emissions between an exhaust emissions test with an ambient temperature start and the same test with the engine and emission control systems already at operating temperature. As such, the units for start emission rates are instantaneous grams/start. The model uses vehicle population information to sort the vehicle population into source bins defined by vehicle source type, fuel type (gas, diesel, etc.), regulatory class, model year and age. The model uses default data from instrumented vehicles (or user-provided values) to estimate the number of starts for each source bin and to allocate them among eight operating mode bins defined by the amount of time parked (“soak time”) prior to the start. Thus, the model accounts for different amounts of cooling of the engine and emission control systems. Each source bin and operating mode has an associated g/start emission rate. Start emissions are also adjusted to account for fuel characteristics, inspection and maintenance programs, and ambient temperatures.

MOVES defines “hoteling” as any long period of time (e.g., > 1 hour) that drivers spend in their long-haul combination truck vehicles during mandated rest times. Hoteling is differentiated from off-network idling because the engines are often idling under load while hoteling (e.g., to maintain cabin climate or run accessories). MOVES computes hoteling emissions only for diesel long-haul combination trucks. The default MOVES hoteling hours are computed as a fixed ratio to the miles these trucks travel on restricted access roads. Hoteling activity is allocated among four operating modes: engine idle (“extended idle”), diesel auxiliary power unit use, battery, or plug-in, and “All Engines and Accessories Off.” This allocation varies by model year. MOVES computes emissions for the first two modes based on the hours and source-bin specific emission rates.

Crankcase emissions include combustion products that pass by the piston rings of a compression ignition engine as well as oil droplets from the engine components and engine crankcase that are vented to the atmosphere. In MOVES, onroad crankcase emissions are computed as a ratio to the exhaust emissions, with separate values for running, start and hoteling (extended idle mode only). The crankcase ratio varies by pollutant, source type, fuel type, model year and exhaust process.

MOVES estimates brake wear from on road vehicles using weighted average g/hour rates that consider brake pad composition, number and type of brakes and braking intensity. Brake pads lose material during braking. A portion of this lost material becomes airborne particulate matter. This “brake wear” differs from exhaust particulate matter in its size and chemical composition. The emission rates in MOVES vary by vehicle regulatory class to account for average vehicle weight. Braking activity is modeled as a portion of running activity. In MOVES, the running operating modes for braking, idling and coasting are all modeled as including some amount of braking.

Contact between tires and the road surface causes tires to wear, and a portion of this material becomes airborne. This tire wear differs from exhaust particulate matter in its size and chemical composition. MOVES tire wear rates in g/hr are based on analysis of light-duty vehicle tire wear rates as a function of vehicle speed, extrapolated to other vehicles based on the number and size of tires. The tire wear operating mode bins differ from those used for running emissions and brake wear because they account only for speed and not for acceleration.

Permeation is the migration of hydrocarbons through materials in the fuel system. Permeation emissions are strongly influenced by the materials used for fuel tank walls, hoses and seals, and by the temperature, vapor pressure and ethanol content of the fuel. In MOVES, permeation is estimated only for vehicles using gasoline-based fuels (including E-85). Permeation is estimated for every hour of the day, regardless of activity. Permeation rates in g/hour vary by model year to account for the phase-in of tighter standards. Permeation emissions are adjusted to account for gasoline fuel properties and ambient temperatures.

When gasoline fuel tank temperatures rise due to vehicle operation or increased ambient temperatures, hydrocarbon vapors are generated within the fuel tank. The escape of these vapors is called Tank Vapor Venting or

Evaporative Fuel Vapor Venting. This vapor venting may be eliminated with a fully sealed metal fuel tank. More commonly, venting is reduced by using an activated charcoal canister to adsorb the vapors as they are generated; vapors from the canister are later consumed during vehicle operation. However, to prevent pressure build-up, canisters are open to the atmosphere, and after several days without operating, fuel vapors can diffuse through the charcoal or pass freely through a completely saturated canister. Tampering, mal-maintenance, vapor leaks, and system failure can also result in excess vapor venting.

MOVES calculates vapor venting only for vehicles using gasoline-based fuels (including E-85). The tank vapor generated depends on the rise in fuel tank temperature, fuel vapor pressure, ethanol content and altitude. Fuel tank temperature changes are modeled as a function of 24-hour temperature patterns and default vehicle activity, with different vapor generation rates for vehicles that are operating, “hot soaking” (parked, but still warm) and “cold soaking” (parked at ambient temperature). Vapor venting is modeled as a function of vapor generated, days cold soaking, model-year specific vehicle fuel system characteristics, and age and model year related vapor leak rates.

Evaporative fuel leaks (liquid leaks) are fuels escaping the gasoline fuel system in a non-vapor form. In MOVES, they are referred to as evaporative fuel leaks because they subsequently evaporate into the atmosphere after escaping the vehicle. These leaks may occur due to failures with fuel system materials, or due to tampering or mal-maintenance. Liquid spillage during refueling is modeled separately as part of the refueling process. In MOVES, fuel leak frequency is estimated as a function of vehicle age and vehicle emission standards. Fuel leak size (g/hour) is a function of age and vehicle operating mode (cold soaking, hot soaking or operating).

Refueling emissions are the displaced fuel vapors when liquid fuel is added to the vehicle tank. Refueling spillage is the vapor emissions from any liquid fuel that is spilled during refueling and subsequently evaporates. Diesel vehicles are assumed to have negligible vapor displacement, but MOVES does compute emissions for onroad diesel fuel spillage. Refueling vapor and spillage emissions are estimated from the total volume of fuel dispensed (gallons). This volume is based on previously calculated fuel consumption. In addition, refueling emissions are a function of gasoline vapor pressure, ambient temperatures, the presence of an on-board refueling vapor recovery system on the vehicles, and the use of Stage II vapor recovery controls at the refueling pump.

The MOVES nonroad module estimates emissions as the product of an adjusted emission factor multiplied by rated power, load factor, engine population and activity. Starting with base-year equipment populations by technology type and model year, the model uses growth factors to estimate the population in the analysis year. Estimates of median life at full load, load factors, activity and age distributions are then combined to generate estimates of nonroad emissions by equipment type, fuel type and age. National equipment populations are allocated to the county level using surrogate data. The model uses estimates of annual activity for each equipment type, e.g., expressed in terms of hours of operations or gallons of fuel used per year, to calculate yearly emission inventories. MOVES will also calculate inventories on a seasonal (i.e., summer, fall, winter, spring), monthly, or daily (i.e., weekday or weekend day) basis by allocating annual activity to these smaller time periods. The MOVES nonroad module includes the following emissions processes: running exhaust, crankcase exhaust, refueling displacement vapor and spillage loss (gasoline only), fuel vapor venting (diurnal, hot soak, and running loss), and fuel system permeation (gasoline only).

The MOVES database contains the required emission factors, adjustment factors, fuel data, and default vehicle population and activity data for all U.S. counties to support model runs for calendar years 1990 and 1999–2060. User databases may contain any of the tables that are in the default input database and are used to add or replace records as input by the user. These databases typically contain region-specific fuels, vehicle populations, age distributions, activity, and where applicable, I/M program characteristics. Vehicle and equipment emissions vary by location and time. However, for the most accurate results for a given time and location, MOVES is run for a specific case using accurate local inputs. In contrast, the national results generated with model defaults are calculated based on average inputs that do not fully capture the variation in emissions from time to time and place to place. MOVES allows user input of many parameters, and therefore, the quality of model output will depend on the quality of these inputs, as well as the appropriateness of the model defaults relied on.

The MOVES model is subject to review and evaluation in several different ways, including: peer review, a stakeholder work group, beta testing, evaluation by an industry-funded research group, and comparisons to independent data.

Updates to MOVES model data and algorithms are regularly peer reviewed, following EPA's peer review policies and procedures. The peer review process encompasses the over two dozen technical reports (<https://www.epa.gov/moves/moves-onroad-technical-reports> and <https://www.epa.gov/moves/nonroad-technical-reports>) that document the model's default inputs and algorithms. Reviewer comments and EPA's responses to comments are available at <https://cfpub.epa.gov/si/index.cfm>.

The MOVES Review Work Group provides MOVES-related recommendations to EPA via the Mobile Sources Technical Review Subcommittee of the Clean Air Act Advisory Committee. Members of the work group represent a variety of stakeholders and mobile source emissions modeling experts, including vehicle and engine manufacturers, fuel producers, state and local emission modelers, academic researchers, environmental advocates, and affected federal agencies. Throughout the development of MOVES, the EPA presents ongoing analyses, model evaluation, and MOVES updates to the work group. Notes and presentations from past work group meetings are available at <https://www.epa.gov/moves/moves-model-review-work-group>.

Prior to public release, draft versions of the model are tested by a small group of experienced users who alert EPA to potential errors in the code and provide comments on new model features (e.g., updates to the graphical user interface, installer).

Although not conducted regularly, MOVES has been subject to review by the Coordinating Research Council (CRC), a non-profit corporation supported by the energy and mobility industries. The CRC's most recent review in 2014 included three distinct elements: (1) a critical evaluation of modeling methods, (2) inventory analyses applied to three locations, and (3) a validation of the fuel methodology using independent data sources. The resulting report provided detailed recommendations in 10 key areas. These recommendations helped to prioritize efforts for model development and EPA published a detailed response to the review (EPA 2016).

Evaluating the performance of the MOVES model in comparison to independent data is useful for assessing the model's performance in accurately estimating current emission inventories and forecasting emission trends. It also helps identify areas in need of improvement, guiding future work and research. However, it is not appropriate to evaluate MOVES with comparisons against measurements based only on a few vehicles, or without sufficiently customizing MOVES inputs to account for the measurement conditions (e.g., fleet composition, vehicle activity, meteorology).

One approach to assess the MOVES model's fidelity to real-world vehicle activity is to compare macro-scale/top-down gasoline and diesel fuel sales estimates with bottom-up fuel consumption modeled by MOVES. A study conducted by EPA (Han, 2021) compared fuel consumption estimated from MOVES3 output with national fuel sales data published by FHWA (FHWA Highway Statistics Table MF-27), for calendar years 2005, 2007, 2009, and 2011-2019. The study notes several limitations of the comparison, including: potential inaccuracies in state-level fuel tax data collected by FHWA, inconsistencies between MOVES and FHWA's methodology for allocating highway and off-road fuel use, uncertainties in MOVES activity estimates and fleet characterization (e.g., FHWA excludes "public" vehicles while MOVES includes these sources), and uncertainties in the average fuel energy content values used to convert MOVES total energy output to fuel consumption volumes. Given these limitations, the study found that overall, MOVES3 fuel consumption is higher than FHWA reported data. For calendar years 2016 and later, MOVES3 gasoline and diesel fuel consumption estimates are within 4 percent and 10 percent, respectively, of FHWA estimates. For earlier years, MOVES3 gasoline consumption estimates are within 9 percent of FHWA data while MOVES3 diesel fuel consumption is within 20 percent of FHWA reported values. Note that greater uncertainties exist in the diesel fuel volume data and methodology (e.g., many of the "public" vehicles that are excluded from FHWA fuel sales data but are included in MOVES are diesel-fueled vehicles such as refuse trucks and buses).

Past efforts to evaluate MOVES have prioritized comparisons for the major sources of emissions (e.g., light-duty gasoline, heavy-duty diesel) and local geographic areas where significant independent data are available. In assessing the results, systematic bias observed across multiple data sources was considered indicative of model

underperformance. On the other hand, if the model predictions are within the variability of independent measurements, it gives confidence that the model is predicting real-world emissions reasonably well.

Evaluating MOVES emission rates may include comparisons to data from sources such as dynamometer tests, remote sensing devices and portable emission monitoring systems. To capture rare (but influential) high emitters, it is important that the data samples are large and diverse, and it is useful when the comparison data represent known operating conditions. Such controlled comparisons are particularly valuable because the emission rates from the study can be compared with MOVES emission rates using the same activity and fleet variables such as vehicle mix, vehicle age, and vehicle operating mode. EPA has undertaken several studies comparing MOVES emission rates with real-world measurements (e.g., Choi et al. (2017), U.S. EPA (2022)) and found that MOVES is generally within the variability of the measured data.

Other studies compare “localized composite” emissions, using composite emission measurements from many vehicles by tunnel or roadside emission monitors where vehicle emissions are predominant and vehicle activity and fleet mix can be accounted for to some degree. A strength of tunnel and roadside measurements is that they can capture the large sample sizes of vehicles operating in real-world conditions needed to measure “fleet-average” emission rates. However, such comparisons only assess the narrow operating conditions represented at the specific location.

At a more general level, some MOVES evaluations compare regional air quality model results from models such as the Community Multiscale Air Quality Modeling System with air quality monitor and deposition data and satellite data. These “top-down studies” are useful to assess the overall emissions contribution from all relevant emission sources to air quality measurements. Discrepancies between air quality modeling predictions and measurements can point to deficiencies in the emissions inventory but may be confounded with deficiencies in the air quality model (e.g., modeling transport, boundary layer, deposition, transformation, and other physical and chemical processes). In addition, top-down studies on their own cannot identify the individual sources in the emissions inventory that are responsible for the modeling discrepancy.

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3.3. Methodology for Estimating Emissions from Commercial Aircraft Jet Fuel Consumption

Activity data on civilian domestic and international aircraft fuel consumption for 2023 was not available at the time of this report. Therefore, data for 2023 was proxied based on 2022 data. The methodology used for estimating emissions from civilian international bunker fuels is consistent with previous Inventories. The 2023 data will be updated in future reports as needed.

3.4. Methodology for Estimating CH₄ Emissions from Coal Mining

EPA uses an IPCC Tier 3 method for estimating CH₄ emissions from underground mining and an IPCC Tier 2 method for estimating CH₄ emissions from surface mining and post-mining activities (for both coal production from underground mines and surface mines). The methodology for estimating CH₄ emissions from coal mining consists of two steps:

- **Estimate emissions from underground mines.** These emissions have two sources: ventilation systems and degasification systems. They are estimated using mine-specific data, then summed to determine total CH₄ liberated. The CH₄ recovered and used is then subtracted from this total, resulting in an estimate of net emissions to the atmosphere.
- **Estimate emissions from surface mines and post-mining activities.** This step does not use mine-specific data; rather, it consists of multiplying coal-basin-specific coal production by coal-basin-specific gas content and an emission factor.

Step 1: Estimate CH₄ Liberated and CH₄ Emitted from Underground Mines

Underground mines generate CH₄ from ventilation systems and degasification systems. Some mines recover and use the generated CH₄, thereby reducing emissions to the atmosphere. Total CH₄ emitted from underground mines equals the CH₄ liberated from ventilation systems, plus the CH₄ liberated from degasification systems, minus CH₄ recovered and used.

Step 1.1: Estimate CH₄ Liberated from Ventilation Systems

All coal mines with detectable CH₄ emissions use ventilation systems to ensure that CH₄ levels remain within safe concentrations. Many coal mines do not have detectable levels of CH₄; others emit several million cubic feet per day (MMCFD) from their ventilation systems. On a quarterly basis, the U.S. Mine Safety and Health Administration (MSHA) measures CH₄ concentration levels at underground mines. MSHA maintains a database of measurement data from all underground mines with detectable levels of CH₄ in their ventilation air (MSHA 2024).⁶⁰ Based on quarterly measurements, MSHA estimates average daily CH₄ liberated at each of these underground mines.

For 1990 through 1999, average daily CH₄ emissions from MSHA were multiplied by the number of days in the year (i.e., coal mine assumed in operation for all four quarters) to determine the annual emissions for each mine. For 2000 through 2023, the average daily CH₄ emission rate for each mine is determined using the CH₄ total for all data measurement events conducted during the calendar year and total duration of all data measurement events (in days). The calculated average daily CH₄ emissions were then multiplied by 365 days to estimate annual ventilation emissions (or 366 in the case of a leap year).

Total ventilation emissions for a particular year are estimated by summing emissions from individual mines.

Since 2011, the nation's "gassiest" underground coal mines—those that liberate more than 36,500,000 cubic feet of CH₄ per year (about 17,525 MT CO₂ Eq.)—have been required to report to EPA's GHGRP (EPA 2024).⁶¹ Mines that report to EPA's GHGRP must report quarterly measurements of CH₄ emissions from ventilation systems; they have the option of recording their own measurements, or using the measurements taken by MSHA as part of that agency's quarterly safety inspections of all mines in the U.S. with detectable CH₄ concentrations.

⁶⁰ MSHA records coal mine methane readings with concentrations of greater than 50 ppm (parts per million) methane. Readings below this threshold are considered non-detectable.

⁶¹ Underground coal mines report to EPA under subpart FF of EPA's GHGRP (40 CFR Part 98). In 2023, 58 underground coal mines reported to the program.

Since 2013, ventilation emission estimates have been calculated based on both EPA's GHGRP⁶² data submitted by underground mines, and on mine-specific CH₄ measurement data obtained directly from MSHA for the remaining mines. The CH₄ liberated from ventilation systems is estimated by summing the emissions from the mines reporting to EPA's GHGRP and emissions based on MSHA measurements for the remaining mines not reporting to EPA's GHGRP.

Table A-95: Mine-Specific Data Used to Estimate Ventilation Emissions

Year	Individual Mine Data Used
1990	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total) ^a
1991	1990 Emission Factors Used Instead of Mine-Specific Data
1992	1990 Emission Factors Used Instead of Mine-Specific Data
1993	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total) ^a
1994	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total) ^a
1995	All Mines Emitting at Least 0.5 MMCFD (Assumed to Account for 94.1% of Total) ^a
1996	All Mines Emitting at Least 0.5 MMCFD (Assumed to Account for 94.1% of Total) ^a
1997	All Mines with Detectable Emissions (Assumed to Account for 100% of Total)
1998	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total) ^a
1999	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total) ^a
2000	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total) ^a
2001	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total) ^a
2002	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total) ^a
2003	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total) ^a
2004	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total) ^a
2005	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total) ^a
2006	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total) ^a
2007	All Mines with Detectable Emissions (Assumed to Account for 100% of Total)
2008	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 98.96% of Total) ^b
2009	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 98.96% of Total) ^b
2010	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 98.96% of Total) ^b
2011	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 98.96% of Total) ^b
2012	All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 98.96% of Total) ^b
2013	All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% of Total)
2014	All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% of Total)
2015	All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% of Total)
2016	All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% of Total)
2017	All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% of Total)
2018	All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% of Total)
2019	All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% of Total)
2020	All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% of Total)
2021	All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% of Total)
2022	All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% of Total)
2023	All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% of Total)

^a Factor derived from a complete set of individual mine data collected for 1997.

^b Factor derived from a complete set of individual mine data collected for 2007.

⁶² In implementing improvements and integrating data from EPA's GHGRP, the EPA followed the latest guidance from the IPCC on the use of facility-level data in national inventories (IPCC 2011).

Step 1.2: Estimate CH₄ Liberated from Degasification Systems

Coal mines use several types of degasification systems to remove CH₄, including pre-mining vertical and horizontal wells (to recover CH₄ before mining) and post-mining vertical wells and horizontal boreholes (to recover CH₄ during mining of the coal seam). Post-mining gob wells and cross-measure boreholes recover CH₄ from the overburden (i.e., gob area) after mining of the seam (primarily in longwall mines).

Nineteen mines employed degasification systems in 2023, and all of these mines reported the CH₄ liberated through these systems to the EPA's GHGRP (EPA 2024). Eleven of the 19 mines with degasification systems had operational CH₄ recovery and use projects, including one mine with two recovery and use projects, and the other eight mines reported emitting CH₄ from degasification systems to the atmosphere. Several of the mines venting CH₄ from degasification systems use a small portion of the gas to fuel gob well blowers or compressors in remote locations where electricity is not available. However, this CH₄ use is not considered to be a formal recovery and use project.

Degasification information reported to EPA's GHGRP by underground coal mines is the primary source of data used to develop estimates of CH₄ liberated from degasification systems. Data reported to EPA's GHGRP were used exclusively to estimate CH₄ liberated from degasification systems at 14 of the 19 mines that used degasification systems in 2023.

Degasification volumes for the life of mined-through, pre-mining wells are attributed to the mine as emissions in the year in which the well is mined through.⁶³ EPA's GHGRP does not require gas production from virgin coal seams (coalbed methane) to be reported by coal mines under Subpart FF. Most pre-mining wells drilled from the surface are considered coalbed methane wells and are reported under another subpart of the program (Subpart W, "Petroleum and Natural Gas Systems"). As a result, for the five mines with degasification systems that include pre-mining wells that were mined through in 2023, EPA's GHGRP information was supplemented with historical data from state gas well production databases and mine-specific information regarding the dates on which pre-mining wells were mined through (GSA 2024; JWR 2010; El Paso 2009; ERG 2024). For pre-mining wells, the cumulative CH₄ production from the well is totaled using gas sales data and is considered liberated from the mine's degasification system the year in which the well is mined through.

Reports to EPA's GHGRP with CH₄ liberated from degasification systems are reviewed for errors in reporting. For some mines, GHGRP data are corrected for the *Inventory* based on expert judgment. Common errors include reporting CH₄ liberated as CH₄ destroyed and vice versa. Other errors include reporting CH₄ destroyed without reporting any CH₄ liberated by degasification systems. In the rare cases where GHGRP data are inaccurate and gas sales data are unavailable, estimates of CH₄ liberated are based on historical CH₄ liberation rates. No QA/QC issues or errors were identified in the 2023 subpart FF data.

Step 1.3: Estimate CH₄ Recovered from Ventilation and Degasification Systems, and Utilized or Destroyed (Emissions Avoided)

There were 11 active coal mines with operational CH₄ recovery and use projects in 2023, including one mine that had two recovery and use projects (for a total of 12 recovery and use projects overall, located at these 11 mines). All of these projects involved degasification systems. Ten of these 11 mines sold the recovered CH₄ to a pipeline, including one mine that used CH₄ to fuel a thermal coal dryer. One mine destroyed the recovered CH₄ using enclosed flares.

The CH₄ recovered and used (or destroyed) at the eleven coal mines described above were estimated using the following methods:

- EPA's GHGRP data was exclusively used to estimate the CH₄ recovered and used from six mines that deployed degasification systems in 2023. Based on quarterly measurements of gas flow and CH₄

⁶³ A well is "mined through" when coal mining development or the working face intersects the borehole or well.

concentrations, the GHGRP summary data for degasification destruction at each mine were added together to estimate the CH₄ recovered and used from degasification systems.

- State sales data were used to supplement the GHGRP data to estimate CH₄ recovered and used from five mines that deployed degasification systems in 2023 (DMME 2024; GSA 2024; ERG 2024; WVGES 2024). All of these mines intersected pre-mining wells in 2023. Supplemental information was used for these mines because estimating CH₄ recovery and use from pre-mining wells requires additional data (data not reported under Subpart FF of EPA's GHGRP; see discussion in step 1.2 above) to account for the emissions avoided prior to the well being mined through. The 2023 data came from state gas production databases (GSA 2024; ERG 2024), as well as mine-specific information on the timing of mined-through, pre-mining wells (JWR 2010; El Paso 2009, ERG 2019-2024). For pre-mining wells, the cumulative CH₄ production from the wells was totaled using gas sales data and was considered to be CH₄ recovered and used from the mine's degasification system in the year in which the well was mined through.

Step 2: Estimate CH₄ Emitted from Surface Mines and Post-Mining Activities

Mine-specific data are not available for estimating CH₄ emissions from surface coal mines or for post-mining activities. For surface mines, basin-specific coal production data obtained from the Energy Information Administration's *Annual Coal Report* are multiplied by basin-specific gas contents and a 150 percent emission factor (to account for CH₄ from over- and under-burden) to estimate CH₄ emissions (King 1994; Saghafe 2013). For post-mining activities, basin-specific coal production data are multiplied by basin-specific gas contents and a mid-range 32.5 percent emission factor accounting for CH₄ desorption during coal transportation and storage (Creedy 1993). Basin-specific *in situ* gas content data were compiled from AAPG (1984) and USBM (1986). Beginning in 2006, revised data on *in situ* CH₄ content and emission factors have been used (EPA 1996, 2005).

Step 2.1: Define the Geographic Resolution of the Analysis and Collect Coal Production Data

The first step in estimating CH₄ emissions from surface mining and post-mining activities is to define the geographic resolution of the analysis and to collect coal production data at that level of resolution. The analysis is conducted by coal basin as defined in Table A-96, which presents coal basin definitions by basin and by state.

The Energy Information Administration's *Annual Coal Report* (EIA 2024) includes state- and county-specific underground and surface coal production by year. To calculate production by basin, the state-level data are grouped into coal basins using the basin definitions listed in Table A-96. For two states—West Virginia and Kentucky—county-level production data are used for the basin assignments because coal production occurred in geologically distinct coal basins within these states. Table A-97 presents the coal production data aggregated by basin.

Step 2.2: Estimate Emission Factors for Each Emissions Type

Emission factors for surface-mined coal were developed from the *in situ* CH₄ content of the surface coal in each basin. Based on analyses conducted in Canada and Australia on coals similar to those present in the United States (King 1994; Saghafe 2013), the surface mining emission factor used was conservatively estimated to be 150 percent of the *in situ* CH₄ content of the basin. Furthermore, the post-mining emission factors used were estimated to be 25 to 40 percent of the average *in situ* CH₄ content in the basin. For this analysis, the post-mining emission factor was determined to be 32.5 percent of the *in situ* CH₄ content in the basin. Table A-98 presents the average *in situ* content for each basin, along with the resulting emission factor estimates.

Step 2.3: Estimate CH₄ Emitted

The total amount of CH₄ emitted from surface mines and post-mining activities is calculated by multiplying the coal production in each basin by the appropriate emission factors.

Table A-96 lists each of the major coal mine basins in the United States and the states in which they are located. As shown in Figure A-5, several coal basins span several states. Table A-97 shows annual underground, surface, and total coal production (in short tons) for each coal basin. Table A-98 shows the surface, post-surface, and post-

underground emission factors used for estimating CH₄ emissions for each of the categories. For underground mines, Table A-99 presents annual estimates of CH₄ emissions for ventilation and degasification systems, and CH₄ recovered and used. Table A-100 presents annual estimates of total CH₄ emissions from underground, post-underground, surface, and post-surface activities.

Table A-96: Coal Basin Definitions by Basin and by State

Basin	States
Northern Appalachian Basin	Maryland, Ohio, Pennsylvania, West Virginia North
Central Appalachian Basin	Kentucky East, Tennessee, Virginia, West Virginia South
Warrior Basin	Alabama, Mississippi
Illinois Basin	Illinois, Indiana, Kentucky West
Southwest and Rockies Basin	Arizona, California, Colorado, New Mexico, Utah
North Great Plains Basin	Montana, North Dakota, Wyoming
West Interior Basin	Arkansas, Iowa, Kansas, Louisiana, Missouri, Oklahoma, Texas
Northwest Basin	Alaska, Washington
State	Basin
Alabama	Warrior Basin
Alaska	Northwest Basin
Arizona	Southwest and Rockies Basin
Arkansas	West Interior Basin
California	Southwest and Rockies Basin
Colorado	Southwest and Rockies Basin
Illinois	Illinois Basin
Indiana	Illinois Basin
Iowa	West Interior Basin
Kansas	West Interior Basin
Kentucky (east)	Central Appalachian Basin
Kentucky (west)	Illinois Basin
Louisiana	West Interior Basin
Maryland	Northern Appalachian Basin
Mississippi	Warrior Basin
Missouri	West Interior Basin
Montana	North Great Plains Basin
New Mexico	Southwest and Rockies Basin
North Dakota	North Great Plains Basin
Ohio	Northern Appalachian Basin
Oklahoma	West Interior Basin
Pennsylvania	Northern Appalachian Basin
Tennessee	Central Appalachian Basin
Texas	West Interior Basin
Utah	Southwest and Rockies Basin
Virginia	Central Appalachian Basin
Washington	Northwest Basin
West Virginia South	Central Appalachian Basin
West Virginia North	Northern Appalachian Basin
Wyoming	North Great Plains Basin

Figure A-5: Locations of U.S. Coal Basins

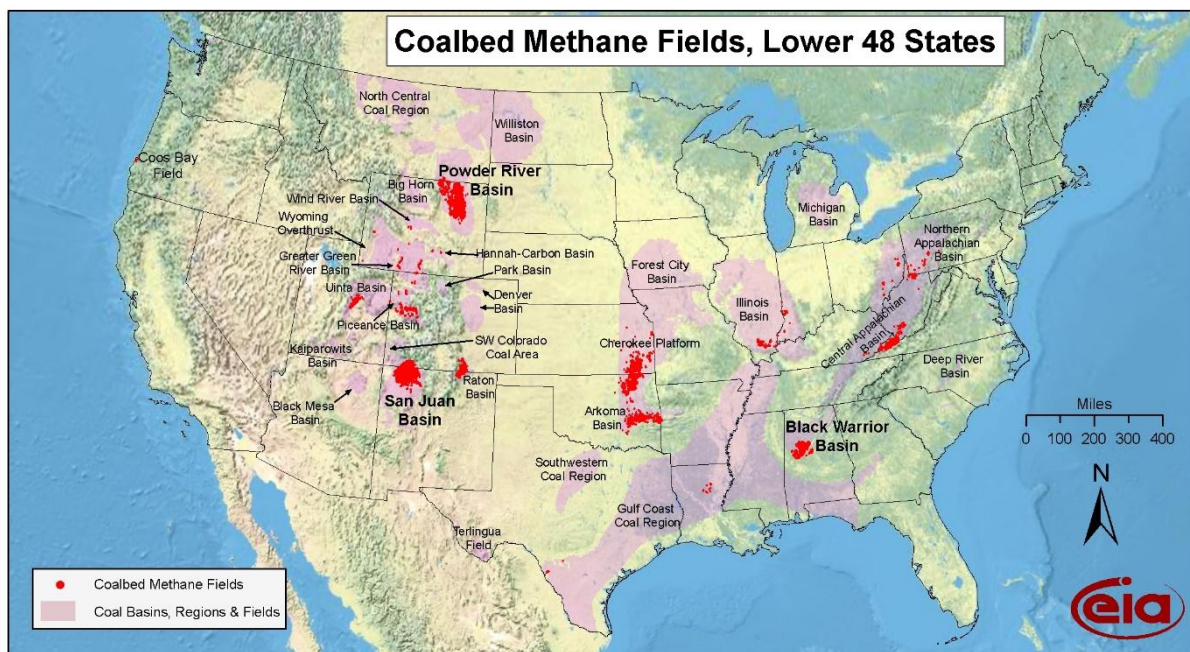


Table A-97: Annual Coal Production (Thousand Short Tons)

Basin	1990	2005	2019	2020	2021	2022	2023
Underground Coal Production	423,556	368,612	267,373	195,528	220,597	222,143	217,928
N. Appalachia	103,865	111,151	97,905	71,998	84,265	83,269	82,757
Cent. Appalachia	198,412	123,082	39,957	30,249	34,562	35,571	36,410
Warrior	17,531	13,295	11,980	10,451	7,959	9,121	11,130
Illinois	69,167	59,180	81,061	54,334	62,667	66,407	65,753
S. West/Rockies	32,754	60,866	27,257	20,049	20,702	20,344	14,297
N. Great Plains	1,722	572	9,213	8,447	10,442	7,431	7,581
West Interior	105	465	0	0	0	0	0
Northwest	0	0	0	0	0	0	0
Surface Coal Production	602,753	762,190	438,445	339,450	356,203	371,468	359,728
N. Appalachia	60,761	28,873	8,476	6,215	6,677	7,416	7,729
Cent. Appalachia	94,343	112,222	32,742	17,921	20,299	23,846	26,498
Warrior	11,413	11,599	4,841	4,288	4,581	4,656	3,598
Illinois	72,000	33,703	18,591	13,098	9,713	11,084	10,827
S. West/Rockies	43,863	42,756	18,394	13,420	12,872	13,722	12,982
N. Great Plains	249,356	474,056	329,164	262,968	283,424	292,263	282,839
West Interior	64,310	52,262	25,261	20,519	17,595	17,467	14,246
Northwest	6,707	6,720	975	1,021	1,042	1,014	1,009
Total Coal Production	1,026,309	1,130,802	705,818	534,978	576,800	593,611	577,656
N. Appalachia	164,626	140,023	106,381	78,213	90,942	90,685	90,486
Cent. Appalachia	292,755	235,305	72,700	48,170	54,861	59,417	62,908
Warrior	28,944	24,894	16,822	14,739	12,540	13,777	14,728
Illinois	141,167	92,883	99,652	67,432	72,380	77,491	76,580
S. West/Rockies	76,617	103,622	45,652	33,469	33,574	34,066	27,279

N. Great Plains	251,078	474,629	338,376	271,415	293,866	299,694	290,420
West Interior	64,415	52,727	25,261	20,519	17,595	17,467	14,246
Northwest	6,707	6,720	975	1,021	1,042	1,014	1,009

Note: Totals may not sum due to independent rounding.

Table A-98: Coal Underground, Surface, and Post-Mining CH₄ Emission Factors (ft³ per Short Ton)

Basin	Surface Average <i>In Situ</i> Content	Underground Average <i>In Situ</i> Content	Surface Mine Factors	Post-Mining Surface Factors	Post-Mining Underground Factors
Northern Appalachia	59.5	138.4	89.3	19.3	45.0
Central Appalachia (WV)	24.9	136.8	37.4	8.1	44.5
Central Appalachia (VA)	24.9	399.1	37.4	8.1	129.7
Central Appalachia (E KY)	24.9	61.4	37.4	8.1	20.0
Warrior	30.7	266.7	46.1	10.0	86.7
Illinois	34.3	64.3	51.5	11.1	20.9
Rockies (Piceance Basin)	33.1	196.4	49.7	10.8	63.8
Rockies (Uinta Basin)	16.0	99.4	24.0	5.2	32.3
Rockies (San Juan Basin)	7.3	104.8	11.0	2.4	34.1
Rockies (Green River Basin)	33.1	247.2	49.7	10.8	80.3
Rockies (Raton Basin)	33.1	127.9	49.7	10.8	41.6
N. Great Plains (WY, MT)	20.0	15.8	30.0	6.5	5.1
N. Great Plains (ND)	5.6	15.8	8.4	1.8	5.1
West Interior (Forest City, Cherokee Basins)	34.3	64.3	51.5	11.1	20.9
West Interior (Arkoma Basin)	74.5	331.2	111.8	24.2	107.6
West Interior (Gulf Coast Basin)	11.0	127.9	16.5	3.6	41.6
Northwest (AK)	16.0	160.0	24.0	5.2	52.0
Northwest (WA)	16.0	47.3	24.0	5.2	15.4

Sources: 1986 USBM Circular 9067, *Results of the Direct Method Determination of the Gas Contents of U.S. Coal Basins*; U.S. DOE Report DOE/METC/83-76, *Methane Recovery from Coalbeds: A Potential Energy Source*; 1986–1988 Gas Research Institute Topical Report, *A Geologic Assessment of Natural Gas from Coal Seams*; 2005 U.S. EPA Draft Report, *Surface Mines Emissions Assessment*.

Table A-99: Underground Coal Mining CH₄ Emissions (Billion Cubic Feet)

Activity	1990	2005	2019	2020	2021	2022	2023
Ventilation Output	112	75	62	60	57	52	53
Adjustment Factor for Mine Data	98%	98%	100%	100%	100%	100%	100%
Adjusted Ventilation Output	114	77	62	60	57	52	53
Degasification System Liberated	54	47	43	40	40	52	57
Total Underground Liberated	168	124	105	100	97	104	110
Recovered & Used	(14)	(37)	(34)	(34)	(36)	(46)	(48)
Total	154	87	71	65	61	58	62

Note: Totals may not sum due to independent rounding.

Table A-100: Total Coal Mining CH₄ Emissions (Billion Cubic Feet)

Activity	1990	2005	2019	2020	2021	2022	2023
Underground Mining	154	87	71	65	61	58	62
Surface Mining	22	25	13	10	11	11	11
Post-Mining (Underground)	19	16	11	8	9	9	9

Post-Mining (Surface)	5	5	3	2	2	2	2
Total	200	133	98	86	83	81	84

Note: Totals may not sum due to independent rounding.

Table A-101: Total Coal Mining CH₄ Emissions by State (Million Cubic Feet)

State	1990	2005	2019	2020	2021	2022	2023
Alabama	32,097	15,831	9,494	9,767	8,220	7,059	6,562
Alaska	50	42	28	30	30	30	29
Arizona	151	161	51	0	0	0	0
Arkansas	5	+	0	0	0	0	0
California	1	0	0	0	0	0	0
Colorado	10,187	13,441	1,730	1,380	1,392	1,139	1,418
Illinois	10,180	6,488	5,661	4,100	4,267	5,008	5,419
Indiana	2,232	3,303	6,807	6,067	6,388	5,531	5,607
Iowa	24	0	0	0	0	0	0
Kansas	45	11	0	0	0	0	0
Kentucky	10,018	6,898	2,264	1,765	2,164	2,734	2,387
Louisiana	64	84	36	14	6	6	6
Maryland	474	361	119	92	113	145	114
Mississippi	0	199	151	145	179	189	150
Missouri	166	37	12	10	3	5	9
Montana	1,373	1,468	1,038	775	816	797	823
New Mexico	363	2,926	1,446	723	1,661	948	106
North Dakota	299	306	276	270	271	273	246
Ohio	4,406	3,120	1,283	793	852	494	398
Oklahoma	226	825	116	367	+	+	+
Pennsylvania	21,864	17,904	23,513	18,931	19,100	17,864	20,177
Tennessee	276	115	17	7	0	0	0
Texas	1,119	922	468	395	346	343	277
Utah	3,587	4,787	811	845	770	769	636
Virginia	46,041	8,649	6,959	6,726	6,198	5,579	5,856
Washington	146	154	0	0	0	0	0
West Virginia	48,335	29,745	25,556	24,277	21,416	23,052	25,361
Wyoming	6,671	14,745	10,409	8,099	8,621	8,933	8,660
Total	200,399	132,523	98,247	85,579	82,813	80,898	84,242

+ Does not exceed 0.5 million cubic feet.

Note: The emission estimates provided above are inclusive of emissions from underground mines, surface mines and post-mining activities. The totals include CH₄ liberated, minus CH₄ recovered and used (i.e., representing total “net” emissions). The following states have neither underground nor surface mining and thus report no emissions as a result of coal mining: Connecticut, Delaware, Florida, Georgia, Hawaii, Idaho, Maine, Massachusetts, Michigan, Minnesota, Nebraska, Nevada, New Hampshire, New Jersey, New York, North Carolina, Oregon, Rhode Island, South Carolina, South Dakota, Vermont, and Wisconsin. Totals may not sum due to independent rounding.

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3.5. Methodology for Estimating CH₄, CO₂, and N₂O Emissions from Petroleum Systems

For details on the emissions, emission factors, activity data, data sources, and methodologies for each year from 1990 to 2023 please see the spreadsheet file annexes for the current (i.e., 1990 to 2023) *Inventory*, available at <https://www.epa.gov/ghgemissions/stakeholder-process-natural-gas-and-petroleum-systems-1990-2023-inventory>.

As described in the main body text on Petroleum Systems, the *Inventory* methodology involves the calculation of CH₄, CO₂, and N₂O emissions for approximately 100 emissions sources, and then the summation of emissions for each petroleum systems segment. The approach for calculating emissions for petroleum systems generally involves the application of emission factors to activity data.

Emission Factors

Table 3.5-2, Table 3.5-7, and Table 3.5-10 show CH₄, CO₂, and N₂O emissions, respectively, for all sources in Petroleum Systems, for all time series years. Table 3.5-3, Table 3.5-8, and Table 3.5-11 show the CH₄, CO₂, and N₂O average emission factors, respectively, for all sources in Petroleum Systems, for all time series years. These emission factors are calculated by dividing net emissions by activity. Therefore, in a given year, these emission factors reflect the estimated contribution from controlled and uncontrolled fractions of the source population.

Additional detail on the basis for emission factors used across the time series is provided in Table 3.5-4, Table 3.5-9, Table 3.5-12, and below.

In addition to the Greenhouse Gas Reporting Program (GHGRP), key references for emission factors for CH₄ and non-combustion-related CO₂ emissions from the U.S. petroleum industry include a 1999 EPA/Radian report *Methane Emissions from the U.S. Petroleum Industry* (EPA/Radian 1999), which contained the most recent and comprehensive determination of CH₄ emission factors for CH₄-emitting activities in the oil industry at that time, a 1999 EPA/ICF draft report *Estimates of Methane Emissions from the U.S. Oil Industry* (EPA/ICF 1999) which is largely based on the 1999 EPA/Radian report, and a detailed study by the Gas Research Institute and EPA *Methane Emissions from the Natural Gas Industry* (EPA/GRI 1996). These studies still represent best available data in many cases—in particular, for the early years of the time series.

Data from studies and EPA's GHGRP (EPA 2024b) allows for emission factors to be calculated that account for adoption of control technologies and emission reduction practices. For several sources, EPA has developed control category-specific emission factors from recent data that are used over the time series (paired with control category-specific activity data that fluctuates to reflect control adoption over time). For oil well completions with hydraulic fracturing, controlled and uncontrolled emission factors were developed using GHGRP data. For associated gas, separate emission estimates are developed from GHGRP data for venting and flaring. For oil tanks, emissions estimates were developed for large and small tanks with flaring or VRU control, without control devices, and with upstream malfunctioning separator dump valves. For pneumatic controllers, separate estimates are developed for low bleed, high bleed, and intermittent controllers. Some sources in Petroleum Systems that use methodologies based on GHGRP data use a basin-level aggregation approach, wherein EPA calculates basin-specific emissions and/or activity factors for basins that contribute at least 10 percent of total annual emissions (on a CO₂ Eq. basis) from the source in any year—and combines all other basins into one grouping. This methodology is applied for associated gas venting and flaring and miscellaneous production flaring. Other sources in the onshore production segment use basin-specific emissions and/or activity factors for all basins that reported data to subpart W and use subpart W averages for all basins that did not report data to the GHGRP. This methodology is applied to pneumatic controllers, chemical injection pumps, wellpad equipment leaks, production storage tanks, and completions and workovers (EPA 2023a; EPA 2024a). Produced Water CH₄ estimates are calculated using annual produced water quantities (Enverus 2023 and EPA 2023b and an emission factor from EPA's *Nonpoint Oil and Gas Emission Estimation Tool* (EPA 2017b).

For the refining segment, EPA has directly used the GHGRP data for all emission sources for recent years (2010 forward) (EPA 2024b) and developed source level throughput-based emission factors from GHGRP data to estimate emissions in earlier time series years (1990 to 2009). For some sources within refineries, EPA continues to apply the historical emission factors for all time series years. All refineries have been required to report CH₄, CO₂, and N₂O emissions to GHGRP for all major activities since 2010. The national totals of these emissions for each activity were used for the 2010 to 2023 emissions. The national emission totals for each activity were divided by refinery feed rates for four *Inventory* years (2010 to 2013) to develop average activity-specific emission factors, which were used to estimate national emissions for each refinery activity from 1990 to 2009 based on national refinery feed rates for each year (EPA 2015b).

Offshore emissions are taken from analysis of the *Gulfwide Emission Inventory Studies* and GHGRP data (BOEM 2024a-d; EPA 2024b; EPA 2024c; EPA 2020). Emission factors are calculated for offshore facilities located in the Gulf of America, Pacific, and Alaska regions.

When a CO₂-specific emission factor is not available for a source, the CO₂ emission factors were derived from the corresponding source CH₄ emission factors. The amount of CO₂ in the crude oil stream changes as it passes through various equipment in petroleum production operations. As a result, four distinct stages/streams with varying CO₂ contents exist. The four streams that are used to estimate the emissions factors are the associated gas stream separated from crude oil, hydrocarbons flashed out from crude oil (such as in storage tanks), whole crude oil itself when it leaks downstream, and gas emissions from offshore oil platforms. For this approach, CO₂ emission factors are estimated by multiplying the existing CH₄ emissions factors by a conversion factor, which is the ratio of CO₂ content to methane content for the particular stream. Ratios of CO₂ to CH₄ volume in emissions are presented in Table 3.5-1.

N₂O emission factors were calculated using GHGRP data. For each flaring emission source calculation methodology that uses GHGRP data, the existing source-specific methodology was applied to calculate N₂O emission factors.

Activity Data

Table 3.5-5 shows the activity data for all sources in Petroleum Systems, for all time series years. Additional detail on the basis for activity data used across the time series is provided in Table 3.5-6, and below.

For many sources, complete activity data were not available for all years of the time series. In such cases, one of three approaches was employed. Where appropriate, the activity data were calculated from related statistics using ratios developed based on EPA 1996, and/or GHGRP data. For major equipment (equipment leak categories), pneumatic controllers, chemical injection pumps, oil tanks, and completions and workovers, GHGRP Subpart W data were used to develop activity factors (e.g., count per well) that are applied to calculated activity in recent years; to populate earlier years of the time series, linear interpolation is used to connect GHGRP-based estimates with existing estimates in earlier years of the time series (e.g., 1990 to 1992). In other cases, the activity data were held constant from 1990 through 2014 based on EPA (1999). Lastly, the previous year's data were used when data for the current year were unavailable.

For offshore production in the GOA, the number of active major and minor complexes are used as activity data. For offshore production in the Pacific and Alaska region, the activity data are region-specific production. The activity data for the total crude transported in the transportation segment are not available, therefore the activity data for the refining sector (i.e., refinery feed in 1000 bbl/year) was also used for the transportation sector, applying an assumption that all crude transported is received at refineries. In the few cases where no data were located, oil industry data based on expert judgment were used. In the case of non-combustion CO₂ and N₂O emission sources, the activity factors are the same as for CH₄ emission sources. In some instances, where recent time series data (e.g., year 2023) are not yet available, year 2022 data were used as proxy.

Methodology for well counts and events

EPA used DrillingInfo and Prism, production databases maintained by Enverus Inc. (Enverus 2023), covering U.S. oil and natural gas wells to populate time series activity data for active oil wells, oil wells drilled, and oil well completions and workovers with hydraulic fracturing. Revised data for 2023 were not available from Enverus for

public review estimates, therefore EPA used 2022 data as proxy for 2023. For more information on Enverus data processing, please see Annex 3.6 Methodology for Estimating CH₄, CO₂, and N₂O from Natural Gas Systems.

Reductions data: Federal regulations

Regulatory actions reducing emissions in the current *Inventory* include the New Source Performance Standards (NSPS) and National Emission Standards for Hazardous Air Pollutants (NESHAP) regulations for dehydrator vents in the production segment.

The *Inventory* reflects the NSPS for oil and gas through the use of a net factor approach that captures shifts to lower emitting technologies required by the regulation. Examples include separating oil well completions and workovers with hydraulic fracturing into four categories and developing control technology-specific methane emission factors and year-specific activity data for each category; establishing control category-specific emission factors and associated year-specific activity data for oil tanks; and calculating year-specific activity data for pneumatic controller bleed categories.

In regard to the oil and natural gas industry, the NESHAP regulation addresses HAPs from the oil and natural gas production sectors and the natural gas transmission and storage sectors of the industry. Though the regulation deals specifically with HAPs reductions, methane emissions are also incidentally reduced.

NESHAP driven reductions from storage tanks are estimated with net emission methodologies that take into account controls implemented due to regulations.

Methane, Carbon Dioxide, and Nitrous Oxide Emissions by Emission Source for Each Year

Annual CH₄, CO₂, and N₂O emissions for each source were calculated by multiplying the activity data for each year by the corresponding emission factor. These annual emissions for each activity were then summed to estimate the total annual CH₄, CO₂, and N₂O emissions, respectively. Emissions at a segment level are shown in Table 3.5-2, Table 3.5-7, and Table 3.5-10.

Refer to the 1990-2023 *Inventory* section at <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems> for the following data tables, in spreadsheet format:

- Table 3.5-1: Ratios of CO₂ to CH₄ Volume in Emissions from Petroleum Production Field Operations
- Table 3.5-2: CH₄ Emissions (kt) for Petroleum Systems, by Segment and Source, for All Years
- Table 3.5-3: Average CH₄ Emission Factors (kg/unit activity) for Petroleum Systems Sources, for All Years
- Table 3.5-4: CH₄ Emission Factors for Petroleum Systems, Data Sources/Methodology
- Table 3.5-5: Activity Data for Petroleum Systems Sources, for All Years
- Table 3.5-6: Activity Data for Petroleum Systems, Data Sources/Methodology
- Table 3.5-7: CO₂ Emissions (kt) for Petroleum Systems, by Segment and Source, for All Years
- Table 3.5-8: Average CO₂ Emission Factors (kg/unit activity) for Petroleum Systems Sources, for All Years
- Table 3.5-9: CO₂ Emission Factors for Petroleum Systems, Data Sources/Methodology
- Table 3.5-10: N₂O Emissions (kt) for Petroleum Systems, by Segment and Source, for All Years
- Table 3.5-11: Average N₂O Emission Factors (kg/unit activity) for Petroleum Systems Sources, for All Years
- Table 3.5-12: N₂O Emission Factors for Petroleum Systems, Data Sources/Methodology
- Table 3.5-13: Annex 3.5 Electronic Tables – References
- Table 3.5-14: Basin-Level CH₄ Emissions (kt) for Select Petroleum Systems Onshore Production Sources
- Table 3.5-15: Basin-Level CO₂ Emissions (kt) for Select Petroleum Systems Onshore Production Sources
- Table 3.5-16: Basin-Level Activity Factors for Select Petroleum Systems Onshore Production Sources
- Table 3.5-17: Basin-Level Activity Data for Select Petroleum Systems Onshore Production Sources
- Table 3.5-18: Average Basin-Level CH₄ Emission Factors (kg/unit activity) for Select Petroleum Systems Onshore Production Sources, for All Years

- Table 3.5-19: Average Basin-Level CO₂ Emission Factors (kg/unit activity) for Select Petroleum Systems Onshore Production Sources, for All Years
- Table 3.5-20: Basin-Level Activity Data for Select Petroleum Systems Onshore Production Sources, Data Sources/Methodology
- Table 3.5-21: Basin-Level CH₄ Emission Factors for Select Petroleum Systems Onshore Production Sources, Data Sources/Methodology
- Table 3.5-22: Basin-Level CO₂ Emission Factors for Select Petroleum Systems Onshore Production Sources, Data Sources/Methodology
- Table 3.5-23: Basin-Level References

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3.6. Methodology for Estimating CH₄, CO₂, and N₂O Emissions from Natural Gas Systems

For details on the emissions, emission factors, activity data, data sources, and methodologies for each year from 1990 to 2023 please see the spreadsheet file annexes for the current (i.e., 1990 to 2023) *Inventory*, available at <https://www.epa.gov/ghgemissions/stakeholder-process-natural-gas-and-petroleum-systems-1990-2023-inventory>.

As described in the main body text on Natural Gas Systems, the *Inventory* methodology involves the calculation of CH₄, CO₂, and N₂O emissions for over 100 emissions sources, and the summation of emissions for each natural gas segment. The approach for calculating emissions for natural gas systems generally involves the application of emission factors to activity data. For many sources, the approach uses technology-specific emission factors or emission factors that vary over time and take into account changes to technologies and practices, which are used to calculate net emissions directly. For others, the approach uses what are considered “potential methane factors” and reduction data to calculate net emissions.

Emission Factors

Table 3.6-1, Table 3.6-10, and Table 3.6-14 show CH₄, CO₂, and N₂O emissions, respectively, for all sources in Natural Gas Systems, for all time series years. Table 3.6-2, Table 3.6-12, and Table 3.6-15 show the CH₄, CO₂, and N₂O average emission factors, respectively, for all sources in Natural Gas Systems, for all time series years. These emission factors are calculated by dividing net emissions by activity. Therefore, in a given year, these emission factors reflect the estimated contribution from controlled and uncontrolled fractions of the source population and any source-specific reductions (see below section “Reductions Data”); additionally, for sources based on the GRI/EPA study, the values take into account methane compositions from GTI 2001 adjusted year to year using gross production for National Energy Modeling System (NEMS) oil and gas supply module regions from the EIA. These adjusted region-specific annual CH₄ compositions are presented in Table 3.6-3 (for general sources), Table 3.6-4 (for gas wells without hydraulic fracturing), and Table 3.6-5 (for gas wells with hydraulic fracturing).

Additional detail on the basis for the CH₄, CO₂, and N₂O emission factors used across the time series is provided in Table 3.6-6, Table 3.6-13, Table 3.6-16, and below.

Key references for emission factors for CH₄ and non-combustion-related CO₂ emissions from the U.S. natural gas industry include the 1996 Gas Research Institute (GRI) and EPA study (GRI/EPA 1996), the Greenhouse Gas Reporting Program (GHGRP) (EPA 2024d), and others.

The GRI/EPAGRI/EPA study developed over 80 CH₄ emission factors to characterize emissions from the various components within the operating stages of the U.S. natural gas system for base year 1992. Since the time of this study, practices and technologies have changed. This study still represents best available data in many cases—in particular, for early years of the time series.

Data from studies and EPA’s GHGRP (EPA 2024d) allow for emission factors to be calculated that account for adoption of control technologies and emission reduction practices. For some sources, EPA has developed control category-specific emission factors from recent data that are used over the time series (paired with control category-specific activity data that fluctuates to reflect control adoption over time). In other cases, EPA retains emission factors from the GRI/EPA study for early time series years (1990 to 1992), applies updated emission factors in recent years (e.g., 2011 forward), and uses interpolation to calculate emission factors for intermediate years. For some sources, EPA continues to apply the GRI/EPA emission factors for all time series years, and accounts for emission reductions through data reported to Gas STAR or estimated based on regulations (see below section “Reductions Data”). For the following sources in the exploration and production segments, EPA has used GHGRP data to calculate net emission factors and establish source type and/or control type subcategories:

- For gas well completions and workovers with hydraulic fracturing, separate emissions estimates were developed for hydraulically fractured completions and workovers that vent, flared hydraulic

fracturing completions and workovers, hydraulic fracturing completions and workovers with reduced emissions completions (RECs), and hydraulic fracturing completions and workovers with RECs that flare. The estimates were developed for each basin that reported to subpart W.

- For gas well completions without hydraulic fracturing, separate emissions estimates were developed for completions that vent and completions that flare. The estimates were developed for each basin that reported to subpart W.
- For liquids unloading, separate emissions estimates were developed for each basin that reported to Subpart W for wells with plunger lifts and wells without plunger lifts.
- For condensate tanks, emissions estimates were developed for each basin that reported to subpart W for large and small tanks with flaring or vapor recovery unit (VRU) control, without control devices, and with upstream malfunctioning separator dump valves.
- For pneumatic controllers, separate estimates are developed for low bleed, high bleed, and intermittent controllers for each basin that reported to subpart W.
- Chemical injection pumps estimates are calculated with a basin-specific emission factor developed with GHGRP data for each basin that reported to subpart W.

For most sources in the processing, transmission and storage, and distribution segments, net emission factors have been developed for application in recent years of the time series, while the existing emission factors are applied in early time series years.

When a CO₂-specific emission factor is not available for a source, the CO₂ emission factors were derived from the corresponding source CH₄ emission factors using default gas composition data. CO₂ emission factors are estimated by multiplying the CH₄ emission factors by the ratio of the CO₂-to-CH₄ gas content. This approach is applied for certain sources in the natural gas production, gas processing (only for early time series years), transmission and storage, and distribution segments. The default gas composition data are specific to segment and are provided in Table 3.6-11. The default values were derived from GRI/EPA (1996), EIA (1994), and GTI (2001).

N₂O emission factors were calculated using GHGRP data. For each flaring emission source calculation methodology that uses GHGRP data, the source-specific methodology used to estimate CO₂ was applied to calculate N₂O emission factors.

1990-2023 Inventory updates to emission factors

EPA incorporated new emissions data available for year 2021 from the Bureau of Ocean Energy Management (BOEM) to update the methodology for offshore production in the Gulf of America region. The details are presented in a memorandum,⁶⁴ *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2023: Updates Under Consideration to Use New Offshore Data* (EPA 2024a), as well as the “Recalculations Discussion” section of the main body text.

Activity Data

Table 3.6-7 shows the activity data for all sources in Natural Gas Systems, for all time series years. Additional detail on the basis for activity data used across the time series is provided in Table 3.6-8, and below.

For a few sources, recent direct activity data were not available. For these, either 2022 data were used as proxy for 2023 data or a set of industry activity data drivers was developed and was used to update activity data. Key drivers include statistics on gas production, number of wells, system throughput, miles of various kinds of pipe, and other statistics that characterize the changes in the U.S. natural gas system infrastructure and operations.

⁶⁴ Stakeholder materials including EPA memoranda for the *Inventory* are available at <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>.

Methodology for well counts and events

EPA used datasets from Enverus (Enverus 2025), covering U.S. oil and natural gas wells to populate time series activity data for active gas wells, gas wells drilled, and gas well completions and workovers with hydraulic fracturing (for 1990 to 2010). EPA queried the Enverus datasets for relevant data on an individual well basis—including location, natural gas and liquids (i.e., oil and condensate) production by year, drill type (e.g., horizontal or vertical), and date of completion or first production. Non-associated gas wells were classified as any well that had non-zero gas production in a given year, and with a gas-to-oil ratio (GOR) of greater than 100 mcf/bbl in that year. Oil wells were classified as any well that had non-zero liquids production in a given year, and with a GOR of less than or equal to 100 mcf/bbl in that year. Gas wells with hydraulic fracturing were assumed to be the subset of the non-associated gas wells that had fracking fluid data within Enverus or were horizontally drilled and/or located in an unconventional formation (i.e., shale, tight sands, or coalbed). Unconventional formations were identified based on well basin, reservoir, and field data reported in the Enverus datasets referenced against a formation type crosswalk developed by EIA (EIA 2012).

For 1990 through 2010, gas well completions with hydraulic fracturing were identified as a subset of the gas wells with hydraulic fracturing that had a date of completion or first production in the specified year. To calculate workovers for all time series years, EPA developed year- and basin-specific subpart W AFs for 2015 forward that represent the number of HF workovers per gas well; year 2015 subpart W AFs were applied to all prior years for each basin. For 2011 forward, EPA used GHGRP data for the total number of well completions. The GHGRP data represents a subset of the national completions, due to the reporting threshold, and therefore using this data without scaling it up to national level results in an underestimate. However, because EPA's GHGRP counts of completions were higher than national counts of completions (estimated using the Enverus datasets), EPA directly used the GHGRP data to estimate national activity for years 2011 forward.

EPA calculated the percentage of gas well completions and workovers with hydraulic fracturing in each of the four control categories using year- and basin-specific GHGRP data. EPA assumed no REC use from 1990 through 2000, used a REC use percentage calculated from basin-specific GHGRP data for 2011 forward, and then used linear interpolation between the 2000 and 2011 percentages for each basin. For flaring, EPA averaged the percent of completions and workovers that were flared in 2011 and 2012 GHGRP data. EPA used this average as a basin-specific percent flaring from 1990 through 2010 to recognize that some flaring has occurred over that time period. For 2011 forward, EPA used a flaring percentage calculated from GHGRP data. For basins without subpart W data available, EPA applied national average activity factors (unweighted average of all subpart W reported data).

Reductions Data

As described under “Emission Factors” above, some sources in Natural Gas Systems rely on CH₄ emission factors developed from the 1996 GRI/EPA study. Application of these emission factors across the time series represents potential emissions and does not take into account any use of technologies or practices that reduce emissions. To take into account use of such technologies for emission sources that use potential factors, data were collected on relevant voluntary and regulatory reductions.

Voluntary and regulatory emission reductions by segment, for all time series years, are included in Table 3.6-1. Reductions by emission source, for all time series years, are shown in Table 3.6-9.

Voluntary reductions

Voluntary reductions included in the *Inventory* were those reported to Gas STAR and Methane Challenge for activities such as replacing gas engines with electric compressor drivers and installing automated air-to-fuel ratio controls for engines.

The latest reported data for each program were paired with sources in the *Inventory* that use potential emissions approaches and incorporated into the estimates (e.g., gas engines). Reductions data are only included in the *Inventory* if the emission source uses “potential” emission factors, and for Natural Gas STAR reductions, short-term emission reductions are assigned to the reported year only, while long-term emission reductions are assigned

to the reported year and every subsequent year in the time series. See Recalculations Discussion for more information.

Federal regulations

Regulatory actions reducing emissions in the current *Inventory* include the New Source Performance Standards (NSPS) and National Emission Standards for Hazardous Air Pollutants (NESHAP) regulations for dehydrator vents in the production segment.

The *Inventory* reflects the NSPS for oil and gas through the use of a net factor approach that captures shifts to lower emitting technologies required by the regulation. Examples include separating gas well completions and workovers with hydraulic fracturing into four categories and developing control technology-specific methane emission factors and year-specific activity data for each category; establishing control category-specific emission factors and associated year-specific activity data for condensate tanks; calculating year-specific activity data for pneumatic controller bleed categories; and estimating year-specific activity data for wet versus dry seal centrifugal compressors.

With regards to the oil and natural gas industry, the NESHAP regulation addresses HAPs from the oil and natural gas production segments and the natural gas transmission and storage segments of the industry. Though the regulation deals specifically with HAPs reductions, methane emissions are also incidentally reduced.

The NESHAP regulation requires that glycol dehydration unit vents that have HAP emissions and exceed a gas throughput threshold be connected to a closed loop emission control system that reduces emissions by 95 percent. The emissions reductions achieved as a result of NESHAP regulations for glycol dehydrators in the production segment were calculated using data provided in the Federal Register Background Information Document (BID) for this regulation. The BID provides the levels of control measures in place before the enactment of regulation. The emissions reductions were estimated by analyzing the portion of the industry without control measures already in place that would be impacted by the regulation.

NESHAP-driven reductions from storage tanks and from dehydrators in the processing segment are estimated with net emission methodologies that take into account controls implemented due to regulations.

Methane, Carbon Dioxide, and Nitrous Oxide Emissions by Emission Source for Each Year

Annual CH₄, CO₂, and N₂O emissions for each source were estimated by multiplying the activity data for each year by the corresponding emission factor. These annual emissions for each activity were then summed to estimate the total annual CH₄, CO₂, and N₂O emissions, respectively. As a final step for CH₄ emissions, any relevant reductions data from each segment is summed for each year and deducted from the total calculated emissions in that segment to estimate net CH₄ emissions for the *Inventory*. CH₄ potential emissions, reductions, and net emissions at a segment level are shown in Table 3.6-1. CO₂ emissions by segment and source are summarized in Table 3.6-10. N₂O emissions by segment and source are summarized in Table 3.6-14.

Refer to the 1990-2023 *Inventory* section at <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems> for the following data tables, in spreadsheet format:

- Table 3.6-1: CH₄ Emissions (kt) for Natural Gas Systems, by Segment and Source, for All Years. Emissions presented are net and include GasSTAR or Methane Challenge reductions.
- Table 3.6-2: Average CH₄ Emission Factors (kg/unit activity) for Natural Gas Systems Sources, for All Years
- Table 3.6-3: U.S. Production Sector CH₄ Content in Natural Gas by NEMS Region (General Sources)
- Table 3.6-4: U.S. Production Sector CH₄ Content in Natural Gas by NEMS Region (Gas Wells Without Hydraulic Fracturing)
- Table 3.6-5: U.S. Production Sector CH₄ Content in Natural Gas by NEMS Region (Gas Wells With Hydraulic Fracturing)
- Table 3.6-6: CH₄ Emission Factors for Natural Gas Systems, Data Sources/Methodology
- Table 3.6-7: Activity Data for Natural Gas Systems Sources, for All Years

- Table 3.6-8: Activity Data for Natural Gas Systems, Data Sources/Methodology
- Table 3.6-9: Voluntary and Regulatory CH₄ Reductions for Natural Gas Systems (kt)
- Table 3.6-10: CO₂ Emissions (kt) for Natural Gas Systems, by Segment and Source, for All Years
- Table 3.6-11: Default Gas Content by Segment, for All Years
- Table 3.6-12: Average CO₂ Emission Factors (kg/unit activity) for Natural Gas Systems Sources, for All Years
- Table 3.6-13: CO₂ Emission Factors for Natural Gas Systems, Data Sources/Methodology
- Table 3.6-14: N₂O Emissions (kt) for Natural Gas Systems, by Segment and Source, for All Years
- Table 3.6-15: Average N₂O Emission Factors (kg/unit activity) for Natural Gas Systems Sources, for All Years
- Table 3.6-16: N₂O Emission Factors for Natural Gas Systems, Data Sources/Methodology
- Table 3.6-17: Electronic Tables – References
- Table 3.6-18: Basin-Level CH₄ Emissions (kt) for Select Natural Gas Systems Onshore Production Sources
- Table 3.6-19: Basin-Level CO₂ Emissions (kt) for Select Natural Gas Systems Onshore Production Sources
- Table 3.6-20: Basin-Level Activity Factors for Select Natural Gas Systems Onshore Production Sources
- Table 3.6-21: Basin-Level Activity Data for Select Natural Gas Systems Onshore Production Sources
- Table 3.6-22: Average Basin-Level CH₄ Emission Factors (kg/unit activity) for Select Natural Gas Systems Onshore Production Sources, for All Years
- Table 3.6-23: Average Basin-Level CO₂ Emission Factors (kg/unit activity) for Select Natural Gas Systems Onshore Production Sources, for All Years
- Table 3.6-24: Basin-Level Activity Data for Select Natural Gas Systems Onshore Production Sources, Data Sources/Methodology
- Table 3.6-25: Basin-Level CH₄ Emission Factors for Select Natural Gas Systems Onshore Production Sources, Data Sources/Methodology
- Table 3.6-26: Basin-Level CO₂ Emission Factors for Select Natural Gas Systems Onshore Production Sources, Data Sources/Methodology
- Table 3.6-27: Basin-Level References

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3.7. Methodology for Estimating CO₂, CH₄, and N₂O Emissions from the Incineration of Waste

Emissions of CO₂ from the combustion of waste include CO₂ generated by the combustion of plastics, synthetic rubber and synthetic fibers in municipal solid waste (MSW), which, in the United States, tends to occur at waste-to-energy facilities or industrial facilities, and the combustion of tires (which are composed in part of synthetic rubber and C black) in a variety of other combustion facilities (e.g., cement kilns). Waste combustion also results in emissions of CH₄ and N₂O. The emission estimates are calculated for all MSW sources on a mass-basis based on the data available, with the emissions from the combustion of tires calculated separately. The methodology for calculating emissions from waste combustion sources is described in this Annex.

Municipal Solid Waste Combustion

To determine both CO₂ and non-CO₂ emissions from the combustion of waste, the tonnage of waste combusted and an estimated emissions factor are needed. Emission estimates from the combustion of tires are discussed separately. Data for total waste combusted, excluding tires, was derived from *BioCycle* (van Haaren et al. 2010), EPA Facts and Figures Report, Energy Recovery Council (ERC 2018), EPA's Greenhouse Gas Reporting Program (GHGRP) (EPA 2024), and the U.S. Energy Information Administration (EIA 2019). Multiple sources were used to ensure a complete, quality dataset, as each source encompasses a different timeframe.

EPA's Greenhouse Gas Reporting Program (GHGRP) collects data from facilities on methane (CH₄) and nitrous oxide (N₂O) emissions by fuel type under Subpart C. From these reported emissions for MSW fuel, EPA back-calculated the tonnage of waste combusted using GHGRP default emission factors for CH₄ and N₂O for 2011 through 2023. Reporters can report CO₂ emissions using a number of different tiers under the GHGRP. For some tiers, input fuel values could be determined, but not for all facilities. However, the methods for reporting CH₄ and N₂O emissions from MSW combustion under GHGRP generally rely on applying default emission factors to fuel input values. Therefore, back calculating fuel input based on the default CH₄ and N₂O emissions factors was determined to be the best method for consistently estimating fuel input values for all MSW fuel combustion across all facilities and over time. Where values for fuel input were directly available from MSW combustion through GHGRP it was determined to be consistent with the back calculated values.

EPA Facts and Figures Reports detail materials combusted with energy recovery in the municipal waste stream. This tonnage is estimated as a percentage of total MSW after recycling and composting. These data exclude major appliances, tires and lead-acid batteries, and food. Waste-to-energy data is reported to EIA and available at the plant level. Biogenic and non-biogenic combusted waste tonnage are both reported on a monthly and annual basis starting in 2006 (EIA 2019). The sum total is used in the following calculations. Similarly, ERC's *2018 Directory of Waste and Energy Facilities* reports throughput data in tons of MSW for waste-to-energy facilities operating in the United States. Both *BioCycle* and ERC data include the tons of tires combusted in their raw data reporting. To determine total MSW combusted using these data, combusted tire tonnage is subtracted.

EPA determined the MSW combusted tonnages based on data availability and accuracy throughout the time series, and the two estimates were averaged together and converted to MSW tonnage.

- 1990-2006: MSW combustion tonnages are from BioCycle combustion data. Tire combustion data from the U.S. Tire Manufacturers Association (USTMA) are removed to arrive at MSW combusted without tires.
- 2006-2010: MSW combusted tonnages are an average of BioCycle (with USTMA tire data tonnage removed), U.S. EPA Facts and Figures, EIA, and Energy Recovery Council data (with USTMA tire data tonnage removed).
- 2011-2023: MSW combustion tonnages are from EPA's GHGRP data.

Table A-102 provides the estimated tons of MSW combusted including and excluding tires.

Table A-102: Municipal Solid Waste Combusted (Short Tons)

Year	1990	2005	2019	2020	2021	2022	2023
Waste							
Combusted	33,344,83	26,486,41	28,174,31	27,586,27	27,867,44	26,338,13	25,676,43
- excluding tires	9	4	1	1	6	0	2
Waste							
Combusted -	33,766,23	28,631,05	29,821,14	29,106,68	29,261,44	27,808,13	27,222,43
including tires	9	4	1	6	6	0	2

Sources: *BioCycle*, EPA Facts and Figures, ERC, GHGRP, EIA, USTMA.

CO₂ Emissions from MSW Excluding Scrap Tires

Fossil CO₂ emission factors were calculated from EPA's GHGRP data for non-biogenic sources. MSW tonnage using GHGRP data, excluding tires, was calculated following the method outlined previously. Dividing fossil CO₂ emissions from GHGRP FLIGHT data for facilities classified as MSW combustors by the estimated tonnage from those facilities yielded an annual CO₂ emission factor. Note the MSW tonnage calculated for facilities characterized as MSW combustors is smaller than the total MSW tonnage back calculated from emissions by fuel type data. This indicates MSW could be co-fired at facilities whose main purpose is not waste combustion alone. As this data was only available following 2011, the CO₂ emission factor was proxied using an average of the CO₂ emission factors from years 2011 through 2015.

Finally, CO₂ emissions were calculated by multiplying the annual tonnage estimates, excluding tires, by the calculated emissions factor. Calculated fossil CO₂ emission factors are shown in Table A-103.

Table A-103: Calculated Fossil CO₂ Content per Ton Waste Combusted (kg CO₂/Short Ton Combusted)

Year	1990	2005	2019	2020	2021	2022	2023
CO ₂ Emission Factors	366	366	363	377	365	382	384

CO₂ from Combustion of Synthetic Rubber and Carbon Black in Tires

Calculating emissions from tire combustion requires two pieces of information: the amount of tires combusted and the C content of the tires. "2023 End-of-Life Tire Management Report" (USTMA 2024) reports that 1,546 thousand of the 3,512 thousand tons of scrap tires generated in 2023 (approximately 44 percent of generation) were used for fuel purposes. Using USTMA's estimates of average tire composition and weight, the mass of synthetic rubber and C black in scrap tires was determined:

- Synthetic rubber in tires was estimated to be 90 percent C by weight, based on the weighted average C contents of the major elastomers used in new tire consumption.⁶⁵ Table A-104 shows consumption and C content of elastomers used for tires and other products in 2002, the most recent year for which data are available.
- C black is 100 percent C (Aslett Rubber Inc. n.d.).

Multiplying the mass of scrap tires combusted by the total C content of the synthetic rubber, C black portions of scrap tires, and then by a 98 percent oxidation factor, yields CO₂ emissions, as shown in Table A-105. The disposal rate of rubber in tires (0.3 MMT C/year) is smaller than the consumption rate for tires based on summing the elastomers listed in Table A-104 (1.3 MMT/year); this is due to the fact that much of the rubber is lost through tire wear during the product's lifetime and may also reflect the lag time between consumption and disposal of tires.

⁶⁵ The carbon content of tires (1,174 kt C) divided by the mass of rubber in tires (1,307 kt) equals 90 percent.

Tire production and fuel use for 1990 through 2023 were taken from USTMA 2006; USTMA 2009; USTMA 2013; USTMA 2014; USTMA 2016; USTMA 2018; USTMA 2020; USTMA 2022; USTMA 2024. For years where data were not reported, data were linearly interpolated or, for the ends of time series, set equal to the closest year with reported data.

In 2009, USTMA changed the reporting of scrap tire data from millions of tires to thousands of short tons of scrap tire. As a result, the average weight and percent of the market of light duty and commercial scrap tires was used to convert the previous years from millions of tires to thousands of short tons (STMC 1990 through 1997; USTMA 2002 through USTMA 2006; USTMA 2009; USTMA 2013; USTMA 2014; USTMA 2016; USTMA 2018; USTMA 2020; USTMA 2022; USTMA 2024).

Table A-104: Elastomers Consumed in 2002 (kt)

Elastomer	Consumed	Carbon Content	Carbon Equivalent
Styrene butadiene rubber solid	768	91%	700
For Tires	660	91%	602
For Other Products ^a	108	91%	98
Polybutadiene	583	89%	518
For Tires	408	89%	363
For Other Products	175	89%	155
Ethylene Propylene	301	86%	258
For Tires	6	86%	5
For Other Products	295	86%	253
Polychloroprene	54	59%	32
For Tires	0	59%	0
For Other Products	54	59%	32
Nitrile butadiene rubber solid	84	77%	65
For Tires	1	77%	1
For Other Products	83	77%	64
Polyisoprene	58	88%	51
For Tires	48	88%	42
For Other Products	10	88%	9
Others	367	88%	323
For Tires	184	88%	161
For Other Products	184	88%	161
Total	2,215	NA	1,950
For Tires	1,307	NA	1,174

NA (Not Applicable)

^a Used to calculate C content of non-tire rubber products in municipal solid waste.

Note: Totals may not sum due to independent rounding.

Table A-105: Scrap Tire Constituents and CO₂ Emissions from Scrap Tire Combustion in 2023

Material	Weight of Material (MMT)	Fraction Oxidized	Carbon Content	Emissions (MMT CO ₂ Eq.)
Synthetic Rubber	0.3	98%	90%	1.2
Carbon Black	0.4	98%	100%	1.4
Total	0.7	NA	NA	2.6

NA (Not Applicable)

Note: Totals may not sum due to independent rounding.

CH₄ and N₂O from the Combustion of Waste

Estimates of N₂O emissions from the combustion of waste in the United States are based on the methodology outlined in the EPA's Compilation of Air Pollutant Emission Factors (EPA 1995) and presented in the *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures* reports (EPA 1999 through 2003, 2005 through 2014), *Advancing Sustainable Materials Management: Facts and Figures: Assessing Trends in Material Generation, Recycling and Disposal in the United States* (EPA 2015; EPA 2016; EPA 2018; EPA 2019; EPA 2020) and unpublished backup data (Schneider 2007). According to this methodology, emissions of N₂O from waste combustion are the product of the mass of waste combusted, an emission factor of N₂O emitted per unit mass of waste combusted, and an N₂O emissions control removal efficiency. The tonnage of MSW waste derived as described previously, including tires, is used in this calculation. An emission factor of 50 g N₂O/metric ton MSW based on the 2006 IPCC Guidelines and an estimated emissions control removal efficiency of zero percent were used (IPCC 2006). It was assumed that all MSW combustors in the United States use continuously-fed stoker technology (Bahor 2009; ERC 2009).

Estimates of CH₄ emissions from the combustion of waste in the United States are based on the methodology outlined in IPCC's 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006). According to this methodology, emissions of CH₄ from waste combustion are the product of the mass of waste combusted and an emission factor of CH₄ emitted per unit mass of waste combusted. Similar to the N₂O emissions methodology, the mass of waste combusted including tires was derived following the methods previously outlined. An emission factor of 0.20 kg CH₄/kt MSW was used based on the 2006 IPCC Guidelines and assuming that all MSW combustors in the United States use continuously-fed stoker technology (Bahor 2009; ERC 2009).

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3.8. Methodology for Estimating Emissions from International Bunker Fuels used by the U.S. Military

Bunker fuel emissions estimates for the Department of Defense (DoD) were developed using data generated by the Defense Logistics Agency Energy (DLA Energy, 2025) for aviation and naval fuels. DLA Energy prepared a special report based on data in the Fuels Automated System (FAS) for calendar year 2023 fuel sales in the Continental United States (CONUS).⁶⁶ The methodology used for estimating emissions from international bunker fuels used by the U.S. Military is consistent with previous *Inventories*. This methodology is currently under review and will be updated in future as needed.

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⁶⁶ FAS contains data for 1995 through 2021, but the dataset was not complete for years prior to 1995. Using DLA aviation and marine fuel procurement data, fuel quantities from 1990 to 1994 were estimated based on a back-calculation of the 1995 data in the legacy database, the Defense Fuels Automated Management System (DFAMS). The back-calculation was refined in 1999 to better account for the jet fuel conversion from JP4 to JP8 that occurred within DoD between 1992 and 1995.

3.9. Methodology for Estimating Emissions from Other Fluorochemical Production

The 2006 IPCC Guidelines as elaborated by the 2019 Refinement include Tier 1, Tier 2, and Tier 3 methods for estimating fluorinated GHG emissions from production of fluorinated compounds. The Tier 1 method calculates emissions by multiplying a default emission factor by total production. Specific default emission factors exist for production of SF₆ and NF₃; a more general default emission factor covers production of all other fluorinated GHGs. (The more general default emission factor was developed based on data from U.S. facilities collected under the GHGRP between 2011 and 2016.) The Tier 2 method calculates emissions using a mass-balance approach. The Tier 3 method is based on the collection of plant-specific data on the types and quantities of fluorinated GHGs emitted from process vents, leaks, container venting, and other sources, considering any abatement technology. The Tier 3 method is often implemented by developing and applying facility-specific emission factors indexed to production.

Based on available data on emissions and activity, EPA used a form of the IPCC Tier 3 method to estimate fluorinated GHG emissions from most U.S. production of fluorinated compounds. Emissions from U.S. production for which there are fewer data are based on the Tier 1 method.

Overview of GHGRP Data for this Source Category

As discussed further below, much of the data used to develop the estimates presented here come from the GHGRP. The data were collected under two sections of the GHGRP regulation—Subpart L, Fluorinated Gas Production; and Subpart OO, Suppliers of Industrial Greenhouse Gases. Under Subpart L, certain fluorinated gas production facilities must report their emissions from a range of processes and sources, detailed further below. Data collected under Subpart L include emissions data for calendar years 2011 through 2023. Under Subpart OO, fluorinated GHG suppliers (including fluorinated GHG producers) must report the quantities of each fluorinated GHG that they produce, transform, destroy, import, or export. Data collected under Subpart OO include production and transformation data for calendar years 2010 through 2023. Facilities' production and transformation data are not shown here because they are considered confidential business information under the GHGRP.

Emissions Reported Under Subpart L of the GHGRP

Under Subpart L, facilities that produce a fluorinated gas must report their greenhouse gas emissions if the facility emits 25,000 MT CO₂ Eq. or more per year in combined emissions from fluorinated gas production, stationary fuel combustion units, miscellaneous uses of carbonate, and all other applicable source categories listed in the rule. (For purposes of calculating emissions from fluorinated gas production for inclusion in the total that is compared to the threshold, emissions are assumed to be uncontrolled.) Facilities must report their fluorinated GHG emissions from the production and transformation of fluorinated gases, from venting of residual fluorinated GHGs from containers, and from destruction of previously produced fluorinated GHGs. The emissions reported from production and transformation include both emissions from process vents and emissions from equipment leaks.

Under the GHGRP, "fluorinated GHGs," whose emissions must be reported, include SF₆, NF₃, and any fluorocarbon except for substances with vapor pressures below 1 Torr at 25 degrees C and substances that are regulated as "controlled substances" under EPA's ozone-protection regulations at 40 CFR Part 82, Subpart A (e.g., chlorofluorocarbons [CFCs], hydrochlorofluorocarbons [HCFCs], and halons). In addition to SF₆ and NF₃, this definition includes hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), hydrofluoroethers (HFEs), fully fluorinated tertiary amines, perfluoropolyethers (including PFPME), and hydrofluoropolyethers, and others.

“Fluorinated gases,” from whose production or transformation emissions must be reported, include the fluorinated GHGs detailed above as well as CFCs and HCFCs.⁶⁷

Facilities calculate emissions from process vents using one of two methods. For vents that emit 10,000 MT CO₂ Eq. or more (considering controls) of fluorinated GHGs from continuous processes, facilities must use emissions testing to establish an emission factor at least every ten years, or sooner if the process changes in a way that will significantly affect emissions from the vent. For other process vents, facilities may use measurements, engineering calculations, or engineering assessments to establish the emission factor. Facilities then calculate their annual emissions based on the measured or calculated emission factor and related activity data, considering the extent to which the process is controlled and any destruction device or process malfunctions.

To calculate emissions from equipment leaks, facilities that report under Subpart L are required to collect information on the number and type of pieces of equipment; service of each piece of equipment; concentration of each fluorinated GHG in the stream; and the time period each piece of equipment was in service. Facilities use one or more of the following methods to calculate emissions from equipment leaks (EPA 1995):

- Average Emission Factor Approach in EPA Protocol for Equipment Leak Estimates.
- Other Approaches in EPA Protocol for Equipment Leak Estimates in conjunction with EPA Method 21.
- Other Approaches in EPA Protocol for Equipment Leak Estimates in conjunction with site-specific leak detection methods.
- Site-specific leak detection methods.

Most emissions are reported by chemical; the exceptions are (1) fluorinated GHGs that are emitted in quantities of 1,000 MT CO₂ Eq. or less across all production and transformation processes at a facility and (2) fluorinated GHGs that are emitted from facilities that produce only one fluorinated GHG, where the emitted fluorinated GHG is not the fluorinated gas produced. In these cases, the emissions are reported in CO₂ Eq. by fluorinated GHG group. There are 12 fluorinated GHG groups, each of which encompasses a set of GHGs with roughly similar atmospheric behavior, including similar GWPs and atmospheric lifetimes. These include, e.g., fully fluorinated GHGs such as PFCs and SF₆, saturated HFCs with two or fewer carbon-hydrogen bonds, saturated HFCs with more than two carbon-hydrogen bonds, unsaturated HFCs and PFCs, and others (see Table A-106 for a full list).

Table A-106: Fluorinated GHG Groups Under Which Certain Emissions Are Reported Under Subpart L of the GHGRP and Associated GWPs

Fluorinated GHG Group	GHGRP Default Global Warming Potential (100-yr.)
Fully fluorinated GHGs	10,000
Saturated hydrofluorocarbons (HFCs) with 2 or fewer carbon-hydrogen bonds	3,700
Saturated HFCs with 3 or more carbon-hydrogen bonds	930
Saturated hydrofluoroethers (HFEs) and hydrochlorofluoroethers (HCFEs) with 1 carbon-hydrogen bond	5,700
Saturated HFEs and HCFEs with 2 carbon-hydrogen bonds	2,600
Saturated HFEs and HCFEs with 3 or more carbon-hydrogen bonds	270
Fluorinated formates	350
Fluorinated acetates, carbonofluoridates, and fluorinated alcohols other than fluorotelomer alcohols	30

⁶⁷ HCFC-22 is considered a fluorinated gas under the GHGRP, but emissions from HCFC-22 production are reported separately from emissions from production of other fluorinated gases.

Unsaturated PFCs, unsaturated HFCs, unsaturated HCFCs, unsaturated halogenated ethers, unsaturated halogenated esters, fluorinated aldehydes, and fluorinated ketones	1
Fluorotelomer alcohols	1
Fluorinated GHGs with carbon-iodine bond(s)	1
Other fluorinated GHGs	2,000

Two other datasets reported under Subpart L are relevant to estimating uncontrolled emission factors. (As discussed further below, such uncontrolled emission factors are applied to years before Subpart L reporting began (for CY 2011) and before emission controls were put into place.) First, in addition to reporting emissions by chemical at the facility level, facilities report emissions from each production and transformation process at the facility in tons of CO₂ Eq. by fluorinated GHG group. To calculate CO₂ Eq. emissions, facilities use a chemical-specific 100-year GWP where one is available for the compound of interest. If no chemical-specific 100-year GWP is available for the compound of interest, facilities use the GHGRP default GWP for the fluorinated GHG group of which the compound is a member. These default GWPs are shown in Table A-106.

Second, for each process, facilities also report the extent to which emissions are abated (the effective destruction efficiency or EDE) as a range. The EDE is calculated as follows:

$$EDE = 1 - \frac{CE_{PV}}{UE_{PV}}$$

where:

- EDE = Effective destruction efficiency of the process
- CE_{PV} = Actual GWP-weighted controlled emissions from all vents for the process, MT CO₂ Eq.
- UE_{PV} = Hypothetical GWP-weighted uncontrolled emissions from all vents for the process, MT CO₂ Eq. (CE_{PV} will equal UE_{PV} if the process is not controlled, resulting in a calculated EDE of 0).

Note that the EDE is based on the extent to which emissions from process vents are controlled. Emissions from equipment leaks are not included in the EDE calculation. Table A-107 provides the EDE ranges available for facilities to report and the arithmetic means of each range. The use of these datasets to calculate uncontrolled emission factors is discussed in more detail in the “1990-2010 Emissions Estimates” section below.

Verification of GHGRP Reports

Data reported under the GHGRP, including emissions and production, are electronically verified using range checks, internal consistency checks, and time-series consistency checks. Where the data fail a preliminary check, EPA contacts the facility to see whether there is an explanation for the issue or whether the data are indeed erroneous. In the latter case, facilities are required to correct the data. Where one or more of the anomalous data elements is not explained or corrected, the report for that facility for that year is considered unverified.

1990-2010 Emissions Estimates

For 14 of the 17 fluorinated gas production facilities that have reported their emissions under the GHGRP, 1990 through 2010 emissions are estimated using (1) facility- and chemical-specific emission factors based on the emissions data discussed under “2011-2023 Emissions” below, (2) reported or estimated production and transformation of fluorinated GHGs at each facility in each year, i.e., activity data, and (3) reported and estimated levels of emissions control at each facility in each year. (For the other 3 fluorinated gas production facilities that have reported their emissions under the GHGRP, 1990 through 2010 emissions were estimated using data submitted by the company, as explained further below.)

Facility- and Chemical-Specific Emission Factors Reflecting Emissions Controls

Facility- and chemical-specific emission factors were developed based on the 2011 to 2015 emissions reported under the GHGRP (discussed above) and the 2011 to 2015 production and transformation of fluorinated GHGs

reported under the GHGRP. (Production and transformation of CFCs and HCFCs are not reported under the GHGRP.) For each emitted fluorinated GHG at each facility, emissions of the fluorinated GHG were summed over the five-year period. This sum was then divided by the sum of the quantities of all fluorinated GHGs produced or transformed at the facility over the five-year period.⁶⁸ As discussed further below in the Uncertainty section, emissions of any particular fluorinated GHG are likely to occur only from a subset of the production or transformation processes at each facility, but in the absence of information on chemical-specific emissions at the process level, it was assumed that all fluorinated GHG production and transformation processes at the facility emit all fluorinated GHGs at the facility. This yielded the emission factors for each fluorinated GHG at each facility. Both emissions and activity (production + transformation) totals were summed over the five-year period to account for the intermittent and variable nature of some emissions and production/transformation processes. Compounds that were not emitted or produced/transformed between 2011 and 2015 but that were emitted or produced/transformed later were assumed not to have been emitted or produced/transformed (as applicable) before 2011.

Facility- and Chemical-Specific Emission Factors Reflecting No Emissions Controls

The 2011 to 2015 emissions reported under the GHGRP reflect emissions controls to the extent those are implemented at each facility. Because facilities have not always controlled their fluorinated GHG emissions since 1990, uncontrolled emission factors were developed for each facility to apply to years when the facility's emissions were not believed to be controlled. To estimate uncontrolled emissions, GHGRP data were first used to assess the 2011 to 2015 levels of control for each production or transformation process at each facility.

To calculate uncontrolled emissions from each process and fluorinated GHG group, a point estimate of the effective destruction efficiency (EDE, described above) was required and was estimated using the arithmetic mean of the lower and upper bounds of the EDE range reported for the process.⁶⁹ This was consistent with the approach taken in the *2019 Refinement* to develop the Tier 1 factor for fluorinated gas production facilities. The reported vented emissions for each process and fluorinated GHG group were divided by (1 - arithmetic mean EDE) to obtain the estimated uncontrolled emissions from process vents for that process and fluorinated GHG group. For each fluorinated GHG group at a facility, the controlled emissions across processes (including emissions from both vents and leaks) and the uncontrolled emissions across processes (including emissions from both vents and leaks) were then summed, and the first was divided by the second. This yielded an average level of control for each fluorinated GHG group at each facility. All fluorinated GHGs within each fluorinated GHG group at each facility were assumed to be controlled to the same level. To estimate the uncontrolled emissions of each fluorinated GHG within each group at each facility, the emissions of each fluorinated GHG were divided by the level of control estimated for its fluorinated GHG group at the facility. The same procedure was used to estimate uncontrolled emission factors as had been used to estimate controlled emission factors: the estimated uncontrolled 2011 to 2015 emissions of each fluorinated GHG were summed, and this sum was divided by the sum of the quantities of all fluorinated GHGs produced or transformed at the facility from 2011 to 2015.

Table A-107: Destruction Efficiency Range Values Used to Estimate Pre-Abatement Emissions for Production and Transformation Processes

DE ranges	Lower Bound	Upper Bound	Arithmetic Mean of Bounds
>=0% to <75%	0.0	0.75	0.375

⁶⁸ Permit data for two facilities indicated that they began controlling emissions at some point between 2011 and 2015. However, the actual emissions reported by these facilities did not change substantially after the date when the permit indicated that controls were imposed. For this reason, the reported 2011 to 2015 emissions and emission factors are believed to be representative of emissions for these facilities before 2011.

⁶⁹ Note that facilities would report a range of 0% to 75% even if they do not abate emissions at all; thus, the assumption that emissions are 37.5 percent controlled may overestimate the hypothetical uncontrolled emissions of some facilities, e.g., those that do not abate any emissions.

>=75% to <95%	0.75	0.95	0.85
>=95% to <99%	0.95	0.99	0.97
>=99%	0.99	0.9999	0.995

Estimated Levels of Emissions Controls

As discussed above, both uncontrolled emission factors and controlled emission factors were developed for each facility and fluorinated GHG; these emission factors were developed for estimating emissions from production and transformation processes for years 1990 to 2010. The following information and assumptions were used to determine whether and when emissions from facilities were likely to have been controlled from 1990 to 2010. For the estimated status of emissions controls at each facility reporting under Subpart L, and, where relevant, the starting year for those controls, see Table A-108.

- Facilities with publicly available information on the presence and use of control devices were assumed to control their emissions starting in the year specified in the publicly available information. Publicly available information included operating permits, news articles on facility modifications, company press releases, etc. Where the publicly available information documents that a control device was in place beginning in a certain year, the facility was assumed to control process emissions beginning in that year, and the controlled emission factor was used in estimating emissions for that year and the following years. The uncontrolled emission factor was used to estimate emissions in earlier years.
- In the absence of other control information, facilities that never reported DRE ranges other than “>=0% to <75%” for their production and transformation processes during reporting years 2011 and 2012 were assumed to have no control devices in place during the time period 1990 to 2012.
- Facilities that reported DRE ranges other than “>=0% to <75%” for at least one production or transformation process for 2011 or 2012 but for which other control information was not available were assumed to have begun controlling their emissions in 2005.

Table A-108: Estimated Starting Years for Emission Controls at Each Fluorinated Gas Production Facility Reporting under Subpart L of the GHGRP

Facility Name	Estimated Start Year	Basis of Estimation
3M COMPANY	No controls	Never reported a DRE range other than “>=0% to <75%”
3M CORDOVA	2003	Climate News Article ⁷⁰
3M Cottage Grove Center - Site	2016	Reported a DRE range other than “>=0% to <75%” for the first time in 2016
Airgas Therapeutics LLC - Scott Medical Products	No controls	Never reported a DRE range other than “>=0% to <75%”
ANDERSON DEVELOPMENT COMPANY	No controls	Never reported a DRE range other than “>=0% to <75%”
ARKEMA, INC.	2005	Reported a DRE range other than “>=0% to <75%” in 2011
Chemours - Corpus Christi Plant	No controls	Never reported a DRE range other than “>=0% to <75%”
CHEMOURS CHAMBERS WORKS	2000	Facility correspondence indicates controls were in place by 2000; also reported a DRE range other than “>=0% to <75%” in 2011

⁷⁰ See <https://insideclimatenews.org/news/29122022/3m-cordova-illinois-pfas-cf4-pollution/>.

CHEMOURS COMPANY - FAYETTEVILLE WORKS	2015	Reported a DRE range other than “>=0% to <75%” for the first time in 2015
CHEMOURS EL DORADO	2005	Reported a DRE range other than “>=0% to <75%” in 2011
CHEMOURS LOUISVILLE WORKS	No controls	Never reported a DRE range other than “>=0% to <75%”
CHEMOURS WASHINGTON WORKS	2000	Facility indicated controls were in place by 2000 in comments on GHG Inventory estimates.
DAIKIN AMERICA INC.	1993	Title V operating permit ⁷¹
HONEYWELL INTERNATIONAL INC - BATON ROUGE PLANT	2012	Title V operating permit ⁷²
HONEYWELL INTERNATIONAL INC - GEISMAR COMPLEX	2011	Title V operating permit ⁷³
Honeywell Metropolis	No controls	Never reported a DRE range other than “>=0% to <75%” (did not report under Subpart L)
MEXICHEM FLUOR INC.	1993	Title V operating permit ⁷⁴
Versum Materials US, LLC	No controls	Never reported a DRE range other than “>=0% to <75%”

Activity Data

The activity data for production and transformation of fluorinated compounds for 1990 to 2010 are based on production and transformation data reported to EPA by certain facilities for certain years, on production capacity data, and on fluorinated GHG production and consumption trends estimated for the various fluorinated GHG-consuming industries.

Production and Production Capacity Data

Production data are available from reporting to the U.S. GHGRP under Subpart OO, Suppliers of Industrial Greenhouse Gases, and from an industry survey conducted by U.S. EPA in 2008 and 2009. Production and transformation data were reported under Subpart OO for 2010 and later years. The responses to the industry survey included production data for certain fluorinated gases at certain facilities for the years 2004, 2005, and 2006. 2004 to 2006 production data are available for 15 fluorinated compounds. Year 2006 production at an SF₆-producing facility was estimated based on production capacity data as described below (Rand 2007). Production of certain compounds at one other facility was estimated based on 2003 production capacity estimates from SRI 2004.

Estimated Production

Estimated production for facilities and fluorinated GHGs for which production or production capacity data were available for some years before 2010.

For facilities and fluorinated GHGs for which production or production capacity data were available for 2006 or 2003, production between 2006 or 2003 (as applicable) and 2010 (or 2011) was estimated by interpolating between the 2006 production or 2003 production capacity value and the 2010 (or 2011) production value reported under Subpart OO. To account for production occurring in some years but not others, production for 2009 was estimated to be the average production for 2010 to 2015.

⁷¹ Daikin (2013) <http://lf.adem.alabama.gov/WebLink/DocView.aspx?id=29951882&dbid=0>.

⁷² Honeywell (2011) <https://edms.deq.louisiana.gov/app/doc/view?doc=8579001>.

⁷³ Honeywell (2012) <https://edms.deq.louisiana.gov/app/doc/view?doc=7812895>.

⁷⁴ See <https://edms.deq.louisiana.gov/app/doc/view?doc=1309650>.

For the years before the earliest year with production or production capacity data (e.g., years 1990 to 2002 or 2003), production was estimated based on growth or consumption trends for the major industries using each fluorinated GHG.

- For fluorinated compounds that are commonly emitted in the semiconductor industry, estimates of U.S. layer-weighted semiconductor production (Total Manufactured Layer Area, or TMLA) were used to inform the fluorinated compound production estimates (EPA 2023c). Fluorinated compound production values were assumed to vary with TMLA from 1990 to 2002 or 2003. For example, 1998 production of PFC-14 at a particular facility was estimated by multiplying the 2003 production of PFC-14 at that facility by the ratio between the TMLA estimated for 1998 and the TMLA estimated for 2003. Fluorinated compounds for which TMLA was used to estimate production include PFC-14, PFC-116, PFC-218, perfluorocyclobutane (c-C₄F₈), and NF₃. (Note that the TMLA data were also extrapolated from year 1995 to 1990 based on the average change per year from 1995 to 2009.)
- SF₆ is commonly used in electric power systems, magnesium production, and electronics manufacturing. SF₆ consumption estimates across these three industries for 1990 to 2003 were used to inform the SF₆ production data (EPA 2023d); SF₆ production was assumed to vary with consumption totals from 1990 to 2003.
- For HFCs commonly used as replacements for ozone-depleting substances (ODS), such as HFCs used as substitutes for CFCs and HCFCs in air-conditioning and refrigeration equipment, HFC production data for certain fluorinated compounds from the Vintaging Model (VM) were used to inform the HFC production estimates (EPA 2023b). HFC production values were assumed to vary with the VM estimates of production. The industry trend data were applied to the list of HFCs in Table A-109.

Table A-109: List of Saturated HFCs, Unsaturated HFCs (Hydrofluoroolefins or HFOs), and Unsaturated HCFCs (Hydrochlorofluoroolefins or HCFOs) whose 1990-2009 Production Was Estimated Using Vintaging Model, Virgin Manufacturing by Chemical

Fluorinated Gas
HFC-23
HFC-32
HFC-125
HFC-134a
HFC-143a
HFC-152a
HFC-236fa
HFC-245fa
HFC-365mfc
HCFO-1233zd(E)
HFO-1234yf
HFO-1234ze
HFO-1336mzz(Z)
HFC-4310mee

Estimated production for facilities and fluorinated GHGs for which production data before 2010 were not available.

In the absence of production data for the period 1990 to 2009, the production data reported to the GHGRP under Subpart OO were extrapolated backward based on the industry trends discussed above. For compounds for which industry trend data were unavailable, production was assumed to have remained constant over the time series.

In both cases, 2009 production was estimated by conducting a trend analysis on the Subpart OO production data for years 2010 to 2015. In instances where there did not appear to be a trend, the average of the production values

for years 2010 to 2015 was used as the estimated production for year 2009. In instances where there was a trend, the year 2010 (or 2011) production value was used as the estimated production for year 2009.

If the industry trend information discussed above was applicable to a fluorinated compound, it was assumed that production varied with the industry trend from 1990 to 2009. If no industry trend information was available, it was assumed that production from 1990 to 2008 remained constant at the 2009 value.

For facilities and fluorinated compounds where information was available on annual production capacity, the estimated activity data was reviewed and compared to the known production capacity. For instances where the estimated activity data exceeded known production capacity for a certain year, the production estimate was set equal to the capacity value. In addition, where information was available on the starting year for production of a fluorinated GHG at a facility, production was only estimated beginning in the process startup year through 2009.

Estimated Emissions for 3M Facilities

3M provided 1990, 1995, 2000, and 2002 through 2010 emissions data for three facilities: 3M Cordova, 3M Company, and 3M Cottage Grove Center - Site.⁷⁵ Therefore, speciated 1990-2010 emissions at these facilities were estimated using a different methodology than that described above.⁷⁶

3M emissions data were provided by facility and by fluorinated GHG group in metric tons of CO₂ Eq., weighted by 100-year GWPs from various IPCC Assessment Reports. The fluorinated GHG groups included HFCs, PFCs, SF₆, HFEs, and other fluorinated GHGs. (3M noted that the “other fluorinated GHG” category included NF₃.) GWPs from the IPCC *Third Assessment Report* (TAR) were used to report totals for 1990, 1995, 2000, and 2003 to 2006. GWPs from the IPCC *Fifth Assessment Report* (AR5) were used to report totals for 2002, and GWPs from the IPCC *Fourth Assessment Report* (AR4) were used to report totals for 2007 to 2010. The emissions were also categorized as emissions from electrochemical fluorination (ECF) processes and downstream (DS) emissions. The DS emissions for 1990, 1995, and 2000 were reported as a total for each facility rather than by fluorinated GHG group.

To present emissions estimates by compound, EPA needed to disaggregate the data provided by 3M. The first step was to disaggregate the 1990, 1995, and 2000 DS emissions into fluorinated GHG groups. Since the 2003 to 2006 data were calculated using the same set of GWPs as the 1990, 1995, and 2000 data, the DS emissions of each group at each facility for 2003 to 2006 were divided by the total DS 2003 to 2006 emissions at that facility to obtain a set of fractions. These fractions were then multiplied by the 1990, 1995, and 2000 DS totals to sort those emissions into groups.

For 2002, ECF and DS emissions were only reported under the PFC group. (3M noted that chemical classifications were not preserved when 2002 emissions were recalculated using GWP values from AR5.) Since data for every other year showed emissions reported from multiple fluorinated GHG groups, and since 2004 was the closest year with emissions well sorted into fluorinated GHG groups, the ECF and DS emissions for 2002 were separated into multiple fluorinated GHG groups using the 2004 ECF and DS groups shares for each facility.

The next step was to disaggregate the emissions of each fluorinated GHG group into emissions of the relevant compounds in that group. To accomplish this, EPA assumed that emissions of each fluorinated GHG group before 2011 consisted of the same fluorinated GHGs, in the same proportions, as from 2011 through 2015. However, each

⁷⁵ For 1990, 1995, and 2000, 3M provided emissions data for a Pilot Development Center in addition to the other three facilities. Emissions by group from the Pilot Development Center were added to and are represented by the emissions by group for 3M Cottage Grove Center – Site.

⁷⁶ 3M’s methods for estimating its emissions are described in detail in “3M Global EHS Laboratory Response to EPA Data Request on Fluorochemical Emissions,” February 2024 (3M, 2024). In brief, 3M estimated emissions from its processes using emission factors that were developed using methods similar to those used for developing emission factors under the GHGRP. As under the GHGRP, emission factors were multiplied by different types of activity data (e.g., production) to estimate emissions for each facility and year. In 2003 and later years, 3M also accounted for emission reductions attributable to operation of the thermal oxidizer at the Cordova plant.

compound's share of the GWP-weighted emissions of the group in a given year depends on the GWPs used for that compound and for the other compounds in the group in that year. To account for this, EPA multiplied the reported 2011 to 2015 emissions of each compound in metric tons by the corresponding GWPs for that compound from the TAR, AR4, and AR5 to generate three sets of emissions by compound in metric tons of CO₂ Eq. For each set, the sum of emissions across 2011 to 2015 for each compound were divided by the total emissions for the corresponding fluorinated GHG group for those five years to calculate shares for each group.

The 3M emissions data by group for 1990, 1995, 2000, and 2002 to 2010 were then speciated by compound using the appropriate set of share values for each year. Since 3M Company only reported emissions of one compound in 2011 to 2015 but had emissions from multiple fluorinated GHG groups in 1990, 1995, 2000, and 2002 to 2010, the share values for 3M Cordova were used to speciate the 1990, 1995, 2000, and 2002-2010 emissions by group for 3M COMPANY. The speciated emissions in metric tons of CO₂ Eq. by compound for each facility were then divided by the appropriate TAR, AR4, or AR5 GWP for each compound to obtain the estimated emissions in metric tons of each compound for 1990, 1995, 2000, and 2002 to 2010.

Linear interpolation was then used to estimate emissions for 1991 to 1994, 1996 to 1999, and 2001 for each compound for these three facilities.

Estimated Emissions for Facilities that Produce Fluorinated GHGs but Do Not Report Under Subpart L

There is a subset of facilities that report production and transformation of fluorinated gases under Subpart OO and that also have emission levels less than the threshold value for reporting under Subpart L (i.e., uncontrolled emissions below the 25,000-MT CO₂ Eq. threshold). For these facilities, EPA developed emission estimates based on aggregated production estimates and the Tier 1 default emission factor in the 2019 Refinement. Because the specific fluorinated GHGs emitted are not known, the emissions were assumed to consist of the fluorinated GHGs shown in Table 3.28b of chapter 3.10.2 of Volume 3 IPPU (IPCC 2019), in the proportions shown in that table. Emissions are assumed to have been flat at the 2010 value in the years before 2010.

Estimated Emissions for SF₆ Production Facility

For an SF₆ production facility that ceased production in 2010, the year before emissions from fluorinated gas production were required to be reported under the GHGRP, SF₆ emissions were estimated using historical production capacity, the global growth rate of SF₆ sales reported in RAND 2007, and the Tier 1 default emission factor for production of SF₆ in the 2019 Refinement. For this plant, a 1982 SF₆ production capacity of 1,200 short tons (Perkins 1982) was multiplied by the ratio between the RAND survey SF₆ sales totals for 2006 and 1982, 1.52 (RAND 2007), resulting in estimated production of 1,652 metric tons in 2006. This production was assumed to have declined linearly to zero in 2011.

2011-2023 Emissions Estimates

For the 17 fluorinated gas production facilities that have reported their emissions under the GHGRP, 2011 to 2023 emissions are estimated using the fluorinated GHG emissions reported under Subpart L of the GHGRP.

As discussed above, most emissions reported under Subpart L are reported by chemical, but some emissions are reported only by fluorinated GHG group in MT CO₂ Eq. Between 2011 and 2023, the share of total CO₂ Eq. emissions reported only by fluorinated GHG group has ranged between 1 and 2 percent. In this analysis, to ensure that all emissions are reported by species, emissions that are reported only by fluorinated GHG group are assumed to consist of the fluorinated GHGs in that group that are reported by chemical at the facility in that year. When no fluorinated GHGs in the group are reported by chemical by that facility in that year, the emissions are assumed to consist of fluorinated GHGs in that group reported in other years at that facility. If no fluorinated GHGs in that group were ever reported by chemical by the facility, the emissions are assumed to consist of fluorinated GHGs in that group reported across the industry for that year. Because 3M facilities emitted many more individual compounds than the rest of the industry, fluorinated GHG groups at non-3M facilities were assumed to consist of fluorinated GHGs in groups as reported at other non-3M facilities. In each of these scenarios, fractions of gases emitted in mtCO₂e from each fluorinated GHG group were established and applied to the total mtCO₂e emitted from a fluorinated GHG group to calculate emissions in mtCO₂e of each individual fluorinated GHG. As discussed

further in the Uncertainty section, this is likely to result in incorrect speciation of some emissions, but the impact of this incorrect speciation is expected to be small.

Estimated Emissions for Facilities that Produce Fluorinated GHGs but Do Not Report Under Subpart L

As discussed above, for facilities that produce fluorinated GHGs but that do not report their emissions under subpart L, EPA developed emission estimates based on aggregated production estimates and the Tier 1 default emission factor in the 2019 Refinement. Because the specific fluorinated GHGs emitted are not known, the emissions were assumed to consist of the fluorinated GHGs shown in Table 3.28b of chapter 3.10.2 of Volume 3 IPPU (IPCC 2019), in the proportions shown in that table.

Uncertainty

The estimates in this memo are subject to a number of uncertainties. These uncertainties are generally greater for years before 2011, when reporting of fluorinated GHG emissions from fluorinated gas production began under the GHGRP, than for 2011 and following years. However, the emissions estimated from 2011 to 2023 are also subject to various uncertainties. The uncertainties for both the 1990 to 2010 and 2011 to 2023 periods are discussed in more detail below.

1990-2010 Uncertainty

The uncertainty of emissions estimated for 1990 through 2010 is considerably greater than that for emissions for 2011 through 2023 because emissions were not reported under the GHGRP. EPA has estimated emissions using estimated emission rates, fluorochemical production and transformation activity, and levels of control, and each set of estimates is subject to uncertainty.

Uncertainty regarding activity data

Identity of emitting processes

In reality, emissions of particular fluorinated GHGs are linked to production and/or transformation of particular fluorinated gases at facilities. However, GHGRP information/data does not link emissions of specific fluorinated GHGs to production or transformation of specific fluorinated gases. For the estimates presented here, therefore, all emissions are indexed to total production across all fluorinated gases. This may not capture trends in emissions that are driven by trends in production or transformation of subsets of the fluorinated gases produced at a facility.

Produced and emitted gases change over time

The set of gases produced at a facility, and therefore the set of fluorinated GHGs that are emitted by that facility, may change over time. It is likely that certain production and transformation processes that existed from 2011 to 2015 (the basis of the emission factors used to back-cast emissions in this analysis) did not exist throughout the entire previous time series (1990 to 2010). In such cases, emissions of the fluorinated GHGs emitted from the new processes will be overestimated by this analysis for certain years before 2011. On the other hand, it is also likely that some production and transformation processes, and their associated fluorinated GHG emissions, occurred only during the 1990 to 2010 period and not later, meaning that their emissions are not represented in the emission factors developed based on the 2011 to 2015 emissions and production data collected under the GHGRP. Such emissions will therefore not be captured by this analysis. The most prominent example of the second situation is probably production of CFCs and HCFCs other than HCFC-22 between 1990 and 2009, which has declined steadily since 1990 as the production of CFCs and HCFCs for emissive uses has been phased out in the United States and Globally. Production of CFCs and HCFCs can sometimes result in emissions of HFCs or PFCs.

Quantity of produced gases

Where production or production capacity data were available for certain fluorinated gases, facilities, and years before 2010, those data were incorporated into this analysis. However, even for facilities and compounds for which data were available in certain years, there were several years for which data were not available. For multiple produced compounds, data were available only in 2010. To estimate trends in production of compounds for years

before production or production capacity data were available, production of certain compounds was indexed to known national production or consumption trends for those compounds. This is the case for most HFCs, several PFCs, SF₆, and NF₃. National production estimates are available for HFCs, increasing confidence in country-level production estimates, but the distribution of production among the various HFC-producing facilities is uncertain. Where estimated production was indexed to consumption (for several PFCs, SF₆, and NF₃), the uncertainty is larger than for HFCs because changes in net imports/exports (which are not known) may also affect the production trend.

For certain fluorinated gases, trend information was not available; therefore, production was back-cast by assuming that it had remained constant at the 2010 level from 1990 through 2009. This is a highly uncertain assumption.

Some production and transformation activity is not reported under Subpart OO or modeled in back-casting

Under Subpart OO, quantities of fluorinated GHGs that are produced and transformed at the same facility are not reported to us, although any emissions from such processes are reported under Subpart L. Such unreported production and transformation are therefore not captured in the 1990 to 2010 activity estimates used to estimate 1990 through 2010 emissions. To the extent that such unreported production and transformation drive emissions and change over time, the trends will not be captured by this analysis.

Facilities that no longer produce fluorinated gases or that started producing them after 1990

Some facilities may have produced fluorinated gases at some point between 1990 and 2010 that no longer produced those compounds after 2010. One SF₆ producer is known to fall into this category and its 1990 to 2010 emissions were estimated, but there may be other facilities that are not included in this analysis. On the other hand, some facilities for which 1990 to 2010 emissions were estimated may not have produced them over the entire time series, in which case emissions of the compounds those facilities are assumed to have emitted could be overestimated.

Uncertainty regarding emission factors

Emission rates change over time

The emission factors used to estimate 1990 to 2010 emissions are based on the emissions and production reported from 2011 to 2015, reflecting emission rates during that period. For processes that have been used throughout the timeseries, emission rates may have changed over time as the process was optimized to increase efficiency, decreasing by-product emissions, or alternatively, as the process was optimized to maximize production, which sometimes increases by-product emissions. Emission rates also depend on the extent to which emissions are controlled at the facility, the uncertainties for which are discussed further below.

Emissions from container venting and destruction may not scale with production

In this analysis, emissions from container venting and destruction of previously produced fluorinated GHGs were included in the emission factors used to estimate 1990 to 2010 emissions. This implicitly assumes that such emissions scale with production and transformation. While this seems likely to be broadly true, there may be exceptions. However, since emissions from container venting and destruction are generally a small share of facility emissions (2 percent, on average), the impact of such exceptions is expected to be small.

Uncertainty regarding levels of control

In this analysis, the arithmetic mean of the DRE range reported by each facility for each process was used to estimate the DRE for that process and the uncontrolled emissions for that process. Since the emissions implied by

the bounds of each DRE range span at least a factor of four,⁷⁷ this is an uncertain assumption. The uncertainty is mitigated somewhat by the fact that there are generally several processes at each facility, meaning that departures from the assumed mean average out to some extent. There is also uncertainty in the assumptions that (1) all fluorinated GHGS within a particular fluorinated GHG group are abated to the same extent and (2) facilities for which control device start dates are unavailable began to control emissions in 2005.

Quantitative uncertainty estimate for uncontrolled emission factors from 2019 Refinement

As noted above, 2011 to 2016 data from the GHGRP was used to develop the Tier 1 default uncontrolled emission factor for the *2019 Refinement*, using methods similar to those described here. A Monte Carlo analysis performed to assess the uncertainty of the Tier 1 default factor indicated that the uncertainty for each facility's uncontrolled emission factor was less than 50 percent. This uncertainty estimate considered the uncertainty regarding the levels of control, but not the uncertainty of applying factors from one time period at the facility to much earlier time period (although the variability of each facility's emission factor over the 6-year span of the *2019 Refinement* analysis was found to be relatively low).

Uncertainty regarding the identity of 3M emitted compounds

For the three 3M facilities that submitted their 1990 through 2010 emissions by fluorinated GHG group, it is assumed that the emissions of each group consist of the compounds in that group that were reported by species by the facility from 2011 through 2014. However, 3M indicated that the mix of products made at its facilities had changed over time, which would have affected the identities of the fluorinated GHGs emitted. For example, at one facility, only one compound was reported to be emitted for 2011-2015 but 3M's historical emissions data showed multiple fluorinated GHG groups for that facility for 1990 to 2010. For that facility, it is assumed that emissions consisted of the compounds in each gas type that were reported by species by the 3M facility that was determined to be the most similar. Additionally, there were a few years of data for these three facilities where some emissions were reported as a total rather than separated by group. For these years, the group shares were assumed to be the same as in nearby years. There is uncertainty involved with each of the assumptions made while speciating emissions for these three facilities, though the uncertainty is minimal regarding total emissions in metric tons of CO₂ Eq. In at least one case, the speciation method appears to have resulted in an overestimate for an individual compound. In this analysis, 3M's emissions of C₄F₈O are estimated to have peaked at around 410 MT in 2000, but at least one study has inferred considerably lower global emissions (around 120 MT) for that year based on atmospheric measurements of C₄F₈O (Vollmer et al. 2019).

2011-2023 Uncertainty

Emissions from 2011 to 2023 reflect reporting by fluorinated gas production facilities under the GHGRP. As discussed above, emissions reported under the GHGRP are based on facility- and process-specific measurements or calculations and are therefore expected to be reasonably accurate for the reporting facilities. (Emissions from the largest sources, process vents emitting 10,000 MT CO₂ Eq. or more annually, are estimated using Tier 3 methods.)

Unverified reports Ninety-four percent (184/196) of the Subpart L reports submitted by fluorinated gas production facilities from 2011 to 2023 are considered to be fully verified; seven percent (12/196) of the reports include one or more data elements that are not verified. One facility accounts for 58 percent (7/12) of the unverified reports. Many of the issues in the unverified reports for this facility relate to time-series inconsistencies that have arisen as the facility updates reports for recent years, but not previous years, to reflect refinements to estimated emission rates. This facility has accounted for between 6 percent (in 2011) and 29 percent (in 2022) of the GWP-weighted

⁷⁷ For example, the DRE range 0 to 75% implies emissions of (1-0) x uncontrolled emissions to (1-75%) x uncontrolled emissions, or, rearranging and calculating, 0.25 x uncontrolled emissions to 1 x uncontrolled emissions, a factor of four.

emissions reported for this source category. The uncertainties for this facility therefore have an appreciable impact on the uncertainty of the estimates for the source category as a whole.

Facilities that do not produce fluorinated gases but may emit fluorinated GHGs from other fluorochemical production processes

Under the GHGRP, EPA collects information from facilities that produce fluorinated gases. While this likely includes most, and possibly all, U.S. facilities that produce fluorochemicals of any kind, it is possible that some fluorochemical producers do not report either their production of fluorochemicals or their emissions of fluorinated GHGs to EPA under the GHGRP. In this case, emissions estimates based only on GHGRP reporting would underestimate actual emissions.

At fluorinated gas production facilities that currently report their emissions under the GHGRP, it is possible that some processes that emit fluorinated GHGs neither produce nor transform a fluorinated gas, in which case their emissions would not be reported under the GHGRP. In that case, emissions estimates based only on GHGRP reporting would underestimate actual emissions.

Exclusion of nitrous oxide

The GHGRP does not currently require facilities to report emissions of nitrous oxide (N₂O) from fluorinated gas production or transformation, but the IPCC *2019 Refinement* includes a default emission factor for N₂O from production of NF₃, implying such emissions may occur. The GHGRP data (and this analysis) may therefore underestimate emissions of N₂O from fluorinated gas production. Because the GWP of N₂O is considerably lower than that of saturated HFCs, PFCs, and other fluorinated GHGs, any underestimate is expected to be relatively small.

Identity of emitted compounds

In this analysis, it is assumed that emissions that are reported only in MT CO₂ Eq. by fluorinated GHG group consist of the compounds in that group that are reported by species by the facility. However, if that were actually the case, emissions of those compounds would have been included in the speciated emissions rather than reported separately in MT CO₂ Eq. This analysis therefore incorrectly speciates some emissions. As noted in the Methodology section, the share of total CO₂ Eq. emissions reported only by fluorinated GHG group is small, ranging between 1 and 2 percent. Moreover, while the emissions are not assigned to the exact species emitted, they are assigned to a species that is closely related and likely to have similar atmospheric impacts (e.g., another saturated HFC with two or fewer carbon-hydrogen bonds). The impact of this uncertainty is therefore limited.

Quantities of Reactants Consumed or Fluorinated Gases Produced

The emissions reported under Subpart L are required to be calculated using process activity data, such as the quantity of reactants consumed or the quantity of the fluorinated gas product produced. In general, the uncertainties in process activity levels are expected to be small. The *2019 Refinement* places such uncertainties “in the region of 1 percent.”

Because the uncertainties enumerated above are either small or difficult to quantify, EPA did not attempt to include them in the 2023 quantitative uncertainty estimate for this source category. The 2023 quantitative uncertainty estimate includes the following uncertainties:

Process Vent Emission Factors

Process vent emission factors that were developed based on stack testing (for continuous process vents emitting 10,000 MT CO₂ Eq. or more) were estimated to have an uncertainty (95-percent confidence interval) of ±35 percent

based on Subpart L requirements.⁷⁸ Process vent emission factors that were developed based on calculations (for batch process vents and for continuous process vents emitting less than 10,000 MT CO₂ Eq.) were estimated to have a larger uncertainty of ±50 percent. Continuous processes were assumed to have two vents per process; batch processes were assumed to have five vents per process.⁷⁹

Equipment Leak Estimates

The estimated equipment leaks reported by each facility for each process were estimated to have an uncertainty of ± 90 percent. The uncertainty of leak estimates depends on the method used to estimate leaks; there are multiple methods. For simplicity, this analysis uses a conservatively high uncertainty estimate that is appropriate for the Average EF Approach.

Venting of Residual Gas in Containers

The reported emissions of fluorinated GHGs from venting of residual gas in returned containers were estimated to have an uncertainty of ± 30 percent for each facility. This estimate is based on the Subpart L requirement to either measure the contents of each container or to measure the contents of at least 30 representative containers for each compound and container size and type.

Facilities that produce fluorinated gases but do not report their emissions to the GHGRP

EPA estimated emissions for fluorinated gas production facilities that do not report their emissions under Subpart L of the GHGRP. The estimates presented here for 2011 to 2024 are based on aggregated production estimates, the Tier 1 default emission factor in the *2019 Refinement*, and the default fluorinated GHG speciation from Table 3.28b (chapter 3.10.2 of *2019 Refinement*). There is considerable uncertainty in both the magnitude of the emissions and the identity of the emitted compounds. The *2019 Refinement* estimates the uncertainty of the Tier 1 emission factor as -98 percent to +470 percent. (In the quantitative uncertainty estimate below, which is based on error propagation, values of ±98 percent were used because error propagation requires the assumption of symmetric uncertainty bounds.) In 2024, estimated emissions from the six non-reporting facilities accounted for 50 percent of total estimated U.S. emissions from production of fluorinated gases other than HCFC-22. In contrast, production and transformation by these facilities accounted for less than three percent of total fluorinated GHG production and transformation (excepting HCFC-22 production) across all facilities. Because the emissions estimated for several of the six facilities exceeded the 25,000 MT CO₂ Eq. reporting threshold under Subpart L, but these facilities have not reported their emissions under Subpart L, it appears likely that emissions from at least some facilities are overestimated.

Quantitative uncertainty estimate

The uncertainties in process vent emission factors (±35% for emission factors based on emissions testing; ±50% for emission factors based on engineering calculations), equipment leak estimates (±90%), the quantities of residual gas vented from containers (±30%), and emissions from facilities that produce fluorinated gases but do not report their emissions to the GHGRP (±98%) were convolved using error propagation to arrive at an overall uncertainty estimate for 2023. The results of the Approach 1 quantitative uncertainty analysis are summarized in Table A-110. Emissions of HFCs, PFCs, SF₆, and NF₃ from production of fluorochemicals other than HCFC-22 were

⁷⁸ *Technical Support Document for Emissions from Production of Fluorinated Gases*, Office of Air and Radiation, U.S. Environmental Protection Agency, November 5, 2010. Available online at: https://www.epa.gov/sites/default/files/2015-02/documents/subpart-L_techsuppdoc.pdf.

⁷⁹ *Economic Impact Analysis for the Mandatory Reporting of Greenhouse Gas Emissions F-Gases: Subparts I, L, DD, QQ, SS*, U.S. Environmental Protection Agency, November 2010. Available online at: <https://www.regulations.gov/document/EPA-HQ-OAR-2009-0927-0179>.

estimated to fall between 3.40 and 5.15 MMT CO₂ Eq. at the 95 percent confidence level. This indicates a range of approximately 20 percent below and 20 percent above the emission estimate of 4.27 MMT CO₂ Eq.

Table A-110: Approach 1 Quantitative Uncertainty Estimates for HFC, PFC, SF₆, and NF₃ from Production of Fluorochemicals other than HCFC-22 (MMT CO₂ Eq. and Percent)

Source	Gas	2023 Emission Estimate (MMT CO ₂ Eq.)	Uncertainty Range Relative to Emission Estimate			
			(MMT CO ₂ Eq.)		(%)	
			Lower Bound ^a	Upper Bound ^a	Lower Bound	Upper Bound
Production of Fluorochemicals other than HCFC- 22	HFCs, PFCs, SF ₆ , and NF ₃	4.27	3.40	5.15	-20%	+20-%

^a Absolute lower and upper bounds were calculated using the corresponding lower and upper bounds in percentages.

3.10. Methodology and QA/QC and Verification Details for Estimating HFC, PFC, and CO₂ Emissions from Substitution of Ozone Depleting Substances

Methodology for Estimating HFC, PFC, and CO₂ Emissions from Substitution of Ozone Depleting Substances

Emissions of HFCs, PFCs, and CO₂ from the substitution of ozone depleting substances (ODS) are developed using a country-specific modeling approach. The Vintaging Model⁸⁰ was developed as a tool for estimating the annual chemical emissions from industrial sectors that have historically used ODS in their products. HFCs, PFCs, and CO₂ from the substitution of ozone depleting substances (ODS) are developed using a country-specific modeling approach. The Vintaging Model⁸¹ was developed as a tool for estimating the annual chemical emissions from industrial sectors that have historically used ODS in their products. The domestic U.S. consumption of ODS—chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl chloroform, and hydrochlorofluorocarbons (HCFCs)—has been drastically reduced, forcing these industrial sectors to transition to more ozone-friendly chemicals. As these industries have moved toward ODS alternatives such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and carbon dioxide (CO₂), the Vintaging Model has evolved into a tool for estimating the rise in consumption and emissions of these alternatives, and the decline of ODS consumption and emissions.

The Vintaging Model estimates emissions from five ODS substitute, HFC-emitting end-use sectors: refrigeration and air-conditioning, foams, aerosols, solvents, and fire extinguishing. Within these sectors, there are 82 independently modeled end-uses. The model requires information on the market growth for each of the end-uses, a history of the market transition from ODS to alternatives, and the characteristics of each end-use such as market size, charge size, and loss rate. As ODS are phased out, a percentage of the market share originally filled by the ODS is allocated to each of its substitutes.

The model, named for its method of tracking the emissions of annual “vintages” of new equipment that enter into service, is a “bottom-up” model. It models the consumption of chemicals based on estimates of the quantity of equipment or products sold, serviced, and retired each year, and the amount of the chemical required to manufacture and/or maintain the equipment. The Vintaging Model makes use of this market information to build an inventory of the in-use stocks of the equipment, ODS, and ODS substitute in each of the end-uses. The simulation is considered to be a “business-as-usual” baseline case and does not incorporate measures to reduce or eliminate the emissions of these gases other than those regulated by U.S. law or otherwise common in the industry. Emissions are estimated by applying annual leak rates, service emission rates, and disposal emission rates to each population of equipment. By aggregating the emission and consumption output from the different end-uses, the model produces estimates of total annual use and emissions of each chemical.

The Vintaging Model synthesizes data from a variety of sources, including data from the ODS Tracking System maintained by the Stratospheric Protection Division, the Greenhouse Gas Reporting Program maintained by the Climate Change Division, and information from submissions to EPA under the Significant New Alternatives Policy (SNAP) program. Published sources include documents prepared by the United Nations Environment Programme (UNEP) Technical Options Committees, reports from the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS), conference proceedings from the International Conferences on Ozone Protection Technologies and Earth Technologies Forums, and numerous technical reports and corporate announcements. EPA also coordinates extensively with numerous trade associations and individual companies. For example, the Alliance for Responsible Atmospheric Policy; the Air-Conditioning, Heating and Refrigeration Institute; the Association of Home Appliance

⁸⁰ Vintaging Model version VM IO file_v5.1_1.23.2025 was used for all *Inventory* estimates.

⁸¹ Vintaging Model version VM IO file_v5.1_1.23.2025 was used for all *Inventory* estimates.

Manufacturers; the American Automobile Manufacturers Association; and many of their member companies have provided valuable information over the years.

In some instances, the unpublished information that the EPA uses in the model is classified as Confidential Business Information (CBI). The annual emissions inventories of chemicals are aggregated in such a way that CBI cannot be inferred. Full public disclosure of the inputs to the Vintaging Model would jeopardize the security of the CBI that has been entrusted to the EPA. In addition, emissions of certain gases (including HFC-152a, HFC-227ea, HFC-245fa, HFC 365mfc, HFC-43-10mee, HCFO-1233zd(E), HFO-1234yf, HFO-1234ze(E), HFO-1336mzz(Z), C₄F₁₀, and PFC/PFPEs, the latter being a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications) are marked as confidential because they are produced or imported by a small number of chemical providers and in such small quantities or for such discrete applications that reporting national data would effectively be reporting the chemical provider's output, which is considered confidential business information. These gases are modeled individually in the Vintaging Model but are aggregated and reported as two unspecified mixes of ODS substitutes.

The Vintaging Model is regularly updated to incorporate up-to-date market information, including equipment stock estimates, leak rates, and sector transitions. In addition, comparisons against published emission and consumption sources are performed when available. Independent peer reviews of the Vintaging Model are periodically performed, including one conducted in 2017 (EPA 2018), to confirm Vintaging Model estimates and identify updates.

The following sections discuss the emission equations used in the Vintaging Model for each broad end-use category. These equations are applied separately for each chemical used within each of the different end-uses. In the majority of these end-uses, more than one ODS substitute chemical is used.

In general, the modeled emissions are a function of the amount of chemical consumed in each end-use market. Estimates of the consumption of ODS alternatives can be inferred by determining the transition path of each regulated ODS used in the early 1990s. Using data gleaned from a variety of sources, assessments are made regarding which alternatives have been used, and what fraction of the ODS market in each end-use has been captured by a given alternative. By combining this with estimates of the total end-use market growth, a consumption value can be estimated for each chemical used within each end-use.

Methodology

The Vintaging Model estimates the use and emissions of ODS alternatives by taking the following steps:

1. *Gather historical data.* The Vintaging Model is populated with information on each end-use, taken from published sources and industry experts.
2. *Simulate the implementation of new, non-ODS technologies.* The Vintaging Model uses detailed characterizations of the existing uses of the ODS, as well as data on how the substitutes are replacing the ODS, to simulate the implementation of new technologies that enter the market in compliance with ODS phase-out policies. As part of this simulation, the ODS substitutes are introduced in each of the end-uses over time as seen historically and as needed to comply with the ODS phase-out and other regulations.
3. *Estimate emissions of the ODS substitutes.* The chemical use is estimated from the amount of substitutes that are required each year for the manufacture, installation, use, or servicing of products. The emissions are estimated from the emission profile for each vintage of equipment or product in each end-use. By aggregating the emissions from each vintage, a time profile of emissions from each end-use is developed.

Each set of end-uses is discussed in more detail in the following sections.

Refrigeration and Air Conditioning

For refrigeration and air conditioning products, emission calculations are split into three categories: emissions at first-fill, which arise during manufacture or installation, emissions during equipment lifetime, which arise from annual leakage and service losses, and disposal emissions, which occur at the time of discard. This methodology

is consistent to the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories, where the total refrigerant emissions from refrigeration and air conditioning equipment is the sum of first-fill emissions, annual operational and servicing emissions, and disposal emissions under the Tier 2a emission factor approach (IPCC 2006). Three separate steps are required to calculate the lifetime emissions from installation, leakage and service, and the emissions resulting from disposal of the equipment. The model assumes that equipment is serviced annually so that the amount equivalent to average annual emissions for each product (and hence for the total of what was added to the bank in a previous year in equipment that has not yet reached end-of-life) is replaced/applied to the starting charge size (or chemical bank). For any given year, these first-fill emissions (for new equipment), lifetime emissions (for existing equipment), and disposal emissions (from discarded equipment) are summed to calculate the total emissions from the refrigeration and air-conditioning sector. As new technologies replace older ones, it is generally assumed that there are improvements in their leak, service, and disposal emission rates, due to improvement in technology and equipment/component design, such as the use of micro-channel heat exchangers, reduction in piping and joints, more advanced controls and leak detection to identify leaks faster, and other optimizations.

At disposal, refrigerant that is recovered from discarded equipment is assumed to be reused to the extent necessary in the following calendar year. The Vintaging Model does not make any explicit assumption whether recovered refrigerant is reused as-is (allowed under U.S. regulations if the refrigerant is reused in the same owner's equipment), recycled (commonly practiced even when re-used directly), or reclaimed (brought to new refrigerant purity standards and available to be sold on the open market).

Step 1: Calculate first-fill emissions

The first-fill emission equation assumes that a certain percentage of the chemical charge will be emitted to the atmosphere when the equipment is charged with refrigerant during manufacture or installation. First-fill emissions are considered for all refrigerants in all refrigeration and air conditioning equipment that are charged with refrigerant within the United States, including those which are produced for export, and excluding those that are imported pre-charged. First-fill emissions are thus a function of the quantity of chemical contained in new equipment and the proportion of equipment that are filled with refrigerant in the United States:

Equation A-8: Calculation of Emissions from Refrigeration and Air-conditioning Equipment First-fill

$$Ef_j = Qc_j \times l_r \times A_j$$

where:

Ef	=	Emissions from Equipment First-fill. Emissions in year j from filling new equipment.
Qc	=	Quantity of Chemical in New Equipment. Total amount of a specific chemical used to charge new equipment in year j , by weight.
l_r	=	First-fill Leak Rate. Average leak rate during installation or manufacture of new equipment (expressed as a percentage of total chemical charge).
A	=	Applicability of First-fill Leak Rate. Percentage of new equipment that are filled with refrigerant in the United States in year j .
j	=	Year of emission.

Step 2: Calculate lifetime emissions

Emissions from any piece of equipment include both the amount of chemical leaked during equipment operation and the amount emitted during service. Emissions from leakage and servicing can be expressed as follows:

Equation A-9: Calculation of Emissions from Refrigeration and Air-conditioning Equipment Serviced

$$Es_j = (l_a + l_s) \times \sum Qc_{j-i+1} \quad \text{for } i = 1 \rightarrow k$$

where:

Es	=	Emissions from Equipment Serviced. Emissions in year j from normal leakage and servicing (including recharging) of equipment.
l_a	=	Annual Leak Rate. Average annual leak rate during normal equipment operation (expressed as a percentage of total chemical charge).
l_s	=	Service Leak Rate. Average leakage during equipment servicing (expressed as a percentage of total chemical charge).
Qc	=	Quantity of Chemical in New Equipment. Total amount of a specific chemical used to charge new equipment in a given year by weight.
i	=	Counter, runs from 1 to lifetime (k).
j	=	Year of emission.
k	=	Lifetime. The average lifetime of the equipment.

Step 3: Calculate disposal emissions

The disposal emission equations assume that a certain percentage of the chemical charge will be emitted to the atmosphere when that vintage is discarded, while remaining refrigerant is assumed to be recovered and reused. Disposal emissions are thus a function of the quantity of chemical contained in the retiring equipment fleet and the proportion of chemical released at disposal:

Equation A-10: Calculation of Emissions from Refrigeration and Air-conditioning Equipment Disposed

$$Ed_j = Qc_{j-k+1} \times [1 - (rm \times rc)]$$

where:

Ed	=	Emissions from Equipment Disposed. Emissions in year j from the disposal of equipment.
Qc	=	Quantity of Chemical in New Equipment. Total amount of a specific chemical used to charge new equipment in year $j-k+1$, by weight.
rm	=	Chemical Remaining. Amount of chemical remaining in equipment at the time of disposal (expressed as a percentage of total chemical charge).
rc	=	Chemical Recovery Rate. Amount of chemical that is recovered just prior to disposal (expressed as a percentage of chemical remaining at disposal (rm)).
j	=	Year of emission.
k	=	Lifetime. The average lifetime of the equipment.

Step 4: Calculate total emissions

Finally, first-fill, lifetime, and disposal emissions are summed to provide an estimate of total emissions.

Equation A-11: Calculation of Total Emissions from Refrigeration and Air-conditioning Equipment

$$E_j = E_{fj} + E_{sj} + E_{dj}$$

where:

E	=	Total Emissions. Emissions from refrigeration and air conditioning equipment in year j .
E_f	=	Emissions from first Equipment Fill. Emissions in year j from filling new equipment.
E_s	=	Emissions from Equipment Serviced. Emissions in year j from leakage and servicing (including recharging) of equipment.
E_d	=	Emissions from Equipment Disposed. Emissions in year j from the disposal of equipment.
j	=	Year of emission.

Assumptions

The assumptions used by the Vintaging Model to trace the transition of each type of equipment away from ODS are presented in Table A-111, below, including the average equipment lifetimes, charge sizes, one-time emissions rates (for first-fill and disposal), and annual emission rates (for servicing and leaks) for each refrigeration and air-conditioning end-use modeled by the Vintaging Model. As new technologies replace older ones, it is generally assumed that there are improvements in their leak, service, and disposal emission rates. Additionally, the market for each equipment type is assumed to grow independently, according to annual growth rates, which are applied to new equipment within each end-use.

Table A-111: Refrigeration and Air-Conditioning Market Transition and Lifetime Assumptions

Substitute Type	Substitute Name	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Charge Size (kg)	First-fill Emission Rate ^b	Annual Emission Rate	Disposal Emission Rate ^c	Lifetime	Average Growth Rate ^d
Centrifugal Chillers										
Initial	CFC-11	1985	1985	100%	500	0.5%	20%	20%	25	1.6%
Primary	HFC-123	1993	1993	45%	440	0.2%	1%	10%		
Secondary	HCFO-1233zd(E)	2016	2016	0.5%	440	0.2%	1%	10%		
	R-514A	2017	2017	0.5%	440	0.2%	1%	10%		
	HCFO-1233zd(E)	2017	2020	22%	440	0.2%	1%	10%		
	R-514A	2018	2020	22%	440	0.2%	1%	10%		
Primary Improvement	HCFC-22	1991	1993	16%	700	0.2%	14%	20%		
	HCFC-22	1996	1996	16%	720	0.2%	5%	20%		
Secondary	HFC-134a	2000	2010	16%	700	0.2%	2%	10%		
Tertiary	R-450A	2017	2017	0.1%	700	0.2%	2%	10%		
	R-513A	2017	2017	0.1%	700	0.2%	2%	10%		
	R-450A	2018	2024	8%	700	0.2%	2%	10%		
	R-513A	2018	2024	8%	700	0.2%	2%	10%		
Primary	HFC-134a	1992	1993	39%	700	0.2%	2%	10%		
Secondary	R-450A	2017	2017	0.2%	700	0.2%	2%	10%		
	R-513A	2017	2017	0.2%	700	0.2%	2%	10%		
	R-450A	2018	2024	19%	700	0.2%	2%	10%		
	R-513A	2018	2024	19%	700	0.2%	2%	10%		
Initial	CFC-12	1985	1985	100%	727	0.5%	11%	20%	27	1.5%
Primary	HFC-134a	1992	1994	53%	720	0.2%	2%	10%		
Secondary	R-450A	2017	2017	0.3%	720	0.2%	2%	10%		
	R-513A	2017	2017	0.3%	720	0.2%	2%	10%		
	R-450A	2018	2024	26%	720	0.2%	2%	10%		
	R-513A	2018	2024	26%	720	0.2%	2%	10%		
Primary Improvement	HCFC-22	1991	1994	16%	720	0.2%	8%	20%		
	HCFC-22	1996	1996	16%	720	0.2%	5%	20%		
Secondary	HFC-134a	2000	2010	16%	720	0.2%	2%	10%		
Tertiary	R-450A	2017	2017	0.1%	720	0.2%	2%	10%		

Substitute Type	Substitute Name	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Charge Size (kg)	First-fill Emission Rate ^b	Annual Emission Rate	Disposal Emission Rate ^c	Lifetime	Average Growth Rate ^d
Primary	R-513A	2017	2017	0.1%	720	0.2%	2%	10%		
	R-450A	2018	2024	15%	720	0.2%	2%	10%		
	R-513A	2018	2024	15%	720	0.2%	2%	10%		
	HCFC-123	1993	1994	31%	453	0.2%	1%	10%		
Secondary	HCFO-1233zd(E)	2016	2016	0.3%	453	0.2%	1%	10%		
	R-514A	2017	2017	0.3%	453	0.2%	1%	10%		
	HCFO-1233zd(E)	2017	2020	15%	453	0.2%	1%	10%		
	R-514A	2018	2020	15%	453	0.2%	1%	10%		
Initial	R-500	1985	1985	100%	873	0.5%	15%	20%	27	1.5%
Primary	HFC-134a	1992	1994	53%	926	0.2%	2%	10%		
Secondary	R-450A	2017	2017	1%	926	0.2%	2%	10%		
	R-513A	2017	2017	1%	926	0.2%	2%	10%		
	R-450A	2018	2024	26%	926	0.2%	2%	10%		
	R-513A	2018	2024	26%	926	0.2%	2%	10%		
Primary Improvement	HCFC-22	1991	1994	16%	926	0.2%	11%	20%		
	HCFC-22	1996	1996	16%	926	0.2%	5%	20%		
Secondary	HFC-134a	2000	2010	16%	926	0.2%	2%	10%		
Tertiary	R-450A	2017	2017	0.1%	926	0.2%	2%	10%		
	R-513A	2017	2017	0.1%	926	0.2%	2%	10%		
	R-450A	2018	2024	8%	926	0.2%	2%	10%		
	R-513A	2018	2024	8%	926	0.2%	2%	10%		
Primary	HFC-123	1993	1994	31%	582	0.2%	1%	10%		
Secondary	HCFO-1233zd(E)	2016	2016	0.3%	582	0.2%	1%	10%		
	R-514A	2017	2017	0.3%	582	0.2%	1%	10%		
	HCFO-1233zd(E)	2017	2020	15%	582	0.2%	1%	10%		
	R-514A	2018	2020	15%	582	0.2%	1%	10%		
Initial	CFC-114	1985	1985	100%	540	0.5%	14%	20%	20	1.4%
Primary Improvement	HFC-236fa	1993	1994	100%	702	0.2%	8%	10%		
	HFC-236fa	1996	1996	100%	702	0.2%	5%	10%		
Secondary	HFC-134a	1998	2009	100%	630	0.2%	2%	10%		
Cold Storage										

Substitute Type	Substitute Name	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Charge Size (kg)	First-fill Emission Rate ^b	Annual Emission Rate	Disposal Emission Rate ^c	Lifetime	Average Growth Rate ^d
Initial	CFC-12	1985	1985	100%	0.07 ^e	1%	25%	20%	20	2.7%
Primary	HCFC-22	1990	1993	65%	0.07 ^e	1%	20%	20%		
Secondary	R-404A	1996	2010	49%	0.06 ^e	1%	15%	10%		
	R-507	1996	2010	16%	0.06 ^e	1%	15%	10%		
Improvement	R-404A	2010	2010	49%	0.01 ^e	1%	11%	10%		
	R-507	2010	2010	16%	0.01 ^e	1%	11%	10%		
Tertiary	R-717	2017	2023	32%	0.0004 ^e	1%	11%	10%		
	CO ₂	2017	2023	14%	0.0005 ^e	1%	11%	10%		
	R-407F	2017	2023	2%	0.01 ^e	1%	11%	10%		
	R-717	2017	2023	11%	0.0004 ^e	1%	11%	10%		
	CO ₂	2017	2023	5%	0.0005 ^e	1%	11%	10%		
	R-407F	2017	2023	1%	0.01 ^e	1%	11%	10%		
Primary	R-404A	1994	1996	26%	0.06 ^e	1%	20%	20%		
Secondary	R-407F	2017	2023	26%	0.01 ^e	1%	15%	10%		
Primary	R-507	1994	1996	9%	0.01 ^e	1%	15%	10%		
Secondary	R-407F	2017	2023	9%	0.01 ^e	1%	15%	10%		
Initial	HCFC-22	1985	1985	100%	0.7 ^e	1%	23%	20%	25	1.8%
Primary	HCFC-22	1992	1993	100%	0.07 ^e	1%	21%	20%		
Secondary	R-404A	1996	2009	8%	0.06 ^e	1%	15%	10%		
	R-507	1996	2009	3%	0.06 ^e	1%	15%	10%		
	R-404A	2009	2010	68%	0.06 ^e	1%	15%	10%		
	R-507	2009	2010	23%	0.06 ^e	1%	15%	10%		
Improvement	R-404A	2010	2010	8%	0.01 ^e	1%	11%	10%		
	R-507	2010	2010	3%	0.01 ^e	1%	11%	10%		
	R-404A	2010	2010	68%	0.01 ^e	1%	11%	10%		
	R-507	2010	2010	23%	0.01 ^e	1%	11%	10%		
Tertiary	R-717	2017	2023	5%	0.0004 ^e	1%	11%	10%		
	CO ₂	2017	2023	2%	0.0005 ^e	1%	11%	10%		
	R-407F	2017	2023	0.4%	0.01 ^e	1%	11%	10%		
	R-717	2017	2023	2%	0.0004 ^e	1%	11%	10%		
	CO ₂	2017	2023	1%	0.0005 ^e	1%	11%	10%		

Substitute Type	Substitute Name	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Charge Size (kg)	First-fill Emission Rate ^b	Annual Emission Rate	Disposal Emission Rate ^c	Lifetime	Average Growth Rate ^d
	R-407F	2017	2023	0.1%	0.01 ^e	1%	11%	10%		
	R-717	2017	2023	45%	0.0004 ^e	1%	11%	10%		
	CO ₂	2017	2023	20%	0.0005 ^e	1%	11%	10%		
	R-407F	2017	2023	3.4%	0.01 ^e	1%	11%	10%		
	R-717	2017	2023	15%	0.0004 ^e	1%	11%	10%		
	CO ₂	2017	2023	7%	0.0005 ^e	1%	11%	10%		
	R-407F	2017	2023	1%	0.01 ^e	1%	11%	10%		
Initial	R-502	1985	1985	100%	0.07 ^e	1%	25%	20%		
Primary	HCFC-22	1990	1993	40%	0.07 ^e	1%	32%	20%		
Secondary	R-404A	1996	2010	15%	0.06 ^e	1%	15%	10%		
	R-507	1996	2010	5%	0.06 ^e	1%	15%	10%		
	R-717	1996	2010	20%	0.01 ^e	1%	15%	10%		
<i>Improvement</i>	<i>R-404A</i>	<i>2010</i>	<i>2010</i>	<i>15%</i>	<i>0.01^e</i>	<i>1%</i>	<i>11%</i>	<i>10%</i>		
	<i>R-507</i>	<i>2010</i>	<i>2010</i>	<i>5%</i>	<i>0.01^e</i>	<i>1%</i>	<i>11%</i>	<i>10%</i>		
	<i>R-717</i>	<i>2010</i>	<i>2010</i>	<i>20%</i>	<i>0.01^e</i>	<i>1%</i>	<i>11%</i>	<i>10%</i>		
Tertiary	R-717	2017	2023	10%	0.0004 ^e	1%	11%	10%		
	CO ₂	2017	2023	4%	0.0005 ^e	1%	11%	10%		
	R-407F	2017	2023	1%	0.01 ^e	1%	11%	10%		
	R-717	2017	2023	3%	0.0004 ^e	1%	11%	10%	25	1.4%
	CO ₂	2017	2023	1%	0.0005 ^e	1%	11%	10%		
	R-407F	2017	2023	0.2%	0.01 ^e	1%	11%	10%		
Primary <i>Improvement</i>	R-404A	1993	1996	45%	0.01 ^e	1%	15%	10%		
	<i>R-404A</i>	<i>2010</i>	<i>2010</i>	<i>45%</i>	<i>0.01^e</i>	<i>1%</i>	<i>11%</i>	<i>10%</i>		
Secondary	R-717	2017	2023	30%	0.0004 ^e	1%	11%	10%		
	CO ₂	2017	2023	13%	0.0005 ^e	1%	11%	10%		
	R-407F	2017	2023	2%	0.01 ^e	1%	11%	10%		
Primary <i>Improvement</i>	R-507	1994	1996	15%	0.01 ^e	1%	15%	10%		
	<i>R-507</i>	<i>2010</i>	<i>2010</i>	<i>15%</i>	<i>0.01^e</i>	<i>1%</i>	<i>11%</i>	<i>10%</i>		
Secondary	R-717	2017	2023	10%	0.0004 ^e	1%	11%	10%		
	CO ₂	2017	2023	4%	0.0005 ^e	1%	11%	10%		
	R-407F	2017	2023	1%	0.01 ^e	1%	11%	10%		

Substitute Type	Substitute Name	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Charge Size (kg)	First-fill Emission Rate ^b	Annual Emission Rate	Disposal Emission Rate ^c	Lifetime	Average Growth Rate ^d
Commercial Unitary Air Conditioners (Large)										
Initial	HCFC-22	1985	1985	100%	15	1%	11%	60%	15	1.8%
Primary	HCFC-22	1992	1993	100%	15	1%	10%	60%		
Secondary	R-410A	2001	2005	5%	13	1%	8%	35%		
	R-407C	2006	2009	1%	13	1%	8%	30%		
	R-410A	2006	2009	9%	13	1%	8%	35%		
	R-407C	2009	2010	5%	13	1%	8%	30%		
	R-410A	2009	2010	81%	13	1%	8%	35%		
Improvement	R-410A	2015	2015	5%	13	1%	8%	18%		
	R-407C	2015	2015	1%	13	1%	8%	15%		
	R-410A	2015	2015	9%	13	1%	8%	18%		
	R-407C	2015	2015	5%	13	1%	8%	15%		
	R-410A	2015	2015	81%	13	1%	8%	18%		
Commercial Unitary Air Conditioners (Small)										
Initial	HCFC-22	1985	1985	100%	8	1%	12%	65%	15	2.0%
Primary	HCFC-22	1992	1993	100%	8	0.5%	11%	65%		
Secondary	R-410A	1996	2000	3%	7	0.5%	9%	40%		
	R-410A	2001	2005	18%	7	0.5%	9%	40%		
	R-410A	2006	2009	8%	7	0.5%	9%	40%		
	R-410A	2009	2010	71%	7	0.5%	9%	40%		
	R-410A	2015	2015	3%	7	0.5%	9%	20%		
Improvement	R-410A	2015	2015	18%	7	0.5%	9%	20%		
	R-410A	2015	2015	8%	7	0.5%	9%	20%		
	R-410A	2015	2015	71%	7	0.5%	9%	20%		
	R-410A	2015	2015	71%	7	0.5%	9%	20%		
Dehumidifiers										
Initial	HCFC-22	1985	1985	100%	0.2	1%	1%	50%	11	1.3%
Primary	HFC-134a	1997	1997	89%	0.2	0.5%	1%	50%		
	R-410A	2007	2010	11%	0.2	0.5%	1%	50%		
Ice Makers										
Initial	CFC-12	1985	1985	100%	3.0	2%	7%	90%	8	2.1%
Primary	HFC-134a	1993	1995	27%	2.6	1%	5%	49%		

Substitute Type	Substitute Name	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Charge Size (kg)	First-fill Emission Rate ^b	Annual Emission Rate	Disposal Emission Rate ^c	Lifetime	Average Growth Rate ^d
<i>Improvement</i>	<i>HFC-134a</i>	2005	2005	27%	2.6	1%	3%	49%		
Primary	R-404A	1993	1995	73%	2.6	1%	5%	49%		
<i>Improvement</i>	<i>R-404A</i>	2005	2005	73%	2.6	1%	3%	49%		
Secondary	R-410A	2013	2019	23%	2.6	1%	3%	49%		
Industrial Process Refrigeration										
Initial	CFC-11	1985	1985	100%	680	1.0%	19%	20%	25	3.2%
Primary	HCFC-123	1992	1994	70%	598	1.0%	5%	10%		
Secondary	HCFO-1233zd(E)	2017	2017	1%	598	1.0%	5%	10%		
	R-514A	2017	2017	1%	598	1.0%	5%	10%		
	HCFO-1233zd(E)	2018	2020	34%	598	1.0%	5%	10%		
	R-514A	2018	2020	34%	598	1.0%	5%	10%		
Primary	HFC-134a	1992	1994	15%	952	1.0%	5%	10%		
Primary	HCFC-22	1991	1994	15%	952	1.0%	10%	20%		
Secondary	HFC-134a	1995	2010	15%	952	1.0%	5%	10%		
Initial	CFC-12	1985	1985	100%	1,000	1%	10%	20%	25	3.1%
Primary	HCFC-22	1991	1994	10%	992	1%	10%	20%		
Secondary	HFC-134a	1995	2010	2%	992	1%	5%	10%		
	R-404A	1995	2010	5%	708	1%	5%	10%		
	R-410A	1999	2010	2%	878	1%	5%	10%		
	R-507A	1995	2010	2%	708	1%	5%	10%		
<i>Improvement</i>	<i>HFC-134a</i>	2010	2010	2%	992	1%	4%	10%		
	<i>R-404A</i>	2010	2010	5%	708	1%	4%	10%		
	<i>R-410A</i>	2010	2010	2%	878	1%	4%	10%		
	<i>R-507A</i>	2010	2010	2%	708	1%	4%	10%		
Primary	HCFC-123	1992	1994	35%	623	1%	5%	10%		
<i>Improvement</i>	<i>HCFC-123</i>	2005	2005	35%	623	1%	4%	10%		
Secondary	HCFO-1233zd(E)	2017	2017	0.4%	623	1%	4%	10%		
	R-514A	2017	2017	0.4%	623	1%	4%	10%		
	HCFO-1233zd(E)	2018	2020	17%	623	1%	4%	10%		
	R-514A	2018	2020	17%	623	1%	4%	10%		
Primary	HFC-134a	1992	1994	50%	992	1%	5%	10%		

Substitute Type	Substitute Name	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Charge Size (kg)	First-fill Emission Rate ^b	Annual Emission Rate	Disposal Emission Rate ^c	Lifetime	Average Growth Rate ^d
<i>Improvement</i>	<i>HFC-134a</i>	2005	2005	50%	992	1%	4%	10%		
Primary	R-401A	1995	1996	5%	850	1%	5%	10%		
Secondary	HFC-134a	1997	2000	5%	992	1%	4%	10%		
Initial	HCFC-22	1985	1985	100%	9,100	1%	16%	20%	25	3.0%
Primary	HCFC-22	1992	1993	100%	9,100	1%	12%	20%		
Secondary	HFC-134a	1995	2009	2%	9,100	1%	12%	10%		
	R-404A	1995	2009	5%	6,500	1%	12%	10%		
	R-410A	1999	2009	2%	8,060	1%	12%	10%		
	R-507	1995	2008	2%	6,500	1%	12%	10%		
	HFC-134a	2009	2010	14%	9,100	1%	12%	10%		
	R-404A	2009	2010	45%	6,500	1%	12%	10%		
	R-410A	2009	2010	18%	8,060	1%	12%	10%		
	R-507	2009	2010	14%	6,500	1%	12%	10%		
<i>Improvement</i>	<i>HFC-134a</i>	2010	2010	2%	9,100	1%	8%	10%		
	<i>R-404A</i>	2010	2010	5%	6,500	1%	8%	10%		
	<i>R-410A</i>	2010	2010	2%	8,060	1%	8%	10%		
	<i>R-507</i>	2010	2010	2%	6,500	1%	8%	10%		
	<i>HFC-134a</i>	2010	2010	14%	9,100	1%	8%	10%		
	<i>R-404A</i>	2010	2010	45%	6,500	1%	8%	10%		
	<i>R-410A</i>	2010	2010	18%	8,060	1%	8%	10%		
	<i>R-507</i>	2010	2010	14%	6,500	1%	8%	10%		
Mobile Air Conditioners (Passenger Cars)										
Initial	CFC-12	1985	1985	100%	1.00	0.5%	41%	50%	16	0.0%
Primary	HFC-134a	1992	1994	100%	0.85	0.2%	37%	43%		
<i>Improvement</i>	<i>HFC-134a</i>	1998	1998	100%	0.85	0.2%	18%	43%		
	<i>HFC-134a</i>	2002	2002	100%	0.85	0.2%	10%	43%		
	<i>HFC-134a</i>	2002	2005	100%	0.66	0.2%	10%	43%		
	<i>HFC-134a</i>	2005	2005	100%	0.66	0.2%	7%	43%		
	<i>HFC-134a</i>	2007	2007	100%	0.56	0.2%	7%	43%		
	<i>HFC-134a</i>	2008	2013	100%	0.56	0.2%	6%	43%		
Secondary	HFO-1234yf	2012	2015	1%	0.56	0.2%	6%	43%		

Substitute Type	Substitute Name	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Charge Size (kg)	First-fill Emission Rate ^b	Annual Emission Rate	Disposal Emission Rate ^c	Lifetime	Average Growth Rate ^d
	HFO-1234yf	2016	2021	99%	0.56	0.2%	6%	43%		
Mobile Air Conditioners (Light Duty Trucks)										
Initial	CFC-12	1985	1985	100%	1.14	0.50%	41%	50%	16	1.7%
Primary	HFC-134a	1993	1994	100%	1.05	0.20%	37%	43%		
	HFC-134a	1995	1997	38%	0.95	0.20%	37%	43%		
Improvement	HFC-134a	1998	2002	63%	0.95	0.20%	18%	43%		
	HFC-134a	1998	1998	38%	0.95	0.20%	18%	43%		
	HFC-134a	2002	2002	63%	0.95	0.20%	10%	43%		
	HFC-134a	2003	2005	38%	0.90	0.20%	18%	43%		
	HFC-134a	2003	2005	63%	0.90	0.20%	10%	43%		
	HFC-134a	2005	2005	38%	0.90	0.20%	15%	43%		
	HFC-134a	2005	2005	63%	0.90	0.20%	7%	43%		
	HFC-134a	2006	2006	38%	0.79	0.20%	15%	43%		
	HFC-134a	2006	2006	63%	0.79	0.20%	7%	43%		
	HFC-134a	2008	2013	38%	0.79	0.20%	13%	43%		
	HFC-134a	2008	2013	63%	0.79	0.20%	6%	43%		
	Secondary	HFO-1234yf	2012	2015	0.4%	0.79	0.20%	13%		
HFO-1234yf		2016	2021	37%	0.79	0.20%	13%	43%		
HFO-1234yf		2012	2015	1%	0.79	0.20%	6%	43%		
HFO-1234yf		2016	2021	67%	0.79	0.20%	6%	43%		
Mobile Air Conditioners (Heavy Duty Vehicles)										
Initial	CFC-12	1985	1985	100%	1.3	0.5%	35%	50%	16	0.7%
Primary	HFC-134a	1993	1994	100%	1.1	0.2%	35%	43%		
Improvement	HFC-134a	2000	2002	38%	1.1	0.2%	13%	43%		
	HFC-134a	2010	2010	38%	1.1	0.2%	13%	43%		
Mobile Air Conditioners (School and Tour Buses)										
Initial	CFC-12	1985	1985	100%	5.8	0.5%	44%	50%	12	0.0%
Primary	HCFC-22	1994	1995	1%	50	0.2%	10%	50%		
Secondary	HFC-134a	2006	2007	0.5%	5.0	0.2%	10%	50%		
Primary	HFC-134a	1994	1997	99.5%	5.0	0.2%	10%	50%		
Mobile Air Conditioners (Transit Buses)										

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Initial	HCFC-22	1985	1985	100%	8.5	0.5%	44%	50%	12	0.0%
Primary	HFC-134a	1995	2009	100%	7.2	0.2%	10%	50%		
Mobile Air Conditioners (Trains)										
Initial	HCFC-22	1985	1985	100%	22	0.5%	44%	50%	5	0.0%
Primary	HFC-134a	2002	2009	50%	19	0.2%	2%	50%		
	R-407C	2008	2009	50%	19	0.2%	2%	50%		
Packaged Terminal Air Conditioners and Heat Pumps										
Initial	HCFC-22	1985	1985	100%	0.7	1%	5%	65%	12	3.0%
Improvement	HCFC-22	1992	1993	100%	0.7	1%	5%	65%		
Primary	R-410A	2006	2009	10%	0.6	1%	4%	40%		
	R-410A	2009	2010	90%	0.6	1%	4%	40%		
Positive Displacement Chillers (Reciprocating and Screw)										
Initial	HCFC-22	1985	1985	100%	300	0.5%	6%	20%	20	4.3%
Improvement	HCFC-22	1996	1996	100%	300	0.5%	2%	20%		
Primary	HFC-134a	2000	2009	9%	300	0.2%	1%	10%		
Secondary	R-407C	2010	2020	5%	300	0.2%	1%	10%		
Tertiary	R-450A	2017	2017	0.03%	300	0.2%	1%	10%		
	R-513A	2017	2017	0.03%	300	0.2%	1%	10%		
	R-450A	2018	2024	3%	300	0.2%	1%	10%		
	R-513A	2018	2024	3%	300	0.2%	1%	10%		
Secondary	R-410A	2010	2020	4%	300	0.2%	1%	10%		
Tertiary	R-450A	2017	2017	0.02%	300	0.2%	1%	10%		
	R-513A	2017	2017	0.02%	300	0.2%	1%	10%		
	R-450A	2018	2024	2%	300	0.2%	1%	10%		
	R-513A	2018	2024	2%	300	0.2%	1%	10%		
Primary	R-407C	2000	2009	1%	300	0.2%	1%	10%		
Secondary	R-450A	2017	2017	0.01%	300	0.2%	1%	10%		
	R-513A	2017	2017	0.01%	300	0.2%	1%	10%		
	R-450A	2018	2024	0.5%	300	0.2%	1%	10%		
	R-513A	2018	2024	0.5%	300	0.2%	1%	10%		
Primary	HFC-134a	2009	2010	81%	300	0.2%	1%	10%		

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Secondary	R-407C	2010	2020	49%	300	0.2%	1%	10%	20	2.5%
Tertiary	R-450A	2017	2017	0.2%	300	0.2%	1%	10%		
	R-513A	2017	2017	0.2%	300	0.2%	1%	10%		
	R-450A	2018	2024	24%	300	0.2%	1%	10%		
	R-513A	2018	2024	24%	300	0.2%	1%	10%		
Secondary	R-410A	2010	2020	32%	300	0.2%	1%	10%		
	R-450A	2017	2017	0.2%	300	0.2%	1%	10%		
Tertiary	R-513A	2017	2017	0.2%	300	0.2%	1%	10%		
	R-450A	2018	2024	16%	300	0.2%	1%	10%		
	R-513A	2018	2024	16%	300	0.2%	1%	10%		
Primary	R-407C	2009	2010	9%	300	0.2%	1%	10%		
Secondary	R-450A	2017	2017	0.05%	300	0.2%	1%	10%		
	R-513A	2017	2017	0.05%	300	0.2%	1%	10%		
	R-450A	2018	2024	4%	300	0.2%	1%	10%		
	R-513A	2018	2024	4%	300	0.2%	1%	10%		
Positive Displacement Chillers (Scroll)										
Initial Improvement	HCFC-22	1985	1985	100%	240	6%	1%	20%	20	2.5%
	HCFC-22	1996	1996	100%	240	0.5%	1%	20%		
Primary	HFC-134a	2000	2009	9%	240	0.2%	1%	10%		
Secondary	R-407C	2010	2020	5%	240	0.2%	1%	10%		
Tertiary	R-452B	2024	2024	5%	240	0.2%	1%	10%		
Secondary	R-410A	2010	2020	4%	240	0.2%	1%	10%		
Tertiary	R-452B	2024	2024	4%	240	0.2%	1%	10%		
Primary	R-407C	2000	2009	1%	240	0.2%	1%	10%		
Secondary	R-452B	2024	2024	1%	240	0.2%	1%	10%		
Primary	HFC-134a	2009	2010	81%	240	0.2%	1%	10%		
Secondary	R-407C	2010	2020	49%	240	0.2%	1%	10%		
Tertiary	R-452B	2024	2024	49%	240	0.2%	1%	10%		
Secondary	R-410A	2010	2020	32%	240	0.2%	1%	10%		
Tertiary	R-452B	2024	2024	32%	240	0.2%	1%	10%		
Primary	R-407C	2009	2010	9%	240	0.2%	1%	10%		

Substitute Type	Substitute Name	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Charge Size (kg)	First-fill Emission Rate ^b	Annual Emission Rate	Disposal Emission Rate ^c	Lifetime	Average Growth Rate ^d
Secondary	R-452B	2024	2024	9%	240	0.2%	1%	10%		
Refrigerated Appliances										
Initial	CFC-12	1985	1985	100%	0.2	0.9%	1%	50%	14	1.7%
Primary	HFC-134a	1994	1995	100%	0.1	0.8%	1%	42%		
Improvement	HFC-134a	2005	2005	100%	0.1	0.6%	1%	42%		
Secondary	HCs	2019	2021	86%	0.1	0.6%	1%	42%		
	R-450A	2021	2021	7%	0.1	0.6%	1%	42%		
	R-513A	2021	2021	7%	0.1	0.6%	1%	42%		
Refrigerated Food Processing and Dispensing Equipment										
Initial	CFC-12	1985	1985	100%	0.6	2%	1%	90%	10	1.0%
Primary	HCFC-22	1990	1994	100%	0.5	1%	1%	79%		
Secondary	HFC-134a	1995	1998	70%	0.5	1%	1%	68%		
Secondary	R-404A	1995	1998	30%	0.5	1%	1%	68%		
Tertiary	R-448A	2021	2021	15%	0.5	1%	1%	68%		
	R-449A	2021	2021	15%	0.5	1%	1%	68%		
Residential Unitary Air Conditioners										
Initial	HCFC-22	1985	1985	100%	1	1%	15%	65%	15	2.8%
Improvement	HCFC-22	1992	1993	100%	3	0.2%	14%	65%		
Primary	HCFC-22	2006	2006	70%	4	0.2%	5%	65%		
Secondary	R-410A	2007	2010	20%	4	0.2%	5%	40%		
	R-410A	2015	2015	20%	4	0.2%	5%	20%		
Secondary	R-410A	2010	2010	50%	4	0.2%	5%	40%		
	R-410A	2015	2015	50%	4	0.2%	5%	20%		
Primary	R-410A	2000	2005	5%	3	0.2%	11%	40%		
	R-410A	2006	2006	5%	4	0.2%	5%	40%		
	R-410A	2015	2015	5%	4	0.2%	5%	20%		
Primary	R-410A	2000	2006	5%	3	0.2%	11%	40%		
	R-410A	2015	2015	5%	4	0.2%	5%	20%		
Primary	R-410A	2006	2006	20%	4	0.2%	5%	40%		
	R-410A	2015	2015	20%	4	0.2%	5%	20%		
Retail Food (Large; Technology Transitions)										

Substitute Type	Substitute Name	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Charge Size (kg)	First-fill Emission Rate ^b	Annual Emission Rate	Disposal Emission Rate ^c	Lifetime	Average Growth Rate ^d
Initial	DX ^f	1985	2006	100%	Assumptions shown in detail for Refrigerant Transitions.				18	1.7%
Primary	DX	2001	2006	67.5%						
Secondary	DX	2006	2015	42%						
	DR ^g	2000	2015	16%						
	SLS ^h	2000	2015	10%						
Primary	DR	2000	2006	22.5%						
Primary	SLS	2000	2006	10%						
Retail Food (Large; Refrigerant Transitions)										
Initial	R-502 or CFC-12	1985	1985	100%	1,800	2%	33%	20%	18	1.7%
	HCFC-22 or R-502	1990	1993	100%	1,800	2%	33%	20%		
Primary Improvement	HCFC-22	1995	2000	75%	1,800	2%	30%	20%		
	HCFC-22	2000	2000	75%	1,360	2%	30%	20%		
Secondary	R-407A	2001	2005	0.5%	680	2%	19%	10%		
	R-407A	2001	2005	0.5%	1,360	2%	25%	10%		
	R-407A	2001	2005	9.5%	1,360	2%	25%	10%		
	R-407A	2006	2010	5%	680	2%	19%	10%		
	R-407A	2006	2010	5%	408	2%	14%	10%		
Secondary	HCFC-22	2001	2005	10%	680	2%	19%	10%		
Tertiary	R-404A	2006	2010	10%	680	2%	19%	10%		
Secondary	R-404A	2001	2005	6.6%	680	2%	19%	10%		
	R-404A	2001	2005	2%	1,360	2%	25%	10%		
	R-507	2001	2005	5%	1,360	2%	25%	10%		
	R-404A	2001	2005	0.5%	408	2%	14%	10%		
	R-404A	2006	2010	1%	680	2%	19%	10%		
	R-404A	2006	2010	4.5%	408	2%	14%	10%		
Tertiary	R-407F	2017	2017	6.6%	680	2%	19%	10%		
	R-407F	2017	2017	2%	1,360	2%	25%	10%		
	R-407F	2011	2015	5%	1,360	2%	25%	10%		
	R-407F	2017	2017	0.5%	408	2%	14%	10%		
	R-407F	2017	2017	1%	680	2%	19%	10%		
	R-407F	2017	2017	4.5%	408	2%	14%	10%		

Substitute Type	Substitute Name	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Charge Size (kg)	First-fill Emission Rate ^b	Annual Emission Rate	Disposal Emission Rate ^c	Lifetime	Average Growth Rate ^d
Secondary	R-404A	2006	2010	26%	1,360	2%	25%	10%	20	1.5%
Tertiary	R-407F	2011	2015	6%	1,360	2%	25%	10%		
	R-407F	2011	2015	10%	680	2%	19%	10%		
	R-407F	2011	2015	10%	408	2%	14%	10%		
Primary Improvement	R-404A	1995	2000	18%	1,800	2%	30%	20%		
	R-404A	2000	2000	18%	1,360	2%	30%	10%		
Secondary	R-404A	2000	2000	1%	680	2%	19%	10%		
	R-404A	2000	2000	0.1%	408	2%	14%	10%		
Tertiary	R-407F	2017	2017	1%	680	2%	19%	10%		
	R-407F	2017	2017	0.1%	408	2%	14%	10%		
Secondary	R-407F	2011	2015	11%	1,360	2%	30%	10%		
	R-407F	2017	2017	6%	1,360	2%	30%	10%		
Primary Improvement	R-507	1995	2000	8%	1,800	2%	30%	20%		
	R-507	2000	2000	8%	1,360	2%	30%	20%		
Secondary	R-507	2001	2005	5%	680	2%	19%	10%		
Tertiary	R-407A	2006	2010	3.8%	680	2%	19%	10%		
Tertiary	R-404A	2006	2010	1.5%	1,360	2%	30%	10%		
Quaternary	R-407F	2017	2017	1.5%	680	2%	19%	10%		
Secondary	R-404A	2006	2010	2%	680	2%	19%	10%		
Tertiary	R-407A	2017	2017	2%	1,360	2%	30%	10%		
Retail Food (Large Condensing Units)										
Initial	HCFC-22	1985	1985	100%	25	3%	15%	20%	20	1.5%
Primary	R-402A	1995	2005	5%	25	0.5%	15%	20%		
Secondary	R-404A	2006	2006	5%	21	0.5%	15%	10%		
Tertiary	R-407A	2018	2018	5%	21	0.5%	15%	10%		
Primary	R-404A	1995	2005	25%	21	0.5%	15%	10%		
Secondary	R-407A	2018	2018	25%	21	0.5%	15%	10%		
Primary	R-507	1995	2005	10%	21	0.5%	15%	10%		
Secondary	R-407A	2018	2018	10%	21	0.5%	15%	10%		
Primary	R-404A	2008	2010	45%	21	0.5%	15%	10%		
Secondary	R-407A	2018	2018	25%	21	0.5%	15%	10%		

Substitute Type	Substitute Name	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Charge Size (kg)	First-fill Emission Rate ^b	Annual Emission Rate	Disposal Emission Rate ^c	Lifetime	Average Growth Rate ^d
Primary	R-507	2008	2010	15%	21	0.5%	15%	10%		
Secondary	R-407A	2018	2018	25%	21	0.5%	15%	10%		
Retail Food (Small Condensing Units)										
Initial	HCFC-22	1985	1985	100%	3.0	3%	8%	20%	20	1.6%
Primary	R-401A	1995	2005	6%	3.0	0.5%	8%	20%		
Secondary	HFC-134a	2006	2006	6%	2.6	0.5%	8%	10%		
Primary	R-402A	1995	2005	4%	3.0	0.5%	8%	20%		
Secondary	HFC-134a	2006	2006	6%	2.6	0.5%	8%	10%		
Primary	HFC-134a	1993	2005	30%	2.6	0.5%	8%	10%		
Primary	R-404A	1995	2005	30%	2.6	0.5%	8%	10%		
Secondary	R-407A	2018	2018	30%	2.6	0.5%	8%	10%		
Primary	R-404A	2008	2010	30%	2.6	0.5%	8%	10%		
Secondary	R-407A	2018	2018	30%	2.6	0.5%	8%	10%		
Retail Food (Small)										
Initial	CFC-12	1985	1985	100%	0.5	2%	1%	65%	10	1.6%
Primary	HCFC-22	1990	1993	91%	0.5	1%	1%	65%		
Secondary	HFC-134a	1993	1995	83%	0.4	1%	1%	35%		
Tertiary	CO ₂	2012	2017	1%	0.4	1%	1%	19%		
	R-290	2014	2019	26%	0.2	1%	1%	19%		
	R-450A	2016	2020	19%	0.4	1%	1%	19%		
	R-513A	2016	2020	19%	0.4	1%	1%	19%		
Secondary	HFC-134a	2000	2009	8%	0.4	1%	1%	35%		
Tertiary	R-290	2014	2019	2.5%	0.15	1%	1%	35%		
	R-450A	2016	2020	2.9%	0.4	1%	1%	35%		
	R-513A	2016	2020	2.9%	0.4	1%	1%	35%		
Primary	R-404A	1990	1993	9%	0.5	1%	1%	65%		
Secondary	R-290	2016	2016	2.7%	0.2	1%	1%	35%		
	R-448A	2019	2020	3.2%	0.5	1%	1%	35%		
	R-449A	2019	2020	3.2%	0.5	1%	1%	35%		
Transport Refrigeration (Road Transport)										
Initial	CFC-12	1985	1985	100%	4.9	0.2%	42%	65%	12	4.1%

Substitute Type	Substitute Name	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Charge Size (kg)	First-fill Emission Rate ^b	Annual Emission Rate	Disposal Emission Rate ^c	Lifetime	Average Growth Rate ^d
Primary	HFC-134a	1993	1995	10%	4.5	0.2%	36%	33%	25	5.2%
Improvement	HFC-134a	2000	2000	10%	4.5	0.2%	23%	33%		
Primary	R-404A	1993	1995	60%	4.5	0.2%	36%	33%		
Improvement	R-404A	2000	2000	60%	4.5	0.2%	23%	33%		
Secondary	R-452A	2017	2021	3%	4.5	0.2%	23%	33%		
	R-452A	2022	2022	57%	4.5	0.2%	23%	33%		
Primary	HCFC-22	1993	1995	30%	4.9	0.2%	36%	65%		
Improvement	HCFC-22	2000	2000	30%	4.9	0.2%	33%	65%		
Secondary	R-410A	2000	2003	1.5%	4.5	0.2%	23%	33%		
Secondary	R-404A	2006	2010	29%	4.5	0.2%	23%	33%		
Tertiary	R-452A	2017	2021	1.4%	4.5	0.2%	23%	33%		
	R-452A	2022	2022	27%	4.5	0.2%	23%	33%		
Transport Refrigeration (Intermodal Containers)										
Initial	CFC-12	1985	1985	100%	5.0	0.2%	37%	65%	25	5.2%
Primary	HFC-134a	1993	1993	60%	4.5	0.2%	31%	33%		
Improvement	HFC-134a	1999	1999	60%	4.5	0.2%	26%	33%		
	HFC-134a	2000	2010	60%	4.5	0.2%	19%	33%		
	Secondary	CO ₂	2017	2021	3%	4.5	0.2%	19%		
Primary	R-404A	1993	1993	5%	4.5	0.2%	31%	33%		
Improvement	R-404A	1999	1999	5%	4.5	0.2%	26%	33%		
	R-404A	2000	2010	5%	4.5	0.2%	19%	33%		
	Secondary	CO ₂	2017	2021	0.3%	4.5	0.2%	19%		
Primary	HCFC-22	1993	1993	35%	5.0	0.2%	31%	65%		
Improvement	HCFC-22	1999	1999	35%	5.0	0.2%	26%	65%		
Secondary	HFC-134a	2000	2010	35%	4.5	0.2%	23%	33%		
Tertiary	CO ₂	2017	2021	2%	4.5	0.2%	23%	33%		
Transport Refrigeration (Merchant Fishing Transport)										
Initial	HCFC-22	1985	1985	100%	385	1%	47%	20%	25	3.1%
Primary	HFC-134a	1993	1995	10%	385	1%	41%	10%		
Improvement	HFC-134a	2000	2000	10%	176	1%	33%	10%		
Primary	R-507	1994	1996	10%	385	1%	41%	10%		

Substitute Type	Substitute Name	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Charge Size (kg)	First-fill Emission Rate ^b	Annual Emission Rate	Disposal Emission Rate ^c	Lifetime	Average Growth Rate ^d
Improvement	R-507	2000	2000	10%	176	1%	33%	10%		
Primary	R-404A	1993	1996	10%	385	1%	41%	10%		
Improvement	R-404A	2000	2000	10%	176	1%	33%	10%		
Primary	HCFC-22	1993	1996	70%	385	1%	41%	20%		
Improvement	HCFC-22	2000	2000	70%	176	1%	33%	20%		
Secondary	R-407C	2000	2005	2%	176	1%	33%	10%		
	R-507	2006	2010	34%	176	1%	33%	10%		
	R-404A	2006	2010	34%	176	1%	33%	10%		
Tertiary	R-410A	2005	2007	2%	176	1%	33%	10%		
Transport Refrigeration (Reefer Ships)										
Initial	HCFC-22	1985	1985	100%	2,500	1%	37%	20%	25	5.2%
Improvement	HCFC-22	1993	1995	90%	2,500	1%	31%	20%		
Primary	HFC-134a	2006	2010	23%	750	1%	23%	10%		
Primary	R-507	2006	2010	23%	750	1%	23%	10%		
Primary	R-404A	2006	2010	23%	750	1%	23%	10%		
Primary	R-407C	2006	2010	23%	750	1%	23%	10%		
Primary	HFC-134a	1993	1995	3%	750	1%	31%	10%		
	HFC-134a	2000	2010	3%	750	1%	23%	10%		
Primary	R-507	1994	1995	3%	750	1%	31%	10%		
	R-507	2000	2010	3%	750	1%	23%	10%		
Primary	R-404A	1993	1995	3%	750	1%	31%	10%		
	R-404A	2000	2010	3%	750	1%	23%	10%		
Transport Refrigeration (Vintage Rail Transport)										
Initial	CFC-12	1985	1985	100%	15	0.2%	42%	65%	40	-100.0%
Primary	HCFC-22	1993	1995	100%	15	0.2%	36%	65%		
Secondary (Retrofit)	HFC-134a	1996	2000	-i	15	-i	36%	65%		
Transport Refrigeration (Modern Rail Transport)										
Initial	HFC-134a	1999	1999	100%	7.5	0.2%	36%	33%	9	0.5%
Primary	R-404A	1999	1999	50%	7.5	0.2%	36%	18%		
	R-404A	2005	2005	50%	7.5	0.2%	33%	18%		
Secondary	R-452B	2022	2022	25%	7.5	0.2%	33%	18%		

Substitute Type	Substitute Name	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Charge Size (kg)	First-fill Emission Rate ^b	Annual Emission Rate	Disposal Emission Rate ^c	Lifetime	Average Growth Rate ^d
Primary	HFC-134a	2005	2005	50%	7.5	0.2%	33%	33%		
Vending Machines										
Initial	CFC-12	1985	1985	100%	0.2	2.0%	1%	90%	10	0.2%
Primary	HFC-134a	1995	1998	90%	0.3	0.5%	1%	79%		
Secondary	R-290	2014	2014	1%	0.2	0.5%	1%	68%		
	R-290	2019	2019	79%	0.2	0.5%	1%	68%		
	R-450A	2019	2019	5%	0.3	0.5%	1%	68%		
	R-513A	2019	2019	5%	0.3	0.5%	1%	68%		
Secondary	CO ₂	2012	2012	1%	0.2	0.5%	1%	100%		
Tertiary	Propane	2019	2019	1%	0.2	0.5%	1%	68%		
Primary	R-404A	1995	1998	10%	0.3	0.5%	1%	79%		
Secondary	R-450A	2019	2019	5%	0.2	0.5%	1%	68%		
	R-513A	2019	2019	5%	0.2	0.5%	1%	68%		
Water-Source and Ground-Source Heat Pumps										
Initial	HCFC-22	1985	1985	100%	4.1	1%	5%	50%	20	1.3%
Improvement	HCFC-22	1992	1993	100%	4.1	1%	5%	43%		
Primary	R-407C	2000	2006	5%	3.5	1%	4%	43%		
	R-410A	2000	2006	5%	3.6	1%	4%	43%		
	HFC-134a	2000	2009	2%	3.5	1%	4%	43%		
	R-407C	2006	2009	3%	3.5	1%	4%	43%		
	R-410A	2006	2009	5%	3.6	1%	4%	43%		
	HFC-134a	2009	2010	18%	3.5	1%	4%	43%		
	R-407C	2009	2010	23%	3.5	1%	4%	43%		
	R-410A	2009	2010	41%	3.6	1%	4%	43%		
Window Units										
Initial	HCFC-22	1985	1985	100%	0.6	1.0%	1%	50%	12	1.9%
Primary	R-410A	2008	2009	10%	0.5	0.5%	1%	50%		
Secondary	HFC-32	2015	2019	5%	0.3	0.5%	1%	50%		
Primary	R-410A	2009	2010	90%	0.5	0.5%	1%	50%		
Secondary	HFC-32	2015	2019	45%	0.3	0.5%	1%	50%		

- ^a Transitions between the start year and date of full penetration in new equipment are assumed to be linear so that in total 100 percent of the market is assigned to the original ODS or the various ODS substitutes. Some transitions may not sum to 100 percent due to rounding.
- ^b For some equipment, first-fill emissions are adjusted to account for equipment that are produced in the United States, including those which are produced for export, and excluding those that are imported pre-charged.
- ^c Disposal emissions rates are developed based on consideration of the original charge size, the percentage of refrigerant likely to remain in equipment at the time of disposal, and recovery practices assumed to vary by gas type. Because equipment lifetime emissions are annualized, equipment is assumed to reach the end of its lifetime with a full charge. Therefore, recovery rate is equal to 100 percent - Disposal Loss Rate (%).
- ^d Growth Rate is the average annual growth rate for individual market sectors from the base year of the Vintaging Model to 2030.
- ^e Charge sizes for cold storage are modeled on a kilogram per cubic foot of refrigerated space basis.
- ^f DX refers to direct expansion systems where the compressors are mounted together in a rack and share suction and discharge refrigeration lines that run throughout the store, feeding refrigerant to the display cases in the sales area.
- ^g DR refers to distributed refrigeration systems that consist of multiple smaller units that are located close to the display cases that they serve such as on the roof above the cases, behind a nearby wall, or on top of or next to the case in the sales area.
- ^h SLS refers to secondary loop systems wherein a secondary fluid such as glycol or carbon dioxide is cooled by the primary refrigerant in the machine room and then pumped throughout the store to remove heat from the display equipment.
- ⁱ Vintage rail transport HFC systems are assumed to be retrofitted from existing CFC-12 systems.
- ^j Vintage rail transport HFC systems are retrofitted from existing systems and therefore have no HFC first-fill emission rate.

Aerosols

ODSs, HFCs, and many other chemicals are used as propellant aerosols. Pressurized within a container, a nozzle releases the chemical, which allows the product within the can to also be released. Three types of aerosol products are modeled: metered dose inhalers (MDI), consumer aerosols, and technical aerosols. In the United States, the use of CFCs in consumer aerosols was banned in 1978, and many products transitioned to hydrocarbons or “not-in-kind” technologies, such as solid deodorants and finger-pump hair sprays. However, MDIs and certain technical aerosols continued to use CFCs and HCFCs as propellants because their use was deemed essential. CFC use in MDIs was limited to the treatment of asthma and chronic obstructive pulmonary disease. Under the Clean Air Act, the use of CFCs and HCFCs was also exempted in technical aerosols for several applications, including industrial cleaners, pesticides, mold release agents, certain dusters, and lubricants.

All HFCs used in aerosols are assumed to be emitted in the year of manufacture. Since there is currently no aerosol recycling, it is assumed that all of the annual production of aerosol propellants is released to the atmosphere. The following equation describes the emissions from the aerosols sector.

Equation A-12: Calculation of Emissions from Aerosols

$$E_j = Qc_j$$

where:

E	=	Emissions. Total emissions of a specific chemical in year j from use in aerosol products, by weight.
Qc	=	Quantity of Chemical. Total quantity of a specific chemical contained in aerosol products sold in year j , by weight.
j	=	Year of emission.

Transition Assumptions

Transition assumptions and growth rates for those items that use ODSs or HFCs as propellants, including vital medical devices and specialty consumer products, are presented in Table A-112.

Table A-112: Aerosol Product Transition Assumptions

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate ^b
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	
MDIs													
CFC Mix ^c	HFC-134a	1997	1997	6%	None								3.8%
	Non-ODP/GWP	1998	2007	7%	None								
	CFC Mix ^a	2000	2000	87%	HFC-134a	2001	2011	28%	Non-ODP/GWP	2012	2018	64%	
									HFC-227ea	2015	2015	1%	
					Non-ODP/GWP	2001	2014	67%	None				
					HFC-227ea	2007	2013	5%	Non-ODP/GWP	2015	2018	44%	
Consumer Aerosols (Non-MDIs)													
NA ^d	HFC-152a	1990	1991	50%	None								4.2%
	HFC-134a	1995	1995	50%	HFC-152a	1997	1998	44%	None				
					HFC-152a	2001	2005	38%	None				
					HFO-1234ze(E)	2016	2018	16%	None				
Technical Aerosols (Non-MDIs)													
CFC-12	HCFC-142b	1994	1994	10%	HFC-152a	2001	2010	90%	None				4.2%
					HFC-134a	2001	2010	10%	None				
	Non-ODP/GWP	1994	1994	5%	None								
	HCFC-22	1994	1994	50%	HFC-134a	2001	2010	100%	HFO-1234ze(E)	2012	2016	10%	
	HFC-152a	1994	1994	10%	None								
	HFC-134a	1994	1994	25%	None								

^a Transitions between the start year and date of full penetration in new products are assumed to be linear so that in total 100% of the market is assigned to the original ODS or the various ODS substitutes.

^b Growth Rate is the average annual growth rate for individual market sectors from the base year to 2030.

^c CFC Mix consists of CFC-11, CFC-12 and CFC-114 and represents the weighted average of several CFCs consumed for essential use in MDIs from 1993 to 2008. It is assumed that CFC mix was stockpiled in the United States and used in new products through 2013.

^d Consumer Aerosols transitioned away from ODS prior to 1985, the year in which the Vintaging Model begins. The portion of the market that is now using HFC propellants is modeled.

Solvents

ODSs, HFCs, PFCs and other chemicals are used as solvents to clean items. For example, electronics may need to be cleaned after production to remove any manufacturing process oils or residues left. Solvents are applied by moving the item to be cleaned within a bath or stream of the solvent. Generally, most solvents are assumed to remain in the liquid phase and are not emitted as gas. Thus, emissions are considered “incomplete,” and are a fixed percentage of the amount of solvent consumed in a year. The solvent is assumed to be recycled or continuously reused through a distilling and cleaning process until it is eventually almost entirely emitted. The remainder of the consumed solvent is assumed to be entrained in sludge or wastes and disposed of by incineration or other destruction technologies without being released to the atmosphere (U.S. EPA 2004). The following equation calculates emissions from solvent applications.

Equation A-13: Calculation of Emissions from Solvents

$$E_j = l \times Qc_j$$

where:

E	=	Emissions. Total emissions of a specific chemical in year j from use in solvent applications, by weight.
l	=	Percent Leakage. The percentage of the total chemical that is leaked to the atmosphere, assumed to be 90 percent (U.S. EPA 2004).
Qc	=	Quantity of Chemical. Total quantity of a specific chemical sold for use in solvent applications in the year j , by weight.
j	=	Year of emission.

Transition Assumptions

The transition assumptions and growth rates used within the Vintaging Model for electronics cleaning, metals cleaning, precision cleaning, and adhesives, coatings and inks, are presented in Table A-113.

Table A-113: Solvent Market Transition Assumptions

Initial Market Segment	Primary Substitute				Secondary Substitute				Growth Rate ^b
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	
Adhesives									
CH ₃ CCl ₃	Non-ODP/GWP	1994	1995	100%	None				2.0%
Electronics									
CFC-113	Semi-Aqueous	1994	1995	52%	None				2.0%
	HCFC-225ca/cb	1994	1995	0.2%	Unknown				
	HFC-43-10mee	1995	1996	0.7%	None				
	HFE-7100	1994	1995	0.7%	None				
	nPB	1992	1996	5%	None				
	Methyl Siloxanes	1992	1996	0.8%	None				
	No-Clean	1992	2013 ^c	40%	None				
CH ₃ CCl ₃	Non-ODP/GWP	1996	1997	99.8%	None				2.0%
	PFC/PFPE	1996	1997	0.2%	ODP/GWP	2000	2003	90%	
					Non-	2005	2009	10%	

Initial Market Segment	Primary Substitute				Secondary Substitute				Growth Rate ^b
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	
					ODP/GWP				
Metals									
CH ₃ CCl ₃	Non-ODP/GWP	1992	1996	100%	None				2.0%
CFC-113	Non-ODP/GWP	1992	2013 ^c	100%	None				2.0%
CCl ₄	Non-ODP/GWP	1992	1996	100%	None				2.0%
Precision									
CH ₃ CCl ₃	Non-ODP/GWP	1995	1996	99.3%	None				2.0%
	HFC-43-10mee	1995	1996	0.6%	None				
	PFC/PFPE	1995	1996	0.1%	Non-ODP/GWP	2000	2003	90%	
					Non-ODP/GWP	2005	2009	10%	
CFC-113	Non-ODP/GWP	1995	2013 ^c	90%	None				2.0%
	Methyl Siloxanes	1995	1996	6%					
	HCFC-225ca/cb	1995	1996	1%	Unknown				
	HFE-7100	1995	1996	3%	None				

^a Transitions between the start year and date of full penetration in new equipment or chemical supply are assumed to be linear so that in total 100 percent of the market is assigned to the original ODS or the various ODS substitutes.

^b Growth Rate is the average annual growth rate for individual market sectors from the base year to 2030.

^c Transition assumed to be completed in 2013 to mimic CFC-113 stockpile use.

Note: Non-ODP/GWP includes chemicals with zero ODP and low GWP, such as hydrocarbons and ammonia, as well as not-in-kind alternatives such as “no clean” technologies.

Fire Extinguishing

ODSs, HFCs, PFCs and other chemicals are used as fire extinguishing agents, in both hand-held “streaming” applications as well as in built-up “flooding” equipment similar to water sprinkler systems. Although these systems are generally built to be leak-tight, some leaks do occur and emissions occur when the agent is released. Total emissions from fire extinguishing are assumed, in aggregate, to equal a percentage of the total quantity of chemical in operation at a given time. For modeling purposes, it is assumed that fire extinguishing equipment leaks at a constant rate for an average equipment lifetime, as shown in the equation below. In streaming systems, non-halon emissions are assumed to be 3.5 percent of all chemical in use in each year, while in flooding systems 2.5 percent of the installed base of chemical is assumed to leak annually. Halon systems are assumed to leak at higher rates. The equation is applied for a single year, accounting for all fire protection equipment in operation in that year. The model assumes that equipment is serviced annually so that the amount equivalent to average annual emissions for each product (and hence for the total of what was added to the bank in a previous year in equipment that has not yet reached end-of-life) is replaced/applied to the starting charge size (or chemical bank). Each fire protection agent is modeled separately. In the Vintaging Model, streaming applications have a 6-year lifetime, which reflects internal inspection timelines and not necessarily extinguisher lifetimes, and flooding applications have a 33-year lifetime. At end-of-life, remaining agent is recovered from equipment being disposed and is reused.

Equation A-14: Calculation of Emissions from Fire Extinguishing

$$E_j = r \times \sum Q_{C_{j+1}} \text{ for } i=1 \rightarrow k$$

where:

E	=	Emissions. Total emissions of a specific chemical in year j for fire extinguishing equipment, by weight.
r	=	Percent Released. The percentage of the total chemical in operation that is released to the atmosphere.
Q_c	=	Quantity of Chemical. Total amount of a specific chemical used in new fire extinguishing equipment in a given year, $j-i+1$, by weight.
i	=	Counter, runs from 1 to lifetime (k).
j	=	Year of emission.
k	=	Lifetime. The average lifetime of the equipment.

Transition Assumptions

Transition assumptions and growth rates for these two fire extinguishing types are presented in Table A-114.

Table A-114: Fire Extinguishing Market Transition Assumptions

Initial Market Segment	Primary Substitute				Secondary Substitute				Growth Rate ^b
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	
Flooding Agents									
Halon-1301	Halon-1301 ^c	1994	1994	4%	Unknown				2.2%
	HFC-23	1994	1999	0.2%	None				
	HFC-227ea	1994	1999	50.2%	FK-5-1-12	2003	2020	35%	
					HFC-125	2001	2012	10%	
					Non-ODP/GWP	2005	2020	13%	
	Non-ODP/GWP	1994	1994	22%	FK-5-1-12	2003	2020	7%	
	Non-ODP/GWP	1995	2003	7%	None				
	CO ₂	1998	2006	7%	None				
	C ₄ F ₁₀	1994	1999	0.5%	FK-5-1-12	2003	2003	100%	
	HFC-125	1997	2006	9.1%	FK-5-1-12	2003	2020	35%	
				Non-ODP/GWP	2005	2020	10%		
				Non-ODP/GWP	2005	2019	3%		
Streaming Agents									
Halon-1211	Halon-1211 ^c	1992	1992	5%	Unknown				3.0%
	HFC-236fa	1997	1999	3%	None				
	Halotron	1994	1995	0.1%	Unknown				
	Halotron	1996	2000	5.4%	Non-ODP/GWP	2020	2020	56%	
	Non-ODP/GWP	1993	1994	56%	None				
	Non-ODP/GWP	1995	2024	20%	None				

Initial Market Segment	Primary Substitute				Secondary Substitute				Growth Rate ^b
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	
	Non-ODP/GWP	1999	2018	10%	None				

^a Transitions between the start year and date of full penetration in new equipment are assumed to be linear so that in total 100 percent of the market is assigned to the original ODS or the various ODS substitutes.

^b Growth Rate is the average annual growth rate for individual market sectors from the base year to 2030.

^c Despite the 1994 consumption ban, a small percentage of new halon systems are assumed to continue to be built and filled with stockpiled or recovered supplies.

Foam Blowing

ODSs, HFCs, and other chemicals are used to produce foams, including such items as the foam insulation panels around refrigerators, insulation sprayed on buildings, etc. The chemical is used to create pockets of gas within a substrate, increasing the insulating properties of the item. Foams are given emission profiles depending on the foam type (open cell or closed cell). Open cell foams are assumed to be 100 percent emissive in the year of manufacture. Closed cell foams are assumed to emit a portion of their total HFC content upon manufacture, a portion at a constant rate over the lifetime of the foam, a portion at disposal, and a portion after disposal; these portions vary by end-use.

Step 1: Calculate manufacturing emissions (open-cell and closed-cell foams)

Manufacturing emissions occur in the year of foam manufacture and are calculated as presented in the following equation. Manufacturing emissions are considered for all foam equipment that are filled with foam within the United States, including those which are produced for export, and excluding those that are imported pre-filled.

Equation A-15: Calculation of Emissions from Foam Blowing Manufacturing

$$Em_j = lm \times Qc_j$$

where:

Em_j	=	Emissions from manufacturing. Total emissions of a specific chemical in year j due to manufacturing losses, by weight.
lm	=	Loss Rate. Percent of original blowing agent emitted during foam manufacture. For open-cell foams, lm is 100%.
Qc	=	Quantity of Chemical. Total amount of a specific chemical used to manufacture closed-cell foams in a given year.
j	=	Year of emission.

Step 2: Calculate lifetime emissions (closed-cell foams)

Lifetime emissions occur annually from closed-cell foams throughout the lifetime of the foam, as calculated as presented in the following equation.

Equation A-16: Calculation of Emissions from Foam Blowing Lifetime Losses (Closed-cell Foams)

$$Eu_j = lu \times \sum Qc_{j-i+1} \text{ for } i=1 \rightarrow k$$

where:

Eu_j	=	Emissions from Lifetime Losses. Total emissions of a specific chemical in year j due to lifetime losses during use, by weight.
lu	=	Leak Rate. Percent of original blowing agent emitted each year during lifetime use.
Qc	=	Quantity of Chemical. Total amount of a specific chemical used to manufacture closed-cell foams in a given year.
i	=	Counter, runs from 1 to lifetime (k).
j	=	Year of emission.
k	=	Lifetime. The average lifetime of foam product.

Step 3: Calculate disposal emissions (closed-cell foams)

Disposal emissions occur in the year the foam is disposed, and are calculated as presented in the following equation.

Equation A-17: Calculation of Emissions from Foam Blowing Disposal (Closed-cell Foams)

$$Ed_j = ld \times Qc_{j-k}$$

where:

Ed_j	=	Emissions from disposal. Total emissions of a specific chemical in year j at disposal, by weight.
ld	=	Loss Rate. Percent of original blowing agent emitted at disposal.
Qc	=	Quantity of Chemical. Total amount of a specific chemical used to manufacture closed-cell foams in a given year.
j	=	Year of emission.
k	=	Lifetime. The average lifetime of foam product.

Step 4: Calculate post-disposal emissions (closed-cell foams)

Post-disposal emissions occur in the years after the foam is disposed; for example, emissions might occur while the disposed foam is in a landfill. Currently, five foam types are assumed to have post-disposal emissions.

Equation A-18: Calculation of Emissions from Foam Blowing Post-disposal (Closed-cell Foams)

$$Ep_j = lp \times \sum Qc_{j-m} \text{ for } m=k \rightarrow k+26$$

where:

Ep_j	=	Emissions from post disposal. Total post-disposal emissions of a specific chemical in year j, by weight.
lp	=	Leak Rate. Percent of original blowing agent emitted post disposal.
Qc	=	Quantity of Chemical. Total amount of a specific chemical used to manufacture closed-cell foams in a given year.
k	=	Lifetime. The average lifetime of foam product.
m	=	Counter. Runs from lifetime (k) to (k+26).
j	=	Year of emission.

Step 5: Calculate total emissions (open-cell and closed-cell foams)

To calculate total emissions from foams in any given year, emissions from all foam stages must be summed, as presented in the following equation.

Equation A-19: Calculation of Total Emissions from Foam Blowing (Open-cell and Closed-cell Foams)

$$E_j = Em_j + Eu_j + Ed_j + Ep_j$$

where:

E_j	=	Total Emissions. Total emissions of a specific chemical in year j , by weight.
Em_j	=	Emissions from manufacturing. Total emissions of a specific chemical in year j due to manufacturing losses, by weight.
Eu_j	=	Emissions from Lifetime Losses. Total emissions of a specific chemical in year j due to lifetime losses during use, by weight.
Ed_j	=	Emissions from disposal. Total emissions of a specific chemical in year j at disposal, by weight.
Ep_j	=	Emissions from post disposal. Total post-disposal emissions of a specific chemical in year j , by weight.

Assumptions

The Vintaging Model contains thirteen foam types, whose transition assumptions away from ODS and growth rates are presented in Table A-115. The emission profiles of these thirteen foam types are shown in Table A-116.

Table A-115: Foam Blowing Market Transition Assumptions

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate ^b
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	
Vending Machine Foam													
CFC-11	HCFC-141b	1993	1995	100%	HFC-245fa	2001	2004	100%	Non-ODP/GWP	2004	2006	45%	-0.03%
									Non-ODP/GWP	2007	2009	5%	
									Non-ODP/GWP	2007	2009	25%	
									Non-ODP/GWP	2010	2010	10%	
									Non-ODP/GWP	2017	2017	2%	
									Non-ODP/GWP	2017	2017	8%	
									Non-ODP/GWP	2017	2017	8%	
Stand-alone Equipment Foam													
CFC-11	HCFC-141b	1990	1995	44%	HFC-245fa	2003	2005	19.4%	HCFO-1233zd(E)	2019	2020	25%	2.2%
					HFC-134a	2003	2005	40.3%	None				
					Non-ODP/GWP	2003	2005	40.3%	None				
	HCFC-22	1990	1995	56%	HFC-134a	2004	2008	46%	Non-ODP/GWP	2010	2018	32%	
					Non-ODP/GWP	2004	2008	54%	HCFO-1233zd(E)	2019	2020	36%	
Ice Machine Foam													
CFC-11	HCFC-141b	1989	1996	40%	CO ₂	2002	2003	69%	None				2.1%
					HFC-134a	2002	2003	31%	CO ₂	2017	2020	47%	

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate ^b				
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration					
	HCFC-142b	1989	1996	8%	CO ₂	2002	2003	69%	HCFO-1233zd(E)	2017	2020	20%					
					HFC-134a	2002	2003	31%	None								
	HCFC-22	1989	1996	52%	CO ₂	2002	2003	69%	CO ₂	2017	2020	47%					
									HFC-134a	2002	2003	31%		HCFO-1233zd(E)	2017	2020	20%
									None								
									CO ₂	2017	2020	47%					
HCFO-1233zd(E)	2017	2020	20%														
Refrigerated Food Processing and Dispensing Equipment Foam																	
CFC-11	HCFC-22	1989	1997	100%	HFC-134a	2004	2008	75%	Non-ODP/GWP	2015	2021	30%	2.1%				
						2009	2010	20%	HCFO-1233zd(E)	2020	2021	3%					
									HFO-1234ze(E)	2020	2021	3%					
					Non-ODP/GWP	2004	2008	25%	None								
Small Walk-in Cooler Foam																	
CFC-11	HCFC-141b	1990	1995	50%	HFC-245fa	2001	2003	100%	None				1.6%				
	HCFC-22	1990	1995	50%	HFC-134a	2000	2001	10%	None								
					HFC-245fa	2009	2010	50%	HCFO-1233zd(E)	2020	2020	20%					
					HFC-134a	2009	2010	40%	None								
Large Walk-in Cooler Foam																	
CFC-11	HCFC-141b	1990	1995	50%	HFC-245fa	2001	2003	100%	None				1.5%				
	HCFC-22	1990	1995	50%	HFC-134a	2000	2001	10%	None								

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate ^b
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	
					HFC-245fa	2009	2010	50%	HCFO-1233zd(E)	2020	2020	20%	
					HFC-134a	2009	2010	40%	None				
Display Case Foam													
CFC-11	HCFC-141b	1991	1992	50%	HFC-245fa	2003	2003	100%	None				1.7%
	HCFC-142b	1991	1992	50%	HFC-245fa	2004	2004	100%	None				
CFC-12	HCFC-22	1991	1993	100%	HFC-134a	2003	2007	100%	HCFO-1233zd(E)	2015	2020	60%	
Road Transport Foam													
CFC-11	HCFC-141b	1989	1996	19%	HCFC-22	1999	2001	37%	HFC-245fa	2005	2007	100%	5.5%
					CO ₂	1999	2001	11%	None				
					Non-ODP/GWP	1999	2001	53%	None				
	HCFC-22	1989	1996	81%	HFC-134a	2005	2007	37%	None				
					HFC-245fa	2005	2007	63%	HCFO-1233zd(E)	2020	2020	76%	
Intermodal Container Foam													
CFC-11	HCFC-141b	1989	1996	19%	HCFC-22	1999	2001	37%	HFC-245fa	2005	2007	100%	7.3%
					CO ₂	1999	2001	11%	None				
					Non-ODP/GWP	1999	2001	53%	None				
	HCFC-22	1989	1996	81%	HFC-134a	2005	2007	37%	None				
					HFC-245fa	2005	2007	63%	HCFO-1233zd(E)	2020	2020	76%	
Flexible PU Foam: Integral Skin Foam													
HCFC-141b ^c	HFC-134a	1996	2000	50%	HFC-245fa	2003	2010	96%	HCFO-1233zd(E)	2017	2017	83% ^e	2.0%

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate ^b
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	
	CO ₂	1996	2000	50%	Non-ODP/GWP None	2003	2010	4%	Non-ODP/GWP HFO-1336mzz(Z) None	2017 2017	2017 2017	6% 10%	
Flexible PU Foam: Slabstock Foam, Moulded Foam													
CFC-11	Non-ODP/GWP	1992	1992	100%	None								2.0%
Phenolic Foam													
CFC-11	HCFC-141b	1989	1990	100%	Non-ODP/GWP	1992	1992	100%	None				2.0%
Polyolefin Foam													
CFC-114	HFC-152a	1989	1993	10%	Non-ODP/GWP	2005	2010	100%	None				2.0%
	HCFC-142b	1989	1993	90%	Non-ODP/GWP	1994	1996	100%	None				
PU and PIR Rigid: Boardstock													
CFC-11	HCFC-141b	1993	1996	100%	Non-ODP/GWP	2000	2003	100%	None				4.8%

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate ^b
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	
PU Rigid: Domestic Refrigerator and Freezer Insulation													
CFC-11	HCFC-141b	1993	1995	100%	HFC-134a	1996	2001	7%	Non-ODP/GWP	2002	2003	100%	0.8%
					HFC-245fa	2001	2003	50%	Non-ODP/GWP	2015	2020	50%	
					HFC-245fa	2006	2009	10%	HCFO-1233zd(E)	2015	2020	50%	
									Non-ODP/GWP	2015	2020	50%	
									HCFO-1233zd(E)	2015	2020	50%	
					Non-ODP/GWP	2002	2005	10%	None				
					Non-ODP/GWP	2006	2009	3%	None				
Non-ODP/GWP	2009	2014	20%	None									
PU Rigid: One Component Foam													
CFC-12	HCFC-142b/22 Blend	1989	1996	70%	Non-ODP/GWP	2009	2010	80%	None				4.0%
					2009	2010	10%	HFO-1234ze(E)	2018	2020	100%		
	HCFC-22	1989	1996	30%	HFC-134a	2009	2010	10%	None				
					Non-ODP/GWP	2009	2010	80%	None				
					HFC-134a	2009	2010	10%	HFO-1234ze(E)	2018	2020	100%	
				HFC-152a	2009	2010	10%	None					

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate ^b
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	
PU Rigid: Other: Slabstock Foam													
CFC-11	HCFC-141b	1989	1996	100%	CO ₂	1999	2003	45%	None				2.0%
					Non-ODP/GWP	2001	2003	45%	None				
					HCFC-22	2003	2003	10%	Non-ODP/GWP	2009	2010	100%	
PU Rigid: Sandwich Panels: Continuous and Discontinuous													
HCFC-141b ^d	HCFC-22/Water Blend	2001	2003	20%	HFC-245fa/CO ₂ Blend	2009	2010	50%	HCFO-1233zd(E)	2015	2020	100%	6.0%
					Non-ODP/GWP	2009	2010	50%	None				
		HFC-245fa/CO ₂ Blend	2002	2004	20%	HCFO-1233zd(E)	2015	2020	100%	None			
HCFC-22	Non-ODP/GWP	2001	2004	40%	None								
	HFC-134a	2002	2004	20%	Non-ODP/GWP	2015	2020	100%	None				
	HFC-245fa/CO ₂ Blend	2009	2010	40%	HCFO-1233zd(E)	2015	2020	100%	None				
	Non-ODP/GWP	2009	2010	20%	None								
	CO ₂	2009	2010	20%	None								
	HFC-134a	2009	2010	20%	Non-ODP/GWP	2015	2020	100%	None				
PU Rigid: High Pressure Two-Component Spray Foam													

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate ^b
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	
CFC-11	HCFC-141b	1989	1996	100%	HFC-245fa	2002	2003	C	HFO-1336mzz(Z)	2016	2020	100%	0.8%
					HFC-245fa/CO ₂ Blend	2002	2003	C	HFO-1336mzz(Z)/CO ₂ Blend	2016	2020	100%	
					HFC-227ea/HF C-365mfc Blend	2002	2003	C	HCFO-1233zd(E)	2016	2020	100%	
PU Rigid: Low Pressure Two-Component Spray Foam													
CFC-12	HCFC-22	1989	1996	100%	HFC-245fa	2002	2003	15%	HCFO-1233zd(E)	2017	2021	100%	0.8%
					HFC-134a	2002	2003	85%	HFO-1234ze(E)	2017	2021	100%	
XPS: Boardstock Foam													
CFC-12	HCFC-142b/22 Blend	1989	1994	10%	HFC-134a	2009	2010	70%	Non-ODP/GWP	2021	2021	100%	2.5%
					HFC-152a	2009	2010	10%	None				
					CO ₂	2009	2010	10%	None				
					Non-ODP/GWP	2009	2010	10%	None				
	HCFC-142b	1989	1994	90%	HFC-134a	2009	2010	70%	Non-ODP/GWP	2021	2021	100%	
					HFC-152a	2009	2010	10%	None				
					CO ₂	2009	2010	10%	None				
					Non-ODP/GWP	2009	2010	10%	None				
XPS: Sheet Foam													

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate ^b
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	
CFC-12	CO ₂	1989	1994	1%	None								2.0%
	Non-ODP/GWP	1989	1994	99%	CO ₂	1995	1999	9%	None				
					HFC-152a	1995	1999	10%	None				

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^a Transitions between the start year and date of full penetration in new equipment are assumed to be linear so that in total 100 percent of the market is assigned to the original ODS or the various ODS substitutes.

^b Growth Rate is the average annual growth rate for individual market sectors from the base year to 2030.

^c CFC-11 was the initial blowing agent used for through 1989. This transition is not shown in the table in order to provide the HFC transitions in greater detail.

^d The CFC-11 PU Rigid: Sandwich Panels: Continuous and Discontinuous market for new systems transitioned to 82 percent HCFC-141b and 18 percent HCFC-22 from 1989 to 1996. These transitions are not shown in the table in order to provide the HFC transitions in greater detail.

^e A linear transition to HFO-1336mzz(Z) from the HCFO-1233zd(E) market is assumed to take place beginning in 2020 and reaching 88 percent of the market by 2030. This transition is not shown in the table.

Table A-116: Emission Profile for the Foam End-Uses

Foam End-Use	Loss at			Annual Post-life Loss (%)	Loss at Disposal (%)	Total ^a (%)
	Manufacturing (%)	Annual Leakage Rate (%)	Leakage Lifetime (years)			
Flexible PU Foam: Slabstock Foam, Moulded Foam	100	0	1	0	0	100
Vending Machine Foam	4	0.25	10	0	93.5	100
Stand-alone Equipment Foam	4	0.25	10	0	93.5	100
Ice Machine Foam	4	0.25	8	0	94.0	100
Refrigerated Food Processing and Dispensing Equipment Foam	4	0.25	10	0	93.5	100
Small Walk-in Cooler Foam	4	0.25	20	0	91.0	100
Large Walk-in Cooler Foam	4	0.25	20	0	91.0	100
CFC-11 Display Case Foam	4	0.25	18	0	91.5	100
CFC-12 Display Case Foam	4	0.25	18	0	91.5	100
Road Transport Foam	4	0.25	12	0	93.0	100
Intermodal Container Foam	4	0.25	15	0	92.3	100

Rigid PU: High Pressure Two-Component Spray Foam	15	1.5	50	0	10.0	100
Rigid PU: Low Pressure Two-Component Spray Foam	15	1.5	50	0	10.0	100
Rigid PU: Slabstock and Other ^a	20	1	15	1.5	22.5	57.5
Phenolic Foam	28	0.875	32	0	44.0	100
Polyolefin Foam	40	3	20	0	0	100
Rigid PU: One Component Foam	95	2.5	2	0	0	100
XPS: Sheet Foam	50	25	2	0	0	100
XPS: Boardstock Foam	25	0.75	25	0	56.25	100
Flexible PU Foam: Integral Skin Foam	95	2.5	2	0	0	100
Rigid PU: Domestic Refrigerator and Freezer Insulation (HFC-134a) ^a	6.5	0.5	14	2.0	37.2	50.7
Rigid PU: Domestic Refrigerator and Freezer Insulation (all others) ^a	3.75	0.25	14	2.0	39.9	47.15
PU and PIR Rigid: Boardstock ^a	10	1	40	1.5	22.5	72.5
PU Sandwich Panels: Continuous and Discontinuous ^a	15	0.5	75	1.25	22.5	75

PIR (Polyisocyanurate)

PU (Polyurethane)

XPS (Extruded Polystyrene)

^aTotal emissions from foam end-uses are assumed to be 100 percent. In the Rigid PU: Slabstock and Other, Rigid PU Domestic Refrigerator and Freezer Insulation, PU and PIR Boardstock, and PU Sandwich Panels end-uses, the source of emission rates and lifetimes did not yield 100 percent emissions; the remainder is assumed to be emitted post-disposal at the annual post-life loss rate until remaining blowing agent is 100 percent emitted.

Sterilization

Sterilants kill microorganisms on medical equipment and devices. The principal ODS used in this sector was a blend of 12 percent ethylene oxide (EtO) and 88 percent CFC-12, known as “12/88.” In that blend, ethylene oxide sterilizes the equipment and CFC-12 is a diluent solvent to form a non-flammable blend. The sterilization sector is modeled as a single end-use. For sterilization applications, all chemicals that are used in the equipment in any given year are assumed to be emitted in that year, as shown in the following equation.

Equation A-20: Calculation of Total Emissions from Sterilization

$$E_j = Qc_j$$

where:

E	=	Emissions. Total emissions of a specific chemical in year j from use in sterilization equipment, by weight.
Qc	=	Quantity of Chemical. Total quantity of a specific chemical used in sterilization equipment in year j , by weight.
j	=	Year of emission.

Assumptions

The Vintaging Model contains one sterilization end-use, whose transition assumptions away from ODS and growth rates are presented in Table A-117.

Table A-117: Sterilization Market Transition Assumptions

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment ^a	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	
12/88	EtO	1994	1995	95%	None								2.0%
	Non-ODP/GWP	1994	1995	0.8%	None								
	HCFC-124/EtO Blend	1993	1994	1.4%	Non-ODP/GWP	2015	2015	100%	None				
	HCFC-22/HCFC-124/EtO Blend	1993	1994	3.1%	Non-ODP/GWP	2010	2010	100%	None				

^a Transitions between the start year and date of full penetration in new equipment are assumed to be linear so that in total 100 percent of the market is assigned to the original ODS or the various ODS substitutes.

Model Output

By repeating these calculations for each year, the Vintaging Model creates annual profiles of use and emissions for ODS and ODS substitutes. The results can be shown for each year in two ways: 1) on a chemical-by-chemical basis, summed across the end-uses, or 2) on an end-use or sector basis. Values for use and emissions are calculated both in metric tons and in million metric tons of CO₂ equivalent (MMT CO₂ Eq.). The conversion of metric tons of chemical to MMT CO₂ Eq. is accomplished through a linear scaling of tonnage by the global warming potential (GWP) of each chemical.

Throughout its development, the Vintaging Model has undergone annual modifications. As new or more accurate information becomes available, the model is adjusted in such a way that both past and future emission estimates are often altered.

Bank of ODS and ODS Substitutes

The bank of an ODS or an ODS substitute is “the cumulative difference between the chemical that has been consumed in an application or sub-application and that which has already been released” (IPCC 2006). For any given year, the bank is equal to the previous year’s bank, less the chemical in equipment disposed of during the year, plus chemical in new equipment entering the market during that year, less the amount emitted but not replaced, plus the amount added to replace chemical emitted prior to the given year, as shown in the following equation:

Equation A-21: Calculation of Chemical Bank (All Sectors)

$$Bc_j = Bc_{j-1} - Qd_j + Qp_j - E_e + Q_r$$

where:

- Bc_j = Bank of Chemical. Total bank of a specific chemical in year j , by weight.
- Qd_j = Quantity of Chemical in Equipment Disposed. Total quantity of a specific chemical in equipment disposed of in year j , by weight.
- Qp_j = Quantity of Chemical Penetrating the Market. Total quantity of a specific chemical that is entering the market in year j , by weight.
- E_e = Emissions of Chemical Not Replaced. Total quantity of a specific chemical that is emitted during year j but is not replaced in that year. The Vintaging Model assumes all chemical emitted from refrigeration, air conditioning and fire extinguishing equipment is replaced in the year it is emitted, hence this term is zero for all sectors except foam blowing.
- Q_r = Chemical Replacing Previous Year’s Emissions. Total quantity of a specific chemical that is used to replace emissions that occurred prior to year j . The Vintaging Model assumes all chemical emitted from refrigeration, air conditioning and fire extinguishing equipment is replaced in the year it is emitted, hence this term is zero for all sectors.
- j = Year of emission.

Table A-118 provides the bank for ODS and ODS substitutes by chemical grouping in metric tons (MT) for 1990 to 2023.

Table A-118: Banks of ODS and ODS Substitutes, 1990-2023 (MT)

Year	CFC	HCFC	HFC
1990	738,863	198,632	872
1995	782,398	440,183	50,674

2000	639,439	849,643	192,785
2001	609,276	919,683	222,529
2002	583,327	976,250	255,462
2003	557,801	1,020,211	297,754
2004	531,840	1,064,432	341,593
2005	500,745	1,110,697	388,162
2006	468,643	1,152,868	440,561
2007	439,042	1,182,828	494,645
2008	414,558	1,199,798	546,466
2009	399,443	1,191,562	603,784
2010	383,399	1,158,047	674,674
2011	369,031	1,116,419	748,149
2012	356,082	1,071,791	823,607
2013	345,407	1,021,356	901,504
2014	336,080	970,674	980,806
2015	328,106	921,144	1,055,663
2016	321,374	870,023	1,128,367
2017	314,957	819,487	1,193,263
2018	311,208	766,061	1,254,881
2019	309,251	711,093	1,307,528
2020	307,434	652,546	1,351,670
2021	306,576	599,898	1,379,054
2022	306,529	552,382	1,403,558
2023	306,483	509,265	1,428,482

Comparisons to Other Information on Supply and Emissions of HFCs

Comparison of Reported Consumption to Modeled Consumption of HFCs

As noted in Section 4.25 of the *Inventory* report, EPA conducted a quality assurance check of the Vintaging Model used for estimating emissions of HFCs, PFCs, and CO₂ used as ODS substitutes. EPA evaluated the consumption of saturated HFCs that the model estimates on an end-use by end-use (“bottom up”) manner and compared these results to the supply of saturated HFCs as reported under Subparts OO and QQ of the Greenhouse Gas Reporting Program (GHGRP), and for 2022-2023 as reported under the American Innovation and Manufacturing (AIM) Act regulations. This allows for an overall quality control check on the modeled demand for new chemical in the Vintaging Model as a proxy for total amount supplied, which is similar to net supply, as an input to the emission calculations in the model.

GHGRP data reported under Subparts QQ and OO are not used directly to estimate emissions of ODS Substitutes because they do not include complete information on the sectors or end-uses in which that chemical will be used. Therefore, it does not provide the data that would be needed to calculate the source or time that a chemical is emitted. For instance, pure HFCs might be imported, then later mixed to make specific refrigerant blends, sold to an equipment manufacture, charged into equipment by that manufacture, and then equipment could be warehoused, sold to distributors, resold to technicians, and finally installed and placed into use. Reports to the GHGRP on production and bulk import (Subpart OO) do not currently include any information on expected end-uses. Published data on fluorinated gases contained in pre-charged equipment and closed-cell foams (Subpart QQ) does not provide detailed information on the type of product imported or exported. Furthermore, the information from both subparts do not capture the entire market in the United States.

Reported Net Supply (GHGRP and American Innovation and Manufacturing Act Top-Down Estimate). Consumption patterns demonstrated through data reported under GHGRP Subpart OO (Suppliers of Industrial Greenhouse Gases) and Subpart QQ (Importers and Exporters of Fluorinated Greenhouse Gases Contained in Pre-Charged

Equipment or Closed-Cell Foams), and beginning in 2022 the American Innovation and Manufacturing Act, were compared to the modeled demand for new saturated HFCs used as ODS substitutes from the Vintaging Model. The collection of data from suppliers of HFCs enables EPA to calculate the reporters' aggregated net supply—the sum of the quantities of chemical produced or imported into the United States less the sum of the quantities of chemical transformed (used as a feedstock in the production of other chemicals), destroyed, or exported from the United States.⁸² This allows for an overall quality assurance check on the modeled demand for new chemical in the Vintaging Model as a proxy for total amount supplied, which is similar to net supply, as an input to the emission calculations in the model. Under EPA's GHGRP, suppliers (i.e., producers, importers, and exporters) of HFCs under Subpart OO⁸³ began annually reporting their production, transformation, destruction, imports, and exports to EPA in 2011 (for supply that occurred in 2010) and suppliers of HFCs under Subpart QQ began annually reporting their imports and exports to EPA in 2012 (for supply that occurred in 2011). The HFC phasedown regulations under the American Innovation and Manufacturing Act took effect in 2022, with requirements for all HFC producers and importers to report. As noted above, this comparison has limitations. For instance, the model does not account for the stockpiles of chemical that might be imported or produced, and reported under the GHGRP or the American Innovation and Manufacturing Act, and that may not be used immediately. Furthermore, the GHGRP does not require reporting from companies that import lower amounts of HFCs.

Modeled Consumption (Vintaging Model Bottom-Up Estimate). The Vintaging Model, used to estimate emissions from this source category, calculates chemical demand based on the quantity of equipment and products sold, serviced and retired each year, and the amount of the chemical required to manufacture and/or maintain the equipment and products on an end-use basis.⁸⁴ It is assumed that the total demand equals the amount supplied by either new production, chemical import, or quantities recovered (often reclaimed) and placed back on the market. In the Vintaging Model, demand for new chemical, as a proxy for consumption, is calculated as any chemical demand (either for new equipment or for servicing existing equipment) that cannot be met through recycled or recovered material.⁸⁵ No distinction is made in the Vintaging Model between whether that need is met through domestic production or imports. To calculate emissions, the Vintaging Model estimates the quantity released from equipment over time, which varies by product type as detailed above. Thus, verifying the Vintaging Model's calculated consumption against GHGRP and American Innovation and Manufacturing Act reported data, which does not provide details on the end-uses where the chemical is used, is not an exact comparison of the Vintaging Model's emission estimates, but is believed to provide an overall check of the underlying data.

There are eleven saturated HFC species modeled in the Vintaging Model: HFC-23, HFC-32, HFC-125, HFC-134a, HFC-143a, HFC-152a, HFC-227ea, HFC-236fa, HFC-245fa, HFC-365mfc, and HFC-43-10mee. Some amounts of additional, less-used, saturated HFCs, including isomers of those included in the Vintaging Model, are reportable under EPA's GHGRP and under the American Innovation and Manufacturing Act. The GHGRP data are believed to represent an amount comparable to the modeled estimates as a quality assurance check. For instance, the

⁸² Chemical that is exported, transformed, or destroyed—unless otherwise imported back to the United States—will never be emitted in the United States.

⁸³ Among other provisions, the American Innovation and Manufacturing Act of 2020 directed EPA to develop a U.S. production baseline and a U.S. consumption baseline and to phase down HFC production and consumption relative to those baselines. Data reported to the GHGRP under Subpart OO are relevant to the production and consumption baselines. The data shown in Annex 3.10 include aggregated Subpart OO data for American Innovation and Manufacturing Act-listed HFCs for reporting years 2013 through 2021 from all companies that reported American Innovation and Manufacturing Act-listed HFCs, though not all species were reported in each reporting year.

⁸⁴ The model builds an inventory of the in-use stock of equipment and products and ODSs and HFCs in each of the sub-applications. Emissions are subsequently estimated by applying annual and disposal emission rates to each population of equipment and products. See the above discussion in Annex 3.10. for further details on the model.

⁸⁵ The Vintaging Model does not calculate "consumption" as commonly defined because the model includes chemical supplied to pre-charge equipment made overseas and sent to the domestic market and does not include chemical produced or imported in the United States but placed in products shipped to foreign markets.

consumption of other HFCs reported under the American Innovation and Manufacturing Act (HFC-41, HFC-134, and HFC-236ea) was approximately 0.13% of the total HFC consumption in 2023 (EPA, 2024a).

Comparison Results and Discussion

Comparing the estimates of consumption from these two approaches (i.e., reported and modeled) ultimately supports and improves estimates of emissions, as noted in the *2006 IPCC Guidelines* (which refer to fluorinated greenhouse gas consumption based on supplies as “potential emissions”):

[W]hen considered along with estimates of actual emissions, the potential emissions approach can assist in validation of completeness of sources covered and as a QC check by comparing total domestic consumption as calculated in this ‘potential emissions approach’ per compound with the sum of all activity data of the various uses (IPCC 2006).

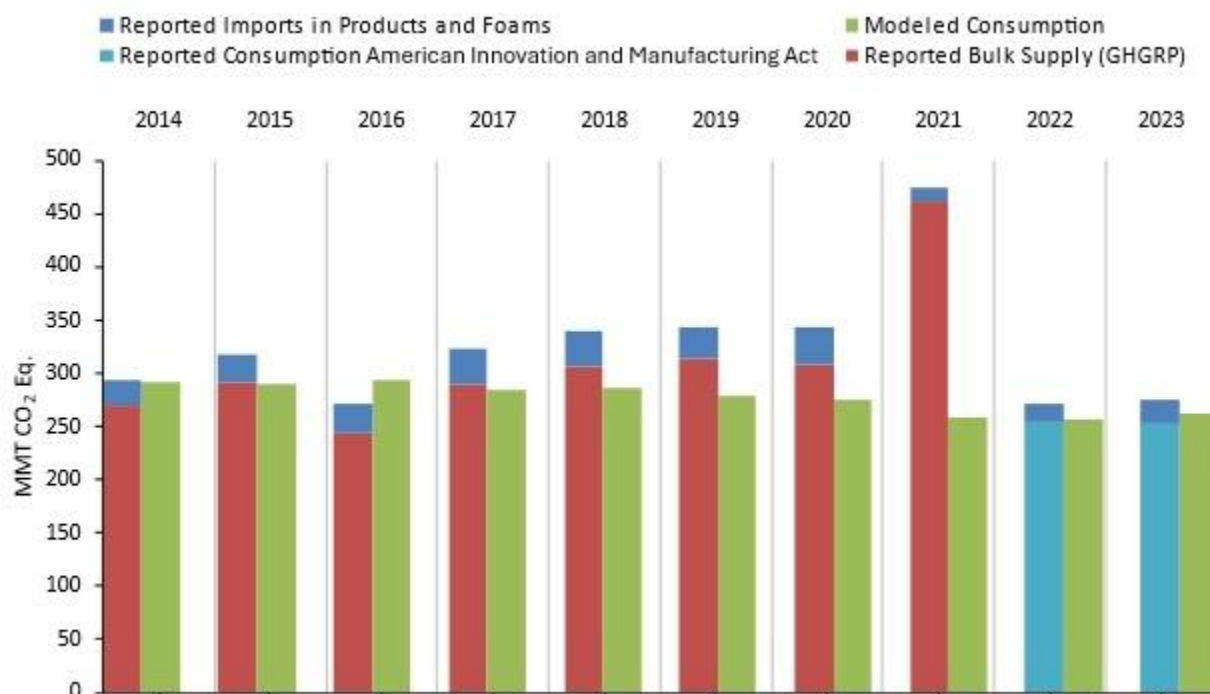
Table A-119 and Figure A-6 compare the published net supply of saturated HFCs in MMT CO₂ Eq. as determined from Subpart OO (supply of HFCs in bulk) and Subpart QQ (supply of HFCs in products and foams) of EPA’s GHGRP for the years 2012 through 2023 (EPA 2021a; EPA 2024c), with the exception that beginning in 2022, data from the American Innovation and Manufacturing Act are used for bulk supply (EPA 2024a), and the chemical demand as calculated by the Vintaging Model for the same time series. For comparison purposes, Vintaging Model estimates are presented using 100-year global warming potentials (GWPs) provided in the IPCC Fourth Assessment Report (AR4) (IPCC 2007), as reported net supply from GHGRP and the American Innovation and Manufacturing Act are also provided using AR4 GWPs.

Table A-119: U.S. HFC Supply (MMT CO₂ Eq.)

Year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Reported Net Supply	307	294	318	271	322	340	344	344	474	271	275
Industrial GHG Suppliers (GHGRP)	290	269	292	243	290	306	314	309	461	NA	NA
Consumption (American Innovation and Manufacturing Act)	NA	NA	NA	NA	NA	NA	NA	NA	NA	254	253
HFCs in Products and Foams (GHGRP)	17	25	26	28	32	34	30	35	13	17	22
Modeled Supply (Vintaging Model)	286	291	289	293	284	287	279	276	258	257	261
Percent Difference	-7%	-1%	-9%	8%	-12%	-16%	-19%	-20%	-46%	-5%	-5%

NA (Not Applicable)

Figure A-6: U.S. HFC Consumption (MMT CO₂ Eq.)



As shown, the estimates from the Vintaging Model are lower than the GHGRP data by an average of 12.4 percent across the time series (i.e., 2013 through 2023), with the difference growing to an average of 18 percent over the three years prior to 2021 (i.e., 2018 through 2020) and 19 percent over the last 4 years (i.e., 2020 through 2023). The difference in 2021 is much larger, showing that supply greatly exceeded the estimated demand, and is addressed by the sub-bullets below. Potential reasons for the differences between the reported and modeled data include:

- A temporal effect results from the stockpiling of chemicals by suppliers and distributors. Suppliers might decide to produce or import additional quantities of HFCs for various reasons such as expectations that prices may increase, or supplies may decrease, in the future. Such stockpiled material could be used for new equipment produced at a later time and for on-going servicing. Based on information collected by the EPA at the time, such stockpiling behavior was seen during ODS phasedowns, and it is concluded that such behavior similarly existed amongst HFC suppliers in anticipation of controls on HFCs promulgated under the American Innovation and Manufacturing Act. Inventories of HFCs reported at the end of 2022 and 2023 exceeded consumption by 55 percent and 50 percent, respectively (EPA 2024a), indicating stockpiling has been going on for some time. Any such activity would increase the GHGRP/American Innovation and Manufacturing data as compared to the modeled data. This effect is likely the major reason why there is a divergence in the comparison above, with the GHGRP data in 2017 through 2021 significantly higher than the modeled data. Improvements of the model methodology to incorporate a temporal factor could be investigated. Information on U.S. HFC stockpiles could also be used to assess this source of discrepancy. Initial reporting under the American Innovation and Manufacturing Act shows significant stockpiling of HFCs in 2022, the first year HFC production and consumption were limited, and again in 2023. The total underprediction of supply by the model since 2017, as shown above, is similar to the reported end-of-year inventory in 2023 (approximately 480 MMT CO₂ Eq. compared to 380 MMT CO₂ Eq., respectively) (EPA 2024a).

- The 2021 data follow a similar pattern as was seen during the ODS phasedowns. This was the year before HFC consumption was controlled by the EPA under the American Innovation and Manufacturing Act. The so-called “campaign consumption” in 2021 is obvious when looking at the 2021 data and may be evident even in the 2017-2020 timeframe. This is not unlike the year 2003, when the HCFC allocation program started and HCFC supply (in ODP-tons) was 42 percent higher than the average consumption from 1996 to 2002 (UNEP 2023).
- As noted below, additional comparison of the emissions from the Vintaging Model to atmosphere-based emission estimates also show a more apparent difference in the years 2017 through 2019 for HFC-32 and HFC-125, and from 2021 to 2023 for HFC-134a. This could be an indication of a systemic issue wherein the model is underestimating the portion of the supply that is used to replace leaked chemical that has been emitted. This might be related to the supply issues noted above. For instance, if supply of HFCs were plentiful during these years, that could lead to some practices wherein emissions, and supply to replace those emissions, were significantly higher than estimated by the model.
- The fact that the top-down data are reported at the time of actual production or import, and the bottom-up supply data are calculated at the time of placement on the market (e.g., in new equipment or to service existing equipment) introduces another temporal discrepancy when comparing data. A potential improvement would be to incorporate a time lag into the model, which would require obtaining data on the movement of supplies through the point of actual use. Because the GHGRP data and the Vintaging Model estimates generally increase over time (although some year-to-year variations exist, and this trend reverses in 2022 when controls began), EPA would expect the modeled estimates to be slightly lower than the corresponding GHGRP data due to this temporal effect. Regulations under the American Innovation and Manufacturing Act require the reporting of chemical supplies held at the close of the calendar year as noted above; such reports may help investigate this possible factor.
- Under EPA’s GHGRP, all facilities that produce HFCs are required to report their quantities, whereas importers or exporters of HFCs or pre-charged equipment and closed-cell foams that contain HFCs are only required to report if either their total imports or their total exports of greenhouse gases are greater than or equal to 25,000 metric tons of CO₂ Eq. per year. Thus, some imports or exports may not be accounted for in the GHGRP data, leading to further underestimation or overestimation of the model if imports or exports, respectively, are not represented in the reported GHGRP data. In 2022, some companies below the reporting threshold for imports and exports reported to the GHGRP, including data from as early as 2011, for AIM-listed HFCs as part of data collection efforts for the U.S. HFC production and consumption baselines; this data is included in the totals presented above. Data collected and released under the American Innovation and Manufacturing Act are likewise included in the reported totals for 2022 through 2023.
- In some years, imports and exports may be greater than consumption because the excess is being used to increase chemical or equipment stockpiles as discussed above; in other years, the opposite may hold true. Similarly, relocation of manufacturing facilities, recovery from the recessions, or the COVID-19 pandemic could contribute to variability in imports or exports. The Vintaging Model does not reflect the dynamic nature of reported HFC consumption, with significant differences seen in each year. Whereas the Vintaging Model projects demand increasing or decreasing slowly, with some annual fluctuations, actual consumption for specific chemicals or equipment may vary over time and could even switch from positive to negative (indicating more chemical exported, transformed, and destroyed than produced and imported in a given year). Furthermore, consumption as calculated in the Vintaging Model is a function of demand not met by recovery of HFCs from equipment that is being disposed. If, in any given year, a significant number of units is disposed, there will be a large amount of additional recovery in that year that

can cause an unexpected and not modeled decrease in demand and, thus, a decrease in consumption. On the other hand, if market, economic, or other factors cause less than expected disposal or recovery, actual supply would decrease, and consumption would increase to meet that demand not satisfied by recovered quantities, increasing the reported amounts. EPA has published reclamation data, which would encompass a portion of the refrigerant recovered annually. This data could be reviewed to determine if it can be used to improve the modeling of these factors.

- The Vintaging Model is used to estimate the emissions that occur in the United States. As such, all equipment or products that contain ODSs or alternatives, including saturated HFCs, are assumed to consume and emit chemicals equally as like-equipment or products originally produced in the United States. The GHGRP data from Subpart OO (industrial greenhouse gas suppliers) and the American Innovation and Manufacturing Act includes HFCs produced or imported and used to fill or manufacture products that are then exported from the United States. The Vintaging Model estimates of demand and supply are not meant to incorporate such chemical. Likewise, chemicals may be used outside the United States to create products or charge equipment that is then imported to and used in the United States. The Vintaging Model estimates of demand and supply are meant to capture this chemical, as it will lead to emissions inside the United States. The GHGRP data from Subpart QQ (supply of HFCs in products) accounts for most of these differences; however, the scope of Subpart QQ does not cover all such equipment or products and the chemical contained therein. Depending on whether the United States is a net importer or net exporter of such chemical, this factor may account for some of the difference shown above or might lead to a further discrepancy.
- The Vintaging Model does not include every saturated HFC that is reported to EPA's GHGRP or under the American Innovation and Manufacturing Act. Potential improvements in the modeling could include investigation of what sources use and emit such chemicals—which are not necessarily used as ODS substitutes—and to add them into the *Inventory*. However, the additional reported HFCs represent a small fraction of total HFC use for this source category, both in GWP-weighted and unweighted terms, and as such, it is not expected that the additional HFCs reported to EPA are a major driver for the difference between the two sets of estimates. In 2022 and 2023, isomers represented 0.2 percent and 0.1 percent, respectively, of total supply according to data from the American Innovation and Manufacturing Act (EPA 2024a). To the extent lower-GWP isomers were used in lieu of the modeled chemicals (e.g., HFC-134 instead of HFC-134a), lower CO₂ Eq. amounts in the reported data compared to the modeled estimates would be expected.

One factor, however, would only lead to modeled estimates to be even higher than the estimates shown and hence for most years closer to, although possibly higher than, GHGRP data:

- Saturated HFCs are also known to be used and emitted from other sources, such as electronics manufacturing and magnesium production and processing. The Vintaging Model estimates here do not include the amount of HFCs used for these applications, but rather only the amount used for applications that traditionally were served by ODSs. Nonetheless, EPA expects the quantities of HFCs used for these sources, such as electronics and magnesium production, to be very small compared to the ODS substitute use for the years analyzed. EPA estimates that electronics and magnesium production respectively consumed 0.3 MMT CO₂ Eq. and 0.01 MMT CO₂ Eq. of HFCs in 2023, which is much less than the ODS substitute sector in that year (189.0 MMT CO₂ Eq.)

Comparison of Emissions Derived from Atmospheric Measurements to Modeled Emissions

As noted in Section 4.25 of the *Inventory* report, EPA conducted another quality assurance check of the Vintaging Model estimated emissions. Emissions of some fluorinated greenhouse gases are estimated for the contiguous

United States by scientists at the National Oceanic and Atmospheric Administration (NOAA) and were used to perform additional quality control by comparing the emission estimates derived from atmospheric measurements by NOAA to the bottom-up emission estimates from the Vintaging Model. The *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2019)* Volume 1: General Guidance and Reporting, Chapter 6: Quality Assurance, Quality Control and Verification notes that atmospheric concentration measurements can provide independent data sets as a basis for comparison with inventory estimates. Further, it identified fluorinated gases as one of most suitable greenhouse gases for such comparisons. The *2019 Refinement* makes this conclusion on fluorinated gases based on the lack of natural sources, the potential uncertainties in bottom-up inventory methods for some sources, the long lifetimes of many of these gases in the atmosphere, and their well-known loss mechanisms. Unlike the more abundant greenhouse gases in the *Inventory*, since there are no known natural sources of HFCs, the HFC emission sources included in this *Inventory* account for the majority of total emissions detectable in the atmosphere, and the estimates derived from atmospheric measurements are driven solely by anthropogenic emissions.

The *2019 Refinement* provides guidance on conducting such comparisons (as summarized in Table 6.2 of IPCC 2019 Volume 1, Chapter 6) and provides guidance on using such comparisons to identify areas of improvement in national inventories (as summarized in Box 6.5 of IPCC 2019 Volume 1, Chapter 6).

Emission estimates for four key HFCs (HFC-134a, HFC-125, HFC-143a, and HFC-32) are derived from atmosphere measurements since 2008 and have been discussed and updated since the 2022 *Inventory* (EPA 2022b) and are currently provided through 2023 (Hu et al. 2024). This provides a quality check on the modeled emissions reported in Section 4.25 of the *Inventory* report. Potential modifications to the *Inventory* are being considered as a result of the current comparison with atmospheric-derived emission estimates and are noted in the Planned Improvements discussion in Section 4.25 of the *Inventory* report.

Comparison of Results

Table A-120 lists annual mean emissions from EPA's Vintaging Model for the entire United States and from NOAA for the contiguous United States derived from atmospheric measurements as described in Hu et al. (2017) and updated in their recent studies (Hu et al. 2022; Montzka et al. 2023; Hu et al. 2024). NOAA's estimates were derived from inverse modeling driven by two different meteorological inputs and transport models, the North American Mesoscale Forecast system (NAM12) and the Weather and Research Forecasting Model (WRF) meteorology in the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPPLIT) model and the Stochastic Time-Inverted Lagrangian Transport (STILT) model. Results are updated annually on NOAA's U.S. Potent GHG Tracker website (Hu et al. 2024). Figure A-7 below shows the derived emissions graphically for HFC-32, HFC-125, HFC-134a, and HFC-143a. In Hu et al. (2017), uncertainties in annual emission estimates represented one standard deviation of the spread of several inversion calculations, and an uncertainty associated with meteorology is reflected in part by considering two meteorological inputs to each of the models (NAM12 and WRF). Hence, the most appropriate comparisons should be made to the atmosphere estimate that incorporates both of these approaches (the combined estimate in the figures and tables below). Uncertainty results representing one standard deviation derived from individual meteorological input data were also updated in Hu et al. (2022), Montzka et al. (2023), and Hu et al. (2024). These values are provided in the tables and figures below.

There is also uncertainty in the EPA results. Overall, the uncertainty in EPA's total Substitution of ODS emissions (i.e., total CO₂-equivalent emissions from HFCs, PFCs, and CO₂ used as alternatives to ODS) range from -3.1 percent to 19.6 percent (95 percent confidence interval), as shown in Section 4.25. As part of this 2025 update, uncertainties in the 2023 estimates are now also estimated for each individual species at a 95 percent confidence interval. Those uncertainties were -7.5 percent to 7.0 percent for HFC-32, -5.4 percent to 21 percent for HFC-125, -13 percent to 28 percent for HFC-134a, and -18 percent to 59 percent for HFC-143a. Because uncertainty was not estimated for years 2008-2022, the uncertainty for those years were estimated by assuming that the coefficient of variation (i.e., the ratio of the standard of deviation to the mean value) for each chemical in 2023 is held constant across the time series. This was then used to calculate the standard deviation for each year and chemical. This standard deviation is used in the tables and figures below.

Table A-120: U.S. Emissions of HFC-32, HFC-125, HFC-134a and HFC-143a (Gg)

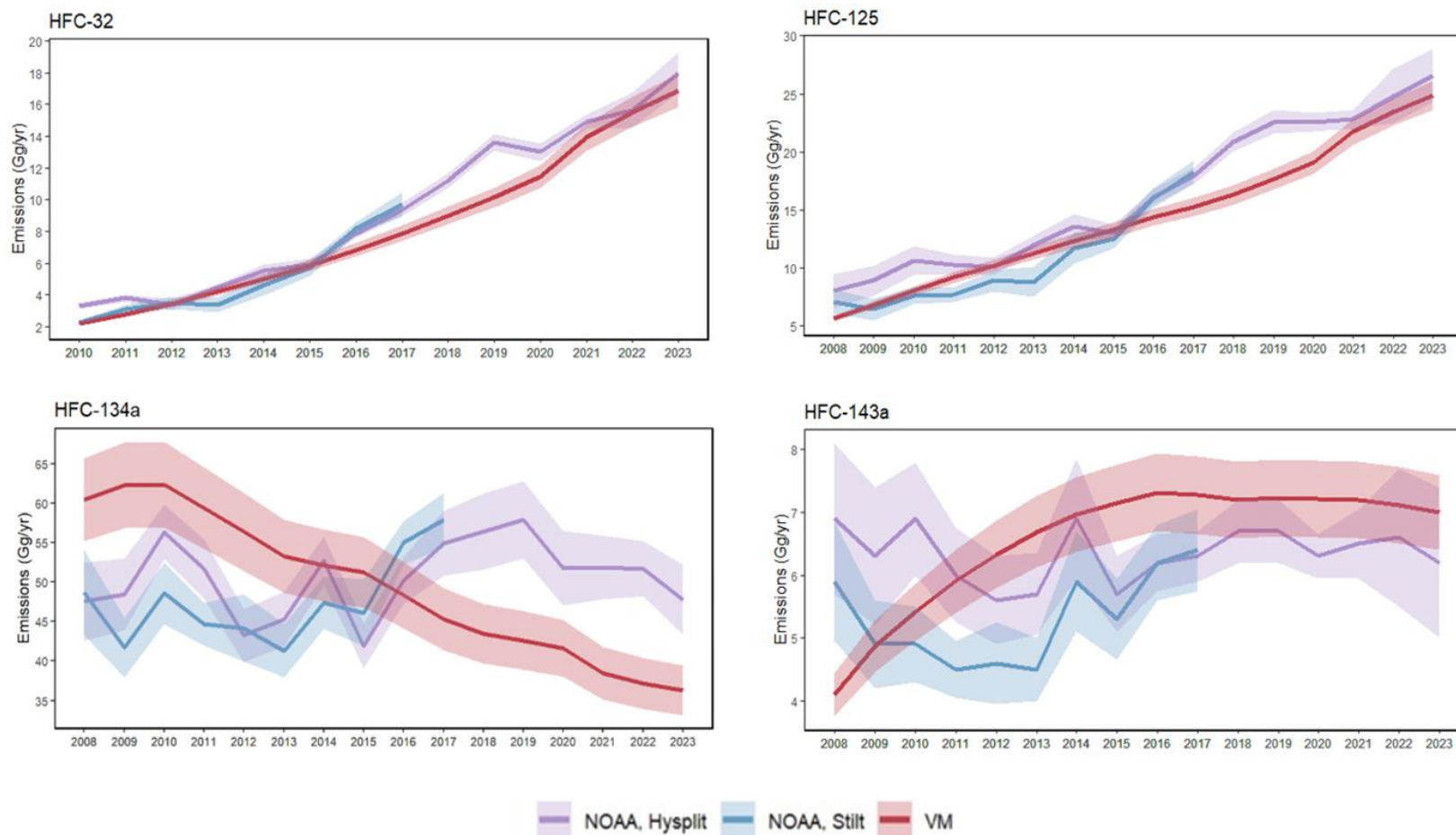
Gas Source	HFC-32 ^a			HFC-125			HFC-134a			HFC-143a		
	EPA	NOAA (HYSPLIT)	NOAA (STILT)	EPA	NOAA (HYSPLIT)	NOAA (STILT)	EPA	NOAA (HYSPLIT)	NOAA (STILT)	EPA	NOAA (HYSPLIT)	NOAA (STILT)
2008	1.2±0.1	NA	NA	5.6±0.3	8±1.5	7.1±1.1	60.5±5.3	47.6±5	48.7±5.5	4.1±0.3	6.9±1.2	5.9±1
2009	1.6±0.1	NA	NA	6.8±0.3	8.9±1.3	6.4±0.9	62.3±5.4	48.5±4.6	41.7±3.8	4.9±0.4	6.3±1.1	4.9±0.7
2010	2.2±0.1	3.3±0.2	2.3±0.1	8.0±0.4	10.6±1.3	7.6±0.8	62.4±5.4	56.4±3.4	48.6±3.9	5.4±0.5	6.9±0.9	4.9±0.6
2011	2.8±0.2	3.8±0.2	3.1±0.3	9.2±0.5	10.3±0.9	7.7±0.6	59.4±5.2	51.7±3.8	44.7±2.7	5.9±0.5	6±0.8	4.5±0.5
2012	3.5±0.2	3.4±0.4	3.5±0.4	10.2±0.5	10.1±0.8	8.9±1	56.4±4.9	43.3±3.4	44.2±4.3	6.3±0.5	5.6±0.7	4.6±0.7
2013	4.2±0.3	4.5±0.2	3.4±0.5	11.3±0.6	12±0.8	8.8±1.3	53.3±4.6	45.3±3.5	41.3±3.4	6.7±0.6	5.7±0.7	4.5±0.5
2014	5±0.3	5.5±0.4	4.6±0.7	12.3±0.6	13.6±1	11.7±1.4	52.1±4.5	52.8±3.1	47.4±3.3	7.0±0.6	6.9±1	5.9±0.8
2015	5.9±0.4	5.9±0.4	5.7±0.5	13.3±0.7	13±0.7	12.5±0.9	51.2±4.5	41.9±2.9	46.1±4.3	7.1±0.6	5.7±0.6	5.3±0.7
2016	6.8±0.4	7.9±0.3	8.2±0.4	14.3±0.7	16.1±0.7	16±0.9	48.4±4.2	50.2±3	55±2.8	7.3±0.6	6.2±0.5	6.2±0.6
2017	7.9±0.5	9.4±0.5	9.7±0.8	15.3±0.8	17.9±0.7	18.3±1	45.3±4.0	55±4.1	57.9±3.5	7.3±0.6	6.3±0.4	6.4±0.7
2018	9.0±0.6	11.2±0.5	NA	16.3±0.8	20.9±0.8	NA	43.5±3.8	56.5±4.9	NA	7.2±0.6	6.7±0.5	NA
2019	10.1±0.6	13.6±0.6	NA	17.6±0.9	22.6±1.1	NA	42.6±3.7	58±4.9	NA	7.2±0.6	6.7±0.5	NA
2020	11.4±0.7	13.0±0.6	NA	19.1±1.0	22.6±0.8	NA	41.6±3.6	51.8±4.7	NA	7.2±0.6	6.3±0.4	NA
2021	13.9±0.9	14.9±0.5	NA	21.7±1.1	22.8±0.8	NA	38.4±3.4	51.9±4	NA	7.2±0.6	6.5±0.6	NA
2022	15.5±1.0	15.6±1.1	NA	23.5±1.2	24.8±2.4	NA	37.1±3.2	51.7±3.5	NA	7.1±0.6	6.6±1.1	NA
2023	16.9±1.0	18.0±1.3	NA	24.9±1.3	26.6±2.3	NA	36.3±3.2	47.8±4.4	NA	7.0±0.6	6.2±1.2	NA

^a Estimates for HFC-32 during 2008 and 2009 were not available from NOAA's atmospheric-based estimates (Hu et al. 2022; Hu et al. 2024; Montzka et al. 2023) and are excluded from this analysis. For information on emissions of HFC-32 during those years, the reader is referred to Hu et al. (2017)

Note: NOAA uncertainty values represent one standard deviation of multiple runs of different prior assumptions; EPA uncertainty ranges represent one standard deviation across Monte Carlo simulations for 2023 and are applied assuming a constant relative uncertainty for all years.

NA is not available

Figure A-7: U.S. Emissions of HFC-32, HFC-125, HFC-134a, and HFC-143a



The

blue and purple lines show emissions estimates from NOAA using the STILT and HYSPLIT atmospheric models, respectively. The red line represents the modeled emissions from the EPA Vintaging Model. The shaded area around each represents the 1 s.d. uncertainty range.

As shown, inventory-modeled estimates of HFC-32, accounting for the uncertainty, were comparable (within 1.5 Gg y⁻¹) with those derived from atmospheric measurements for the years 2010 to 2017 and after 2020, but estimates differed by more than one standard deviation (1 s.d.) from the STILT atmospheric-based estimate in 2016 and from the HYSPLIT estimates in 2010, 2011, and 2016 through 2019. The EPA estimates at 2 s.d. were within the atmospheric-based estimates at 2 s.d. for all years except 2018 and 2019.⁸⁶

Both atmosphere-derived and inventory-modeled estimates show a similar trend of increasing emissions, but inventory-modeled estimates of HFC-32 increase slightly slower than the atmospheric-based estimates from both the HYSPLIT and STILT models after 2015 and through 2019. The inventory-modeled estimate return to within 1 s.d. starting in 2021, when the atmosphere-derived estimates decrease slightly, which might reflect the influence of the COVID-19 pandemic on human behavior and use of these chemicals in 2020, and then begin to rise again. Where the pandemic had effects on lower sales or installation of equipment, that information would be incorporated where known (e.g., in the shipments of unitary air-conditioning equipment); however, only dramatic changes would be easily discerned from the inventory-based estimates. Also, at this time, any other affected activity (e.g., possible lower service and potential related emissions during the initial month of the pandemic), have not been included in the inventory-based modeling due to the lack of confirming information.

Inventory-modeled emissions of HFC-134a have a tendency of being above the atmosphere-based estimates before 2013, but below from 2017 through 2023. While the mean values from NOAA have uncertainties of approximately $\pm 10\%$ and year-to-year variability of similar magnitude, the data after 2019 suggest the emergence of a downward trend. These results contrast with the inventory-modeled result which shows a consistent downward trend since 2010. The downward trend in the atmospheric-based estimates, beginning in 2019, is likely due to more than just pandemic influences, and may reflect the downward trend for processes being captured in the EPA model.

Inventory-modeled estimates for HFC-125 were consistently within 1 s.d. uncertainty of atmosphere-based estimates from 2009 through 2015 but were smaller by more than 1 s.d. between 2016 and 2020. Both the inventory-modeled and atmospheric-based results suggest a substantial upward trend for HFC-125 emissions. As with HFC-32, the estimates derived from atmospheric measurement increase more quickly than the inventory-modeled estimates after 2015, but the inventory-modeled estimates return within 1 s.d. for 2021. Like HFC-32, it is unclear whether this change in trend in atmospheric-based estimates from 2019 to 2021 was due behavioral changes during the beginning of the pandemic; however, after 2021 both the inventory-modeled emission estimates and the atmosphere-based emission estimates rise at roughly the same rate.

HFC-143a emissions calculated for the inventory, accounting for 1 s.d., were comparable to the mean atmospheric-based estimates with either the HYSPLIT or STILT model. Considering the uncertainty ranges, HFC-143a inventory-modeled values agree within 1 s.d. of the HYSPLIT-based estimates for all years except 2008 through 2010, and within 1 s.d. of the STILT-based estimates for years 2009 through 2010, 2014, and 2016 through 2017. Inventory-modeled estimates for HFC-143a trend upward until 2016 and then remain relatively constant through 2023. In the NOAA estimates, no secular trend is discernable from 2008 to 2023 for HFC-143a considering the annual mean uncertainties of approximately 11.8 percent. The mean values from the NOAA estimates, however, are also relatively constant (within approximately 1 Gg y⁻¹ of the overall mean) throughout the entire time series.

Table A-121 shows the differences in the emissions results from EPA's Vintaging Model and the mean results from NOAA (averaged across the HYSPLIT and STILT model results, as applicable) for those years where modeled estimates including the 1 s.d. uncertainty shown were not within the given 1 s.d. uncertainty range in the NOAA results. Years when modeled estimate ranges (from negative to positive uncertainty) are within the 1 s.d. uncertainty range reported by one or both of the NOAA estimates are not shown as those differences are assumed

⁸⁶ Where a specific atmospheric model is not mentioned, to determine if EPA results agreed with the 1 s.d. range of uncertainty in the atmosphere-based estimates from NOAA, EPA compared the range of EPA estimates at 1 s.d. to the range represented by the lowest mean value less one s.d. and the highest mean value plus one s.d., even if these two values came from different atmospheric models (i.e., HYSPLIT and STILT). A similar process was used for 2 s.d. comparisons.

to be insignificant. We also look at the 2 s.d. range in the EPA and NOAA results, which for these results are simply two times the 1 s.d. uncertainty magnitudes. Emissions differences found to be outside that range are shown in bold in the table, indicating more attention may be warranted to understand these results. Comparing the results from the individual gases shows changes over time, for example:

- a. For HFC-32, while the differences for 2016 to 2020 were not within the 1 s.d. uncertainty ranges for NOAA estimates, the differences averaged only -2.0 Gg per year during these five years and were trending towards a smaller difference in the last two years. Results were within the 1 s.d. uncertainty range of the NOAA estimates for the earlier years of 2010 to 2015 and the later years of 2021 to 2023. For 2016 to 2020, the modeled results were an average of 18 percent below the mean of the atmospherically derived values.
- b. For HFC-125, the differences were within the uncertainty range of the NOAA estimates for 2009 to 2015 and 2021 to 2023. The results were within the twice uncertainty range with the exception of 2018 to 2019. For 2018 and 2019, inventory-modeled results were 22 percent below the mean of the atmospherically derived values.
- c. For HFC-134a, the differences ranged from about 39 percent below the 1 s.d. uncertainty range in 2019 and 2021 to 2022 to about 17 percent above the 1 s.d. uncertainty range in 2009. For 2008 to 2009, 2012, and 2017 to 2023, differences were greater than the NOAA estimates at the 1 s.d. uncertainty range. Furthermore, of these differences outside 1 s.d. uncertainty, the 2019 to 2022 estimates were outside the NOAA estimates at twice the uncertainty.
- d. For HFC-143a, the inventory-modeled results were within the 1 s.d. uncertainty range in 2009 through 2023. The 2008 model results were outside the 1 s.d. uncertainty range, where the modeled result was below the NOAA estimates by 36 percent compared to the mean of the atmospherically derived values, yet remained within the 2 s.d. range.

Table A-121: Gigagram (Percentage) Differences between EPA and NOAA HFC Emission Estimates

Year	HFC-32 ^a	HFC-125 ^a	HFC-134a ^a	HFC-143a ^a
2008	NA	-1.9 (-26%)	12.9 (27%)	-2.3 (-36%)
2009	NA		17.8 (40%)	
2010				
2011				
2012			12.6 (29%)	
2013				
2014				
2015				
2016	-1.2 (-15%)	-1.7 (-11%)		
2017	-1.7 (-17%)	-2.8 (-16%)	-12.0 (-21%)	
2018	-2.2 (-20%)	-4.6 (-22%)	-15.1 (-26%)	
2019	-3.5 (-25%)	-5.0 (-22%)	-17.3 (-29%)	
2020	-1.6 (-12%)	-3.5 (-16%)	-12.9 (-24%)	
2021			-15.1 (-28%)	
2022			-14.6 (-28%)	
2023			-11.5 (-24%)	
Average ^b	-2.0 (-18%)	-3.3 (-19%)	-5.5 (-8%)	-2.3 (-36%)

Average of Absolute Values ^b	2.0 (18%)	3.3 (19%)	14.2 (28%)	2.3 (36%)

^aThe values for 1 s.d. and 2 s.d. were derived separately for the HYSPLIT and STILT values plus or minus the respective uncertainties for each HFC and year. These maximum and minimum values were then compared to the EPA estimates at 1 s.d. for each year to see if the inventory-modeled emissions are within 1 s.d. of at least one of the atmospherically-derived emissions. The same process was used to compare the estimates at twice the 1 s.d. (i.e., 2 s.d.). Differences shown are EPA estimates (without uncertainties) less the average of NOAA mean estimates.

^bAverages are for all years 2008-2021, except HFC-32, where averages are for all years 2010-2020.

Notes: Differences smaller than the 1 s.d. uncertainty on the annual NOAA-based estimates compared to the 1 s.d. uncertainty on the EPA estimates are not shown. Differences greater than 2 s.d. shown in bold font.

Discussion and Areas for Additional Research

The following are potential contributing factors to the variation between the results and possible ways these could inform changes to the model that would reduce the differences seen. See Section 4.25 for a discussion of planned improvements to the modeled estimates that could address some of these discrepancies.

- When examining the NOAA combined estimates and uncertainties at the 2 s.d., only a few differences from EPA model results are identified, primarily with HFC-134a in 2019 through 2022, and the 2018 to 2019 period with both HFC-32 and HFC-125. In these cases, the role of meteorology in creating these differences is not currently known, as atmosphere-derived estimates were only available using the single modeling approach HYSPLIT/NAM12. In general, the uncertainties in the NOAA estimates are primarily driven by the frequency and spatial density of the atmospheric sampling, and the accuracy of the meteorology and transport used in the simulations. There is also inherent uncertainty in measurement of trace gases using gas chromatography related to inconsistent calibration, potential contamination in sampling pumps and flasks, among other factors (Barwick 1999). That uncertainty, however, is likely less than 1 percent for HFC-125, HFC-134a, and HFC-143a, and less than 5 percent for HFC-32 in the NOAA results.
- For HFC-143a, there is no consistent upward or downward trend in the atmosphere-derived emissions through the entire time period, as overall changes are similar to or smaller than the associated uncertainties. For HFC-134a, there is likewise no consistent trend until approximately 2019, when emission estimates decline. This possible downward trend in the atmospheric data, however, comes a decade later than the downward emission trends derived from the activity-based modeling. In the case of HFC-32 and HFC-125, an increasing trend is seen in both the atmosphere and inventory-based estimates, albeit with slightly different rates through 2019. Over the time series available (2010 through 2023), HFC-32 emission estimates grow by 14.7 Gg y⁻¹ in both sets of estimates, and from 2008 through 2023, the atmosphere-based estimates and the inventory-based estimates grow by 18.6 Gg y⁻¹ and 19.3 Gg y⁻¹, respectively. While the inventory-based estimates were more than 2 s.d. lower than the atmosphere-based estimates in 2018 and 2019, by 2021 the two sets of estimates are back within 1 s.d. of each other as they were for 2010 through 2015.
- A thorough discussion of the uncertainties and influencing factors in the NOAA estimates is provided in Hu et al. (2017). That study notes that emissions estimated from inverse modeling of atmospheric data can depend on assumed prior emission distributions and magnitudes, and accordingly the quoted uncertainties on the NOAA results have been augmented to include these influences. In general, in a region where there are fewer atmospheric observations, the NOAA results will inherently tend towards the prior and be impacted by neighboring regions and populations (NOAA/EPA 2020). If the emissions or

emissions per person (depending on which prior is used) are significantly different in these areas compared to the nearby areas, derived emissions for these regions can be biased.

- Uncertainty in atmospheric emission estimates is influenced by the number of NOAA’s atmospheric sampling sites and frequency of measurements at those sites, and both have changed over time. Uncertainties were greatest in 2008 and 2009—i.e., early on in the North American sampling program (Hu et al. 2017)—due to the fewer number of tower sites and available measurements in 2008 and also in 2009 for HFC-134a. This may help explain why none of the EPA results for 2008 were within one standard deviation of the NOAA estimates, although they were all within twice the uncertainty range. Also, changes in the number and location of measurement sites within the air sampling network, which contains over 25 sites, can lead to biases in the year-to-year emission estimates. Uncertainties related to network changes were estimated with separate inversion runs in which sites were removed from the analysis and differences ascertained in Hu et al. (2017) but are not included in NOAA’s current estimates of uncertainty that are given here.
- Uncertainties in the inventory-based model are estimated based on a sum-of-the-squares analysis of the deviation of each Monte Carlo simulation compared to the primary estimate for 2023. Ultimately, the Monte Carlo simulation involves simplifying procedures for the model and is based on expert judgment of the uncertainty in the factors involved. This judgement may be incorrect in either direction. See Section 4.25 for a discussion of the uncertainty analysis for all estimated emissions.
- The Vintaging Model estimated emissions for the entire United States, including all 50 states and territories. Conversely, NOAA limits scope to the contiguous 48 states and the District of Columbia (NOAA/EPA 2020). In that regard, EPA would expect the model to estimate slightly higher emissions than those reported by NOAA, by roughly 2 percent based on population data (U.S. Census 2021). Activity data for Hawaii, Alaska and territories could be researched and, if they were available, adjustments could be made to allow for a more direct comparison to the estimates supplied by NOAA.
- For HFC-125, the EPA model suggests lower emissions in 2008 and 2016 through 2020, outside the 2 s.d. uncertainty range in 2018 through 2019. For HFC-143a, the EPA model suggests lower emissions in 2008, but within 1 s.d. of the atmosphere-derived estimates for all other years. Further research into the refrigeration market might improve the agreement in the estimates for these two gases. As stated in the Introduction to Section 4.25, emissions from the large retail food end-use (e.g., supermarkets) were estimated to have the second highest contribution to the overall HFC emissions. Research in this industry on the shift away from blends such as R-404A (which contains both HFC-125 and HFC-143a) to refrigerants such as R-407A (which contains HFC-125 but not HFC-143a) or lower emission rates in the early years of this analysis could be used to improve the bottom-up model.
- After several years of good consistency in emission estimates and trends for both HFC-32 and HFC-125, deviations grew beginning in 2016, with the atmosphere-derived estimates increasingly larger than the modeled estimates through 2020. The modeled emissions of HFC-32 agreed well with the atmospheric inversion results in absolute terms through 2016, with atmosphere-derived estimates higher by slightly more than 2 s.d. in 2018 through 2019 compared to the modeled estimates, although both data sets show the same increasing trend, with a notable exception from 2019 to 2020 in the atmosphere-derived estimates. Slightly lower model results might imply that the actual emissions from R-410A (a 50:50 by mass ratio of HFC-32 and HFC-125) equipment were slightly higher than modeled. Lower model results could also imply that the model assumed a higher than actual use of “dry-charge” residential AC equipment in lieu of R-410A. EPA investigated this matter and determined that this possibility was not likely to be the cause for the noted differences (EPA 2022b). This difference might also imply that the assumption of a consistent average emission rate during operation, which is used for all products in the *Inventory*, is not accurately representing these gases, in particular from the stationary air conditioning sector. As noted earlier in the GHGRP comparison, the supply reported under the GHGRP in these later

years is also higher than predicted by the Vintaging Model. This might imply that these differences are driven in part by an underestimate of the emissions from existing equipment or of recovery from discarded equipment, which would result in the Vintaging Model estimating lower emissions and lower supply, respectively, which could explain such differences.

- The modeled inventory results for HFC-134a are complicated by an assumed decrease in emissions from motor vehicle air conditioning (due to previous shifts towards lower charge sizes and emission rates, as well as the transition to HFO-1234yf) with concurrent increases in other sectors using HFC-134a, such as for foam blowing given the HCFC bans in foam blowing and other uses. While the inter-annual changes in the NOAA mean values for this gas are small compared to the uncertainties, they show relatively consistent emissions after 2019, when a decrease is discernable, many years subsequent to the decrease apparent in the bottom-up inventory-based emission estimates after 2010. If the EPA model is underestimating the increased use in foam blowing and/or overestimating the decrease in emissions from the motor vehicle air conditioning end-use, that might account for some of the differences seen. Further, other uses of HFC-134a not included in the model could account for these differences. For instance, although the *new* vehicle market has been transitioning out of HFC-134a, which is included in the inventory-based model, it is not clear whether the *existing* fleet of vehicles has an increasing rate of HFC-134a emissions, either from those older vehicles designed for HFC-134a or possibly illegal use of HFC-134a in vehicle air conditioners designed for HFO-1234yf.
- There are data limitations inherent in the bottom-up model. As described above, emissions are estimated by applying assumed emission profiles to multiple end-uses, each of which can have thousands or millions of individual uses in the United States. In some cases where equipment stocks or sales are unknown, estimates are made using an average growth rate and by taking the most recent year where the starting stock or sales of equipment is known or can be reasonably estimated, then accounting for equipment lifetimes, and subsequently estimating the amount of equipment in future and/or preceding years where a value was not available. Such assumptions are evident in the approximately constant slopes of the EPA emission estimates compared to the more varying nature found in NOAA's mean results. Future work could look at whether these variations might be consistent with other factors that influence emissions, such as equipment installations, sales, retirements, or pandemic-related supply issues, which could vary from year to year.

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Data are also taken from various government sources, including rulemaking analyses from the U.S. Department of Energy and from the Motor Vehicle Emission Simulator (MOVES) model from EPA's Office of Transportation and Air Quality.

3.11. Methodology for Estimating CH₄ Emissions from Enteric Fermentation

The steps outlined in this annex were used to estimate methane emissions from enteric fermentation for the years 1990 through 2022. As explained in the Enteric Fermentation Chapter 5.1, a simplified approach was used to estimate emissions for 2023. The methodology used for 2023 relied on 2023 population estimates and 2022 implied emission factors and is explained in further detail within Chapter 5.1 Enteric Fermentation (Source Category 3A). Methane emissions from enteric fermentation were estimated for seven livestock categories: cattle, horses, sheep, swine, goats, American bison, and the non-horse equines (mules and asses). Emissions from cattle represent the majority of U.S. emissions from enteric fermentation; consequently, a more detailed IPCC Tier 2 methodology was used to estimate emissions from cattle. The IPCC Tier 1 methodology was used to estimate emissions for the other types of livestock, including horses, goats, sheep, swine, American bison, and mules and asses (IPCC 2006).

Estimate Methane Emissions from Cattle

This section describes the process used to estimate CH₄ emissions from enteric fermentation from cattle using the Cattle Enteric Fermentation Model (CEFM). The CEFM was developed based on guidance provided in the 2006 *IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) and uses information on population, energy requirements, digestible energy, and CH₄ conversion rates to estimate CH₄ emissions.⁸⁷ The emission methodology consists of the following three steps: (1) characterize the cattle population to account for animal population categories with different emission profiles; (2) characterize cattle diets to generate information needed to estimate emission factors; and (3) estimate emissions using these data and the IPCC Tier 2 equations.

Step 1: Characterize U.S. Cattle Population

The CEFM's state-level cattle population estimates are based on data obtained from the U.S. Department of Agriculture's (USDA) National Agricultural Statistics Service Quick Stats database (USDA 2023a). State-level cattle population estimates are shown by animal type for 2023 in Table A-122. A national-level summary of the annual average populations upon which all livestock-related emissions (both Enteric Fermentation and Manure Management) are based is provided in Table A-123, to ensure consistency. Cattle populations used in the Enteric Fermentation source category for the 1990 to 2022 Inventory were estimated using the cattle transition matrix in the CEFM, which uses January 1 USDA population estimates and weight data to simulate the population of U.S. cattle from birth to slaughter, and results in an estimate of the number of animals in a particular cattle grouping while taking into account the monthly rate of weight gain, the average weight of the animals, and the death and calving rates. The use of supplemental USDA data and the cattle transition matrix in the CEFM results in cattle population estimates for this sector differing slightly from the January 1 or July 1 USDA point estimates and the cattle population data obtained from the Food and Agriculture Organization of the United Nations (FAO). For 2023, state populations were estimated by calculating ratios of 2022 state populations to the 2022 total national population, then applying those state-specific ratios to the 2023 national total population estimates. See the Enteric Fermentation chapter for more details about this approach.

Table A-122: 2023 Cattle Population Estimates, by Animal Type and State (1,000 head)

State	Dairy Repl.		Dairy Repl.		Bulls	Beef Repl.		Beef Repl.		Steer Stockers	Heifer Stockers	
	Dairy Calves	Dairy Cows	7-11 Months	12-23 Months		Beef Calves	Beef Cows	7-11 Months	12-23 Months		Heifer Stockers	Feedlot
Alabama	2	3	1	1	41	334	649	23	56	21	22	7
Alaska	0	0	0	0	4	4	8	0	1	0	0	0
Arizona	98	194	34	81	19	85	165	5	13	128	11	277

⁸⁷ Additional information on the Cattle Enteric Fermentation Model can be found in ICF (2006).

Arkansas	3	5	1	2	53	450	873	28	70	51	32	14
California	870	1724	213	513	58	338	656	24	60	283	99	565
Colorado	102	202	32	78	43	317	616	28	70	354	261	1177
Conn.	9	19	3	6	0	2	4	0	1	0	1	0
Delaware	1	3	0	1	0	1	2	0	0	1	0	0
Florida	53	105	8	20	53	445	864	26	65	11	11	4
Georgia	42	83	7	17	29	242	470	21	52	18	11	5
Hawaii	0	1	0	1	4	39	76	2	6	4	2	1
Idaho	330	653	98	236	38	247	481	20	49	142	99	321
Illinois	41	81	11	28	17	168	327	12	29	87	40	219
Indiana	94	186	17	40	15	91	178	7	18	42	20	109
Iowa	114	225	34	81	58	450	873	34	83	570	261	1192
Kansas	85	169	45	108	82	706	1372	57	141	902	755	2671
Kentucky	22	44	10	24	58	480	932	26	65	97	49	19
Louisiana	5	9	1	2	29	224	435	17	42	10	8	3
Maine	13	26	4	9	1	5	10	1	2	2	1	1
Maryland	21	41	7	18	3	21	41	2	5	6	3	8
Mass.	5	10	2	4	1	4	8	1	2	1	0	0
Michigan	220	435	43	103	14	48	93	5	12	77	20	168
Minn.	233	461	59	142	29	179	347	18	44	217	64	392
Miss.	4	7	1	3	38	237	461	19	47	23	17	7
Missouri	35	69	8	20	106	964	1873	63	156	186	102	86
Montana	6	11	1	3	91	645	1254	67	167	93	82	46
Nebraska	29	58	8	20	106	895	1739	74	182	1128	698	2846
Nevada	16	31	3	6	13	121	236	8	20	15	12	3
N.Hamp.	5	11	2	4	0	2	4	0	1	1	0	0
N.Jersey	2	4	1	2	1	4	8	0	1	1	1	0
N.Mexico	148	293	35	84	24	225	437	15	36	44	31	13
New York	314	621	92	223	19	50	97	8	21	20	18	22
N.Car.	20	39	4	9	30	179	348	13	32	19	11	5
N.Dakota	8	15	2	5	58	464	902	38	95	137	102	42
Ohio	125	249	34	81	29	155	301	14	34	97	26	153
Oklahoma	20	39	6	13	164	1054	2047	84	208	447	238	326
Oregon	63	125	15	37	38	251	487	21	52	75	53	127
Penn	238	471	55	132	19	94	183	11	27	62	22	71
R.Island	0	1	0	0	0	1	1	0	0	0	0	0
S.Car.	5	9	1	3	12	78	152	6	15	5	4	2
S.Dakota	86	170	11	27	101	795	1544	78	193	332	219	457
Tenn.	14	27	6	13	58	444	862	25	63	60	38	17
Texas	316	626	67	162	317	2198	4271	150	370	1163	746	2976
Utah	48	95	15	37	22	164	319	15	36	40	26	22
Vermont	61	120	15	35	3	7	14	1	2	2	3	1
Virginia	36	71	10	24	37	298	578	19	46	66	30	17
Wash.	132	262	36	88	17	111	216	12	29	84	57	229
W.Virg.	3	5	1	1	13	93	181	6	16	17	10	4
Wisconsin	645	1278	185	445	29	147	285	18	44	177	38	271
Wyoming	5	9	1	3	34	338	657	31	76	71	60	71

Table A-123: Cattle Population Estimates from the CEFM Transition Matrix for 1990–2023 (1,000 head)

Livestock Type	1990	1995	2000	2005	2010	2019	2020	2021	2022	2023 ^a
Dairy										
Dairy Calves (0–6 months)	5,369	5,091	4,951	4,628	4,666	4,834	4,813	4,876	4,855	4,744
Dairy Cows	10,015	9,482	9,183	9,004	9,087	9,353	9,343	9,442	9,377	9,398
Dairy Replacements 7–11 months	1,214	1,216	1,196	1,257	1,351	1,391	1,365	1,326	1,289	1,244
Dairy Replacements 12–23 months	2,915	2,892	2,812	2,905	3,194	3,304	3,272	3,216	3,105	2,995
Beef										
Beef Calves (0–6 months)	16,909	18,177	17,431	16,918	16,067	15,892	15,830	15,602	15,244	14,893
Bulls	2,160	2,385	2,293	2,214	2,190	2,253	2,237	2,211	2,110	2,029
Beef Cows	32,455	35,190	33,575	32,674	31,440	31,691	31,339	30,844	29,983	28,939
Beef Replacements 7–11 months	1,269	1,493	1,313	1,363	1,238	1,380	1,367	1,321	1,242	1,155
Beef Replacements 12–23 months	2,967	3,637	3,097	3,171	3,050	3,321	3,253	3,255	3,070	2,856
Steer Stockers	10,321	11,716	8,724	8,185	8,234	7,745	7,614	7,686	7,682	7,387
Heifer Stockers	5,946	6,699	5,371	5,015	5,061	4,500	4,472	4,629	4,584	4,413
Feedlot Cattle	9,549	11,064	13,006	12,652	13,204	14,917	14,949	15,554	15,474	14,966

^a Population estimates for 2023 are based on a simplified calculation approach rather than CEFM output, as noted above and explained in the Enteric Fermentation Chapter 5.1.

The population transition matrix in the CEFM simulates the U.S. cattle population over time and provides an estimate of the population age and weight structure by cattle type on a monthly basis.⁸⁸ Since cattle often do not remain in a single population type for an entire year (e.g., calves become stockers, stockers become feedlot animals), and emission profiles vary both between and within each cattle type, these monthly age groups are tracked in the CEFM to obtain more accurate emission estimates than would be available from annual point estimates of population (such as available from USDA statistics) and weight for each cattle type.

The transition matrix tracks both dairy and beef populations, and divides the populations into males and females, and subdivides the population further into specific cattle groupings for calves, replacements, stockers, feedlot, and mature animals. The matrix is based primarily on two types of data: population statistics and weight statistics (including target weights, slaughter weights, and weight gain). Using the weight data, the transition matrix simulates the growth of animals over time by month. The matrix also relies on supplementary data, such as feedlot placement statistics, slaughter statistics, death rates, and calving rates, described in further detail below.

The basic method for tracking population of animals per category is based on the number of births (or graduates) into the monthly age group minus those animals that die or are slaughtered and those that graduate to the next category (such as stockers to feedlot placements).

Each stage in the cattle lifecycle was modeled to simulate the cattle population from birth to slaughter. This level of detail accounts for the variability in CH₄ emissions associated with each life stage. Given that a stage can last less than one year (e.g., calves are usually weaned between 4 and 6 months of age), each is modeled on a per-month basis. The type of cattle also influences CH₄ emissions (e.g., beef versus dairy). Consequently, there is an

⁸⁸ Mature animal populations are not assumed to have significant monthly fluctuations, and therefore the populations utilized are the January estimates downloaded from USDA (2023).

independent transition matrix for each of three separate lifecycle phases, 1) calves, 2) replacements and stockers, and 3) feedlot animals. In addition, the number of mature cows and bulls are tabulated for both dairy and beef stock. The transition matrix estimates total monthly populations for all cattle subtypes. These populations are then reallocated to the state level based on the percent of the cattle type reported in each state in the January 1 USDA data. Each lifecycle is discussed separately below, and the categories tracked are listed in Table A-124.

Table A-124: Cattle Population Categories Used for Estimating CH₄ Emissions

Dairy Cattle	Beef Cattle
Calves	Calves
Heifer Replacements	Heifer Replacements
Cows	Heifer and Steer Stockers
	Animals in Feedlots (Heifers & Steer)
	Cows
	Bulls ^a

^a Bulls (beef and dairy) are accounted for in a single category.

The key variables tracked for each of these cattle population categories are as follows:

Calves. Although enteric emissions are only calculated for 4- to 6-month old calves, it is necessary to calculate populations from birth as emissions from manure management require total calf populations and the estimates of populations for older cattle rely on the available supply of calves from birth. The number of animals born on a monthly basis was used to initiate monthly cohorts and to determine population age structure. The number of calves born each month was obtained by multiplying annual births by the percentage of births per month. Annual birth information for each year was taken from USDA (2023). For dairy cows, monthly birth data are not readily available, so the number of births is assumed to be distributed equally throughout the year (approximately 8.3 percent per month) while beef births are distributed according to Table A-125, based on approximations from the National Animal Health Monitoring System (NAHMS) (USDA/APHIS/VS 1998, 1994, 1993). To determine whether calves were born to dairy or beef cows, the dairy cow calving rate (USDA/APHIS/VS 2002; USDA/APHIS/VS 1996) was multiplied by the total dairy cow population to determine the number of births attributable to dairy cows, with the remainder assumed to be attributable to beef cows. Total annual calf births are obtained from USDA and distributed into monthly cohorts by cattle type (beef or dairy). Calf growth is modeled by month, based on estimated monthly weight gain for each cohort (approximately 61 pounds per month). The total calf population is modified through time to account for veal calf slaughter at 4 months and a calf death loss of 0.35 percent annually (distributed across age cohorts up to 6 months of age). An example of a transition matrix for calves is shown in Table A-126. Note that 1- to 6-month-old calves in January of each year have been tracked through the model based on births and death loss from the previous year.

Table A-125: Estimated Beef Cow Births by Month

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
7%	15%	28%	22%	9%	3%	2%	2%	3%	4%	3%	3%

Table A-126: Example of Monthly Average Populations from Calf Transition Matrix (1,000 head)

Age (month)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6	1,187	1,179	1,414	1,648	1,585	1,572	2,437	4,522	7,834	6,352	2,982	1,513
5	1,180	1,415	1,649	1,585	1,573	2,438	4,523	7,837	6,355	2,983	1,515	1,139
4	1,448	1,680	1,618	1,601	2,465	4,554	7,869	6,391	3,016	1,545	1,171	1,162
3	1,681	1,619	1,602	2,466	4,555	7,872	6,394	3,017	1,546	1,172	1,163	1,423
2	1,621	1,603	2,467	4,557	7,875	6,396	3,018	1,547	1,172	1,163	1,424	1,650
1	1,604	2,469	4,559	7,878	6,398	3,019	1,547	1,173	1,164	1,425	1,651	1,590
0	2,471	4,562	7,882	6,401	3,020	1,548	1,173	1,164	1,426	1,652	1,591	1,574

Note: As outlined in grey as an example, the cohort starting at age 0 months on July 1 is tracked in order to illustrate how a single cohort moves through the transition matrix. Each month, the cohort reflects the decreases in population due to the estimated 0.35 percent annual death loss, and between months 4 and 5, a more significant loss is seen than in other months due to estimated veal slaughter.

Replacements and Stockers. At 7 months of age, calves “graduate” and are separated into the applicable cattle types: replacements (cattle raised to give birth), or stockers (cattle held for conditioning and growing on grass or other forage diets). First the number of replacements required for beef and dairy cattle are calculated based on estimated death losses and population changes between beginning and end of year population estimates. Based on the USDA estimates for “replacement beef heifers” and “replacement dairy heifers,” the transition matrix for the replacements is back-calculated from the known animal totals from USDA, and the number of calves needed to fill that requirement for each month is subtracted from the known supply of female calves. All female calves remaining after those needed for beef and dairy replacements are removed become “stockers” that can be placed in feedlots (along with all male calves). During the stocker phase, animals are subtracted out of the transition matrix for placement into feedlots based on feedlot placement statistics from USDA (2023).

The data and calculations that occur for the stocker category include matrices that estimate the population of backgrounding heifers and steer, as well as a matrix for total combined stockers. The matrices start with the beginning of year populations in January and model the progression of each cohort. The age structure of the January population is based on estimated births by month from the previous two years, although in order to balance the population properly, an adjustment is added that slightly reduces population percentages in the older populations. The populations are modified through addition of graduating calves (added in month 7, bottom row of Table A-127) and subtraction through death loss and animals placed in feedlots. Eventually, an entire cohort population of stockers may reach zero, indicating that the complete cohort has been transitioned into feedlots. An example of the transition matrix for stockers is shown in Table A-127.

Table A-127: Example of Monthly Average Populations from Stocker Transition Matrix (1,000 head)

Age (month)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
23	190	183	91	28	11	6	5	5	3	1	0	0
22	328	148	43	15	8	6	6	5	3	1	0	186
21	266	70	22	11	8	8	7	5	3	33	186	322
20	126	36	17	11	10	9	7	5	77	270	322	261
19	64	27	17	13	12	9	6	123	382	512	262	123
18	49	27	20	16	11	9	157	497	764	440	123	63
17	48	33	24	15	11	209	582	1,024	676	211	64	48
16	59	38	23	15	269	714	1,217	920	326	297	48	48
15	69	37	22	359	865	1,515	1,101	446	605	62	48	58
14	66	36	547	1,095	1,857	1,380	535	924	80	48	58	67
13	66	888	1,538	2,364	1,697	672	1,214	102	48	58	67	65
12	1,019	1,690	2,658	1,906	796	1,622	272	89	58	68	65	64
11	1,892	2,920	2,143	894	1,976	351	216	161	138	128	119	1,030
10	3,271	2,369	1,002	2,326	456	290	328	436	405	380	1,258	2,429
9	2,656	1,122	2,633	558	431	515	625	589	576	1,445	3,006	5,337
8	1,252	3,062	736	575	726	949	841	853	1,634	3,421	6,313	5,055
7	3,433	869	863	1,069	1,277	1,221	1,212	1,983	3,835	6,777	5,461	2,468

Note: As outlined in grey as an example, the cohort starting at age 7 months on January 1 is tracked in order to illustrate how a single cohort moves through the transition matrix. Each month, the cohort reflects the decreases in population due to the estimated 0.35 percent annual death loss and loss due to placement in feedlots (the latter resulting in the majority of the loss from the matrix).

To ensure a balanced population of both stockers and placements, additional data tables are used in the stocker matrix calculations. The tables summarize the placement data by weight class and month and are based on the total number of animals within the population that are available to be placed in feedlots and the actual feedlot placement statistics provided by USDA (2023). In cases where there are discrepancies between the USDA estimated placements by weight class and the calculated animals available by weight, the model pulls available stockers from the next highest weight category if available. If there are still not enough animals to fulfill requirements, the model pulls animals from the next lowest weight category. In the current time series, this method was able to ensure that total placement data matched USDA estimates, and no shortfalls have occurred.

In addition, average weights were tracked for each monthly age group using starting weight and monthly weight gain estimates. Weight gain (i.e., pounds per month) was estimated based on weight gain needed to reach a set target weight, divided by the number of months remaining before target weight was achieved. Birth weight was assumed to be 88 pounds for both beef and dairy animals. Weaning weights were estimated at 515 pounds. Other reported target weights were available for 12-, 15-, 24-, and 36-month-old animals, depending on the animal type. Beef cow mature weight was taken from measurements provided for a major British Bos taurus breed (Enns 2008) and increased during the time series through 2007.⁸⁹ Bull mature weight was calculated as 1.5 times the beef cow mature weight (Doren et al. 1989). Beef replacement weight was calculated as 70 percent of mature weight at 15 months and 85 percent of mature weight at 24 months. As dairy weights are not a trait that is typically tracked, mature weight for dairy cows was estimated at 1,500 pounds for all years, based on expert judgement by Kris Johnson (2010) and an estimate from Holstein Association USA (2010).⁹⁰ Dairy replacement weight at 15 months was assumed to be 875 pounds and 1,300 pounds at 24 months. Live slaughter weights were estimated from dressed slaughter weight (USDA 2023a) divided by 0.63. This ratio represents the dressed weight (i.e., weight of the carcass after removal of the internal organs), to the live weight (i.e., weight taken immediately before slaughter). The annual typical animal mass for each livestock type is presented in Table A-128.

Weight gain for stocker animals was based on monthly gain estimates from Johnson (1999) for 1989, and from average daily estimates from Lippke et al. (2000), Pinchack et al. (2004), Platter et al. (2003), and Skogerboe et al. (2000) for 2000. Interim years were calculated linearly, as shown in Table A-129, and weight gain was held constant starting in 2000. Table A-129 provides weight gains that vary by year in the CEFM.

⁸⁹ Mature beef weight is held constant after 2007 but future Inventories will incorporate known trends through 2007 and extrapolate to future years, as noted in the Planned Improvements section of 5.1 Enteric Fermentation.

⁹⁰ Mature dairy weight is based solely on Holstein weight, so could be higher than the national average. Future Inventories will consider other dairy breeds, as noted in the Planned Improvements section of 5.1 Enteric Fermentation.

Table A-128: Typical Animal Mass (lbs)⁹¹

Year/Cattle Type	Calves	Dairy Cows ^a	Dairy Replacements ^b	Beef Bulls ^a	Beef Cows ^a	Beef Replacements ^b	Steer Stockers ^b	Heifer Stockers ^b	Steer Feedlot ^b	Heifer Feedlot ^b
1990	269	1,499	899	1,830	1,220	819	691	651	923	845
1991	270	1,499	897	1,836	1,224	821	694	656	933	855
1992	269	1,499	897	1,893	1,262	840	714	673	936	864
1993	270	1,499	898	1,918	1,279	852	721	683	929	863
1994	270	1,499	897	1,918	1,279	853	720	688	943	875
1995	270	1,499	897	1,921	1,281	857	735	700	947	879
1996	269	1,499	898	1,926	1,284	858	739	707	939	878
1997	270	1,499	899	1,927	1,285	860	736	707	938	876
1998	270	1,499	896	1,942	1,295	865	736	709	956	892
1999	270	1,499	899	1,936	1,291	861	730	708	959	894
2000	270	1,499	896	1,906	1,271	849	719	702	960	898
2001	270	1,499	897	1,906	1,271	850	725	707	963	900
2002	270	1,499	896	1,912	1,275	851	725	707	981	915
2003	270	1,499	899	1,960	1,307	871	718	701	972	904
2004	270	1,499	896	1,983	1,322	877	719	702	966	904
2005	270	1,499	894	1,989	1,326	879	717	706	974	917
2006	270	1,499	897	2,010	1,340	889	724	712	983	925
2007	270	1,499	896	2,020	1,347	894	720	706	991	928
2008	270	1,499	897	2,020	1,347	894	720	704	999	938
2009	270	1,499	895	2,020	1,347	894	730	715	1007	947
2010	270	1,499	897	2,020	1,347	896	726	713	996	937
2011	270	1,499	897	2,020	1,347	891	721	712	989	932
2012	270	1,499	899	2,020	1,347	892	714	706	1003	945
2013	270	1,499	898	2,020	1,347	892	718	709	1016	958
2014	270	1,499	895	2,020	1,347	888	720	713	1021	960
2015	270	1,499	896	2,020	1,347	890	717	714	1037	982
2016	270	1,499	898	2,020	1,347	892	721	718	1047	991
2017	270	1,499	896	2,020	1,347	894	714	709	1037	977
2018	270	1,499	898	2,020	1,347	894	708	701	1030	972
2019	270	1,499	897	2,020	1,347	893	710	698	1032	972
2020	271	1,499	899	2,020	1,347	893	710	698	1045	983
2021	273	1,499	900	2,020	1,347	896	711	700	1056	989
2022	271	1,499	899	2,020	1,347	896	716	701	1059	989

^a Input into the model.^b Annual average calculated in model based on age distribution.⁹¹ This table has not been updated for the current (1990 through 2023) Inventory. It will be updated for the next (1990 through 2024) *Inventory*.

Table A-129: Weight Gains that Vary by Year (lbs)

Year/Cattle Type	Steer Stockers to 12 months(lbs/day)	Steer Stockers to 24 months (lbs/day)	Heifer Stockers to 12 months(lbs/day)	Heifer Stockers to 24 months(lbs/day)
1990	1.53	1.23	1.23	1.08
1991	1.56	1.29	1.29	1.15
1992	1.59	1.35	1.35	1.23
1993	1.62	1.41	1.41	1.30
1994	1.65	1.47	1.47	1.38
1995	1.68	1.53	1.53	1.45
1996	1.71	1.59	1.59	1.53
1997	1.74	1.65	1.65	1.60
1998	1.77	1.71	1.71	1.68
1999	1.80	1.77	1.77	1.75
2000–onwards	1.83	1.83	1.83	1.83

Sources: Enns (2008), Johnson (1999), Lippke et al. (2000), NRC (1999), Pinchack et al. (2004), Platter et al. (2003), Skogerboe et al. (2000).

Feedlot Animals. Feedlot placement statistics from USDA provide data on the placement of animals from the stocker population into feedlots on a monthly basis by weight class. The model uses these data to shift a sufficient number of animals from the stocker cohorts into the feedlot populations to match the reported placement data. After animals are placed in feedlots, they progress through two steps. First, animals spend 25 days on a step-up diet to become acclimated to the new feed type (e.g., more grain than forage, along with new dietary supplements); during this time weight gain is estimated to be 2.7 to 3 pounds per day (Johnson 1999). Animals are then switched to a finishing diet (concentrated, high energy) for a period of time before they are slaughtered. Weight gain during finishing diets is estimated to be 2.9 to 3.3 pounds per day (Johnson 1999). The length of time an animal spends in a feedlot depends on the start weight (i.e., placement weight), the rate of weight gain during the start-up and finishing phase of diet, and the target weight (as determined by weights at slaughter). Additionally, animals remaining in feedlots at the end of the year are tracked for inclusion in the following year’s emission and population counts. For 1990 to 1995, only the total placement data were available, therefore placements for each weight category (categories displayed in Table A-130) for those years are based on the average of monthly placements from the 1996 to 1998 reported figures. Placement data is available by weight class for all years from 1996 onward. Table A-130 provides a summary of the reported feedlot placement statistics for 2022.

Table A-130: Feedlot Placements in the United States for 2022 (Number of animals placed/1,000 Head)⁹²

Weight Placed When:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
< 600 lbs	420	365	380	365	365	365	400	430	445	535	535	450
600 – 700 lbs	445	330	330	270	270	270	280	320	330	460	460	425
700 – 800 lbs	550	505	535	415	465	370	405	465	440	445	400	415
> 800 lbs	589	668	760	774	769	629	679	895	865	645	510	494
Total	2,004	1,868	2,005	1,824	1,869	1,634	1,764	2,110	2,080	2,085	1,905	1,784

Note: Totals may not sum due to independent rounding.

Source: USDA (2023).

Mature Animals. Energy requirements and, hence, composition of diets, level of intake, and emissions for mature animals are greatly influenced by whether the animal is pregnant or lactating. Information is therefore needed on

⁹² This table has not been updated for the current (1990 through 2023) Inventory. It will be updated for the next (1990 through 2024) Inventory.

the percentage of all mature animals that are pregnant each month, as well as milk production, to estimate CH₄ emissions. A weighted average percent of pregnant cows each month was estimated using information on births by month and average pregnancy term. For beef cattle, a weighted average total milk production per animal per month was estimated using information on typical lactation cycles and amounts (NRC 1999), and data on births by month. This process results in a range of weighted monthly lactation estimates expressed as pounds per animal per month. The monthly estimates for daily milk production by beef cows are shown in Table A-131. Annual estimates for dairy cows were taken from USDA milk production statistics. Dairy lactation estimates for 1990 through 2022 are shown in Table A-132. Beef and dairy cow and bull populations are assumed to remain relatively static throughout the year, as large fluctuations in population size are assumed to not occur. These estimates are taken from the USDA beginning and end of year population datasets.

Table A-131: Estimates of Average Monthly Milk Production by Beef Cows (lbs/cow)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Beef Cow Milk Production (lbs/head)	3.3	5.1	8.7	12.0	13.6	13.3	11.7	9.3	6.9	4.4	3.0	2.8

Table A-132: Dairy Lactation Rates by State (lbs/ year/cow)⁹³

State/Year	1990	2000	2005	2010	2018	2019	2020	2021	2022
Alabama	12,214	13,920	14,000	14,182	14,600	12,000	14,667	13,000	10,667
Alaska	13,300	14,500	12,273	11,833	9,333	4,455	5,333	6,111	5,556
Arizona	17,500	21,820	22,679	23,452	23,909	24,096	24,445	24,333	24,223
Arkansas	11,841	12,436	13,545	12,750	12,333	13,400	12,800	12,000	11,250
California	18,456	21,130	21,404	23,025	23,301	23,533	23,990	24,338	24,267
Colorado	17,182	21,618	22,577	23,664	25,892	25,844	26,142	25,985	25,922
Connecticut	15,606	17,778	19,200	19,158	22,474	22,526	23,053	22,895	23,889
Delaware	13,667	14,747	16,622	16,981	19,063	17,976	18,553	17,333	17,815
Florida	14,033	15,688	16,591	18,711	19,833	20,224	20,230	20,093	19,928
Georgia	12,973	16,284	17,259	17,658	21,277	21,598	21,877	21,927	22,043
Hawaii	13,604	14,358	12,889	13,316	16,950	4,455	5,333	6,111	5,556
Idaho	16,475	20,816	22,332	22,647	24,870	25,011	25,174	25,172	25,348
Illinois	14,707	17,450	18,827	18,400	20,867	20,810	21,530	21,585	21,425
Indiana	14,590	16,568	20,295	20,094	22,754	22,899	23,683	23,641	23,726
Iowa	15,118	18,298	20,641	20,676	23,955	24,271	24,651	24,504	24,658
Kansas	12,576	16,923	20,505	20,983	23,321	23,429	23,682	23,831	23,948
Kentucky	10,947	12,841	12,896	14,769	18,345	18,840	19,563	19,739	20,578
Louisiana	11,605	12,034	12,400	11,750	13,818	13,500	13,400	14,000	12,444
Maine	14,619	17,128	18,030	18,344	20,600	21,414	21,963	21,185	21,308
Maryland	13,461	16,083	16,099	18,537	20,556	19,535	20,976	20,857	20,537
Massachusetts	14,871	17,091	17,059	17,286	18,364	19,300	20,000	19,500	20,889
Michigan	15,394	19,017	21,635	23,277	26,409	26,725	27,174	27,102	27,430
Minnesota	14,127	17,777	18,091	19,366	21,784	22,147	22,694	22,859	23,128
Mississippi	12,081	15,028	15,280	13,118	14,333	15,750	16,375	15,143	12,857
Missouri	13,632	14,662	16,026	14,596	14,386	14,103	14,276	14,225	14,045
Montana	13,542	17,789	19,579	20,643	22,833	21,583	21,167	22,091	22,300
Nebraska	13,866	16,513	17,950	19,797	24,000	24,293	24,746	24,534	24,842
Nevada	16,400	19,000	21,680	23,714	22,938	23,091	23,879	25,121	24,813
New Hampshire	15,100	17,333	18,875	19,600	20,750	21,727	21,455	20,636	21,900

⁹³ This table has not been updated for the current (1990 through 2023) Inventory. It will be updated for the next (1990 through 2024) Inventory.

New Jersey	13,538	15,250	16,000	17,500	18,333	20,000	20,200	22,500	21,750
New Mexico	18,815	20,944	21,192	24,551	25,106	25,113	24,755	24,541	24,819
New York	14,658	17,378	18,639	20,807	23,888	24,118	24,435	24,785	25,096
North Carolina	15,220	16,746	18,741	19,682	21,295	21,476	21,829	22,925	23,385
North Dakota	12,624	14,292	14,182	18,286	22,267	21,733	21,867	22,333	22,786
Ohio	13,767	17,027	17,567	19,446	21,359	21,614	22,118	21,946	22,076
Oklahoma	12,327	14,440	16,480	17,125	18,125	17,829	17,452	18,077	18,333
Oregon	16,273	18,222	18,876	20,331	20,577	20,913	20,929	20,976	20,921
Pennsylvania	14,726	18,081	18,722	19,847	20,534	20,629	21,326	21,338	21,259
Rhode Island	14,250	15,667	17,000	17,727	16,429	17,667	21,800	20,200	20,000
South Carolina	12,771	16,087	16,000	17,875	17,286	17,167	18,600	17,889	17,889
South Dakota	12,257	15,516	17,741	20,478	22,364	22,480	23,111	23,090	23,117
Tennessee	11,825	14,789	15,743	16,346	17,135	17,219	18,067	18,143	18,296
Texas	14,350	16,503	19,646	21,375	23,948	24,513	24,966	25,079	25,579
Utah	15,838	17,573	18,875	21,898	23,220	23,061	23,229	23,167	23,323
Vermont	14,528	17,199	18,469	18,537	21,126	21,405	21,336	21,392	21,644
Virginia	14,213	15,833	16,990	18,095	19,699	19,867	20,293	20,151	20,343
Washington	18,532	22,644	23,270	23,514	24,318	24,225	24,346	24,000	24,089
West Virginia	11,250	15,588	14,923	15,700	15,857	15,000	14,833	15,000	15,000
Wisconsin	13,973	17,306	18,500	20,630	24,002	24,123	24,423	24,889	25,064
Wyoming	12,337	13,571	14,878	20,067	23,700	24,433	25,173	25,918	25,763

Source: USDA (2023).

Step 2: Characterize U.S. Cattle Population Diets

To support development of digestible energy (DE, the percent of gross energy intake digested by the animal) and CH₄ conversion rate values (Y_m, the fraction of gross energy converted to CH₄) for each of the cattle population categories, data were collected on diets considered representative of different regions. For both grazing animals (stockers, beef cows, and beef replacement heifers) and animals being fed mixed rations (i.e., feedlot steers and heifers), representative regional diets were estimated using information collected from state livestock specialists, the USDA, expert opinion, and other literature sources. The designated regions for this analysis for dairy cattle for all years and foraging beef cattle from 1990 through 2006 are shown in Table A-133. For foraging beef cattle from 2007 onwards, the regional designations were revised based on data available from the NAHMS 2007 through 2008 survey on cow-calf system management practices (USDA:APHIS:VS 2010) and are shown in Table A-134. The data for each of the diets (e.g., proportions of different feed constituents, such as hay or grains) were used to determine feed chemical composition for use in estimating DE and Y_m for each animal type.

Table A-133: Regions used for Characterizing the Diets of Dairy Cattle (all years) and Foraging Cattle from 1990–2006

West	California	Northern Great Plains	Midwestern	Northeast	Southcentral	Southeast
Alaska	California	Colorado	Illinois	Connecticut	Arkansas	Alabama
Arizona		Kansas	Indiana	Delaware	Louisiana	Florida
Hawaii		Montana	Iowa	Maine	Oklahoma	Georgia
Idaho		Nebraska	Michigan	Maryland	Texas	Kentucky
Nevada		North Dakota	Minnesota	Massachusetts		Mississippi
New Mexico		South Dakota	Missouri	New		North
Oregon		Wyoming	Ohio	Hampshire		Carolina
Utah			Wisconsin	New Jersey		South
Washington				New York		Carolina
				Pennsylvania		Tennessee
				Rhode Island		Virginia
				Vermont		
				West Virginia		

Source: USDA (1996).

Table A-134: Regions used for Characterizing the Diets of Foraging Cattle from 2007–2022

West	Central	Northeast	Southeast
Alaska	Illinois	Connecticut	Alabama
Arizona	Indiana	Delaware	Arkansas
California	Iowa	Maine	Florida
Colorado	Kansas	Maryland	Georgia
Hawaii	Michigan	Massachusetts	Kentucky
Idaho	Minnesota	New Hampshire	Louisiana
Montana	Missouri	New Jersey	Mississippi
Nevada	Nebraska	New York	North Carolina
New Mexico	North Dakota	Pennsylvania	Oklahoma
Oregon	Ohio	Rhode Island	South Carolina
Utah	South Dakota	Vermont	Tennessee
Washington	Wisconsin	West Virginia	Texas
Wyoming			Virginia

Note: States in **bold** represent a change in region from the 1990 to 2006 assessment. Region designations were updated to ensure the most accurate representation of foraging diets within each state for the 2007 to 2020 time period.

Source: Based on data from USDA:APHIS:VS (2010).

DE and Y_m vary by diet and animal type. The IPCC recommends Y_m values of 3.0 ± 1.0 percent for feedlot cattle and 6.5 ± 1.0 percent for all other cattle (IPCC 2006). Given the availability of detailed diet information for different regions and animal types in the United States, DE and Y_m values unique to the United States were developed for dairy and beef cattle. Digestible energy and Y_m values were estimated across the time series for each cattle population category based on physiological modeling, published values, and/or expert opinion.

For dairy cows, ruminant digestion models were used to estimate Y_m . The three major categories of input required by the models are animal description (e.g., cattle type, mature weight), animal performance (e.g., initial and final weight, age at start of period), and feed characteristics (e.g., chemical composition, habitat, grain or forage). Data used to simulate ruminant digestion is provided for a particular animal that is then used to represent a group of animals with similar characteristics. The Y_m values were estimated for 1990 using the Donovan and Baldwin model (Donovan 1999; Donovan and Baldwin 1999), which represents physiological processes in the ruminant animals,

as well as diet characteristics from USDA (1996). The Donovan and Baldwin model (1999) is able to account for differing diets (i.e., grain-based or forage-based), so that Y_m values for the variable feeding characteristics within the U.S. cattle population can be estimated. Subsequently, a literature review of dairy diets was conducted and nearly 250 diets were analyzed from 1990 through 2009 across 23 states—the review indicated highly variable diets, both temporally and spatially. Kebreab et al. (2008) conducted an evaluation of models and found that the COWPOLL model was the best model for estimating Y_m for dairy, so COWPOLL was used to determine the Y_m value associated with each of the evaluated diets. The statistical analysis of the resulting Y_m estimates showed a downward trend in predicting Y_m , which inventory team experts modeled using the following best-fit non-linear curve:

Equation A-22: Best Fit Curve for Estimating the Methane Conversion Rate for Dairy Cattle

$$Y_m = 4.52e^{\left(\frac{1.22}{Year-1980}\right)}$$

The inventory team determined that the most comprehensive approach to estimating annual, region-specific Y_m values was to use the 1990 baseline Y_m values derived from Donovan and Baldwin (1999) and then scale these Y_m values for each year beyond 1990 with a factor based on this function. The scaling factor is the ratio of the Y_m value for the year in question to the 1990 baseline Y_m value. The scaling factor for each year was multiplied by the baseline Y_m value. The resulting Y_m equation (incorporating both Donovan and Baldwin (Donovan and Baldwin 1999) and COWPOLL) is shown below (and described in ERG 2016):

Equation A-23: Scaling Factor for the Dairy Cattle Methane Conversion Rate

$$Y_m = Y_m(1990)EXP\left(\frac{1.22}{(Year-1980)}\right)/EXP\left(\frac{1.22}{(1990-1980)}\right)$$

DE values for dairy cows were estimated from the literature search based on the annual trends observed in the data collection effort. The regional variability observed in the literature search was not statistically significant, and therefore DE was not varied by region, but did vary over time, and was grouped by the following years 1990 through 1993, 1994 through 1998, 1999 through 2003, 2004 through 2006, 2007, and 2008 onwards.

Considerably less data was available for dairy heifers and dairy calves. Therefore, for dairy heifers assumptions were based on the relationship of the collected data in the literature on dairy heifers to the data on dairy cow diets. From this relationship, DE was estimated as the mature cow DE minus three percent, and Y_m was estimated as that of the mature dairy cow plus 0.1 percent.

To calculate the DE values for grazing beef cattle, diet composition assumptions were used to estimate weighted DE values for a combination of forage and supplemental diets. The forage portion makes up an estimated 85 to 95 percent of grazing beef cattle diets, and there is considerable variation of both forage type and quality across the United States. Currently there is no comprehensive survey of this data, so for this analysis two regional DE values were developed to account for the generally lower forage quality in the “West” region of the United States versus all other regions in Table A-133 (California, Northern Great Plains, Midwestern, Northeast, Southcentral, Southeast) and Table A-134 (Central, Northeast, and Southeast). For all non-western grazing cattle, the forage DE was an average of the estimated seasonal values for grass pasture diets for a calculated DE of 64.2 percent. For foraging cattle in the west, the forage DE was calculated as the seasonal average for grass pasture, meadow and range diets, for a calculated DE of 61.3 percent. The assumed specific components of each of the broad forage types, along with their corresponding DE value and the calculated regional DE values can be found in Table A-135. In addition, beef cattle are assumed to be fed a supplemental diet, consequently, two sets of supplemental diets were developed, one for 1990 through 2006 (Donovan 1999) and one for 2007 onwards (Preston 2010; Archibeque 2011; USDA:APHIS:VS 2010) as shown in Table A-136 and Table A-137 along with the percent of each total diet that is assumed to be made up of the supplemental portion. By weighting the calculated DE values from the forage and

supplemental diets, the DE values for the composite diet were calculated.⁹⁴ These values are used for steer and heifer stockers and beef replacements. Finally, for mature beef cows and bulls, the DE value was adjusted downward by two percent to reflect the lower digestibility diets of mature cattle based on Johnson (2002). Y_m values for all grazing beef cattle were set at 6.5 percent based on Johnson (2002). The Y_m values and the resulting final weighted DE values by region for 2007 onwards are shown in Table A-138.

For feedlot animals, DE and Y_m are adjusted over time as diet compositions in actual feedlots are adjusted based on new and improved nutritional information and availability of feed types. Feedlot diets are assumed to not differ significantly by state, and therefore only a single set of national diet values is utilized for each year. The DE and Y_m values for 1990 were estimated by Dr. Don Johnson (1999). In the CEFM, the DE values for 1991 through 1999 were linearly extrapolated based on values for 1990 and 2000. DE and Y_m values from 2000 through the current year were estimated using the MOLLY model as described in Kebreab et al. (2008), based on a series of average diet feed compositions from Galyean and Gleghorn (2001) for 2000 through 2006 and Vasconcelos and Galyean (2007) for 2007 onwards. In addition, feedlot animals are assumed to spend the first 25 days in the feedlot on a “step-up” diet to become accustomed to the higher quality feedlot diets. The step-up DE and Y_m are calculated as the average of all state forage and feedlot diet DE and Y_m values.

For calves aged 4 through 6 months, a gradual weaning from milk is simulated, with calf diets at 4 months assumed to be 25 percent forage, increasing to 50 percent forage at age 5 months, and 75 percent forage at age 6 months. The portion of the diet allocated to milk results in zero emissions, as recommended by the IPCC (2006). For calves, the DE for the remainder of the diet is assumed to be similar to that of slightly older replacement heifers (both beef and dairy are calculated separately). The Y_m for beef calves is also assumed to be similar to that of beef replacement heifers (6.5 percent), as literature does not provide an alternative Y_m for use in beef calves. For dairy calves, the Y_m is assumed to be 7.8 percent at 4 months, 8.03 percent at 5 months, and 8.27 percent at 6 months based on estimates provided by Soliva (2006) for Y_m at 4 and 7 months of age and a linear interpolation for 5 and 6 months.

Table A-139 shows the regional DE and Y_m for U.S. cattle in each region for 2022.

Table A-135: Feed Components and Digestible Energy Values Incorporated into Forage Diet Composition Estimates

Forage Type	DE (% of GE)	Grass pasture - June	Grass pasture - July	Grass pasture - Fall	Range June	Range July	Range August	Range September	Range Winter	Meadow - Spring	Meadow - Fall
Bahiagrass Paspalum notatum, fresh	61.38			x							
Bermudagrass Cynodon dactylon, fresh	66.29		x								
Bremudagrass, Coastal Cynodon dactylon, fresh	65.53		x								
Bluegrass, Canada Poa compressa, fresh, early vegetative	73.99	x									
Bluegrass, Kentucky Poa pratensis, fresh, early vegetative	75.62	x									
Bluegrass, Kentucky Poa pratensis, fresh, mature	59.00		x	x							
Bluestem Andropogon spp, fresh, early vegetative	73.17				x						

⁹⁴ For example, the West has a forage DE of 61.3 which makes up 90 percent of the diet and a supplemented diet DE of 67.4 percent was used for 10 percent of the diet, for a total weighted DE of 61.9 percent, as shown in Table A-138.

Forage Type	DE (% of GE)	Grass pasture - June	Grass pasture - July	Grass pasture - August	Grass pasture - September	Grass pasture - October	Grass pasture - November	Grass pasture - December	Grass pasture - January	Grass pasture - February	Grass pasture - March	Grass pasture - April	Grass pasture - May
Bluestem Andropogon spp, fresh, mature	56.82			x	x	x	x						x
Brome Bromus spp, fresh, early vegetative	78.57	x											
Brome, Smooth Bromus inermis, fresh, early vegetative	75.71	x											
Brome, Smooth Bromus inermis, fresh, mature	57.58		x		x								
Buffalograss, Buchloe dactyloides, fresh	64.02												
Clover, Alsike Trifolium hybridum, fresh, early vegetative	70.62	x											
Clover, Ladino Trifolium repens, fresh, early vegetative	73.22	x											
Clover, Red Trifolium pratense, fresh, early bloom	71.27	x											
Clover, Red Trifolium pratense, fresh, full bloom	67.44		x										
Corn, Dent Yellow Zea mays indentata, aerial part without ears, without husks, sun-cured, (stover)(straw)	55.28												
Dropseed, Sand Sporobolus cryptandrus, fresh, stem cured	64.69												
Fescue Festuca spp, hay, sun-cured, early vegetative	67.39	x											
Fescue Festuca spp, hay, sun-cured, early bloom	53.57												
Grama Bouteloua spp, fresh, early vegetative	67.02	x											
Grama Bouteloua spp, fresh, mature	63.38		x		x								
Millet, Foxtail Setaria italica, fresh	68.20	x											
Napiergrass Pennisetum purpureum, fresh, late bloom	57.24		x		x								
Needleandthread Stipa comata, fresh, stem cured	60.36												
Orchardgrass Dactylis glomerata, fresh, early vegetative	75.54	x											
Orchardgrass Dactylis glomerata, fresh, midbloom	60.13		x										
Pearlmillet Pennisetum glaucum, fresh	68.04	x											
Prairie plants, Midwest, hay, sun-cured	55.53												
Rape Brassica napus, fresh, early bloom	80.88	x											

Forage Type	DE (% of GE)	Grass pasture - June	Grass pasture - July	Grass pasture - August	Grass pasture - September	Grass pasture - October	Grass pasture - November	Grass pasture - December	Grass pasture - January	Grass pasture - February	Grass pasture - March
Rye Secale cereale, fresh	71.83	x									
Ryegrass, Perennial Lolium perenne, fresh	73.68	x									
Saltgrass Distichlis spp, fresh, post ripe	58.06			x	x						
Sorghum, Sudangrass Sorghum bicolor sudanense, fresh, early vegetative	73.27	x									
Squirreltail Stanion spp, fresh, stem-cured	62.00		x				x				
Summercypress, Gray Kochia vestita, fresh, stem-cured	65.11				x	x	x				
Timothy Phleum pratense, fresh, late vegetative	73.12	x									
Timothy Phleum pratense, fresh, midbloom	66.87		x								
Trefoil, Birdsfoot Lotus corniculatus, fresh	69.07	x									
Vetch Vicia spp, hay, sun-cured	59.44				x						
Wheat Triticum aestivum, straw	45.77				x						
Wheatgrass, Crested Agropyron desertorum, fresh, early vegetative	79.78	x									
Wheatgrass, Crested Agropyron desertorum, fresh, full bloom	65.89		x			x					
Wheatgrass, Crested Agropyron desertorum, fresh, post ripe	52.99				x				x		x
Winterfat, Common Eurotia lanata, fresh, stem-cured	40.89								x		
Weighted Average DE		72.99	62.45	57.26	1	62.70	2	58.59	7	3	55.11
Forage Diet for West	61.3	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Forage Diet for All Other Regions	64.2	33.3%	33.3%	33.3%	-	-	-	-	-	-	-

Note: Forages marked with an x indicate that the DE from that specific forage type is included in the general forage type for that column (e.g., grass pasture, range, meadow or meadow by month or season).

Sources: Preston (2010) and Archibeque (2011).

Table A-136: DE Values with Representative Regional Diets for the Supplemental Diet of Grazing Beef Cattle for 1990–2006

Feed	Source of DE (NRC 1984)	Unweighted DE (% of GE)	California ^a	West	Northern Great Plains	Southcentral	Northeast	Midwest	Southeast
Alfalfa Hay	Table 8, feed #006	61.79	65%	30%	30%	29%	12%	30%	
Barley		85.08	10%	15%					
Bermuda	Table 8, feed	66.29							35%

	#030							
Bermuda Hay	Table 8, feed #031	50.79				40%		
Corn	Table 8, feed #089	88.85	10%	10%	25%	11%	13%	13%
Corn Silage	Table 8, feed #095	72.88			25%		20%	20%
Cotton Seed Meal						7%		
Grass Hay	Table 8, feed #126, 170, 274	58.37		40%				30%
Orchard Soybean Meal Supplement	Table 8, feed #147	60.13						40%
		77.15		5%	5%			5%
Sorghum	Table 8, feed #211	84.23						20%
Soybean Hulls		66.86						7%
Timothy Hay	Table 8, feed #244	60.51					50%	
Whole Cotton Seed		75.75	5%				5%	
Wheat Middlings	Table 8, feed #257	68.09			15%	13%		
Wheat	Table 8, feed #259	87.95	10%					
Weighted Supplement DE (%)			70.1	67.4	73.0	62.0	67.6	66.9
Percent of Diet that is Supplement			5%	10%	15%	10%	15%	10%
							5%	

^a Emissions are currently calculated on a state-by-state basis, but diets are applied by the regions shown in the table above. Source of representative regional diets: Donovan (1999).

Table A-137: DE Values and Representative Regional Diets for the Supplemental Diet of Grazing Beef Cattle for 2007–2022⁹⁵

Feed	Source of DE (NRC1984)	Unweighted DE (% of GE)	West ^a	Central ^a	Northeast ^a	Southeast ^a
Alfalfa Hay	Table 8, feed #006	61.79	65%	30%	12%	
Bermuda	Table 8, feed #030	66.29				20%
Bermuda Hay	Table 8, feed #031	50.79				20%
Corn	Table 8, feed #089	88.85	10%	15%	13%	10%
Corn Silage	Table 8, feed #095	72.88		35%	20%	
Grass Hay	Table 8, feed #126, 170, 274	58.37	10%			
Orchard	Table 8, feed #147	60.13				30%

⁹⁵ This table has not been updated for the current (1990 through 2023) Inventory. It will be updated for the next (1990 through 2024) Inventory.

Protein supplement (West)	Table 8, feed #082, 134, 225 ^b	81.01	10%		
Protein Supplement (Central and Northeast)	Table 8, feed #082, 134, 225 ^b	80.76		10%	10%
Protein Supplement (Southeast)	Table 8, feed #082, 134, 101 ^b	77.89			10%
Sorghum	Table 8, feed #211	84.23		5%	10%
Timothy Hay	Table 8, feed #244	60.51			45%
Wheat Middlings	Table 8, feed #257	68.09		5%	
Wheat	Table 8, feed #259	87.95	5%		
Weighted Supplement					
DE		67.4	73.1	68.9	66.6
Percent of Diet that is Supplement		10%	15%	5%	15%

^a Note that emissions are currently calculated on a state-by-state basis, but diets are applied by the regions shown in the table above.

^b Not in equal proportions.

Sources of representative regional diets: Donovan (1999), Preston (2010), Archibeque (2011), and USDA:APHIS:VS (2010).

Table A-138: Foraging Animal DE (% of GE) and Y_m Values for Each Region and Animal Type for 2007–2022⁹⁶

Animal Type	Data	West ^a	Central	Northeast	Southeast
Beef Repl. Heifers	DE ^b	61.9	65.6	64.5	64.6
	Y _m ^c	6.5%	6.5%	6.5%	6.5%
Beef Calves (4–6 mo)	DE	61.9	65.6	64.5	64.6
	Y _m	6.5%	6.5%	6.5%	6.5%
Steer Stockers	DE	61.9	65.6	64.5	64.6
	Y _m	6.5%	6.5%	6.5%	6.5%
Heifer Stockers	DE	61.9	65.6	64.5	64.6
	Y _m	6.5%	6.5%	6.5%	6.5%
Beef Cows	DE	59.9	63.6	62.5	62.6
	Y _m	6.5%	6.5%	6.5%	6.5%
Bulls	DE	59.9	63.6	62.5	62.6
	Y _m	6.5%	6.5%	6.5%	6.5%

^a Note that emissions are currently calculated on a state-by-state basis, but diets are applied by the regions shown in the table above. To see the regional designation per state, please see Table A-134.

^b DE is the digestible energy in units of percent of GE (MJ/Day).

^c Y_m is the methane conversion rate, the fraction of GE in feed converted to methane.

⁹⁶ This table has not been updated for the current (1990 through 2023) Inventory. It will be updated for the next (1990 through 2024) Inventory.

Table A-139: Regional DE (% of GE) and Y_m Rates for Dairy and Feedlot Cattle by Animal Type for 2022⁹⁷

Animal Type	Data	Northern Great Plains Southcentral Northeast Midwest Southeast						
		California ^a	West	Plains	Southcentral	Northeast	Midwest	Southeast
Dairy Repl. Heifers	DE ^b	63.7	63.7	63.7	63.7	63.7	63.7	63.7
	Y _m ^c	5.5%	5.5%	5.2%	5.9%	5.8%	5.2%	6.4%
Dairy Calves (4–6 mo)	DE	63.7	63.7	63.7	63.7	63.7	63.7	63.7
	Y _m	8.0%	8.0%	8.0%	8.0%	8.0%	8.0%	8.0%
Dairy Cows	DE	66.7	66.7	66.7	66.7	66.7	66.7	66.7
	Y _m	5.4%	5.4%	5.1%	5.8%	5.7%	5.1%	6.3%
Steer Feedlot	DE	82.5	82.5	82.5	82.5	82.5	82.5	82.5
	Y _m	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%
Heifer Feedlot	DE	82.5	82.5	82.5	82.5	82.5	82.5	82.5
	Y _m	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%

^aEmissions are currently calculated on a state-by-state basis, but diets are applied in Table A-133 by the regions shown in the table above. To see the regional designation for foraging cattle per state, please see Table A-133.

^b DE is the digestible energy in units of percent of GE (MJ/Day).

^c Y_m is the methane conversion rate, the fraction of GE in feed converted to methane.

Step 3: Estimate CH₄ Emissions from Cattle

Emissions by state were estimated in three steps: a) determine gross energy (GE) intake using the Tier 2 IPCC (2006) equations, b) determine an emission factor using the GE values, Y_m and a conversion factor, and c) sum the daily emissions for each animal type. Finally, the state emissions were aggregated to obtain the national emissions estimate. The necessary data values for each state and animal type include:

- Body Weight (kg)
- Weight Gain (kg/day)
- Net Energy for Activity (C_a, MJ/day)⁹⁸
- Standard Reference Weight (kg)⁹⁹
- Milk Production (kg/day)
- Milk Fat (percent of fat in milk)¹⁰⁰
- Pregnancy (percent of population that is pregnant)
- DE (percent of GE intake digestible)
- Y_m (the fraction of GE converted to CH₄)
- Population

⁹⁷ This table has not been updated for the current (1990 through 2023) *Inventory*. It will be updated for the next (1990 through 2024) *Inventory*.

⁹⁸ Zero for feedlot conditions, 0.17 for high quality confined pasture conditions, and 0.36 for extensive open range or hilly terrain grazing conditions. C_a factor for dairy cows is weighted to account for the fraction of the population in the region that grazes during the year (IPCC 2006).

⁹⁹ Standard Reference Weight is the mature weight of a female animal of the animal type being estimated, used in the model to account for breed potential.

¹⁰⁰ Average milk fat varies by year and is derived from USDA's Economic Research Service Dairy Data set (USDA 2023b).

Step 3a: Determine Gross Energy, GE

As shown in the following equation, GE is derived based on the net energy estimates and the feed characteristics. Only variables relevant to each animal category are used (e.g., estimates for feedlot animals do not require the NE_l factor). All net energy equations are provided in IPCC (2006). Calculated GE values for 2022 are shown by state and animal type in Table A-140.

Equation A-24: Gross Energy Calculation for Enteric Fermentation

$$GE = \left[\frac{\left(\frac{NE_m + NE_a + NE_l + NE_{work} + NE_p}{REM} \right) + \left(\frac{NE_g}{REG} \right)}{\frac{DE\%}{100}} \right]$$

where,

- GE = Gross energy (MJ/day)
- NE_m = Net energy required by the animal for maintenance (MJ/day)
- NE_a = Net energy for animal activity (MJ/day)
- NE_l = Net energy for lactation (MJ/day)
- NE_{work} = Net energy for work (MJ/day)
- NE_p = Net energy required for pregnancy (MJ/day)
- REM = Ratio of net energy available in a diet for maintenance to digestible energy consumed
- NE_g = Net energy needed for growth (MJ/day)
- REG = Ratio of net energy available for growth in a diet to digestible energy consumed
- DE = Digestible energy expressed as a percent of gross energy (percent)

Table A-140: Calculated Annual GE by Animal Type and State, for 2022 (1,000 GJ) ¹⁰¹

State	Dairy		Dairy Replace- ment	Dairy Replace- ment	Bulls	Beef		Beef Replace- ment	Beef Replace- ment	Steer Stockers	Heifer Stockers	Feedlot
	Calves	Cows	Heifers 7- 11 Months	Heifers 12- 23 Months		Calves	Cows	Heifers 7- 11 Months	Heifers 12- 23 Months			
Alabama	13	315	27	97	3,583	3,076	54,157	1,254	3,584	1,071	1,178	339
Alaska	1	12	1	5	400	39	671	19	53	12	10	3
Arizona	867	30,365	1,600	5,817	1,779	845	14,712	313	890	7,115	635	13,234
Arkansas	22	523	40	145	4,582	4,142	72,935	1,568	4,480	2,621	1,696	654
California	7,684	267,756	10,132	36,838	5,336	3,360	58,503	1,441	4,095	15,702	5,711	26,806
Colorado	902	32,997	1,533	5,574	4,002	3,152	54,890	1,691	4,807	19,628	14,975	56,027
Conn.	83	2,871	127	460	42	21	364	23	67	23	35	9
Delaware	13	366	16	58	25	8	137	7	20	62	7	10
Florida	469	14,928	400	1,454	4,582	4,096	72,129	1,452	4,148	570	589	175
Georgia	371	12,507	333	1,212	2,499	2,229	39,248	1,161	3,318	912	589	227
Hawaii	4	47	13	48	356	391	6,814	138	392	221	127	49
Idaho	2,913	104,999	4,666	16,965	3,558	2,460	42,845	1,190	3,383	7,851	5,711	15,456
Illinois	362	11,766	547	1,987	1,466	1,512	26,709	622	1,781	4,356	2,067	10,143
Indiana	831	28,740	800	2,908	1,303	820	14,497	396	1,134	2,134	1,033	5,071
Iowa	1,005	35,610	1,600	5,817	4,887	4,035	71,302	1,811	5,182	28,673	13,547	56,510
Kansas	755	26,265	2,133	7,755	6,923	6,336	111,956	3,055	8,745	45,343	39,264	126,060
Kentucky	197	6,371	467	1,696	4,999	4,421	77,851	1,452	4,148	5,015	2,591	869
Louisiana	40	984	40	145	2,499	2,064	36,346	929	2,655	524	448	147
Maine	116	3,765	173	630	125	46	808	47	133	103	71	26
Maryland	183	5,809	347	1,260	292	193	3,394	105	300	286	142	386
Mass.	42	1,360	73	267	84	37	647	35	100	57	24	12
Michigan	1,939	73,527	2,026	7,368	1,222	428	7,564	260	745	3,845	1,033	7,728
Minn.	2,055	69,972	2,800	10,179	2,443	1,605	28,363	962	2,753	10,891	3,329	18,354
Miss.	31	796	67	242	3,249	2,188	38,522	1,057	3,020	1,185	895	315
Missouri	308	7,975	400	1,454	8,959	8,655	152,925	3,395	9,717	9,335	5,281	3,864
Montana	49	1,637	53	194	8,449	6,418	111,758	4,009	11,394	5,152	4,721	2,077
Nebraska	259	9,222	400	1,454	8,959	8,035	141,974	3,961	11,337	56,679	36,279	136,202
Nevada	138	4,926	120	436	1,156	1,205	20,992	476	1,353	859	711	145

¹⁰¹ This table has not been updated for the current (1990 through 2023) *Inventory*. It will be updated for the next (1990 through 2024) *Inventory*.

State	Dairy		Dairy Replace- ment	Dairy Replace- ment	Bulls	Beef		Beef Replace- ment	Beef Replace- ment	Steer Stockers	Heifer Stockers	Feedlot
	Dairy Calves	Dairy Cows	Heifers 7- 11 Months	Heifers 12- 23 Months		Beef Calves	Beef Cows	Heifers 7- 11 Months	Heifers 12- 23 Months			
N. Hamp.	47	1,545	80	291	42	18	323	14	40	34	19	8
N. Jersey	19	616	37	136	58	36	630	17	50	50	28	12
N. Mexico	1,305	46,404	1,666	6,059	2,224	2,238	38,973	877	2,493	2,454	1,777	594
New York	2,770	99,219	4,399	15,995	1,671	459	8,082	466	1,331	1,029	945	1,063
N. Car.	174	6,087	187	679	2,583	1,652	29,093	720	2,057	957	612	238
N. Dakota	67	2,261	107	388	4,887	4,169	73,666	2,060	5,895	6,890	5,281	1,884
Ohio	1,108	36,675	1,600	5,817	2,443	1,391	24,582	736	2,105	4,890	1,378	7,245
Oklahoma	174	5,190	267	969	14,163	9,708	170,933	4,645	13,273	23,022	12,720	15,214
Oregon	558	17,904	733	2,666	3,558	2,495	43,447	1,253	3,561	4,171	3,046	6,279
Penn.	2,100	67,959	2,600	9,452	1,671	872	15,355	594	1,697	3,201	1,158	3,381
R. Island	2	70	7	24	8	5	89	2	7	7	5	2
S. Car.	40	1,206	67	242	1,000	723	12,733	337	962	251	212	70
S. Dakota	760	25,851	533	1,939	8,552	7,134	126,059	4,187	11,984	16,670	11,366	21,493
Tenn.	121	3,661	267	969	4,999	4,087	71,968	1,394	3,982	3,077	2,002	769
Texas	2,792	101,386	3,199	11,633	27,494	20,253	356,615	8,245	23,560	59,949	39,808	141,515
Utah	424	14,525	733	2,666	2,046	1,630	28,391	877	2,493	2,208	1,523	1,014
Vermont	536	17,537	693	2,520	251	69	1,212	52	150	114	154	40
Virginia	317	10,213	467	1,696	3,166	2,742	48,274	1,034	2,953	3,396	1,625	821
Wash.	1,166	40,710	1,733	6,301	1,601	1,107	19,272	689	1,958	4,662	3,300	10,626
W. Virg.	22	597	27	97	1,170	863	15,193	350	998	892	520	193
Wisconsin	5,696	203,876	8,799	31,991	2,443	1,315	23,242	962	2,753	8,891	1,952	13,041
Wyoming	40	1,464	67	242	3,113	3,365	58,589	1,817	5,163	3,926	3,426	3,333

Step 3b: Determine Emission Factor

The daily emission factor (DayEmit) was determined using the GE value and the methane conversion factor (Y_m) for each category. This relationship is shown in the following equation:

Equation A-25: Daily Emission Factor for Enteric Fermentation Based on Gross Energy Intake and Methane Conversion Factor

$$\text{DayEmit} = \frac{GE \times Y_m}{55.65}$$

where,

- DayEmit = Emission factor (kg CH₄/head/day)
- GE = Gross energy intake (MJ/head/day)
- Y_m = CH₄ conversion rate, which is the fraction of GE in feed converted to CH₄ (%)
- 55.65 = A factor for the energy content of methane (MJ/kg CH₄)

The daily emission factors were estimated for each animal type and state. Calculated annual national emission factors are shown by animal type in Table A-141. State-level emission factors are shown by animal type for 2022 in Table A-142.

Table A-141: Calculated Annual National Enteric Fermentation Emission Factors for Cattle by Animal Type (kg CH₄/head/year)¹⁰²

Cattle Type	1990	1995	2000	2005	2010	2018	2019	2020	2021	2022
Dairy										
Calves	12	12	12	12	12	12	12	12	12	12
Cows	121	122	129	130	138	147	148	150	151	151
Replacements 7–11 months	48	46	46	45	46	46	45	45	45	45
Replacements 12–23 months	73	69	70	67	69	69	69	69	69	68
Beef										
Calves	11	11	11	11	11	11	11	11	11	11
Bulls	91	94	94	97	98	98	98	98	98	98
Cows	88	91	90	93	94	94	94	95	95	95
Replacements 7–11 months	54	57	56	59	60	60	60	60	60	60
Replacements 12–23 months	63	66	66	68	70	70	70	70	70	70
Steer Stockers	55	57	58	58	58	58	58	58	58	58
Heifer Stockers	52	56	60	60	60	60	60	60	60	60
Feedlot Cattle	39	38	39	39	42	43	43	43	44	44

Note: To convert to a daily emission factor, the yearly emission factor can be divided by 365 (the number of days in a year).

¹⁰² This table has not been updated for the current (1990 through 2023) *Inventory*. It will be updated for the next (1990 through 2024) *Inventory*.

Table A-142: Enteric Fermentation Emission Factors for Cattle by Animal Type and State, for 2022 (kg CH₄/head/year)¹⁰³

State	Dairy Calves	Dairy Cows	Dairy Replacement Heifers 7-11 Months	Dairy Replacement Heifers 12-23 Months	Bulls	Beef Calves	Beef Cows	Beef Replacement Heifers 7-11 Months	Beef Replacement Heifers 12-23 Months	Steer Stockers	Heifer Stockers	Feedlot
Alabama	12	119	53	80	97	11	94	60	69	58	60	33
Alaska	12	57	45	69	104	11	100	65	74	62	65	32
Arizona	12	152	45	69	104	11	100	65	74	62	65	34
Arkansas	12	109	49	74	97	11	94	60	69	58	60	32
California	12	151	45	69	104	11	100	65	74	62	65	33
Colorado	12	150	43	65	104	11	100	65	74	62	65	34
Conn.	12	160	48	73	98	11	94	60	69	58	60	33
Delaware	12	134	48	73	98	11	94	60	69	58	60	34
Florida	12	161	53	80	97	11	94	60	69	58	60	31
Georgia	12	170	53	80	97	11	94	60	69	58	60	33
Hawaii	12	57	45	69	104	11	100	65	74	62	65	32
Idaho	12	156	45	69	104	11	100	65	74	62	65	34
Illinois	12	133	43	65	95	10	92	58	68	56	58	33
Indiana	12	142	43	65	95	10	92	58	68	56	58	33
Iowa	12	145	43	65	95	10	92	58	68	56	58	33
Kansas	12	143	43	65	95	10	92	58	68	56	58	33
Kentucky	12	164	53	80	97	11	94	60	69	58	60	33
Louisiana	12	114	49	74	97	11	94	60	69	58	60	32
Maine	12	149	48	73	98	11	94	60	69	58	60	32
Maryland	12	146	48	73	98	11	94	60	69	58	60	34
Mass.	12	147	48	73	98	11	94	60	69	58	60	34
Michigan	12	156	43	65	95	10	92	58	68	56	58	33
Minn.	12	140	43	65	95	10	92	58	68	56	58	33
Miss.	12	128	53	80	97	11	94	60	69	58	60	32
Missouri	12	106	43	65	95	10	92	58	68	56	58	32
Montana	12	137	43	65	104	11	100	65	74	62	65	32
Nebraska	12	146	43	65	95	10	92	58	68	56	58	34
Nevada	12	154	45	69	104	11	100	65	74	62	65	33
N. Hamp.	12	151	48	73	98	11	94	60	69	58	60	33

¹⁰³ This table has not been updated for the current (1990 through 2023) *Inventory*. It will be updated for the next (1990 through 2024) *Inventory*.

N. Jersey	12	151	48	73	98	11	94	60	69	58	60	34
N. Mexico	12	154	45	69	104	11	100	65	74	62	65	33
New York	12	165	48	73	98	11	94	60	69	58	60	33
N. Car.	12	176	53	80	97	11	94	60	69	58	60	33
N. Dakota	12	138	43	65	95	10	92	58	68	56	58	32
Ohio	12	136	43	65	95	10	92	58	68	56	58	33
Oklahoma	12	139	49	74	97	11	94	60	69	58	60	33
Oregon	12	139	45	69	104	11	100	65	74	62	65	35
Penn.	12	149	48	73	98	11	94	60	69	58	60	33
R. Island	12	143	48	73	98	11	94	60	69	58	60	33
S. Car.	12	151	53	80	97	11	94	60	69	58	60	32
S. Dakota	12	140	43	65	95	10	92	58	68	56	58	33
Tenn.	12	153	53	80	97	11	94	60	69	58	60	33
Texas	12	169	49	74	97	11	94	60	69	58	60	34
Utah	12	148	45	69	104	11	100	65	74	62	65	33
Vermont	12	150	48	73	98	11	94	60	69	58	60	34
Virginia	12	163	53	80	97	11	94	60	69	58	60	34
Wash.	12	151	45	69	104	11	100	65	74	62	65	33
W. Virg.	12	123	48	73	98	11	94	60	69	58	60	32
Wisconsin	12	147	43	65	95	10	92	58	68	56	58	34
Wyoming	12	149	43	65	104	11	100	65	74	62	65	33

Note: To convert to a daily emission factor, the yearly emission factor can be divided by 365 (the number of days in a year).

For quality assurance purposes, U.S. emission factors for each animal type were compared to estimates available in national inventory reports from other developed countries (the most recently available summarized results for developed countries are through 2012 only). Results, presented in Table A-143, indicate that U.S. emission factors are comparable to those of other developed countries. Results in Table A-143 are presented along with default Tier 1 emission factors provided by IPCC (2006). Throughout the time series, average beef cattle enteric CH₄ per head is higher than other countries, while dairy cattle enteric CH₄ per head is comparable.

Table A-143: Comparison of Implied Enteric Fermentation Emission Factors for Cattle by Year (kg CH₄/head/year)^{104, 105}

Year	Dairy Cattle		Beef Cattle	
	United States Implied Emission Factor	Mean of Implied Emission Factors from other developed countries (excluding U.S.)	United States Implied Emission Factor	Mean of Implied Emission Factors from other developed countries (excluding U.S.)
1990	105	96	71	53
1991	105	97	71	53
1992	105	96	72	54
1993	104	97	72	54
1994	104	98	72	54
1995	104	98	72	54
1996	104	99	72	54
1997	104	100	72	54
1998	104	101	73	55
1999	108	102	72	55
2000	109	103	72	55
2001	108	104	72	55
2002	109	105	72	55
2003	109	106	73	55
2004	107	107	74	55
2005	108	109	74	55
2006	108	110	74	55
2007	112	111	74	55
2008	112	112	75	55
2009	112	112	75	56
2010	113	113	74	55
2011	113	113	74	55
2012	115	112	74	51
2013	115	NA	74	NA
2014	116	NA	74	NA
2015	115	NA	74	NA
2016	116	NA	74	NA
2017	117	NA	74	NA
2018	118	NA	74	NA
2019	119	NA	74	NA
2020	120	NA	74	NA
2021	122	NA	74	NA
2022	123	NA	74	NA

¹⁰⁴ Excluding calves.

¹⁰⁵ This table has not been updated for the current (1990 through 2023) *Inventory*. It will be updated for the next (1990 through 2024) *Inventory*.

Tier 1 EFs For North America, from IPCC (2006)	121	53
NA (Not Applicable)		

Step 3c: Estimate Total Emissions

Emissions were summed for each month and for each state population category using the daily emission factor for a representative animal and the number of animals in the category. The following equation was used:

Equation A-26: Total Enteric Fermentation Emissions Calculated from Daily Emissions Rate and Population

$$\text{Emissions}_{\text{state}} = \text{DayEmit}_{\text{state}} \times \text{Days/Month} \times \text{SubPop}_{\text{state}}$$

where,

$\text{Emissions}_{\text{state}}$ = Emissions for state during the month (kg CH₄)

$\text{DayEmit}_{\text{state}}$ = Emission factor for the subcategory and state (kg CH₄/head/day)

Days/Month = Number of days in the month

$\text{SubPop}_{\text{state}}$ = Number of animals in the subcategory and state during the month

This process was repeated for each month, and the monthly totals for each state subcategory were summed to achieve an emission estimate for a state for the entire year and state estimates were summed to obtain the national total. The estimates for each of the 10 subcategories of cattle are listed in Table A-144 (in kt) and Table A-145 (in MMT CO₂ Eq.). The emissions for each subcategory were then aggregated to estimate total emissions from beef cattle and dairy cattle for the entire year.

Table A-144: Enteric Fermentation CH₄ Emissions from Cattle (kt)

Cattle Type	1990	1995	2000	2005	2010	2019	2020	2021	2022	2023
Dairy	1,547	1,471	1,492	1,473	1,594	1,732	1,743	1,764	1,748	1,740
Calves (4–6 months)	62	59	59	54	57	59	59	60	60	58
Cows	1,214	1,156	1,182	1,167	1,253	1,383	1,398	1,424	1,417	1,421
Replacements 7–11 months	58	56	55	56	62	63	62	60	58	56
Replacements 12–23 months	212	201	196	196	222	227	225	221	212	205
Beef	4,742	5,396	5,050	4,986	4,963	5,062	5,018	5,010	4,891	4,704
Calves (4–6 months)	182	193	186	179	169	168	167	165	161	158
Bulls	196	225	215	214	215	221	219	217	207	199
Cows	2,862	3,199	3,037	3,035	2,955	2,994	2,963	2,919	2,383	2,739
Replacements 7–11 months	69	85	74	80	75	83	82	80	75	70
Replacements 12–23 months	188	241	204	217	213	232	227	227	214	199
Steer Stockers	563	662	509	473	476	449	440	445	445	428
Heifer Stockers	306	375	323	299	302	271	269	278	275	265
Feedlot Cattle	375	416	502	488	560	644	649	679	676	647
Total	6,289	6,866	6,541	6,460	6,557	6,794	6,761	6,774	6,639	6,444

Note: Totals may not sum due to independent rounding.

Table A-145: Enteric Fermentation CH₄ Emissions from Cattle (MMT CO₂ Eq.)

Cattle Type	1990	1995	2000	2005	2010	2019	2020	2021	2022	2023
Dairy	43.3	41.2	41.8	41.3	44.6	48.5	48.8	49.4	48.9	48.7
Calves (4–6 months)	1.7	1.6	1.6	1.5	1.6	1.7	1.7	1.7	1.7	1.6
Cows	34.0	32.4	33.1	32.7	35.1	38.7	39.1	39.9	39.7	39.8
Replacements 7–11 months	1.6	1.6	1.5	1.6	1.7	1.8	1.7	1.7	1.6	1.6
Replacements 12–23 months	5.9	5.6	5.5	5.5	6.2	6.3	6.3	6.2	5.9	5.7
Beef	132.8	151.1	141.4	139.6	139.0	141.7	140.5	140.3	137.0	131.7
Calves (4–6 months)	5.1	5.4	5.2	5.0	4.7	4.7	4.7	4.6	4.5	4.4
Bulls	5.5	6.3	6.0	6.0	6.0	6.2	6.1	6.1	5.8	5.6
Cows	80.1	89.6	85.0	85.0	82.8	83.8	83.0	81.7	79.5	76.7
Replacements 7–11 months	1.9	2.4	2.1	2.3	2.1	2.3	2.3	2.2	2.1	2.0
Replacements 12–23 months	5.3	6.7	5.7	6.1	6.0	6.5	6.4	6.4	6.0	5.6
Steer Stockers	15.8	18.5	14.2	13.2	13.3	12.6	12.3	12.5	12.5	12.0
Heifer Stockers	8.6	10.5	9.1	8.4	8.4	7.6	7.5	7.8	7.7	7.4
Feedlot Cattle	10.5	11.6	14.0	13.7	15.7	18.0	18.2	19.0	18.9	18.1
Total	176.1	192.3	183.2	180.9	183.6	190.2	189.3	189.7	185.9	180.4

Note: Totals may not sum due to independent rounding.

Emission Estimates from Other Livestock

“Other livestock” include horses, sheep, swine, goats, American bison, and mules and asses. All livestock population data, except for American bison for years prior to 2002, were taken from the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) agricultural statistics database (USDA 2024) or the Census of Agriculture (USDA 2019). The Manure Management Annex 3.12 discusses the methods for obtaining annual average populations and disaggregating into state data where needed and provides the resulting population data for the other livestock that were used for estimating all livestock-related emissions. For each animal category, the USDA publishes monthly, annual, or multi-year livestock population and production estimates. American bison estimates prior to 2002 were estimated using data from the National Bison Association (1999).

Methane emissions from swine, horses, mules and asses were estimated by multiplying national population estimates by the default IPCC emission factor (IPCC 2006). For sheep and goats, default national emission factors were updated to reflect revisions made in the *2019 Refinement to the 2006 IPCC Guidelines*, which best reflects values representative of the United States. The *2019 Refinement to the 2006 IPCC Guidelines* was released to clarify and elaborate on the existing guidance, along with providing updates to default values of emission factors and other parameters based on updated science. For American bison the emission factor for buffalo (IPCC 2006) was used and adjusted based on the ratio of live weights of 300 kg for buffalo (IPCC 2006) and 1,130 pounds (513 kg) for American Bison (National Bison Association 2011) to the 0.75 power. This methodology for determining emission factors is recommended by IPCC (2006) for animals with similar digestive systems. Table A-146 shows the emission factors used for these other livestock. National enteric fermentation emissions from all livestock types are shown in Table A-147 and Table A-148. Enteric fermentation emissions from most livestock types, broken down by state, for 2021 are shown in Table A-149 through Table A-152. Livestock populations are shown in Table A-122.

Table A-146: Enteric Fermentation Emission Factors for Other Livestock (kg CH₄/head/year)

Livestock Type	Emission Factor
Swine	1.5
Horses	18
Sheep	9
Goats	9
American Bison	82.2
Mules and Asses	10.0

Source: IPCC (2006), IPCC (2019),
except American Bison, as described
in text.

Table A-147: CH₄ Emissions from Enteric Fermentation (kt)

Livestock Type	1990	1995	2000	2005	2010	2019	2020	2021	2022	2023
Beef Cattle	4,742	5,396	5,050	4,986	4,963	5,062	5,018	5,010	4,891	4,704
Dairy Cattle	1,547	1,471	1,492	1,473	1,594	1,732	1,743	1,764	1,748	1,740
Swine	81	88	88	92	97	115	115	111	110	112
Horses	40	47	61	70	68	46	43	40	37	35
Sheep	102	81	63	55	51	47	47	47	46	46
Goats	23	21	22	26	26	25	25	25	25	25
American Bison	4	9	16	17	15	16	16	17	17	17
Mules and Asses	1	1	1	2	3	3	3	3	3	3
Total	6,539	7,114	6,793	6,722	6,816	7,045	7,010	7,017	6,878	6,683

Note: Totals may not sum due to independent rounding.

Table A-148: CH₄ Emissions from Enteric Fermentation (MMT CO₂ Eq.)

Livestock Type	1990	1995	2000	2005	2010	2019	2020	2021	2022	2023
Beef Cattle	132.8	151.1	141.4	139.6	139.0	141.7	140.5	140.3	137.0	131.7
Dairy Cattle	43.3	41.2	41.8	41.3	44.6	48.5	48.8	49.4	48.9	48.7
Swine	2.3	2.5	2.5	2.6	2.7	3.2	3.2	3.1	3.1	3.1
Horses	1.1	1.3	1.7	2.0	1.9	1.3	1.2	1.1	1.0	1.0
Sheep	2.9	2.3	1.8	1.5	1.4	1.3	1.3	1.3	1.3	1.3
Goats	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.7
American Bison	0.1	0.2	0.4	0.5	0.4	0.4	0.5	0.5	0.5	0.5
Mules and Asses	+	+	+	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	183.1	199.2	190.2	188.2	190.8	197.3	196.3	196.5	192.6	187.1

+ Does not exceed 0.5 MMT CO₂ Eq.

Note: Totals may not sum due to independent rounding.

Table A-149: CH₄ Emissions from Enteric Fermentation from Cattle (MT), by State, for 2023¹⁰⁶

State	Dairy Calves	Dairy Cows	Dairy Replace-ment Heifers 7-11 Months	Dairy Replace-ment Heifers 12-23 Months	Bulls	Beef Calves	Beef Cows	Beef Replace-ment Heifers 7-11 Months	Beef Replace-ment Heifers 12-23 Months	Steer Stockers	Heifer Stockers	Feedlot	Total
Alabama	19	356	30	107	4,025	3,510	61,054	1,363	3,894	1,203	1,324	317	77,202
Alaska	1	12	1	5	450	44	757	20	58	14	11	3	1,375
Arizona	1,208	29,549	1,526	5,550	1,998	964	16,585	340	967	7,992	714	11,972	79,367
Arkansas	31	547	41	149	5,148	4,727	82,223	1,703	4,867	2,944	1,907	616	104,903
California	10,714	260,560	9,668	35,150	5,995	3,834	65,954	1,565	4,449	17,637	6,422	24,438	446,386
Colorado	1,258	30,378	1,385	5,037	4,496	3,597	61,880	1,838	5,223	22,047	16,840	50,872	204,850
Conn.	115	2,958	128	465	47	24	410	25	72	26	40	8	4,318
Delaware	17	377	16	59	28	9	155	8	22	69	8	9	778
Florida	654	16,903	443	1,610	5,148	4,675	81,315	1,577	4,507	640	662	170	118,304
Georgia	517	14,161	369	1,342	2,808	2,544	44,246	1,262	3,605	1,024	662	213	72,754
Hawaii	5	46	13	46	400	447	7,682	150	426	248	143	46	9,650
Idaho	4,061	102,177	4,452	16,188	3,997	2,808	48,301	1,293	3,675	8,819	6,422	13,885	216,078
Illinois	505	10,832	494	1,796	1,647	1,725	30,110	676	1,936	4,893	2,324	9,453	66,390
Indiana	1,159	26,459	723	2,628	1,464	936	16,343	430	1,232	2,397	1,162	4,726	59,658
Iowa	1,402	32,783	1,446	5,256	5,490	4,605	80,383	1,967	5,631	32,206	15,234	51,518	237,920
Kansas	1,053	24,179	1,927	7,008	7,777	7,231	126,214	3,320	9,502	50,931	44,153	115,439	398,733
Kentucky	274	7,214	517	1,879	5,616	5,045	87,765	1,577	4,507	5,633	2,914	803	123,743
Louisiana	56	1,029	41	149	2,808	2,356	40,975	1,009	2,884	589	503	141	52,540
Maine	162	3,880	175	636	141	52	911	51	145	116	80	25	6,372
Maryland	255	5,987	350	1,272	328	220	3,827	114	325	321	159	342	13,501
Mass.	59	1,401	74	269	94	42	729	38	108	64	27	11	2,916
Michigan	2,703	67,690	1,831	6,658	1,372	488	8,527	283	809	4,319	1,162	7,251	103,094
Minn.	2,865	64,417	2,530	9,198	2,745	1,832	31,975	1,045	2,991	12,233	3,744	16,938	152,514
Miss.	44	901	74	268	3,650	2,497	43,428	1,148	3,281	1,331	1,007	296	57,925
Missouri	430	7,342	361	1,314	10,065	9,876	172,401	3,689	10,557	10,486	5,939	3,728	236,188
Montana	69	1,507	48	175	9,492	7,324	125,991	4,356	12,380	5,787	5,309	1,996	174,433

¹⁰⁶ Because a simplified calculation approach was used for 2023 emissions, state-level emissions for 2023 were estimated by calculating ratios of 2022 state-level emissions to the 2022 total national emissions, then applying those state-specific ratios to the 2023 national total emissions estimate.

Nebraska	361	8,490	361	1,314	10,065	9,169	160,055	4,303	12,317	63,663	40,796	122,937	433,832
Nevada	193	4,793	114	416	1,299	1,376	23,666	517	1,470	965	799	132	35,740
N.Hamp.	65	1,593	81	294	47	21	364	15	43	39	21	7	2,590
N.Jersey	26	634	38	137	66	41	711	19	54	57	32	11	1,825
N.Mexico	1,819	45,157	1,590	5,781	2,498	2,554	43,937	953	2,708	2,756	1,998	547	112,298
NewYork	3,862	102,251	4,441	16,147	1,877	524	9,111	506	1,446	1,156	1,063	969	143,353
N.Car.	243	6,892	207	752	2,901	1,885	32,798	782	2,235	1,075	689	221	50,681
N.Dakota	93	2,082	96	350	5,490	4,758	83,047	2,238	6,405	7,739	5,939	1,820	120,057
Ohio	1,545	33,763	1,446	5,256	2,745	1,588	27,712	799	2,287	5,493	1,549	6,605	90,787
Oklahoma	243	5,425	273	992	15,911	11,078	192,702	5,047	14,421	25,859	14,304	14,076	300,331
Oregon	779	17,423	700	2,544	3,997	2,847	48,980	1,361	3,869	4,685	3,425	5,467	96,076
Penn.	2,928	70,036	2,624	9,542	1,877	996	17,310	646	1,844	3,596	1,302	3,082	115,782
R.Island	3	72	7	24	9	6	100	3	7	8	5	2	246
S.Car.	56	1,365	74	268	1,123	825	14,355	366	1,046	282	238	66	20,065
S.Dakota	1,059	23,799	482	1,752	9,607	8,141	142,113	4,549	13,021	18,725	12,781	19,749	255,778
Tenn.	168	4,146	295	1,074	5,616	4,664	81,133	1,514	4,326	3,456	2,251	718	109,362
Texas	3,893	105,982	3,275	11,909	30,886	23,111	402,030	8,959	25,598	67,336	44,765	128,603	856,348
Utah	592	14,135	700	2,544	2,298	1,860	32,007	953	2,708	2,480	1,713	945	62,934
Vermont	747	18,073	700	2,544	282	79	1,367	57	163	128	173	36	24,349
Virginia	442	11,564	517	1,879	3,557	3,129	54,422	1,123	3,209	3,815	1,828	738	86,221
Wash.	1,626	39,616	1,654	6,013	1,798	1,263	21,726	749	2,128	5,236	3,710	9,893	95,411
W.Virg.	31	615	27	98	1,314	985	17,128	380	1,085	1,002	585	186	23,436
Wisconsin	7,942	187,691	7,951	28,908	2,745	1,501	26,202	1,045	2,991	9,986	2,195	11,683	290,840
Wyoming	56	1,348	60	219	3,497	3,839	66,051	1,974	5,610	4,409	3,853	3,049	93,965

Table A-150: CH₄ Emissions from Enteric Fermentation from Cattle (MMT CO₂ Eq.), by State, for 2023¹⁰⁷

State	Dairy				Bulls	Beef		Beef	Beef	Steer Stockers	Heifer Stocker s	Feedlot	Total
	Calves	Dairy Cows	Replace- ment Heifers	Replace- ment		Replac e-ment Heifers	Replac e-ment Heifers						
			7-11 Months	Heifers 12- 23 Months		7-11 Months	12-23 Months						
Alabama	0.001	0.010	0.001	0.003	0.113	0.098	1.710	0.038	0.109	0.034	0.037	0.009	2.162
Alaska	0.000	0.000	0.000	0.000	0.013	0.001	0.021	0.001	0.002	0.000	0.000	0.000	0.039

¹⁰⁷ Because a simplified calculation approach was used for 2023 emissions, state-level emissions for 2023 were estimated by calculating ratios of 2022 state-level emissions to the 2022 total national emissions, then applying those state-specific ratios to the 2023 national total emissions estimate.

Arizona	0.034	0.827	0.043	0.155	0.056	0.027	0.464	0.010	0.027	0.224	0.020	0.335	2.222
Arkansas	0.001	0.015	0.001	0.004	0.144	0.132	2.302	0.048	0.136	0.082	0.053	0.017	2.937
California													12.49
	0.300	7.296	0.271	0.984	0.168	0.107	1.847	0.044	0.125	0.494	0.180	0.684	9
Colorado	0.035	0.851	0.039	0.141	0.126	0.101	1.733	0.051	0.146	0.617	0.472	1.424	5.736
Conn.	0.003	0.083	0.004	0.013	0.001	0.001	0.011	0.001	0.002	0.001	0.001	0.000	0.121
Delaware	0.000	0.011	0.000	0.002	0.001	0.000	0.004	0.000	0.001	0.002	0.000	0.000	0.022
Florida	0.018	0.473	0.012	0.045	0.144	0.131	2.277	0.044	0.126	0.018	0.019	0.005	3.313
Georgia	0.014	0.397	0.010	0.038	0.079	0.071	1.239	0.035	0.101	0.029	0.019	0.006	2.037
Hawaii	0.000	0.001	0.000	0.001	0.011	0.013	0.215	0.004	0.012	0.007	0.004	0.001	0.270
Idaho	0.114	2.861	0.125	0.453	0.112	0.079	1.352	0.036	0.103	0.247	0.180	0.389	6.050
Illinois	0.014	0.303	0.014	0.050	0.046	0.048	0.843	0.019	0.054	0.137	0.065	0.265	1.859
Indiana	0.032	0.741	0.020	0.074	0.041	0.026	0.458	0.012	0.034	0.067	0.033	0.132	1.670
Iowa	0.039	0.918	0.040	0.147	0.154	0.129	2.251	0.055	0.158	0.902	0.427	1.442	6.662
Kansas													11.16
	0.029	0.677	0.054	0.196	0.218	0.202	3.534	0.093	0.266	1.426	1.236	3.232	5
Kentucky	0.008	0.202	0.014	0.053	0.157	0.141	2.457	0.044	0.126	0.158	0.082	0.022	3.465
Louisiana	0.002	0.029	0.001	0.004	0.079	0.066	1.147	0.028	0.081	0.016	0.014	0.004	1.471
Maine	0.005	0.109	0.005	0.018	0.004	0.001	0.026	0.001	0.004	0.003	0.002	0.001	0.178
Maryland	0.007	0.168	0.010	0.036	0.009	0.006	0.107	0.003	0.009	0.009	0.004	0.010	0.378
Mass.	0.002	0.039	0.002	0.008	0.003	0.001	0.020	0.001	0.003	0.002	0.001	0.000	0.082
Michigan	0.076	1.895	0.051	0.186	0.038	0.014	0.239	0.008	0.023	0.121	0.033	0.203	2.887
Minn.	0.080	1.804	0.071	0.258	0.077	0.051	0.895	0.029	0.084	0.343	0.105	0.474	4.270
Miss.	0.001	0.025	0.002	0.008	0.102	0.070	1.216	0.032	0.092	0.037	0.028	0.008	1.622
Missouri	0.012	0.206	0.010	0.037	0.282	0.277	4.827	0.103	0.296	0.294	0.166	0.104	6.613
Montana	0.002	0.042	0.001	0.005	0.266	0.205	3.528	0.122	0.347	0.162	0.149	0.056	4.884
Nebraska													12.14
	0.010	0.238	0.010	0.037	0.282	0.257	4.482	0.120	0.345	1.783	1.142	3.442	7
Nevada	0.005	0.134	0.003	0.012	0.036	0.039	0.663	0.014	0.041	0.027	0.022	0.004	1.001
N. Hamp.	0.002	0.045	0.002	0.008	0.001	0.001	0.010	0.000	0.001	0.001	0.001	0.000	0.073
N. Jersey	0.001	0.018	0.001	0.004	0.002	0.001	0.020	0.001	0.002	0.002	0.001	0.000	0.051
N. Mexico	0.051	1.264	0.045	0.162	0.070	0.072	1.230	0.027	0.076	0.077	0.056	0.015	3.144
New York	0.108	2.863	0.124	0.452	0.053	0.015	0.255	0.014	0.041	0.032	0.030	0.027	4.014
N. Car.	0.007	0.193	0.006	0.021	0.081	0.053	0.918	0.022	0.063	0.030	0.019	0.006	1.419
N.													
Dakota	0.003	0.058	0.003	0.010	0.154	0.133	2.325	0.063	0.179	0.217	0.166	0.051	3.362
Ohio	0.043	0.945	0.040	0.147	0.077	0.044	0.776	0.022	0.064	0.154	0.043	0.185	2.542
Oklahoma													
a	0.007	0.152	0.008	0.028	0.446	0.310	5.396	0.141	0.404	0.724	0.401	0.394	8.409

Oregon	0.022	0.488	0.020	0.071	0.112	0.080	1.371	0.038	0.108	0.131	0.096	0.153	2.690
Penn.	0.082	1.961	0.073	0.267	0.053	0.028	0.485	0.018	0.052	0.101	0.036	0.086	3.242
R. Island	0.000	0.002	0.000	0.001	0.000	0.000	0.003	0.000	0.000	0.000	0.000	0.000	0.007
S. Car.	0.002	0.038	0.002	0.008	0.031	0.023	0.402	0.010	0.029	0.008	0.007	0.002	0.562
S. Dakota	0.030	0.666	0.013	0.049	0.269	0.228	3.979	0.127	0.365	0.524	0.358	0.553	7.162
Tenn.	0.005	0.116	0.008	0.030	0.157	0.131	2.272	0.042	0.121	0.097	0.063	0.020	3.062
Texas													23.97
	0.109	2.967	0.092	0.333	0.865	0.647	11.257	0.251	0.717	1.885	1.253	3.601	8
Utah	0.017	0.396	0.020	0.071	0.064	0.052	0.896	0.027	0.076	0.069	0.048	0.026	1.762
Vermont	0.021	0.506	0.020	0.071	0.008	0.002	0.038	0.002	0.005	0.004	0.005	0.001	0.682
Virginia	0.012	0.324	0.014	0.053	0.100	0.088	1.524	0.031	0.090	0.107	0.051	0.021	2.414
Wash.	0.046	1.109	0.046	0.168	0.050	0.035	0.608	0.021	0.060	0.147	0.104	0.277	2.672
W. Virg.	0.001	0.017	0.001	0.003	0.037	0.028	0.480	0.011	0.030	0.028	0.016	0.005	0.656
Wisconsin	0.222	5.255	0.223	0.809	0.077	0.042	0.734	0.029	0.084	0.280	0.061	0.327	8.144
Wyoming	0.002	0.038	0.002	0.006	0.098	0.108	1.849	0.055	0.157	0.123	0.108	0.085	2.631

Table A-151: CH₄ Emissions from Enteric Fermentation from Other Livestock (MT), by State, for 2023¹⁰⁸

State	Swine	Horses	Sheep	Goats	American Bison	Mules and Asses	Total
Alabama	40	595	166	451	5	109	1,332
Alaska	2	22	6	9	120	0.3	159
Arizona	225	1,064	912	457	9	25	2,657
Arkansas	225	492	152	287	7	73	1,215
California	130	944	5,241	1146	111	50	7,537
Colorado	818	1,412	3,920	570	961	61	7,699
Connecticut	4	89	53	60	47	10	259
Delaware	4	37	12	10	17	1	80
Florida	11	1,003	165	636	5	125	1,898
Georgia	61	554	167	621	1	117	1,476
Hawaii	11	66	183	176	7	3	433
Idaho	37	591	2,097	348	2,816	25	5,887
Illinois	8,127	403	483	370	60	49	9,465
Indiana	6,636	975	547	396	25	42	8,591
Iowa	35,836	657	1,458	965	245	31	39,120
Kansas	2,918	532	593	503	402	45	4,955
Kentucky	688	1,621	538	503	206	121	3,638
Louisiana	8	459	89	172	6	64	785
Maine	7	85	118	48	18	4	277
Maryland	37	443	157	153	4	23	805
Massachusetts	11	147	117	60	1	14	346
Michigan	1,843	673	793	284	296	38	3,906
Minnesota	13,195	456	1,021	352	225	34	15,256
Mississippi	275	371	112	333	24	84	1,174
Missouri	5,048	896	884	453	32	116	7,395
Montana	344	993	1,732	166	1,974	29	5,226
Nebraska	5,450	547	665	292	2,751	14	9,698
Nevada	0.2	96	547	48	0.3	4	693
New Hampshire	6	82	72	32	26	5	222
New Jersey	11	318	120	122	0.1	17	578
New Mexico	2	600	820	353	395	28	2,172
New York	57	784	729	222	99	28	1,902
North Carolina	12,506	594	264	444	18	123	13,917
North Dakota	237	226	565	77	1,227	9	2,335
Ohio	4,073	1,336	1,158	612	94	85	7,312
Oklahoma	3,266	1,535	474	945	71	185	6,406
Oregon	14	960	1,322	521	199	42	3,018
Pennsylvania	2,065	946	875	498	100	97	4,544
Rhode Island	2	26	16	9	-	1	54
South Carolina	242	532	85	387	1	66	1,283

¹⁰⁸ Because a simplified calculation approach was used for 2023 emissions, state-level emissions for 2023 were estimated by calculating ratios of 2022 state-level emissions to the 2022 total national emissions, then applying those state-specific ratios to the 2023 national total emissions estimate.

South Dakota	3,186	607	2,142	174	2,207	22	8,326
Tennessee	428	1,288	447	942	30	206	3,270
Texas	1,733	4,423	6,381	7212	889	1,017	21,116
Utah	1,232	781	2,461	218	81	10	4,767
Vermont	6	90	153	82	16	-	340
Virginia	444	738	656	426	35	85	2,352
Washington	26	679	456	287	83	30	1,539
West Virginia	8	341	292	251	11	42	926
Wisconsin	528	771	747	1265	631	33	3,880
Wyoming	165	649	3,008	173	830	37	4,850

“-“ Indicates there are no emissions, as there is no significant population of this animal type.

Table A-152: CH₄ Emissions from Enteric Fermentation from Other Livestock (MMT CO₂ Eq.), by State, for 2023¹⁰⁹

State	Swine	Horses	Sheep	Goats	American Bison	Mules and Asses	Total
Alabama	0.0011	0.0167	0.0046	0.0126	0.0001	0.0030	0.0373
Alaska	0.0001	0.0006	0.0002	0.0003	0.0034	+	0.0045
Arizona	0.0063	0.0298	0.0255	0.0128	0.0002	0.0007	0.0744
Arkansas	0.0063	0.0138	0.0043	0.0080	0.0002	0.0020	0.0340
California	0.0036	0.0264	0.1468	0.0321	0.0031	0.0014	0.2110
Colorado	0.0229	0.0395	0.1098	0.0160	0.0269	0.0017	0.2156
Connecticut	0.0001	0.0025	0.0015	0.0017	0.0013	0.0003	0.0073
Delaware	0.0001	0.0010	0.0003	0.0003	0.0005	+	0.0022
Florida	0.0003	0.0281	0.0046	0.0178	0.0001	0.0035	0.0531
Georgia	0.0017	0.0155	0.0047	0.0174	+	0.0033	0.0413
Hawaii	0.0003	0.0019	0.0051	0.0049	0.0002	0.0001	0.0121
Idaho	0.0010	0.0166	0.0587	0.0097	0.0788	0.0007	0.1648
Illinois	0.2276	0.0113	0.0135	0.0104	0.0017	0.0014	0.2650
Indiana	0.1858	0.0273	0.0153	0.0111	0.0007	0.0012	0.2406
Iowa	1.0034	0.0184	0.0408	0.0270	0.0069	0.0009	1.0954
Kansas	0.0817	0.0149	0.0166	0.0141	0.0113	0.0012	0.1387
Kentucky	0.0193	0.0454	0.0151	0.0141	0.0058	0.0034	0.1019
Louisiana	0.0002	0.0129	0.0025	0.0048	0.0002	0.0018	0.0220
Maine	0.0002	0.0024	0.0033	0.0014	0.0005	0.0001	0.0078
Maryland	0.0010	0.0124	0.0044	0.0043	0.0001	0.0006	0.0225
Massachusetts	0.0003	0.0041	0.0033	0.0017	+	0.0004	0.0097
Michigan	0.0516	0.0188	0.0222	0.0080	0.0083	0.0011	0.1094
Minnesota	0.3695	0.0128	0.0286	0.0099	0.0063	0.0009	0.4272
Mississippi	0.0077	0.0104	0.0031	0.0093	0.0007	0.0023	0.0329
Missouri	0.1414	0.0251	0.0248	0.0127	0.0009	0.0033	0.2071
Montana	0.0096	0.0278	0.0485	0.0046	0.0553	0.0008	0.1463
Nebraska	0.1526	0.0153	0.0186	0.0082	0.0770	0.0004	0.2715
Nevada	+	0.0027	0.0153	0.0013	+	0.0001	0.0194
New Hampshire	0.0002	0.0023	0.0020	0.0009	0.0007	0.0001	0.0062
New Jersey	0.0003	0.0089	0.0034	0.0034	+	0.0005	0.0162

¹⁰⁹ Because a simplified calculation approach was used for 2023 emissions, state-level emissions for 2023 were estimated by calculating ratios of 2022 state-level emissions to the 2022 total national emissions, then applying those state-specific ratios to the 2023 national total emissions estimate.

New Mexico	0.0001	0.0168	0.0230	0.0099	0.0111	0.0008	0.0608
New York	0.0016	0.0219	0.0204	0.0062	0.0028	0.0008	0.0533
North Carolina	0.3502	0.0166	0.0074	0.0124	0.0005	0.0035	0.3897
North Dakota	0.0066	0.0063	0.0158	0.0022	0.0344	0.0002	0.0654
Ohio	0.1140	0.0374	0.0324	0.0171	0.0026	0.0024	0.2047
Oklahoma	0.0915	0.0430	0.0133	0.0265	0.0020	0.0052	0.1794
Oregon	0.0004	0.0269	0.0370	0.0146	0.0056	0.0012	0.0845
Pennsylvania	0.0578	0.0265	0.0245	0.0140	0.0028	0.0027	0.1272
Rhode Island	0.0001	0.0007	0.0004	0.0003	-	+	0.0015
South Carolina	0.0068	0.0149	0.0024	0.0108	+	0.0018	0.0359
South Dakota	0.0892	0.0170	0.0600	0.0049	0.0618	0.0006	0.2331
Tennessee	0.0120	0.0361	0.0125	0.0264	0.0008	0.0058	0.0916
Texas	0.0485	0.1238	0.1787	0.2019	0.0249	0.0285	0.5912
Utah	0.0345	0.0219	0.0689	0.0061	0.0023	0.0003	0.1335
Vermont	0.0002	0.0025	0.0043	0.0023	0.0004	-	0.0095
Virginia	0.0124	0.0207	0.0184	0.0119	0.0010	0.0024	0.0659
Washington	0.0007	0.0190	0.0128	0.0080	0.0023	0.0008	0.0431
West Virginia	0.0002	0.0095	0.0082	0.0070	0.0003	0.0012	0.0259
Wisconsin	0.0148	0.0216	0.0209	0.0354	0.0177	0.0009	0.1086
Wyoming	0.0046	0.0182	0.0842	0.0048	0.0232	0.0010	0.1358

“-“ Indicates there are no emissions, as there is no significant population of this animal type.

“+” Indicates emissions fall below 0.00005 MMT CO₂ Eq.

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3.12. Methodology for Estimating CH₄ and N₂O Emissions from Manure Management¹¹⁰

The following steps were used to estimate methane (CH₄) and nitrous oxide (N₂O) emissions from the management of livestock manure for the years 1990 through 2022. As explained in the Manure Management section (Section 5.2 Manure Management), a simplified approach was used to estimate emissions for 2023.

Step 1: Livestock Population Characterization Data

Annual animal population data for 1990 through 2022 for all livestock types, except American bison, goats, horses, mules and asses were obtained from the USDA NASS. The population data used in the emissions calculations for cattle, swine, and sheep were downloaded from the USDA NASS Quick Stats Database (USDA 2023a, 2024a). Poultry population data were obtained from USDA NASS reports (USDA 1995a, 1995b, 1998, 1999, 2004a, 2004b, 2009a, 2009b, 2009c, 2009d, 2010a, 2010b, 2011a, 2011b, 2012a, 2012b, 2013a, 2013b, 2014, 2015, 2016, 2017, 2018, 2019a, 2019b, 2019c, 2021a, 2021b, and 2023a, 2023b, 2023c, 2024b, and 2024c). Goat population data for 1992, 1997, 2002, 2007, 2012, and 2017 were obtained from the Census of Agriculture (USDA 2019d), as were horse, mule and ass population data for 1987, 1992, 1997, 2002, 2007, 2012, and 2017 and American bison population for 2002, 2007, 2012, and 2017. American bison population data for 1990-1999 were obtained from the National Bison Association (1999). Additional data sources used and adjustments to these data sets are described below.

Cattle: For all cattle groups (cows, heifers, steers, bulls, and calves), the USDA data provide cattle inventories from January (for each state) and July (as a U.S. total only) of each year. Cattle inventories change over the course of the year, sometimes significantly, as new calves are born and as cattle are moved into feedlots and subsequently slaughtered; therefore, to develop the best estimate for the annual animal population, the populations and the individual characteristics, such as weight and weight gain, pregnancy, and lactation of each animal type were tracked in the Cattle Enteric Fermentation Model (CEFM—see section 5.1). For animals that have relatively static populations throughout the year, such as mature cows and bulls, the January 1 values were used. For animals that have fluctuating populations throughout the year, such as calves and growing heifers and steer, the populations are modeled based on a transition matrix that uses annual population data from USDA along with USDA data on animal births, placement into feedlots, and slaughter statistics.

Swine: The USDA provides quarterly data for each swine subcategory: breeding, market under 50 pounds (under 23 kg), market 50 to 119 pounds (23 to 54 kg), market 120 to 179 pounds (54 to 81 kg), and market 180 pounds and over (greater than 82 kg). The average of the quarterly data was used in the emission calculations. For states where only the December data is reported, the December data were used directly.

Sheep: The USDA provides total state-level data annually for lambs and sheep. Population distribution data for lambs and sheep on feed are not available after 1993 (USDA 1994). The number of lambs and sheep on feed for 1994 through 2022 were calculated using the average of the percent of lambs and sheep on feed from 1990 through 1993. In addition, all of the sheep and lambs “on feed” are not necessarily on “feedlots;” they may be on pasture/crop residue supplemented by feed. Data for those animals on feed that are in feedlots versus pasture/crop residue were provided only for lamb in 1993. To calculate the populations of sheep and lambs in feedlots for all years, it was assumed that the percentage of sheep and lambs on feed that are in feedlots versus pasture/crop residue is the same as that for lambs in 1993 (Anderson 2000).

Goats: Annual goat population data by state were available for 1992, 1997, 2002, 2007, 2012, and 2017 (USDA 2019d). The data for 1992 were used for 1990 through 1992. Data for 1993 through 1996, 1998 through 2001, 2003

¹¹⁰ Note that direct N₂O emissions from dung and urine spread onto fields either directly as daily spread or after it is removed from manure management systems (e.g., lagoon, pit, etc.) and from livestock dung and urine deposited on pasture, range, or paddock lands are accounted for and discussed in the Agricultural Soil Management source category within the Agriculture Chapter. Indirect N₂O emissions dung and urine spread onto fields after it is removed from manure management systems (e.g., lagoon, pit, etc.) and from livestock dung and urine deposited on pasture, range, or paddock lands are also included in the Agricultural Soil Management source category.

through 2006, 2008 through 2011, and 2013 through 2016 were interpolated based on the 1992, 1997, 2002, 2007, 2012, and 2017 Census data. Data for 2018 through 2022 were extrapolated based on 2017 Census data.

Horses: Annual horse population data by state were available for 1987, 1992, 1997, 2002, 2007, 2012, and 2017 (USDA 2019d). Data for 1990 through 1991, 1993 through 1996, 1998 through 2001, 2003 through 2006, 2008 through 2011, and 2013 through 2016 were interpolated based on the 1987, 1992, 1997, 2002, 2007, 2012, and 2017 Census data. Data for 2018 through 2022 were extrapolated based on 2017 Census data.

Mules and Asses: Annual mule and ass (burro and donkey) population data by state were available for 1987, 1992, 1997, 2002, 2007, 2012, and 2017 (USDA 2019d). Data for 1990 through 1991, 1993 through 1996, 1998 through 2001, 2003 through 2006, 2008 through 2011, and 2013 through 2016 were interpolated based on the 1987, 1992, 1997, 2002, 2007, 2012, and 2017 Census data. Data for 2018 through 2022 were extrapolated based on 2017 Census data.

American Bison: Annual American bison population data by state were available for 2002, 2007, 2012, and 2017 (USDA 2019d). Data for 1990 through 1999 were obtained from the Bison Association (1999). Data for 2000, 2001, 2003 through 2006, 2008 through 2011, and 2013 through 2016 were interpolated based on the Bison Association and 2002, 2007, 2012, and 2017 Census data. Data for 2018 through 2022 were extrapolated based on 2017 Census data.

Poultry: The USDA provides population data for hens (one year old or older), pullets (hens younger than one year old), other chickens, and production (slaughter) data for broilers and turkeys (USDA 1995a, 1995b, 1998, 1999, 2004a, 2004b, 2009b, 2009c, 2009d, 2009e, 2010a, 2010b, 2011a, 2011b, 2012a, 2012b, 2013a, 2013b, 2014, 2015, 2016, 2017, 2018, 2019a, 2019b, 2021a, 2021b, 2023a, 2023b, 2023c, 2024b, and 2024c). All poultry population data were adjusted to account for states that report non-disclosed populations to USDA NASS. The combined populations of the states reporting non-disclosed populations are reported as “other” states. State populations for the non-disclosed states were estimated by using Census of Agriculture data to provide a ratio of the non-disclosed state population to the “other” states’ total population (ERG 2021).

Because only production data are available for broilers and turkeys, population data are calculated by dividing the number of animals produced by the number of production cycles per year, or the turnover rate. Based on personal communications with John Lange, an agricultural statistician with USDA NASS, the broiler turnover rate ranges from 3.4 to 5.5 over the course of the inventory (Lange 2000). For turkeys, the turnover rate ranges from 2.4 to 3.0. A summary of the livestock population characterization data used to calculate CH₄ and N₂O emissions is presented in Table A-153.

Step 2: Waste Characteristics Data

Methane and N₂O emissions calculations are based on the following animal characteristics for each relevant livestock population:

- Volatile solids (VS) excretion rate;
- Maximum methane producing capacity (B₀) for U.S. animal waste;
- Nitrogen excretion rate (N_{ex}); and
- Typical animal mass (TAM).

Table A-154 presents a summary of the waste characteristics used in the emissions estimates. Published sources were reviewed for U.S.-specific livestock waste characterization data that would be consistent with the animal population data discussed in Step 1. The USDA’s Agricultural Waste Management Field Handbook (AWMFH; USDA 1996, 2008) is one of the primary sources of waste characteristics for non-cattle animal groups. Data from the 1996 and 2008 USDA AWMFH were used to estimate VS and N_{ex} for most non-cattle animal groups across the time series of the *Inventory*, as shown in Table A-155 (ERG 2010b and 2010c). The 1996 AWMFH data were based on measured values from U.S. farms; the 2008 AWMFH data were developed using the calculation method created by the American Society of Agricultural and Biological Engineers (ASABE), which is based on U.S. animal dietary intake and performance measures. Since the values from each of the two AWMFHs result from different estimation methods and reflect changes in animal genetics and nutrition over time, both data sources were used to create a time series across the *Inventory* as neither value would be appropriate to use across the entire span of *Inventory* years. Expert sources (USDA NRCS staff) agreed interpolating the two data sources across the time series would be appropriate as each methodology reflect the best available for that time period and the more recent data may

not appropriately reflect the historic time series (ERG 2010b). Although the AWMFH values are lower than the IPCC (2006) values, these values are more appropriate for U.S. systems because they have been calculated using U.S.-specific data. Animal-specific notes about VS and Nex are presented below:

- *Swine*: The VS and Nex data for breeding swine are from a combination of the types of animals that make up this animal group, namely gestating and farrowing swine and boars. It is assumed that a group of breeding swine is typically broken out as 80 percent gestating sows, 15 percent farrowing swine, and 5 percent boars (Safley 2000). Differing trends in VS and Nex values are due to the updated Nex calculation method from 2008 AWMFH. VS calculations did not follow the same procedure and were updated based on a fixed ratio of VS to total solids and past ASABE standards (ERG 2010b).
- *Poultry*: Due to the change in USDA reporting of hens and pullets in 2005, new nitrogen and VS excretion rates were calculated for the combined population of hens and pullets; a weighted average rate was calculated based on hen and pullet population data from 1990 to 2004.
- *Goats, Sheep, Horses, Mules and Asses*: In cases where data were not available in the USDA documents, data from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) or the 2006 IPCC Guidelines were used.

The method for calculating VS excretion and Nex for cattle (including American bison, beef and dairy cows, bulls, heifers, and steers) is based on the relationship between animal performance characteristics such as diet, lactation, and weight gain and energy utilization. The method used is outlined by the IPCC (2019) Tier 2 methodology, and is modeled using the CEFM as described in the enteric fermentation portion of the inventory (documented in Moffroid and Pape 2013) in order to take advantage of the detailed diet and animal performance data assembled as part of the Tier II analysis for cattle. For American bison, VS and Nex were assumed to be the same as beef NOF bulls. The 2019 Refinements offer updated clarity and guidance for several parameters (e.g., emission factors) and methodologies and, where appropriate, EPA is reviewing and applying to reflect the updated science.

The VS content of manure is the fraction of the diet consumed by cattle that is not digested and thus excreted as fecal material; fecal material combined with urinary excretions constitutes manure. The CEFM uses the input of digestible energy (DE) and the energy requirements of cattle to estimate gross energy (GE) intake and enteric CH₄ emissions. GE and DE are used to calculate the indigestible energy per animal as gross energy minus digestible energy plus the amount of gross energy for urinary energy excretion per animal (2 or 4 percent). This value is then converted to VS production per animal using the typical conversion of dietary gross energy to dry organic matter of 18.45 MJ/kg, after subtracting out the ash content of manure. The current equation recommended by the 2006 IPCC Guidelines is:

Equation A-27: VS Production for Cattle

$$\text{VS production (kg)} = [(GE - DE) + (UE \times GE)] \times \frac{1 - ASH}{18.45}$$

where,

GE	=	Gross energy intake (MJ)
DE	=	Digestible energy (MJ)
(UE × GE)	=	Urinary energy expressed as fraction of GE, assumed to be 0.04 except for feedlots which are reduced 0.02 as a result of the high grain content of their diet.
ASH	=	Ash content of manure calculated as a fraction of the dry matter feed intake (assumed to be 0.08 consistent with Equation 10.24, Volume 4, Chapter 10, of the 2006 IPCC Guidelines).
18.45	=	Conversion factor for dietary GE per kg of dry matter (MJ per kg). This value is relatively constant across a wide range of forage and grain-based feeds commonly consumed by livestock.

Total nitrogen ingestion in cattle is determined by dietary protein intake. When feed intake of protein exceeds the nutrient requirements of the animal, the excess nitrogen is excreted, primarily through the urine. To calculate the nitrogen excreted by each animal type, the CEFM utilizes the energy balance calculations recommended by the

2006 IPCC Guidelines for gross energy and the energy required for growth along with inputs of weight gain, milk production, and the percent of crude protein in the diets. The total nitrogen excreted is measured in the CEFM as nitrogen consumed minus nitrogen retained by the animal for growth and in milk. The basic equation for calculating Nex is shown below, followed by the equations for each of the constituent parts, based on the 10th Corrigenda for the 2006 IPCC Guidelines (IPCC 2018).

Equation A-28: Nex Rates for Cattle

$$Nex_{(T)} = N_{intake} \times (1 - N_{retention\_fract(T)})$$

where,

$Nex_{(T)}$	=	Annual N excretion rates (kg N animal ⁻¹ yr ⁻¹)
$N_{intake(T)}$	=	The annual N intake per head of animal of species/category <i>T</i> (kg N animal ⁻¹ yr ⁻¹)
$N_{retention(T)}$	=	Fraction of annual N intake that is retained by animal

N intake is estimated as:

Equation A-29: Daily Nitrogen Intake for Cattle

$$N_{intake(T)} = \frac{GE}{18.45} \times \left(\frac{CP\%}{6.25} \right)$$

where,

$N_{intake(T)}$	=	Daily N consumed per animal of category <i>T</i> (kg N animal ⁻¹ day ⁻¹)
GE	=	Gross energy intake of the animal based on digestible energy, milk production, pregnancy, current weight, mature weight, rate of weight gain, and IPCC constants (MJ animal ⁻¹ day ⁻¹)
18.45	=	Conversion factor for dietary GE per kg of dry matter (MJ kg ⁻¹)
CP%	=	Percent crude protein in diet, input
6.25	=	Conversion from kg of dietary protein to kg of dietary N (kg feed protein per kg N)

The portion of consumed N that is retained as product equals the nitrogen in milk plus the nitrogen required for weight gain. The N content of milk produced is calculated using milk production and percent protein, along with conversion factors. The nitrogen retained in body weight gain by stockers, replacements, or feedlot animals is calculated using the net energy for growth (NE_g), weight gain (WG), and other conversion factors and constants. The equation matches the 10th Corrigenda to the 2006 IPCC Guidelines (IPCC 2018), and is as follows:

Equation A-30: Nitrogen Retention from Milk and Body Weight for Cattle

$$N_{retention(T)} = \left[\frac{Milk \times \left(\frac{Milk\ PR\%}{100} \right)}{6.38} \right] + \left[\frac{WG \times \left[268 - \left(\frac{7.03 \times NE_g}{WG} \right) \right]}{1000 \times 6.25} \right]$$

where,

$N_{retention(T)}$	=	Daily N retained per animal of category <i>T</i> (kg N animal ⁻¹ day ⁻¹)
Milk	=	Milk production (kg animal ⁻¹ day ⁻¹)
268	=	Constant from 2019 IPCC Guidelines
7.03	=	Constant from 2019 IPCC Guidelines
NE _g	=	Net energy for growth, calculated in livestock characterization, based on current weight, mature weight, rate of weight gain, and IPCC constants, (MJ day ⁻¹)
1,000	=	Conversion from grams to kilograms (g kg ⁻¹)
6.25	=	Conversion from kg dietary protein to kg dietary N (kg protein per kg N)
Milk PR%	=	Percent of protein in milk (%)

6.38	=	Conversion from milk protein to milk N (kg protein per kg N)
WG	=	Weight gain, as input into the CEFM transition matrix (kg day ⁻¹)

The VS and N equations above were used to calculate VS and Nex rates for each state, animal type (heifers and steer on feed, heifers and steer not on feed, bulls and American bison), and year. Table A-156 presents the state-specific VS and Nex production rates used for cattle in 2022. As shown in Table A-164, the differences in the VS daily excretion and Nex rate trends between dairy cattle animal types is due to milk production. Milk production by cow varies from state to state and is used in calculating net energy for lactating, which is used to calculate VS and Nex for dairy cows. Milk production is zero for dairy heifers (dairy heifers do not produce milk because they have not yet had a calf). Over time, the differences in milk production are also a big driver for the higher variability of VS and Nex rates in dairy cows.

Step 3: Waste Management System Usage Data

Table A-157 and Table A-158 summarize 2022 manure distribution data among waste management systems (WMS) at beef feedlots, dairies, dairy heifer facilities, and swine, layer, broiler, and turkey operations. Manure from the remaining animal types (beef cattle not on feed, American bison, goats, horses, mules and asses and sheep) is managed on pasture, range, or paddocks, on dry lot, or with solids storage systems. Note that the *Inventory* WMS estimates are based on state or regional WMS usage data and not built upon farm-level WMS estimates. Additional information on the development of the manure distribution estimates for each animal type is presented below. Definitions of each WMS type are presented in Table A-159.

Beef Cattle, Dairy Heifers and American Bison: The beef feedlot and dairy heifer WMS data were developed using regional information from EPA's Office of Water's engineering cost analyses conducted to support the development of effluent limitations guidelines for Concentrated Animal Feeding Operations (EPA 2002b). Based on EPA site visits and state contacts supporting this work and additional personal communication with the national USDA office to estimate the percent of beef steers and heifers in feedlots (Milton 2000), feedlot manure is almost exclusively managed in dry lots. In addition, there is a small amount of manure contained in runoff, which may or may not be collected in runoff ponds. Using EPA and USDA data and expert opinions (ERG assumptions documented in ERG 2000a), the runoff from feedlots was calculated by region in *Calculations: Percent Distribution of Manure for Waste Management Systems* and was used to estimate the percentage of manure managed in runoff ponds in addition to dry lots; this percentage ranges from 0.4 to 1.3 percent (ERG 2000a, 2023). For beef feedlot, these data were applied to 1990 through 2002. For 2018, WMS data were captured from a survey of NRCS regional staff (i.e., expert judgement). Data for 2019 through 2022 were assumed equal to 2018. WMS data for 2003 through 2017 were linearly interpolated consistent with IPCC time-series consistency techniques (ERG 2023). The remaining population categories of beef cattle outside of feedlots are managed through pasture, range, or paddock systems, which are utilized for the majority of the population of beef cattle in the country. American bison WMS data were assumed to be the same as beef cattle NOF.

Dairy Cows: The WMS data for dairy cows were developed using state and regional data from the Census of Agriculture, EPA's Office of Water, USDA, and the expert sources noted below. Farm-size distribution data are reported in the 1992, 1997, 2002, 2007, 2012, and 2017 Census of Agriculture (USDA 2019d). It was assumed that the Census data provided for 1992 were the same as that for 1990 and 1991, and data provided for 2017 were the same as that for 2018. Data for 1993 through 1996, 1998 through 2001, and 2003 through 2006, 2008 through 2011, and 2013 through 2016 were interpolated using the 1992, 1997, 2002, 2007, 2012, and 2017 Census data. The percent of waste by system was estimated using the USDA data broken out by geographic region and farm size.

For 1990 through 1996 the following methodology and sources were used to estimate dairy WMS:

Based on EPA site visits and the expert opinion of state contacts, manure from dairy cows at medium (200 through 700 head) and large (greater than 700 head) operations are managed using either flush systems or scrape/slurry systems (ERG 2000a). In addition, they may have a solids separator in place prior to their storage component. Estimates of the percent of farms that use each type of system (by geographic region) were developed by EPA's Office of Water and were used to estimate the percent of waste managed in lagoons (flush systems), liquid/slurry systems (scrape systems), and solid storage (separated solids) (EPA 2002b).

Manure management system data for small (fewer than 200 head) dairies were obtained at the regional level from USDA's Animal and Plant Health Inspection Service (APHIS)'s National Animal Health Monitoring System (Ott

2000). These data are based on a statistical sample of farms in the 20 U.S. states with the most dairy cows. Small operations are more likely to use liquid/slurry and solid storage management systems than anaerobic lagoon systems. The reported manure management systems were deep pit, liquid/slurry (includes slurry tank, slurry earth-basin, and aerated lagoon), anaerobic lagoon, and solid storage (includes manure pack, outside storage, and inside storage).

Data regarding the use of daily spread and pasture, range, or paddock systems for dairy cattle were obtained from personal communications with personnel from several organizations. These organizations include state NRCS offices, state extension services, state and private universities, USDA NASS, and other experts (Deal 2000; Johnson 2000; Miller 2000; Stettler 2000; Sweeten 2000; and Wright 2000). Contacts at Cornell University provided survey data on dairy manure management practices in New York (Poe et al. 1999). Census of Agriculture population data for 1992, 1997, 2002, 2007, 2012, and 2017 (USDA 2019d) were used in conjunction with the state data obtained from personal communications to determine regional percentages of total dairy cattle and dairy waste that are managed using these systems.

Of the dairies using systems other than daily spread and pasture, range, or paddock systems, some dairies reported using more than one type of manure management system. Due to limitations in how USDA APHIS collects the manure management data, the total percent of systems for a region and farm size is greater than 100 percent. However, manure is typically partitioned to use only one manure management system, rather than transferred between several different systems. Emissions estimates are only calculated for the final manure management system used for each portion of manure. To avoid double counting emissions, the reported percentages of systems in use were adjusted to equal a total of 100 percent using the same distribution of systems. For example, if USDA reported that 65 percent of dairies use deep pits to manage manure and 55 percent of dairies use anaerobic lagoons to manage manure, it was assumed that 54 percent (i.e., 65 percent divided by 120 percent) of the manure is managed with deep pits and 46 percent (i.e., 55 percent divided by 120 percent) of the manure is managed with anaerobic lagoons (ERG 2000a).

Starting in 2016, EPA estimates dairy WMS based on 2016 USDA Economic Research Service (ERS) Agricultural Resource Management Survey (ARMS) data. These data were obtained from surveys of nationally representative dairy producers. WMS data for 2016 were assumed the same for 2017 through 2022. WMS for 1997 through 2015 were interpolated between the data sources used for the 1990 through 1997 dairy WMS (noted above) and the 2016 ARMs data (ERG 2019).

Finally, the percentage of manure managed with anaerobic digestion (AD) systems with methane capture and combustion was added to the WMS distributions at the state-level. AD system data were obtained from EPA's AgSTAR Program's project database (EPA 2023). This database includes basic information for AD systems in the United States, based on publicly available data and data submitted by farm operators, project developers, financiers, and others involved in the development of farm AD projects.

Swine: The regional distribution of manure managed in each WMS was estimated using data from a 1995 USDA APHIS survey, EPA's Office of Water site visits, and 2009 USDA ERS ARMS data (Bush 1998, ERG 2000a, ERG 2018). The USDA APHIS data are based on a statistical sample of farms in the 16 U.S. states with the most hogs. The ERS ARMS data are based on surveys of nationally representative swine producers. Prior to 2009, operations with less than 200 head were assumed to use pasture, range, or paddock systems and swine operations with greater than 200 head were assigned WMS as obtained from USDA APHIS (Bush 1998). WMS data for 2009 were obtained from USDA ERS ARMS; WMS data for 2010 through 2022 were assumed to be the same as 2009 (ERG 2018). The percent of waste managed in each system was estimated using the EPA and USDA data broken out by geographic region and farm size. Farm-size distribution data reported in the 1992, 1997, 2002, 2007, 2012, and 2017 Census of Agriculture (USDA 2019d) were used to determine the percentage of all swine utilizing the various manure management systems. It was assumed that the swine farm size data provided for 1992 were the same as that for 1990 and 1991. Data for 1993 through 1996, 1998 through 2001, 2003 through 2006, and 2008 through 2011, and 2013 through 2016 were interpolated using the 1992, 1997, 2002, 2007, 2012, and 2017 Census data. Data for 2018 through 2022 were assumed to be the same as 2017 Census data.

Some swine operations reported using more than one management system; therefore, the total percent of systems reported by USDA for a region and farm size was greater than 100 percent. Typically, this means that a portion of the manure at a swine operation is handled in one system (e.g., liquid system), and a separate portion of the manure is handled in another system (e.g., dry system). However, it is unlikely that the same manure is moved

from one system to another, which could result in increased emissions, so reported systems data were normalized to 100 percent for incorporation into the WMS distribution, using the same method as described above for dairy operations. As with dairy, AD WMS were added to the state-level WMS distribution based on data from EPA's AgSTAR database (EPA 2023).

Sheep: WMS data for sheep were obtained from USDA NASS sheep report for years 1990 through 1993 (USDA 1994). Data for 2001 are obtained from USDA APHIS's national sheep report (USDA, APHIS 2003). The USDA APHIS data are based on a statistical sampled of farms in the 22 U.S. states with the most sheep. The data for years 1994-2000 are calculated assuming a linear progression from 1993 to 2001. Due to lack of additional data, data for years 2002 and beyond are assumed to be the same as 2001. Based on expert opinion (NASS staff), it was assumed that all sheep manure not deposited in feedlots was deposited on pasture, range, or paddock lands (Anderson 2000).

Goats, Horses, and Mules and Asses: WMS data for 1990 to 2022 were obtained from Appendix H of *Global Methane Emissions from Livestock and Poultry Manure* (EPA 1992). This report presents state WMS usage in percentages for the major animal types in the United States, based on information obtained from extension service personnel in each state. It was assumed that all manure not deposited in pasture, range, or paddock lands was managed in dry systems. For mules and asses, the WMS was assumed to be the same as horses.

Poultry—Hens (one year old or older), Pullets (hens less than one year old), and Other Chickens: WMS data for 1992 were obtained from *Global Methane Emissions from Livestock and Poultry Manure* (EPA 1992). These data were also used to represent 1990 and 1991. The percentage of layer operations using a shallow pit flush house with anaerobic lagoon or high-rise house without bedding was obtained for 1999 from a United Egg Producers voluntary survey (UEP 1999). These data were augmented for key poultry states (AL, AR, CA, FL, GA, IA, IN, MN, MO, NC, NE, OH, PA, TX, and WA) with USDA data (USDA, APHIS 2000). It was assumed that the change in system usage between 1990 and 1999 is proportionally distributed among those years of the inventory. Data collected for EPA's Office of Water, including information collected during site visits (EPA 2002b), were used to estimate the distribution of waste by management system and animal type. For 2018, WMS data were captured from a survey of NRCS regional staff. Data for 2019 through 2022 were assumed equal to 2018. WMS data for 2000 through 2017 were linearly interpolated consistent with IPCC time-series consistency techniques (ERG 2023). As with dairy and swine, using information about AD WMS from EPA's AgSTAR database (EPA 2023), AD was added to the WMS distribution for poultry operations.

Poultry—Broilers and Turkeys: The percentage of turkeys and broilers on pasture was obtained from the Office of Air and Radiation's *Global Methane Emissions from Livestock and Poultry Manure* (EPA 1992). It was assumed that one percent of poultry waste is deposited in pastures, ranges, and paddocks (EPA 1992). The remainder of waste is assumed to be deposited in operations with bedding management. For broilers, these data were applied to 1990 through 1992. For 2018, WMS data were captured from a survey of NRCS regional staff. Data for 2019 through 2022 were assumed equal to 2018. WMS data for 1993 through 2017 were linearly interpolated consistent with IPCC time-series consistency techniques (ERG 2023). As with dairy, swine, and other poultry, AD systems were used to update the WMS distributions based on information from EPA's AgSTAR database (EPA 2023).

Step 4: Emission Factor and Other Parameter Calculations

Methane conversion factors (MCFs) and N₂O emission factors (EFs) and nitrogen loss factors used in the emission calculations were determined using the methodologies presented below.

Methane Conversion Factors (MCFs)

Climate-based IPCC default MCFs (IPCC 2006; 2019) were used for all dry systems; these factors are presented in Table A-160. A U.S.-specific methodology was used to develop MCFs for all lagoon and liquid systems.

For animal waste managed in dry systems, the appropriate IPCC default MCF was applied based on annual average temperature data. The average county and state temperature data were obtained from the National Climate Data Center (NOAA 2021) and each state and year in the inventory was assigned a climate classification of cool, temperate or warm. Although there are some specific locations in the United States that may be included in the warm climate category, no aggregated state-level annual average temperatures are included in this category. In addition, some counties in a particular state may be included in the cool climate category, although the aggregated state-level annual average temperature may be included in the temperate category. Although considering the temperatures at a state level instead of a county level may be causing some specific locations to be classified into

an inappropriate climate category, using the state level annual average temperature provides an estimate that is appropriate for calculating the national average.

For anaerobic lagoons and other liquid systems, a climate-based approach based on the van't Hoff-Arrhenius equation was developed to estimate MCFs that reflects the seasonal changes in temperatures, and also accounts for long-term retention time, as discussed below. This approach is consistent with the IPCC (2006) guidelines. The van't Hoff-Arrhenius equation, with a base temperature of 30°C, is shown in the following equation (Safley and Westerman 1990):

Equation A-31: VS Proportion Available to Convert to CH₄ Based on Temperature (van't Hoff-Arrhenius *f* factor)

$$f = \exp \left[\frac{E(T_2 - T_1)}{RT_1T_2} \right]$$

where,

<i>f</i>	=	van't Hoff-Arrhenius <i>f</i> factor, the proportion of VS that are biologically available for conversion to CH ₄ based on the temperature of the system
<i>T</i> ₁	=	303.15K
<i>T</i> ₂	=	Ambient temperature (K) for climate zone (in this case, a weighted value for each state)
<i>E</i>	=	Activation energy constant (15,175 cal/mol)
<i>R</i>	=	Ideal gas constant (1.987 cal/K mol)

For those animal populations using liquid manure management systems or manure runoff ponds (i.e., dairy cow, dairy heifer, layers, beef in feedlots, and swine), monthly average state temperatures were based on the counties where the specific animal population resides (i.e., the temperatures were weighted based on the percent of animals located in each county). County population data were calculated from state-level population data from NASS and county-state distribution data from the 1992, 1997, 2002, 2007, 2012, and 2017 Census data (USDA 2019d). County population distribution data for 1990 and 1991 were assumed to be the same as 1992; county population distribution data for 1993 through 1996 were interpolated based on 1992 and 1997 data; county population distribution data for 1998 through 2001 were interpolated based on 1997 and 2002 data; county population distribution data for 2003 through 2006 were interpolated based on 2002 and 2007 data; county population distribution data for 2008 through 2011 were interpolated based on 2007 and 2012 data; county population distribution data for 2013 through 2016 were interpolated based on 2012 and 2017 data; county population distributions for 2018 through 2022 were assumed to be the same as 2017.

Annual MCFs for liquid systems are calculated as follows for each animal type, state, and year of the inventory:

- The weighted-average temperature for a state is calculated using the county population estimates and average monthly temperature in each county. Monthly temperatures are used to calculate a monthly van't Hoff-Arrhenius *f* factor, using the equation presented above. A minimum temperature of 5°C is used for uncovered anaerobic lagoons and 7.5°C is used for liquid/slurry and deep pit systems due to the biological activity in the lagoon which keeps the temperature above freezing.
- Monthly production of VS added to the system is estimated based on the animal type, number of animals present, and the volatile solids excretion rate of the animals.
- For lagoon systems, the calculation of methane includes a management and design practices (MDP) factor. The MDP factor represents management and design factors which cause a system to operate at a less than optimal level. This factor, equal to 0.8, was developed based on model comparisons to empirical CH₄ measurement data from anaerobic lagoon systems in the United States (ERG 2001).
- For all systems other than anaerobic lagoons, the amount of VS available for conversion to CH₄ each month is assumed to be equal to the amount of VS produced during the month (from Step 3). For anaerobic lagoons, the amount of VS available also includes VS that may remain in the system from previous months.
- The amount of VS consumed during the month is equal to the amount available for conversion multiplied by the *f* factor.

- For anaerobic lagoons, the amount of VS carried over from one month to the next is equal to the amount available for conversion minus the amount consumed. Lagoons are also modeled to have a solids clean-out once per year, occurring in the month of October.
- The estimated amount of CH₄ generated during the month is equal to the monthly VS consumed multiplied by B₀.

The annual MCF is then calculated as:

Equation A-32: MCF for Anaerobic Lagoons and Liquid Systems

$$MCF_{\text{annual}} = \frac{CH_4 \text{ generated}_{\text{annual}}}{VS_{\text{produced}}_{\text{annual}} \times B_0}$$

where,

MCF _{annual}	=	Methane conversion factor
VS _{produced} _{annual}	=	Volatile solids excreted annually
B ₀	=	Maximum CH ₄ producing potential of the waste

In order to account for the carry-over of VS from one year to the next, it is assumed that a portion of the VS from the previous year are available in the lagoon system in the next year. For example, the VS from October, November, and December of 2005 are available in the lagoon system starting January of 2006 in the MCF calculation for lagoons in 2006. Following this procedure, the resulting MCF for lagoons accounts for temperature variation throughout the year, residual VS in a system (carry-over), and management and design practices that may reduce the VS available for conversion to CH₄. It is assumed that liquid-slurry systems have a retention time less than 30 days, so the liquid-slurry MCF calculation doesn't reflect the VS carry-over.

The liquid system MCFs are presented in Table A-161 by state, WMS, and animal group for 2022.

Nitrous Oxide Emission Factors and Other Parameters

Direct N₂O: Direct N₂O EFs for manure management systems (kg N₂O-N/kg excreted N) were set equal to the most recent default IPCC factors (IPCC 2006), presented in Table A-162.

Indirect N₂O: Indirect N₂O EFs account for two fractions of nitrogen losses: volatilization of ammonia (NH₃) and NO_x (Frac_{gas}) and runoff/leaching (Frac_{runoff/leach}). IPCC default indirect N₂O EFs were used to estimate indirect N₂O emissions. These factors are 0.010 kg N₂O-N/kg N for volatilization and 0.0075 kg N₂O/kg N for runoff/leaching.

Country-specific estimates of N losses were developed for Frac_{gas} and Frac_{runoff/leach} for the United States. The vast majority of volatilization losses are NH₃. Although there are also some small losses of NO_x, no quantified estimates were available for use and those losses are believed to be small (about 1 percent) in comparison to the NH₃ losses. Therefore, Frac_{gas} values were based on WMS-specific volatilization values estimated from U.S. EPA's *National Emission Inventory - Ammonia Emissions from Animal Agriculture Operations* (EPA 2005). To estimate Frac_{runoff/leach}, data from EPA's Office of Water were used that estimate the amount of runoff from beef, dairy, and heifer operations in five geographic regions of the country (EPA 2002b). These estimates were used to develop U.S. runoff factors by animal type, WMS, and region. Nitrogen losses from leaching are believed to be small in comparison to the runoff losses and there are a lack of data to quantify these losses. Therefore, leaching losses were assumed to be zero and Frac_{runoff/leach} was set equal to the runoff loss factor. Nitrogen losses from volatilization and runoff/leaching are presented in Table A-163.

Step 5: CH₄ Emission Calculations

To calculate CH₄ emissions for animals other than cattle, first the amount of VS excreted in manure that is managed in each WMS was estimated:

Equation A-33: VS Excreted for Animals Other Than Cattle

$$VS \text{ excreted}_{\text{State,Animal,WMS}} = \text{Population}_{\text{State,Animal}} \times \frac{TAM}{1000} \times VS \times WMS \times 365.25$$

where,

VS excreted _{State, Animal, WMS}	=	Amount of VS excreted in manure managed in each WMS for each animal type (kg/yr)
Population _{State, Animal}	=	Annual average state animal population by animal type (head)
TAM	=	Typical animal mass (kg)
VS	=	Volatile solids production rate (kg VS/1000 kg animal mass/day)
WMS	=	Distribution of manure by WMS for each animal type in a state (percent)
365.25	=	Days per year

Using the CEFM VS data for cattle, the amount of VS excreted in manure that is managed in each WMS was estimated using the following equation:

Equation A-34: VS Excreted for Cattle

$$\text{VS excreted}_{\text{State, Animal, WMS}} = \text{Population}_{\text{State, Animal}} \times \text{VS} \times \text{WMS}$$

where,

VS excreted _{State, Animal, WMS}	=	Amount of VS excreted in manure managed in each WMS for each animal type (kg/yr)
Population _{State, Animal}	=	Annual average state animal population by animal type (head)
VS	=	Volatile solids production rate (kg VS/animal/year)
WMS	=	Distribution of manure by WMS for each animal type in a state (percent)

For all animals, the estimated amount of VS excreted into a WMS was used to calculate CH₄ emissions using the following equation:

Equation A-35: CH₄ Emissions for All Animal Types

$$\text{CH}_4 = \sum_{\text{State, Animal, WMS}} (\text{VS excreted}_{\text{State, Animal, WMS}} \times B_0 \times \text{MCF} \times 0.662)$$

where,

CH ₄	=	CH ₄ emissions (kg CH ₄ /yr)
VS excreted _{WMS, State}	=	Amount of VS excreted in manure managed in each WMS (kg/yr)
B ₀	=	Maximum CH ₄ producing capacity (m ³ CH ₄ /kg VS)
MCF _{animal, state, WMS}	=	MCF for the animal group, state and WMS (percent)
0.662	=	Density of methane at 25° C (kg CH ₄ /m ³ CH ₄)

A calculation was developed to estimate the amount of CH₄ emitted from AD systems utilizing CH₄ capture and combustion technology. First, AD systems were assumed to produce 90 percent of B₀ of the manure. This value is applied for all climate regions and AD system types. However, this is a conservative assumption as the actual amount of CH₄ produced by each AD system is very variable and will change based on operational and climate conditions and an assumption of 90 percent is likely overestimating CH₄ production from some systems and underestimating CH₄ production in other systems. The CH₄ production of AD systems is calculated using the equation below:

Equation A-36: CH₄ Production from AD Systems

$$\text{CH}_4 \text{ Production}_{\text{AD System}} = \text{Production}_{\text{AD System}} \times \frac{\text{TAM}}{1000} \times \text{VS} \times B_0 \times 0.662 \times 365.25 \times 0.90$$

where,

CH ₄ Production _{AD system}	=	CH ₄ production from a particular AD system, (kg/yr)
Population _{AD state}	=	Number of animals on a particular AD system
VS	=	Volatile solids production rate (kg VS/1000 kg animal mass-day)

TAM	=	Typical Animal Mass (kg/head)
B ₀	=	Maximum CH ₄ producing capacity (CH ₄ m ³ /kg VS)
0.662	=	Density of CH ₄ at 25° C (kg CH ₄ /m ³ CH ₄)
365.25	=	Days/year
0.90	=	CH ₄ production factor for AD systems

The total amount of CH₄ produced by AD is calculated only as a means to estimate the emissions from AD; i.e., only the estimated amount of CH₄ actually entering the atmosphere from AD is reported in the inventory. The emissions to the atmosphere from AD are a result of leakage from the system (e.g., from the cover, piping, tank, etc.) and incomplete combustion and are calculated using the collection efficiency (CE) and destruction efficiency (DE) of the AD system. The three primary types of AD systems in the United States are covered lagoons, complete mix and plug flow systems. The CE of covered lagoon systems was assumed to be 75 percent, and the CE of complete mix and plug flow AD systems was assumed to be 99 percent (EPA 2008). The CH₄ DE from flaring or burning in an engine was assumed to be 98 percent; therefore, the amount of CH₄ that would not be flared or combusted was assumed to be 2 percent (EPA 2008). The amount of CH₄ produced by systems with AD was calculated with the following equation:

Equation A-37: CH₄ Emissions from AD Systems

$$\text{CH}_4 \text{ Emissions AD} = \sum_{\text{State, Animal, AD Systems}} \left(\left[\text{CH}_4 \text{ Production AD}_{\text{AD system}} \times \text{CE}_{\text{AD system}} \times (1 - \text{DE}) \right] + \left[\text{CH}_4 \text{ Production AD}_{\text{AD system}} \times (1 - \text{CE}_{\text{AD system}}) \right] \right)$$

where,

CH ₄ Emissions AD	=	CH ₄ emissions from AD systems, (kg/yr)
CH ₄ Production AD _{AD system}	=	CH ₄ production from a particular AD system, (kg/yr)
CE _{AD system}	=	Collection efficiency of the AD system, varies by AD system type
DE	=	Destruction efficiency of the AD system, 0.98 for all systems

Step 6: N₂O Emission Calculations

Total N₂O emissions from manure management systems were calculated by summing direct and indirect N₂O emissions. The first step in estimating direct and indirect N₂O emissions was calculating the amount of N excreted in manure and managed in each WMS. For calves and animals other than cattle the following equation was used:

Equation A-38: Nex for Calves and Animal Types Other Than Cattle

$$\text{N excreted}_{\text{State, Animal, WMS}} = \text{Population}_{\text{State, Animal}} \times \text{WMS} \times \frac{\text{TAM}}{1000} \times \text{Nex} \times 365.25$$

where,

N excreted _{State, Animal, WMS}	=	Amount of N excreted in manure managed in each WMS for each animal type (kg/yr)
Population _{state}	=	Annual average state animal population by animal type (head)
WMS	=	Distribution of manure by waste management system for each animal type in a state (percent)
TAM	=	Typical animal mass (kg)
Nex	=	Nitrogen excretion rate (kg N/1000 kg animal mass/day)
365.25	=	Days per year

Using the CEFM Nex data for cattle other than calves, the amount of N excreted was calculated using the following equation:

Equation A-39: Nex from Cattle Other Than Calves

$$\text{N excreted}_{\text{State, Animal, WMS}} = \text{Population}_{\text{State, Animal}} \times \text{WMS} \times \text{Nex}$$

where,

N excreted _{State, Animal, WMS}	=	Amount of N excreted in manure managed in each WMS for each animal type (kg/yr)
Population _{state}	=	Annual average state animal population by animal type (head)
WMS	=	Distribution of manure by waste management system for each animal type in a state (percent)
Nex	=	Nitrogen excretion rate (kg N/animal/year)

For all animals, direct N₂O emissions were calculated as follows:

Equation A-40: Direct N₂O emissions from All Animal Types

$$\text{Direct N}_2\text{O} = \sum_{\text{State, Animal, WMS}} \left(\text{N excreted}_{\text{State, Animal, WMS}} \times \text{EF}_{\text{WMS}} \times \frac{44}{28} \right)$$

where,

Direct N ₂ O	=	Direct N ₂ O emissions (kg N ₂ O/yr)
N excreted _{State, Animal, WMS}	=	Amount of N excreted in manure managed in each WMS for each animal type (kg/yr)
EF _{WMS}	=	Direct N ₂ O emission factor from IPCC guidelines (kg N ₂ O-N /kg N)
44/28	=	Conversion factor of N ₂ O-N to N ₂ O

Indirect N₂O emissions were calculated for all animals with the following equation:

Equation A-41: Indirect N₂O Emissions from All Animal Types

$$\text{Indirect N}_2\text{O} = \sum_{\text{State, Animal, WMS}} \left(\left[\text{N excreted}_{\text{State, Animal, WMS}} \times \frac{\text{Frac}_{\text{gas, WMS}}}{100} \times \text{EF}_{\text{volatilization}} \times \frac{44}{28} \right] + \left[\text{N excreted}_{\text{State, Animal, WMS}} \times \frac{\text{Frac}_{\text{runoff/leach, WMS}}}{100} \times \text{EF}_{\text{runoff/leach}} \times \frac{44}{28} \right] \right)$$

where,

Indirect N ₂ O	=	Indirect N ₂ O emissions (kg N ₂ O/yr)
N excreted _{State, Animal, WMS}	=	Amount of N excreted in manure managed in each WMS for each animal type (kg/yr)
Frac _{gas, WMS}	=	Nitrogen lost through volatilization in each WMS
Frac _{runoff/leach, WMS}	=	Nitrogen lost through runoff and leaching in each WMS (data were not available for leaching so the value reflects only runoff)
EF _{volatilization}	=	Emission factor for volatilization (0.010 kg N ₂ O-N/kg N)
EF _{runoff/leach}	=	Emission factor for runoff/leaching (0.0075 kg N ₂ O-N/kg N)
44/28	=	Conversion factor of N ₂ O-N to N ₂ O

Emission estimates of CH₄ and N₂O by animal type are presented for all years of the inventory in Table A-164 and Table A-166 respectively. Emission estimates for 2023 are presented by animal type and state in Table A-168 and Table A-170 respectively.

Table A-153: Livestock Population (1,000 Head)

Animal Type	1990	2005	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Dairy Cattle	19,512	17,793	18,505	18,517	18,812	18,857	18,923	19,006	18,882	18,792	18,859	18,626	18,380
Dairy Cows	10,015	9,004	9,221	9,209	9,312	9,312	9,369	9,432	9,353	9,343	9,442	9,377	9,398
Dairy Heifer	4,129	4,162	4,523	4,571	4,727	4,785	4,757	4,741	4,695	4,637	4,541	4,394	4,239
Dairy Calves	5,369	4,628	4,761	4,737	4,774	4,760	4,797	4,833	4,834	4,813	4,876	4,855	4,744
Swine^a	53,941	61,073	65,437	64,195	68,178	70,065	72,125	73,430	76,523	76,985	74,104	73,362	74,820
Market <50 lb.	18,359	20,228	19,002	18,939	19,843	20,572	20,973	21,359	21,853	22,423	21,182	21,086	21,460
Market 50-119 lb.	11,734	13,519	16,834	16,559	17,577	18,175	18,767	19,039	20,210	19,888	19,359	19,085	19,422
Market 120-179 lb.	9,440	11,336	12,674	12,281	13,225	13,575	13,982	14,311	14,852	14,850	14,463	14,405	14,873
Market >180 lb.	7,510	9,997	11,116	10,525	11,555	11,714	12,282	12,418	13,153	13,490	12,909	12,638	12,932
Breeding	6,899	5,993	5,812	5,892	5,978	6,030	6,122	6,303	6,455	6,333	6,191	6,147	6,132
Beef Cattle^b	81,576	82,193	76,010	74,966	76,149	79,323	81,385	81,722	81,699	81,060	81,102	79,389	76,640
Feedlot Steers	6,357	8,116	8,613	8,696	8,594	9,017	9,560	9,605	9,714	9,698	10,071	9,960	9,633
Feedlot Heifers	3,192	4,536	4,655	4,518	4,334	4,433	4,786	5,085	5,203	5,251	5,483	5,514	5,333
NOF Bulls	2,160	2,214	2,074	2,038	2,109	2,137	2,244	2,252	2,253	2,237	2,211	2,110	2,029
Beef Calves	16,909	16,918	14,805	14,737	14,998	15,546	15,931	16,221	15,892	15,830	15,602	15,244	14,893
NOF Heifers	10,182	9,550	8,780	8,730	9,291	9,892	9,790	9,460	9,201	9,091	9,205	8,896	8,425
NOF Steers	10,321	8,185	7,451	7,291	7,491	8,133	7,904	7,633	7,745	7,614	7,686	7,682	7,387
NOF Cows	32,455	32,674	29,631	28,956	29,332	30,164	31,171	31,466	31,691	31,339	30,844	29,983	28,939
Sheep	11,358	6,135	5,360	5,235	5,270	5,295	5,270	5,265	5,230	5,200	5,170	5,065	5,130
Sheep On Feed	1,180	2,976	2,658	2,588	2,587	2,624	2,618	2,623	2,616	2,611	2,596	2,550	2,583
Sheep NOF	10,178	3,159	2,702	2,647	2,683	2,671	2,652	2,642	2,614	2,589	2,574	2,515	2,547
Goats	2,516	2,897	2,637	2,652	2,668	2,683	2,699	2,714	2,729	2,745	2,760	2,776	2,791
Poultry^c	1,537,074	2,150,410	2,106,502	2,116,333	2,134,445	2,173,216	2,214,462	2,256,552	2,276,951	2,270,602	2,258,352	2,249,441	2,259,790
Hens >1 yr.	273,467	348,203	361,403	370,637	351,656	377,299	388,006	402,536	403,102	391,526	396,147	377,606	386,408
Pullets	73,167	96,809	106,646	106,490	118,114	112,061	117,173	124,729	121,971	121,171	123,481	128,590	128,488
Chickens	6,545	8,289	6,853	6,403	7,211	6,759	6,859	6,626	7,130	6,826	6,430	6,809	7,682
Broilers	1,066,209	1,613,091	1,551,600	1,553,636	1,579,764	1,595,764	1,620,691	1,643,327	1,668,582	1,676,745	1,660,127	1,666,436	1,664,545
Turkeys	117,685	84,018	80,000	79,167	77,700	81,333	81,733	79,333	76,167	74,333	72,167	70,000	72,667
Horses	2,212	3,875	3,467	3,312	3,157	3,002	2,847	2,692	2,538	2,383	2,228	2,073	1,918
Mules and Asses	63	212	298	303	308	313	318	323	328	333	338	343	348
American Bison	47	212	166	171	175	179	184	188	193	197	203	209	212

^a Prior to 2008, the Market <50 lbs category was <60 lbs and the Market 50-119 lbs category was Market 60-119 lbs; USDA updated the categories to be more consistent with international animal categories.

^b NOF - Not on Feed

^c Pullets includes laying pullets, pullets younger than 3 months, and pullets older than 3 months.

Source(s): See *Step 1: Livestock Population Characterization Data*.

Note: Totals may not sum due to independent rounding.

Table A-154: Waste Characteristics Data

	Typical Animal Mass, TAM		Total Nitrogen Excreted, Nex ^a		Maximum Methane Generation Potential, B ₀		Volatile Solids Excreted, VS ^a	
Animal Group	Value (kg)	Source	Value	Source	Value (m ³ CH ₄ /kg VS added)	Source	Value	Source
Dairy Cows	680	CEFM	Table A-156	CEFM	0.24	Morris 1976	Table A-156	CEFM
Dairy Heifers	406-408	CEFM	Table A-156	CEFM	0.17	Bryant et al. 1976	Table A-156	CEFM
Feedlot Steers	419-457	CEFM	Table A-156	CEFM	0.33	Hashimoto 1981	Table A-156	CEFM
Feedlot Heifers	384-430	CEFM	Table A-156	CEFM	0.33	Hashimoto 1981	Table A-156	CEFM
NOF Bulls	831-917	CEFM	Table A-156	CEFM	0.17	Hashimoto 1981	Table A-156	CEFM
NOF Calves	122-123	CEFM	Table A-156	USDA 1996, 2008	0.17	Hashimoto 1981	Table A-156	USDA 1996, 2008
NOF Heifers	296-407	CEFM	Table A-156	CEFM	0.17	Hashimoto 1981	Table A-156	CEFM
NOF Steers	314-335	CEFM	Table A-156	CEFM	0.17	Hashimoto 1981	Table A-156	CEFM
NOF Cows	554-611	CEFM	Table A-156	CEFM	0.17	Hashimoto 1981	Table A-156	CEFM
American Bison	578.5	Meagher 1986	Table A-156	CEFM	0.17	Hashimoto 1981	Table A-156	CEFM
Market Swine <50 lbs.	13	ERG 2010a	Table A-155	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-155	USDA 1996, 2008
Market Swine <60 lbs.	16	Safley 2000	Table A-155	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-155	USDA 1996, 2008
Market Swine 50-119 lbs.	39	ERG 2010a	Table A-155	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-155	USDA 1996, 2008
Market Swine 60-119 lbs.	41	Safley 2000	Table A-155	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-155	USDA 1996, 2008
Market Swine 120-179 lbs.	68	Safley 2000	Table A-155	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-155	USDA 1996, 2008
Market Swine >180 lbs.	91	Safley 2000	Table A-155	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-155	USDA 1996, 2008
Breeding Swine	198	Safley 2000	Table A-155	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-155	USDA 1996, 2008
Feedlot Sheep	25	EPA 1992	Table A-155	ASAE 1998, USDA 2008	0.36	EPA 1992	Table A-155	ASAE 1998, USDA 2008
NOF Sheep	80	EPA 1992	Table A-155	ASAE 1998, USDA 2008	0.19	EPA 1992	Table A-155	ASAE 1998, USDA 2008
Goats	64	ASAE 1998	Table A-155	ASAE 1998	0.17	EPA 1992	Table A-155	ASAE 1998
Horses	450	ASAE 1998	Table A-155	ASAE 1998, USDA 2008	0.33	EPA 1992	Table A-155	ASAE 1998, USDA 2008
Mules and Asses	130	IPCC 2006	Table A-155	IPCC 2006	0.33	EPA 1992	Table A-155	IPCC 2006
Hens >= 1 yr	1.8	ASAE 1998	Table A-155	USDA 1996, 2008	0.39	Hill 1982	Table A-155	USDA 1996, 2008
Pullets	1.8	ASAE 1998	Table A-155	USDA 1996, 2008	0.39	Hill 1982	Table A-155	USDA 1996, 2008
Other Chickens	1.8	ASAE 1998	Table A-155	USDA 1996, 2008	0.39	Hill 1982	Table A-155	USDA 1996, 2008
Broilers	0.9	ASAE 1998	Table A-155	USDA 1996, 2008	0.36	Hill 1984	Table A-155	USDA 1996, 2008
Turkeys	6.8	ASAE 1998	Table A-155	USDA 1996, 2008	0.36	Hill 1984	Table A-155	USDA 1996, 2008

^a Nex and VS values vary by year; Table A-156 shows state-level values for 2022 only.

Table A-155: Estimated Volatile Solids (VS) and Total Nitrogen Excreted (Nex) Production Rates by year for Swine, Poultry, Sheep, Goats, Horses, Mules and Asses, and Cattle Calves (kg/day/1000 kg animal mass)^a

Animal Type	1990	2005	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
VS																	
Swine, Market <50 lbs.	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8
Swine, Market 50-119 lbs.	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
Swine, Market 120-179 lbs.	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
Swine, Market >180 lbs.	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
Swine, Breeding	2.6	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
NOF Cattle Calves	6.4	7.4	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7
Sheep	9.2	8.6	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3
Goats	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
Hens >1yr.	10.1	10.1	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2
Pullets	10.1	10.1	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2
Chickens	10.8	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
Broilers	15.0	16.5	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0
Turkeys	9.7	8.8	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
Horses	10.0	7.3	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
Mules and Asses	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2
Nex																	
Swine, Market <50 lbs.	0.60	0.84	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
Swine, Market 50-119 lbs.	0.42	0.51	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
Swine, Market 120-179 lbs.	0.42	0.51	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
Swine, Market >180 lbs.	0.42	0.51	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
Swine, Breeding	0.24	0.21	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
NOF Cattle Calves	0.30	0.41	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Sheep	0.42	0.44	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Goats	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45

Animal Type	1990	2005	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Hens >1yr.	0.70	0.77	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79
Pullets	0.70	0.77	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79
Chickens	0.83	1.03	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
Broilers	1.10	1.00	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96
Turkeys	0.74	0.65	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63
Horses	0.30	0.26	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Mules and Asses	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30

^a This table has not been updated for the current (1990 through 2023) Inventory. It will be updated for the next (1990 through 2024) Inventory.

Table A-156: Estimated Volatile Solids (VS) and Total Nitrogen Excreted (Nex) Production Rates by State for Cattle (other than Calves) and American Bison^a for 2022 (kg/animal/year)^a

State	Volatile Solids									Nitrogen Excreted								
			Beef		Beef		Beef		Ameri can Bison ^b			Beef		Beef		Beef	Beef	Ameri can Bison ^b
	Dairy Cow	Dairy Heifer s	Beef NOF Cow	Beef Heifer s	Beef NOF Steer	Beef OF Heifer s	Beef OF Steer	Beef NOF Bull		Dairy Cow	Dairy Heifer s	Beef NOF Cow	Beef Heifer s	Beef NOF Steer	Beef OF Heifer s			
Alabama	1,951	1,255	1,665	1,096	974	637	622	1,721	1,721	122	69	73	50	42	59	61	83	83
Alaska	1,099	1,255	1,892	1,268	1,120	637	622	1,956	1,956	84	69	59	42	33	59	61	69	69
Arizona	2,911	1,255	1,892	1,239	1,120	637	622	1,956	1,956	162	69	59	40	33	59	61	69	69
Arkansas	1,945	1,255	1,665	1,093	974	637	622	1,721	1,721	120	69	73	50	42	59	61	83	83
California	2,895	1,255	1,892	1,219	1,120	637	622	1,956	1,956	160	69	59	39	33	59	61	69	69
Colorado	3,038	1,255	1,892	1,196	1,120	637	622	1,956	1,956	167	69	59	38	33	59	61	69	69
Connecticut	2,886	1,255	1,674	1,093	980	637	622	1,731	1,731	161	69	74	50	42	59	61	84	84
Delaware	2,432	1,255	1,674	1,101	980	637	622	1,731	1,731	141	69	74	51	42	59	61	84	84
Florida	2,644	1,255	1,665	1,108	974	637	623	1,721	1,721	152	69	73	51	42	59	61	83	83
Georgia	2,803	1,255	1,665	1,105	974	637	622	1,721	1,721	159	69	73	51	42	59	61	83	83
Hawaii	1,099	1,255	1,892	1,259	1,120	637	622	1,956	1,956	84	69	59	41	33	59	61	69	69
Idaho	2,995	1,255	1,892	1,213	1,120	637	622	1,956	1,956	165	69	59	39	33	59	61	69	69
Illinois	2,702	1,255	1,589	1,014	927	637	622	1,643	1,643	153	69	75	50	43	59	61	85	85
Indiana	2,874	1,255	1,589	1,020	927	637	622	1,643	1,643	160	69	75	50	43	59	61	85	85
Iowa	2,944	1,255	1,589	993	927	637	622	1,643	1,643	163	69	75	48	43	59	61	85	85
Kansas	2,891	1,255	1,589	982	927	637	622	1,643	1,643	161	69	75	47	43	59	61	85	85
Kentucky	2,693	1,255	1,665	1,082	974	637	622	1,721	1,721	154	69	73	49	42	59	61	83	83
Louisiana	2,034	1,255	1,665	1,106	974	637	622	1,721	1,721	124	69	73	51	42	59	61	83	83
Maine	2,693	1,255	1,674	1,093	980	637	622	1,731	1,731	152	69	74	50	42	59	61	84	84
Maryland	2,635	1,255	1,674	1,095	980	637	621	1,731	1,731	150	69	74	51	42	59	61	84	84
Massachusetts	2,662	1,255	1,674	1,108	980	637	622	1,731	1,731	151	69	74	52	42	59	61	84	84
Michigan	3,151	1,255	1,589	1,009	927	637	622	1,643	1,643	172	69	75	49	43	59	61	85	85

State	Volatile Solids									Nitrogen Excreted								
	Dairy			Beef			Beef			Beef			Beef			Beef		
	Dairy Cow	Dairy Heifers	Beef NOF Cow	Beef NOF Heifers	Beef NOF Steer	Beef OF Heifers	Beef OF Steer	Beef NOF Bull	American Bison ^b	Dairy Cow	Dairy Heifers	Beef NOF Cow	Beef NOF Heifers	Beef NOF Steer	Beef OF Heifers	Beef OF Steer	Beef NOF Bull	American Bison ^b
Minnesota	2,829	1,255	1,589	1,013	927	637	622	1,643	1,643	158	69	75	49	43	59	61	85	85
Mississippi	2,115	1,255	1,665	1,098	974	637	622	1,721	1,721	129	69	73	50	42	59	61	83	83
Missouri	2,150	1,255	1,589	1,033	927	637	622	1,643	1,643	129	69	75	51	43	59	61	85	85
Montana	2,767	1,255	1,892	1,253	1,120	637	622	1,956	1,956	155	69	59	41	33	59	61	69	69
Nebraska	2,957	1,255	1,589	989	927	637	622	1,643	1,643	164	69	75	48	43	59	61	85	85
Nevada	2,955	1,255	1,892	1,247	1,120	637	622	1,956	1,956	164	69	59	40	33	59	61	69	69
New Hampshire	2,737	1,255	1,674	1,095	980	637	622	1,731	1,731	154	69	74	51	42	59	61	84	84
New Jersey	2,726	1,255	1,674	1,091	980	637	621	1,731	1,731	154	69	74	50	42	59	61	84	84
New Mexico	2,956	1,255	1,892	1,239	1,120	637	622	1,956	1,956	164	69	59	40	33	59	61	69	69
New York	2,976	1,255	1,674	1,086	980	637	622	1,731	1,731	164	69	74	50	42	59	61	84	84
North Carolina	2,903	1,255	1,665	1,098	974	637	622	1,721	1,721	163	69	73	50	42	59	61	83	83
North Dakota	2,804	1,255	1,589	1,020	927	637	622	1,643	1,643	157	69	75	50	43	59	61	85	85
Ohio	2,751	1,255	1,589	1,028	927	637	622	1,643	1,643	155	69	75	51	43	59	61	85	85
Oklahoma	2,475	1,255	1,665	1,071	974	637	622	1,721	1,721	143	69	73	48	42	59	61	83	83
Oregon	2,664	1,255	1,892	1,234	1,120	637	621	1,956	1,956	151	69	59	40	33	59	60	69	69
Pennsylvania	2,689	1,255	1,674	1,087	980	637	622	1,731	1,731	152	69	74	50	42	59	61	84	84
Rhode Island	2,595	1,255	1,674	1,086	980	637	622	1,731	1,731	148	69	74	50	42	59	61	84	84
South Carolina	2,492	1,255	1,665	1,103	974	637	622	1,721	1,721	145	69	73	51	42	59	61	83	83
South Dakota	2,828	1,255	1,589	1,019	927	637	622	1,643	1,643	158	69	75	50	43	59	61	85	85
Tennessee	2,522	1,255	1,665	1,087	974	637	622	1,721	1,721	147	69	73	50	42	59	61	83	83
Texas	3,017	1,255	1,665	1,056	974	637	622	1,721	1,721	166	69	73	47	42	59	61	83	83
Utah	2,844	1,255	1,892	1,243	1,120	637	622	1,956	1,956	159	69	59	40	33	59	61	69	69
Vermont	2,718	1,255	1,674	1,076	980	637	622	1,731	1,731	153	69	74	49	42	59	61	84	84
Virginia	2,675	1,255	1,665	1,085	974	637	622	1,721	1,721	153	69	73	49	42	59	61	83	83
Washington	2,901	1,255	1,892	1,213	1,120	637	622	1,956	1,956	161	69	59	39	33	59	61	69	69
West Virginia	2,221	1,255	1,674	1,093	980	637	622	1,731	1,731	132	69	74	51	42	59	61	84	84
Wisconsin	2,974	1,255	1,589	1,026	927	637	622	1,643	1,643	164	69	75	50	43	59	61	85	85
Wyoming	3,026	1,255	1,892	1,241	1,120	637	622	1,956	1,956	167	69	59	40	33	59	61	69	69

^a This table has not been updated for the current (1990 through 2023) Inventory. It will be updated for the next (1990 through 2024) Inventory.

^b Beef NOF Bull values were used for American bison Nex and VS.

Source: CEFM.

Table A-157: 2022 Manure Distribution Among Waste Management Systems by Operation for Cattle (Percent)^a

	Beef Feedlot Operations								Beef Not on Feed Operations
State	Dry Lot ^b	Liquid/ Slurry ^b	Pasture, Range, Paddock ^b	Solid Storage	Deep Pit	Daily Spread ^b	Composting	Cattle Deep Litter	Pasture, Range, Paddock
Alabama	80	0	9	5	0	5	0	2	100
Alaska	67	0	33	0	0	0	0	0	100
Arizona	49	2	3	45	0	0	0	0	100
Arkansas	35	0	28	13	0	18	0	6	100
California	50	2	0	45	0	0	2	0	100
Colorado	52	10	1	37	0	0	0	0	100
Connecticut	35	0	29	20	0	8	2	6	100
Delaware	65	0	14	8	0	9	0	4	100
Florida	100	0	0	0	0	0	0	0	100
Georgia	100	0	0	0	0	0	0	0	100
Hawaii	58	0	17	25	0	0	0	0	100
Idaho	50	0	0	50	0	0	0	0	100
Illinois	8	13	10	12	24	1	0	32	100
Indiana	34	10	6	27	4	0	1	18	100
Iowa	37	0	0	46	8	0	0	9	100
Kansas	27	8	5	32	11	0	2	16	100
Kentucky	57	0	19	13	0	9	0	3	100
Louisiana	35	0	28	13	0	19	0	6	100
Maine	93	0	3	2	0	2	0	1	100
Maryland	58	0	19	11	0	8	1	4	100
Massachusetts	46	0	5	1	0	44	2	2	100
Michigan	32	10	5	28	5	0	1	17	100
Minnesota	31	9	5	29	6	0	1	17	100
Mississippi	100	0	0	0	0	0	0	0	100
Missouri	68	0	0	16	0	0	5	10	100
Montana	48	0	4	48	0	0	0	0	100
Nebraska	45	0	2	49	1	0	0	3	100
Nevada	61	0	4	34	0	0	0	0	100
New Hampshire	35	0	28	14	0	17	0	6	100
New Jersey	20	0	55	20	0	0	0	4	100
New Mexico	50	2	3	45	0	0	0	0	100
New York	44	0	24	14	0	12	1	5	100
North Carolina	50	0	0	25	0	25	0	0	100
North Dakota	37	37	25	1	0	0	0	1	100

Ohio	2	2	0	47	2	1	0	47	100
Oklahoma	49	2	3	45	0	0	0	0	100
Oregon	50	2	0	46	0	0	2	0	100
Pennsylvania	48	0	23	12	0	11	1	5	100
Rhode Island	35	0	29	20	0	8	2	6	100
South Carolina	35	0	29	19	0	9	2	6	100
South Dakota	29	9	5	30	8	0	2	17	100
Tennessee	83	0	8	4	0	3	0	2	100
Texas	49	2	3	45	0	0	0	0	100
Utah	50	1	11	36	0	0	0	0	100
Vermont	61	0	17	9	0	9	1	4	100
Virginia	47	0	39	3	0	2	0	8	100
Washington	50	2	0	45	0	0	2	0	100
West Virginia	59	0	18	9	0	10	0	4	100
Wisconsin	37	18	1	22	3	0	1	19	100
Wyoming	50	2	5	43	0	0	0	0	100

^a This table has not been updated for the current (1990 through 2023) Inventory. It will be updated for the next (1990 through 2024) Inventory.

^b Deep pit systems are their own manure management systems in the U.S. but are included under Liquid Systems in the common data tables due to lack of a separate allocation for those systems within the tables. For Beef Feedlots and Dairy Cows, solid storage and dry lot systems calculated separately in Table A-157, but are reported as “NE” in the common data tables due to lack of a separate allocation for those systems within the tables.

^c In the methane inventory for manure management, the percent of dairy cows and swine with AD systems is estimated using data from EPA’s AgSTAR Program.

	Dairy Cow Farms ^c								Dairy Heifer Facilities			
State	Pasture, Range, Paddock	Daily Spread	Dry Lot	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Anaerobic Digester	Daily Spread ^b	Dry Lot ^b	Liquid/ Slurry ^b	Pasture, Range, Paddock ^b
Alabama	48	0	0	14	2	22	14	0	17	38	0	45
Alaska	25	12	0	26	5	9	22	0	6	90	1	4
Arizona	10	0	11	26	6	15	2	30	10	90	0	0
Arkansas	47	0	0	13	3	23	14	0	15	28	0	57
California	5	0	3	26	2	24	9	30	11	88	1	1
Colorado	11	0	11	41	5	30	2	0	1	98	0	1
Connecticut	15	3	0	16	6	32	26	3	43	51	0	6
Delaware	14	2	0	18	7	29	31	0	44	50	0	6
Florida	48	0	0	7	0	34	4	7	22	61	1	17
Georgia	48	0	0	9	1	36	6	0	18	42	0	40
Hawaii	4	0	4	27	2	54	9	0	0	99	1	1
Idaho	5	0	3	26	2	45	10	8	1	99	0	0
Illinois	24	0	0	23	2	33	18	1	8	87	0	5
Indiana	21	0	0	21	1	21	16	21	13	79	0	8

Iowa	20	0	0	21	2	40	16	1	10	83	0	6
Kansas	14	0	0	16	1	55	13	0	5	92	0	3
Kentucky	51	0	0	14	2	23	11	0	14	24	0	61
Louisiana	48	0	0	13	3	23	12	0	14	26	0	60
Maine	18	4	0	16	5	24	28	6	45	48	0	7
Maryland	21	4	0	16	6	23	29	0	44	49	0	7
Massachusetts	25	5	0	12	0	1	30	27	45	47	0	7
Michigan	11	3	0	22	5	34	22	4	6	91	0	3
Minnesota	16	6	0	24	5	21	23	6	10	84	0	6
Mississippi	50	0	0	14	2	16	11	6	15	28	0	57
Missouri	29	0	0	25	2	26	17	0	14	77	0	8
Montana	19	0	0	21	4	31	18	7	4	93	0	3
Nebraska	15	0	0	18	2	50	15	0	6	90	0	4
Nevada	11	0	0	14	2	61	13	0	0	99	0	0
New Hampshire	21	4	0	17	5	22	31	0	44	49	0	7
New Jersey	27	5	0	16	6	16	29	0	45	47	0	8
New Mexico	10	0	11	42	6	30	2	0	10	90	0	0
New York	14	3	0	15	0	34	25	9	45	48	0	7
North Carolina	48	0	0	10	2	31	9	0	15	31	0	54
North Dakota	18	0	0	19	3	44	16	0	11	83	0	6
Ohio	24	0	0	23	2	32	17	3	14	78	0	8
Oklahoma	11	0	8	41	5	23	12	0	6	94	0	0
Oregon	9	0	3	24	4	17	11	33	0	80	1	20
Pennsylvania	27	6	0	16	2	17	29	3	47	44	0	9
Rhode Island	29	6	0	17	5	14	30	0	47	44	0	9
South Carolina	45	0	0	10	2	33	11	0	15	31	0	54
South Dakota	14	0	0	16	2	53	14	1	8	87	0	5
Tennessee	48	0	0	12	2	26	11	0	15	26	0	59
Texas	11	0	10	41	5	18	3	12	8	92	0	0
Utah	12	0	9	40	3	28	7	1	1	98	0	1
Vermont	14	3	0	16	0	27	26	13	44	49	0	7
Virginia	49	0	0	12	1	26	11	2	15	28	0	57
Washington	8	0	3	25	3	46	10	6	0	83	1	17
West Virginia	29	6	0	17	5	13	30	0	45	48	0	7
Wisconsin	15	5	0	24	3	23	23	7	12	82	0	7
Wyoming	16	0	0	18	2	49	15	0	12	81	0	7

^a This table has not been updated for the current (1990 through 2023) Inventory. It will be updated for the next (1990 through 2024) Inventory.

^b Deep pit systems are their own manure management systems in the U.S. but are included under Liquid Systems in the common data tables due to lack of a separate allocation for those systems within the tables. For Beef Feedlots and Dairy Cows, solid storage and dry lot systems calculated separately in Table A-157, but are reported as “NE” in the common data tables due to lack of a separate allocation for those systems within the tables.

^c In the methane inventory for manure management, the percent of dairy cows and swine with AD systems is estimated using data from EPA’s AgSTAR Program.

Table A-158: 2022 Manure Distribution Among Waste Management Systems by Operation for Livestock Other Than Cattle (Percent)^a

	Swine Operations ^b							Layer Operations ^b							
	Pasture, Range, Paddock	Solid Storage	Liquid/Slurry	Anaerobic Lagoon	Deep Pit (<1 month)	Anaerobic Digester		Anaerobic Lagoon	Poultry without Litter	Poultry with Litter	Pasture, Range, Paddock	Liquid/Slurry	Composting	Solid Storage	Anaerobic Digester
State															
Alabama	15	0	29	30	12	14	0	0	8	50	0	8	0	33	0
Alaska	57	0	3	2	34	4	0	0	0	96	2	0	0	2	0
Arizona	19	0	28	29	11	13	0	0	15	34	2	1	6	42	0
Arkansas	6	0	60	24	5	2	3	0	0	75	0	0	0	25	0
California	15	0	28	29	13	14	0	0	0	68	11	0	11	10	0
Colorado	2	0	52	0	23	22	1	0	0	52	0	0	7	41	0
Connecticut	66	0	2	2	26	4	0	1	21	29	2	10	7	31	0
Delaware	29	0	4	5	56	5	0	0	50	0	0	0	0	50	0
Florida	53	0	20	14	9	5	0	0	25	25	0	25	0	25	0
Georgia	13	0	56	27	3	1	0	0	8	50	0	8	0	33	0
Hawaii	42	0	22	18	11	7	0	0	0	68	11	0	11	10	0
Idaho	16	0	16	3	57	8	0	0	0	46	8	0	15	31	0
Illinois	2	0	15	7	71	5	0	0	50	0	0	0	5	45	0
Indiana	1	0	3	12	78	7	0	0	42	8	4	0	1	45	0
Iowa	1	0	10	4	80	5	0	0	45	2	5	0	0	48	0
Kansas	1	0	13	35	21	30	0	0	42	8	4	0	1	45	0
Kentucky	8	0	19	21	31	21	0	1	18	29	2	10	7	31	3
Louisiana	67	0	17	9	6	2	0	0	0	50	0	0	0	50	0
Maine	74	0	2	1	20	4	0	1	21	29	2	10	7	31	0
Maryland	37	0	10	2	44	6	0	1	17	29	2	10	7	31	4
Massachusetts	60	0	2	2	31	4	0	0	4	44	8	0	21	21	0
Michigan	3	0	12	6	69	9	0	0	42	8	4	0	1	45	0
Minnesota	1	0	3	2	88	5	0	0	42	8	4	0	1	45	0
Mississippi	2	0	31	32	13	18	4	0	8	50	0	8	0	33	0
Missouri	2	0	16	24	34	15	10	1	13	45	10	1	0	31	0
Montana	3	0	21	2	64	9	0	0	10	40	0	3	0	47	0
Nebraska	2	0	9	22	49	19	0	0	48	0	5	0	0	48	0
Nevada	12	0	29	32	12	15	0	0	15	34	2	1	6	42	0
New Hampshire	65	0	2	2	27	4	0	1	21	29	2	10	7	31	0
New Jersey	54	0	3	3	36	4	0	0	50	0	0	50	0	0	0
New Mexico	67	0	17	9	6	2	0	0	15	34	2	1	6	42	0
New York	41	0	6	3	44	5	0	1	21	29	2	10	7	31	0
North Carolina	1	0	33	46	1	16	2	3	0	50	0	0	0	48	0
North Dakota	2	0	21	2	65	9	0	0	42	8	4	0	1	45	0

Ohio	1	0	10	9	67	13	0	0	45	1	2	0	0	49	3
Oklahoma	1	0	11	53	2	32	1	0	15	34	2	1	6	42	0
Oregon	51	0	20	15	9	5	0	0	0	40	20	0	22	18	0
Pennsylvania	1	0	8	4	76	9	2	1	21	29	2	10	7	31	0
Rhode Island	64	0	2	2	28	4	0	1	21	29	2	10	7	31	0
South Carolina	6	0	30	28	13	16	6	0	4	50	0	8	0	33	4
South Dakota	1	0	17	11	57	14	0	0	42	8	4	0	1	45	0
Tennessee	7	0	30	33	13	16	0	1	21	29	2	10	7	31	0
Texas	6	0	31	20	13	17	14	0	15	34	2	1	6	42	0
Utah	1	0	22	2	36	9	30	0	50	0	0	0	0	50	0
Vermont	69	0	2	1	24	4	0	1	21	29	2	10	7	31	0
Virginia	6	0	14	29	15	35	0	0	0	50	0	0	15	35	0
Washington	35	0	12	2	45	7	0	0	0	68	11	0	11	10	0
West Virginia	82	0	1	0	13	3	0	1	21	29	2	10	7	31	0
Wisconsin	15	0	23	1	57	4	0	0	50	0	0	0	0	50	0
Wyoming	3	0	21	2	59	9	5	0	15	34	2	1	6	42	0

^a This table has not been updated for the current (1990 through 2023) *Inventory*. It will be updated for the next (1990 through 2024) *Inventory*.

^b In the methane inventory for manure management, the percent of dairy cows and swine with AD systems is estimated using data from EPA's AgSTAR Program. Deep pit and Poultry with/without litter systems are their own manure management systems in the U.S. but are included under Liquid Systems and Other, respectively, in the common data tables due to lack of a separate allocation for those systems within the tables.

Source: See *Step 3: Waste Management System Usage Data*.

	Broiler Operations ^b						Turkey Operations		Sheep	
State	Pasture, Range, Paddock	Poultry with Litter	Poultry without Litter	Compostin g	Solid Storage	Anaerobic Digester	Pasture, Range, Paddock	Poultry with Litter	Dry Lot	Pasture, Range, Paddock
Alabama	0	58	0	1	41	0	1	99	95	5
Alaska	5	0	90	0	5	0	1	99	31	69
Arizona	3	49	0	7	42	0	1	99	28	72
Arkansas	0	75	0	0	25	0	1	99	83	18
California	3	25	45	0	27	0	1	99	31	69
Colorado	0	50	0	5	45	0	1	99	28	72
Connecticut	4	59	2	3	32	0	1	99	95	5
Delaware	0	50	0	0	50	0	1	99	95	5
Florida	0	50	0	0	50	0	1	99	95	5
Georgia	0	58	0	1	41	0	1	99	95	5
Hawaii	3	25	45	0	27	0	1	99	31	69
Idaho	8	46	0	15	31	0	1	99	28	72
Illinois	0	50	0	0	50	0	1	99	83	18
Indiana	2	56	0	0	42	0	1	99	83	18
Iowa	0	50	0	0	50	0	1	99	83	18

Kansas	2	56	0	0	42	0	1	99	83	18
Kentucky	4	59	2	3	32	0	1	99	95	5
Louisiana	0	50	0	3	48	0	1	99	83	18
Maine	4	59	2	3	32	0	1	99	95	5
Maryland	4	59	2	3	32	0	1	99	95	5
Massachusetts	15	46	9	3	27	0	1	99	95	5
Michigan	2	56	0	0	42	0	1	99	83	18
Minnesota	2	56	0	0	42	0	1	99	83	18
Mississippi	0	58	0	1	41	0	1	99	95	5
Missouri	8	39	0	0	52	0	1	99	83	18
Montana	0	50	0	0	50	0	1	99	28	72
Nebraska	1	50	1	0	47	0	1	99	83	18
Nevada	3	49	0	7	42	0	1	99	28	72
New Hampshire	4	59	2	3	32	0	1	99	95	5
New Jersey	0	100	0	0	0	0	1	99	95	5
New Mexico	3	49	0	7	42	0	1	99	28	72
New York	4	59	2	3	32	0	1	99	95	5
North Carolina	0	50	0	0	50	0	1	99	95	5
North Dakota	2	56	0	0	42	0	1	99	83	18
Ohio	2	96	0	0	2	0	1	99	95	5
Oklahoma	3	49	0	7	42	0	1	99	83	18
Oregon	0	50	0	0	50	0	1	99	31	69
Pennsylvania	4	59	2	3	32	0	1	99	95	5
Rhode Island	4	59	2	3	32	0	1	99	95	5
South Carolina	0	58	0	1	41	0	1	99	95	5
South Dakota	2	56	0	0	42	0	1	99	83	18
Tennessee	4	59	2	3	32	0	1	99	95	5
Texas	3	49	0	7	42	0	1	99	28	72
Utah	3	49	0	7	42	0	1	99	28	72
Vermont	4	59	2	3	32	0	1	99	95	5
Virginia	5	48	0	14	33	0	1	99	95	5
Washington	3	25	45	0	27	0	1	99	31	69
West Virginia	4	59	2	3	32	0	1	99	95	5
Wisconsin	0	50	0	0	50	0	1	99	83	18
Wyoming	3	49	0	7	42	0	1	99	28	72

^a In the methane inventory for manure management, the percent of dairy cows and swine with AD systems is estimated using data from EPA's AgSTAR Program. Deep pit and Poultry with/without Litter systems are their own manure management systems in the U.S. but are included under Liquid Systems and Other, respectively, in the common data tables due to lack of a separate allocation for those systems within the tables.
Source(s): See *Step 3: Waste Management System Usage Data*.

Table A-159: Manure Management System Descriptions

Manure Management System	Description
Pasture, Range, Paddock	The manure from pasture and range grazing animals is allowed to lie as is and is not managed. Methane emissions are accounted for under Manure Management, but the N ₂ O emissions from manure deposited on PRP are included under the Agricultural Soil Management category.
Daily Spread	Manure is routinely removed from a confinement facility and is applied to cropland or pasture within 24 hours of excretion. Methane and indirect N ₂ O emissions are accounted for under Manure Management. Direct N ₂ O emissions from land application are included under the Agricultural Soil Management category.
Solid Storage	The storage of manure, typically for a period of several months, in unconfined piles or stacks. Manure is able to be stacked due to the presence of a sufficient amount of bedding material or loss of moisture by evaporation.
Composting	Composting in windrows with regular (at least daily) turning for mixing and aeration, with or without runoff/leaching containment.
Dry Lot	A paved or unpaved open confinement area without any significant vegetative cover where accumulating manure may be removed periodically. Dry lots are most typically found in dry climates but also are used in humid climates.
Liquid/Slurry	Manure is stored as excreted or with some minimal addition of water to facilitate handling and is stored in either tanks or earthen ponds, usually for periods less than one year.
Anaerobic Lagoon	Uncovered anaerobic lagoons are designed and operated to combine waste stabilization and storage. Lagoon supernatant is usually used to remove manure from the associated confinement facilities to the lagoon. Anaerobic lagoons are designed with varying lengths of storage (up to a year or greater), depending on the climate region, the VS loading rate, and other operational factors. Anaerobic lagoons accumulate sludge over time, diminishing treatment capacity. Lagoons must be cleaned out once every 5 to 15 years, and the sludge is typically applied to agricultural lands. The water from the lagoon may be recycled as flush water or used to irrigate and fertilize fields. Lagoons are sometimes used in combination with a solids separator, typically for dairy waste. Solids separators help control the buildup of nondegradable material such as straw or other bedding materials.
Anaerobic Digester	Animal excreta with or without straw are collected and anaerobically digested in a large containment vessel (complete mix or plug flow digester) or covered lagoon. Digesters are designed and operated for waste stabilization by the microbial reduction of complex organic compounds to CO ₂ and CH ₄ , which is captured and flared or used as a fuel.
Deep Pit	Collection and storage of manure usually with little or no added water typically below a slatted floor in an enclosed animal confinement facility. Typical storage periods range from 5 to 12 months, after which manure is removed from the pit and transferred to a treatment system or applied to land.
Poultry with Litter	Enclosed poultry houses use bedding derived from wood shavings, rice hulls, chopped straw, peanut hulls, or other products, depending on availability. The bedding absorbs moisture and dilutes the manure produced by the birds. Litter is typically cleaned out completely once a year. These manure systems are typically used for all poultry breeder flocks and for the production of meat type chickens (broilers) and other fowl.
Poultry without Litter	In high-rise cages or scrape-out/belt systems, manure is excreted onto the floor below with no bedding to absorb moisture. The ventilation system dries the manure as it is

stored. When designed and operated properly, this high-rise system is a form of passive windrow composting.

^a Manure management system descriptions and the classification of manure as managed or unmanaged are based on the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Volume 4: Agriculture, Forestry and Other Land Use, Chapter 10: Emissions from Livestock and Manure Management, Tables 10.18 and 10.21) and the Development Document for the Final Revisions to the National Pollutant Discharge Elimination System Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations (EPA-821-R-03-001, December 2002).

Table A-160: Methane Conversion Factors (Percent) for Dry Systems

Waste Management System	Temperate Climate		
	Cool Climate MCF	MCF	Warm Climate MCF
Aerobic Treatment	0	0	0
Anaerobic Digester	0	0	0
Cattle Deep Litter (<1 month)	2.75	6.5	18
Cattle Deep Litter (>1 month)	20	39	67.5
Composting - In Vessel	0.5	0.5	0.5
Composting - Static Pile	1	2	2.5
Composting-Extensive/Passive	1	2	2.5
Composting-Intensive	0.5	1	1.5
Daily Spread	0.1	0.5	1
Dry Lot	1	1.5	2
Fuel	10	10	10
Pasture	0.47	0.47	0.47
Poultry with bedding	1.5	1.5	1.5
Poultry without bedding	1.5	1.5	1.5
Solid Storage	2	4	5

Source: IPCC (2019).

Table A-161: Methane Conversion Factors by State for Liquid Systems for 2022 (Percent)¹¹¹

State	Dairy		Swine		Beef	Poultry	
	Anaerobic Lagoon	Liquid/Slurry and Deep Pit	Anaerobic Lagoon	Liquid/Slurry and Pit Storage	Liquid/Slurry and Deep Pit	Anaerobic Lagoon	Liquid/Slurry
Alabama	74	40	74	40	42	74	40
Alaska	48	15	48	15	15	48	15
Arizona	78	58	76	47	44	75	37
Arkansas	74	38	75	41	39	74	39
California	75	34	75	34	45	75	34
Colorado	67	23	70	26	25	66	22
Connecticut	71	27	71	26	27	71	27
Delaware	74	32	74	33	32	74	33
Florida	78	58	77	56	52	77	56
Georgia	75	43	75	41	48	74	40
Hawaii	77	59	77	59	59	77	59

¹¹¹ This table has not been updated for the current (1990 through 2023) *Inventory*. It will be updated for the next (1990 through 2024) *Inventory*.

Idaho	71	25	67	22	23	66	22
Illinois	72	30	72	29	29	72	30
Indiana	71	28	71	28	28	71	28
Iowa	70	26	70	27	27	70	27
Kansas	75	35	75	34	35	75	35
Kentucky	73	33	73	34	32	73	34
Louisiana	76	49	75	48	50	75	47
Maine	65	22	65	22	22	65	22
Maryland	73	31	73	32	31	73	31
Massachusetts	69	25	70	26	26	70	26
Michigan	68	24	68	25	25	68	24
Minnesota	68	24	69	25	25	68	24
Mississippi	75	44	75	43	46	75	44
Missouri	74	34	73	32	32	74	34
Montana	63	20	66	22	22	66	22
Nebraska	73	29	73	29	29	73	29
Nevada	72	27	72	27	25	73	30
New Hampshire	66	23	67	23	22	66	23
New Jersey	73	30	73	30	29	73	30
New Mexico	73	33	71	28	31	72	30
New York	67	23	68	24	24	67	24
North Carolina	73	34	75	39	34	73	35
North Dakota	67	23	66	22	23	67	23
Ohio	70	27	71	28	28	71	28
Oklahoma	76	43	75	39	39	75	43
Oregon	67	23	66	22	23	66	22
Pennsylvania	71	27	71	27	27	72	29
Rhode Island	71	27	71	27	27	71	27
South Carolina	75	41	75	42	39	75	41
South Dakota	70	26	70	26	26	70	26
Tennessee	73	33	74	37	34	73	35
Texas	75	43	75	46	43	76	52
Utah	67	23	66	22	24	68	23
Vermont	64	21	64	21	21	64	21
Virginia	71	29	74	34	29	72	31
Washington	67	22	67	22	24	67	23
West Virginia	70	27	70	27	26	70	26
Wisconsin	66	23	68	24	24	68	25
Wyoming	64	20	65	21	23	65	21

Note: MCFs developed using Tier 2 methods described in 2006 IPCC Guidelines, Section 10.4.2.

Table A-162: Direct Nitrous Oxide Emission Factors (kg N₂O-N/kg N excreted)

Waste Management System	Direct N ₂ O Emission Factor
Aerobic Treatment (forced aeration)	0.005
Aerobic Treatment (natural aeration)	0.01
Anaerobic Digester	0.0006
Anaerobic Lagoon	0
Cattle Deep Bedding/Litter (active mix)	0.07
Cattle Deep Bedding/Litter (no mix)	0.01
Composting_in vessel	0.006
Composting_intensive	0.005
Composting_passive	0.01
Composting_static	0.01
Daily Spread	0

Pit Storage	0.002
Dry Lot	0.02
Fuel	0
Liquid/Slurry	0.005
Pasture	0
Poultry with bedding	0.001
Poultry without bedding	0.001
Solid Storage	0.01

Source: IPCC (2006).

Table A-163: Indirect Nitrous Oxide Loss Factors (Percent)

Animal Type	Waste Management System	Volatilization Nitrogen Loss	Runoff/Leaching Nitrogen Loss ^a				
			Central	Pacific	Mid-Atlantic	Midwest	South
Beef Cattle	Daily Spread	7	0	0	0	0	0
Beef Cattle	Deep Pit	25	0	0	0	0	0
Beef Cattle	Dry Lot	23	1.1	3.9	3.6	1.9	4.3
Beef Cattle	Liquid/Slurry	26	0	0	0	0	0
Beef Cattle	Pasture	0	0	0	0	0	0
Beef Cattle	Solid Storage	45	0.02	0.02	0.02	0.02	0.02
Beef Cattle	Cattle Deep Litter (>1 month)	25	0.035	0.035	0.035	0.035	0.035
Beef Cattle	Composting intensive	65	0.06	0.06	0.06	0.06	0.06
Dairy Cattle	Anaerobic Lagoon	43	0.2	0.8	0.7	0.4	0.9
Dairy Cattle	Daily Spread	10	0	0	0	0	0
Dairy Cattle	Deep Pit	24	0	0	0	0	0
Dairy Cattle	Dry Lot	15	0.6	2	1.8	0.9	2.2
Dairy Cattle	Liquid/Slurry	26	0.2	0.8	0.7	0.4	0.9
Dairy Cattle	Pasture	0	0	0	0	0	0
Dairy Cattle	Solid Storage	27	0.2	0	0	0	0
American Bison	Pasture	0	0	0	0	0	0
Goats	Dry Lot	23	1.1	3.9	3.6	1.9	4.3
Goats	Pasture	0	0	0	0	0	0
Horses	Dry Lot	23	0	0	0	0	0
Horses	Pasture	0	0	0	0	0	0
Mules and Asses	Dry Lot	23	0	0	0	0	0
Mules and Asses	Pasture	0	0	0	0	0	0
Poultry	Anaerobic Lagoon	54	0.2	0.8	0.7	0.4	0.9
Poultry	Liquid/Slurry	26	0.2	0.8	0.7	0.4	0.9
Poultry	Pasture	0	0	0	0	0	0
Poultry	Poultry with bedding	26	0	0	0	0	0
Poultry	Poultry without bedding	34	0	0	0	0	0
Poultry	Solid Storage	8	0	0	0	0	0
Poultry	Composting intensive	65	0.06	0.06	0.06	0.06	0.06
Sheep	Dry Lot	23	1.1	3.9	3.6	1.9	4.3
Sheep	Pasture	0	0	0	0	0	0
Swine	Anaerobic Lagoon	58	0.2	0.8	0.7	0.4	0.9
Swine	Deep Pit	34	0	0	0	0	0
Swine	Liquid/Slurry	26	0.2	0.8	0.7	0.4	0.9
Swine	Pasture	0	0	0	0	0	0
Swine	Solid Storage	45	0	0	0	0	0

^a Data for nitrogen losses due to leaching were not available, so the values represent only nitrogen losses due to runoff.

Source: EPA (2002b, 2005).

Table A-164: Total Methane Emissions from Livestock Manure Management (kt)^a

Animal Type	1990	2005	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Dairy Cattle	572	943	1,140	1,159	1,203	1,232	1,248	1,274	1,227	1,238	1,226	1,193	1,195
Dairy Cows	564	935	1,130	1,150	1,193	1,223	1,238	1,264	1,218	1,229	1,217	1,184	1,187
Dairy Heifer	7	7	8	8	9	9	9	9	8	9	8	8	8
Dairy Calves	1	1	1	1	1	1	1	1	1	1	1	1	1
Swine	621	812	756	719	808	846	840	882	890	888	877	851	868
Market Swine	482	665	623	586	665	699	697	730	739	741	730	707	724
Market <50 lbs.	101	128	88	86	95	101	100	105	104	105	102	99	101
Market 50-119 lbs.	101	131	136	130	145	155	153	160	163	160	159	154	157
Market 120-179 lbs.	136	184	179	169	192	203	200	211	211	211	210	205	212
Market >180 lbs.	144	221	220	201	232	241	244	254	260	265	259	249	254
Breeding Swine	139	147	133	133	143	146	143	152	152	147	147	144	144
Beef Cattle	63	78	111	114	120	132	142	149	148	150	157	154	149
Feedlot Steers	14	22	45	49	53	60	66	69	68	69	74	73	70
Feedlot Heifers	7	13	25	26	28	31	34	38	37	39	41	41	40
NOF Bulls	2	2	2	2	2	2	2	2	2	2	2	2	2
Beef Calves	3	3	3	3	3	3	3	3	3	3	3	3	3
NOF Heifers	5	5	5	5	5	6	6	5	5	5	5	5	5
NOF Steers	5	4	4	4	4	4	4	4	4	4	4	4	4
NOF Cows	27	28	26	26	26	27	28	28	28	28	27	27	26
Sheep	3	2	2	2	2	2	2	2	2	2	2	2	2
Goats	+	+	+	+	+	+	+	+	+	+	+	+	+
Poultry	135	123	105	103	109	108	107	108	111	109	108	108	109
Hens >1 yr.	73	51	31	29	28	26	23	21	23	21	21	20	21
Total Pullets	25	22	24	24	27	26	26	28	29	28	28	29	29
Chickens	4	3	3	3	3	3	3	3	3	3	3	3	3
Broilers	23	39	42	41	46	47	48	50	50	51	50	51	51
Turkeys	10	6	6	6	6	6	6	6	6	6	5	5	5
Horses	4	5	4	4	4	3	3	3	3	3	3	2	2
Mules and Asses	+	+	+	+	+	+	+	+	+	+	+	+	+
American Bison	+	+	+	+	+	+	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

^a Accounts for CH₄ reductions due to capture and destruction of CH₄ at facilities using anaerobic digesters.

Table A-165: Total Methane Emissions from Livestock Manure Management (MMT CO₂ Eq.)^a

Animal Type	1990	2005	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Dairy Cattle	16.0	26.4	31.9	32.5	33.7	34.5	34.9	35.7	34.4	34.7	34.3	33.4	33.5
Dairy Cows	15.8	26.2	31.7	32.2	33.4	34.2	34.7	35.4	34.1	34.4	34.1	33.2	33.2
Dairy Heifer	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Dairy Calves	+	+	+	+	+	+	+	+	+	+	+	+	+
Swine	17.4	22.7	21.2	20.1	22.6	23.7	23.5	24.7	24.9	24.9	24.6	23.8	24.3
Market Swine	13.5	18.6	17.4	16.4	18.6	19.6	19.5	20.4	20.7	20.8	20.4	19.8	20.3
Market <50 lbs.	2.8	3.6	2.5	2.4	2.7	2.8	2.8	2.9	2.9	2.9	2.8	2.8	2.8
Market 50-119 lbs.	2.8	3.7	3.8	3.6	4.1	4.3	4.3	4.5	4.6	4.5	4.5	4.3	4.4
Market 120-179 lbs.	3.8	5.1	5.0	4.7	5.4	5.7	5.6	5.9	5.9	5.9	5.9	5.8	5.9
Market >180 lbs.	4.0	6.2	6.1	5.6	6.5	6.7	6.8	7.1	7.3	7.4	7.2	7.0	7.1
Breeding Swine	3.9	4.1	3.7	3.7	4.0	4.1	4.0	4.3	4.2	4.1	4.1	4.0	4.0
Beef Cattle	1.8	2.2	3.1	3.2	3.4	3.7	4.0	4.2	4.1	4.2	4.4	4.3	4.2
Feedlot Steers	0.4	0.6	1.3	1.4	1.5	1.7	1.8	1.9	1.9	1.9	2.1	2.0	2.0
Feedlot Heifers	0.2	0.4	0.7	0.7	0.8	0.9	1.0	1.1	1.0	1.1	1.2	1.2	1.1
NOF Bulls	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Beef Calves	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
NOF Heifers	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1
NOF Steers	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
NOF Cows	0.8	0.8	0.7	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.7	0.7
Sheep	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+	+	+	+	+	+	+
Poultry	3.8	3.4	2.9	2.9	3.0	3.0	3.0	3.0	3.1	3.0	3.0	3.0	3.0
Hens >1 yr.	2.0	1.4	0.9	0.8	0.8	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.6
Total Pullets	0.7	0.6	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8
Chickens	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Broilers	0.6	1.1	1.2	1.2	1.3	1.3	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Turkeys	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.2
Horses	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Mules and Asses	+	+	+	+	+	+	+	+	+	+	+	+	+
American Bison	+	+	+	+	+	+	+	+	+	+	+	+	+

+ Does not exceed 0.05 MMT CO₂ Eq.

^a Accounts for CH₄ reductions due to capture and destruction of CH₄ at facilities using anaerobic digesters.

Table A-166: Total (Direct and Indirect) Nitrous Oxide Emissions from Livestock Manure Management (kt)

Animal Type	1990	2005	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Dairy Cattle	20.9	20.8	22.0	22.1	22.7	22.9	23.1	23.4	23.4	23.5	23.7	23.4	23.1
<i>Dairy Cows</i>	13.8	12.9	13.6	13.7	14.0	14.1	14.4	14.6	14.6	14.8	15.1	15.1	15.1
<i>Dairy Heifer</i>	7.1	7.8	8.3	8.4	8.7	8.8	8.8	8.8	8.7	8.7	8.6	8.3	8.0
<i>Dairy Calves</i>	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Swine	4.1	5.5	6.0	5.8	6.2	6.3	6.6	6.7	7.0	7.0	6.8	6.7	6.8
Market Swine	3.1	4.7	5.2	5.0	5.4	5.6	5.7	5.8	6.1	6.2	5.9	5.9	6.09
<i>Market <50 lbs.</i>	0.6	0.9	0.7	0.7	0.8	0.8	0.8	0.8	0.9	0.9	0.8	0.8	0.8
<i>Market 50-119 lbs.</i>	0.7	0.9	1.2	1.1	1.2	1.2	1.3	1.3	1.4	1.4	1.3	1.3	1.3
<i>Market 120-179 lbs.</i>	0.9	1.3	1.5	1.5	1.6	1.6	1.7	1.7	1.8	1.8	1.7	1.7	1.8
<i>Market >180 lbs.</i>	0.9	1.5	1.8	1.7	1.8	1.9	2.0	2.0	2.1	2.2	2.1	2.0	2.1
<i>Breeding Swine</i>	1.1	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.9	0.8	0.8	0.8	0.8
Beef Cattle	19.7	22.7	21.2	20.7	20.9	21.7	22.3	22.3	22.7	23.0	24.2	24.1	23.3
<i>Feedlot Steers</i>	13.3	14.7	13.9	13.8	14.0	14.6	15.0	14.7	14.9	15.1	15.8	15.7	15.2
<i>Feedlot Heifers</i>	6.4	8.0	7.3	7.0	6.9	7.1	7.3	7.6	7.8	8.0	8.4	8.4	8.1
Sheep	0.4	1.2	1.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Goats	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Poultry	4.9	6.8	7.5	7.7	7.8	8.2	8.4	8.7	8.8	8.7	8.7	8.6	8.7
<i>Hens >1 yr.</i>	1.2	1.4	1.8	1.9	1.9	2.0	2.1	2.2	2.2	2.2	2.2	2.1	2.2
<i>Total Pullets</i>	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5
<i>Chickens</i>	+	+	+	+	+	+	+	+	+	+	+	+	+
<i>Broilers</i>	2.2	4.2	4.6	4.7	4.8	5.0	5.1	5.3	5.4	5.4	5.4	5.4	5.4
<i>Turkeys</i>	1.2	0.8	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.6
Horses	0.3	0.5	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.2
Mules and Asses	+	+	+	+	+	+	+	+	+	+	+	+	+
American Bison	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Note: American bison are maintained entirely on pasture, range, and paddock. Emissions from manure deposited on pasture are included in the agricultural soils management sector.

+ Does not exceed 0.05 kt.

NA (Not Applicable)

Table A-167: Total (Direct and Indirect) Nitrous Oxide Emissions from Livestock Manure Management (MMT CO₂ Eq.)

Animal Type	1990	2005	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Dairy Cattle	5.5	5.5	5.8	5.9	6.0	6.1	6.1	6.2	6.2	6.2	6.3	6.2	6.1
<i>Dairy Cows</i>	3.6	3.4	3.6	3.6	3.7	3.7	3.8	3.9	3.9	3.9	4.0	4.0	4.0
<i>Dairy Heifer</i>	1.9	2.1	2.2	2.2	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.2	2.1
<i>Dairy Calves</i>	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Swine	1.1	1.5	1.6	1.5	1.6	1.7	1.7	1.8	1.8	1.9	1.8	1.8	1.8
Market Swine	0.8	1.2	1.4	1.3	1.4	1.5	1.5	1.5	1.6	1.6	1.6	1.6	1.6
<i>Market <50 lbs.</i>	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
<i>Market 50-119 lbs.</i>	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.3	0.4
<i>Market 120-179 lbs.</i>	0.2	0.3	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5
<i>Market >180 lbs.</i>	0.3	0.4	0.5	0.4	0.5	0.5	0.5	0.5	0.6	0.6	0.5	0.5	0.5
<i>Breeding Swine</i>	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Beef Cattle	5.2	6.0	5.6	5.5	5.5	5.7	5.9	5.9	6.0	6.1	6.4	6.4	6.2
<i>Feedlot Steers</i>	3.5	3.9	3.7	3.6	3.7	3.9	4.0	3.9	3.9	4.0	4.2	4.2	4.0
<i>Feedlot Heifers</i>	1.7	2.1	1.9	1.8	1.8	1.9	1.9	2.0	2.1	2.1	2.2	2.2	2.2
Sheep	0.1	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Goats	+	+	+	+	+	+	+	+	+	+	+	+	+
Poultry	1.3	1.8	2.0	2.0	2.1	2.2	2.2	2.3	2.3	2.3	2.3	2.3	2.3
<i>Hens >1 yr.</i>	0.3	0.4	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.6
<i>Total Pullets</i>	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
<i>Chickens</i>	+	+	+	+	+	+	+	+	+	+	+	+	+
<i>Broilers</i>	0.6	1.1	1.2	1.2	1.3	1.3	1.4	1.4	1.4	1.4	1.4	1.4	1.4
<i>Turkeys</i>	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Horses	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Mules and Asses	+	+	+	+	+	+	+	+	+	+	+	+	+
American Bison	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

+ Does not exceed 0.05 MMT CO₂ Eq.

NA (Not Applicable)

Note: American bison are maintained entirely on pasture, range, and paddock. Emissions from manure deposited on pasture are included in the agricultural soils management sector.

Table A-168: Methane Emissions by State from Livestock Manure Management for 2023 (kt)^{a,b}

State	Beef Cattle ^b	Dairy Cattle ^b	Swine ^b	Poultry ^b	Sheep	Goats	Horses	Mules and Asses	American Bison	Total
Alabama	0.7629	0.2289	0.4237	13.4987	0.0126	0.0069	0.0400	0.0045	+	14.9782
Alaska	0.0138	0.0033	0.0045	0.0007	0.0002	0.0001	0.0014	+	0.0015	0.0255
Arizona	1.6874	18.3182	2.5234	0.5129	0.0360	0.0070	0.0715	0.0010	0.0001	23.1575
Arkansas	1.0745	0.3837	2.1943	6.9729	0.0105	0.0044	0.0331	0.0030	0.0001	10.6765
California	3.9158	242.3143	1.2871	2.6922	0.2163	0.0176	0.0635	0.0021	0.0014	250.5102
Colorado	7.1936	22.3259	4.9187	0.8966	0.1263	0.0081	0.0880	0.0023	0.0121	35.5718
Connecticut	0.0068	2.6734	0.0099	0.2544	0.0027	0.0009	0.0056	0.0004	0.0005	2.9546
Delaware	0.0033	0.3738	0.0371	1.1269	0.0006	0.0001	0.0023	+	0.0002	1.5444
Florida	0.9660	13.0900	0.0772	4.2479	0.0125	0.0098	0.0674	0.0052	0.0001	18.4760
Georgia	0.5546	11.3567	0.6967	16.0863	0.0126	0.0095	0.0373	0.0049	+	28.7586
Hawaii	0.0999	0.0722	0.1088	0.0160	0.0075	0.0027	0.0045	0.0001	0.0001	0.3119
Idaho	1.4245	111.7687	0.1795	0.3494	0.0676	0.0050	0.0369	0.0009	0.0354	113.8679
Illinois	5.6414	10.5014	59.2933	0.2645	0.0229	0.0053	0.0251	0.0019	0.0006	75.7564
Indiana	1.4655	17.3848	50.0252	2.0812	0.0259	0.0056	0.0608	0.0016	0.0003	71.0509
Iowa	9.9769	35.0743	221.5183	1.9542	0.0691	0.0137	0.0409	0.0012	0.0026	268.6513
Kansas	40.6395	36.6885	35.1296	0.1188	0.0281	0.0072	0.0332	0.0017	0.0043	112.6507
Kentucky	1.1314	4.0808	6.3984	1.7290	0.0274	0.0072	0.1011	0.0046	0.0023	13.4822
Louisiana	0.5123	0.7625	0.0383	1.9539	0.0061	0.0026	0.0309	0.0026	0.0001	3.3094
Maine	0.0152	2.5974	0.0115	0.1966	0.0060	0.0007	0.0053	0.0002	0.0002	2.8331
Maryland	0.0697	4.8485	0.1889	1.3455	0.0080	0.0022	0.0276	0.0009	+	6.4914
Massachusetts	0.0109	0.3849	0.0306	0.0067	0.0060	0.0009	0.0092	0.0005	+	0.4497
Michigan	2.0264	65.9148	11.4257	0.9319	0.0376	0.0040	0.0420	0.0015	0.0031	80.3869
Minnesota	4.9677	45.4686	71.3028	1.4201	0.0484	0.0050	0.0284	0.0013	0.0024	123.2447
Mississippi	0.5597	0.4666	2.9770	8.0038	0.0085	0.0051	0.0249	0.0035	0.0003	12.0494
Missouri	2.4706	6.2895	44.2307	2.4145	0.0419	0.0064	0.0559	0.0045	0.0003	55.5142
Montana	1.8305	1.2165	1.6677	0.3220	0.0558	0.0024	0.0619	0.0011	0.0248	5.1827
Nebraska	11.6703	11.3839	47.0479	0.3572	0.0315	0.0042	0.0341	0.0005	0.0291	70.5587
Nevada	0.3130	7.0275	0.0025	0.0007	0.0176	0.0007	0.0060	0.0002	+	7.3682
New Hampshire	0.0058	1.0550	0.0157	0.0219	0.0037	0.0005	0.0051	0.0002	0.0003	1.1081
New Jersey	0.0100	0.4225	0.0422	0.5405	0.0061	0.0017	0.0198	0.0006	+	1.0436
New Mexico	0.6224	34.8321	0.0079	0.0338	0.0264	0.0050	0.0374	0.0011	0.0050	35.5711
New York	0.2084	86.0625	0.2422	0.5600	0.0371	0.0032	0.0489	0.0011	0.0011	87.1645

North Carolina	0.4235	4.9325	151.0779	13.0864	0.0200	0.0068	0.0400	0.0051	0.0002	169.5924
North Dakota	1.6164	2.3234	1.2970	0.0458	0.0268	0.0011	0.0141	0.0003	0.0130	5.3379
Ohio	2.7790	30.8405	29.5329	2.0499	0.0589	0.0087	0.0833	0.0033	0.0010	65.3576
Oklahoma	4.2552	4.0873	44.7180	2.5456	0.0327	0.0145	0.1032	0.0077	0.0008	55.7648
Oregon	1.0444	8.5424	0.0641	0.3456	0.0438	0.0074	0.0598	0.0016	0.0025	10.1117
Pennsylvania	0.4431	42.3130	13.4625	3.2887	0.0445	0.0071	0.0590	0.0037	0.0011	59.6228
Rhode Island	0.0014	0.0413	0.0057	0.0053	0.0008	0.0001	0.0016	0.0001	+	0.0564
South Carolina	0.1851	1.0954	2.8926	3.0670	0.0064	0.0059	0.0358	0.0027	+	7.2910
South Dakota	7.4325	31.7482	22.2983	0.1548	0.1015	0.0025	0.0378	0.0009	0.0233	61.7997
Tennessee	1.0267	2.6293	4.8360	1.3884	0.0339	0.0144	0.0866	0.0085	0.0003	10.0242
Texas	20.5439	65.7519	19.1553	7.0207	0.2520	0.1106	0.2973	0.0421	0.0098	113.1836
Utah	0.4982	9.5106	6.5966	1.5910	0.0793	0.0031	0.0487	0.0004	0.0010	18.3289
Vermont	0.0234	12.5098	0.0125	0.0156	0.0078	0.0012	0.0056	+	0.0002	12.5759
Virginia	0.7436	6.7932	4.4148	1.6165	0.0334	0.0061	0.0460	0.0033	0.0004	13.6573
Washington	0.9942	41.5279	0.0987	0.4549	0.0151	0.0041	0.0423	0.0011	0.0010	43.1394
West Virginia	0.2275	0.3434	0.0099	0.5670	0.0148	0.0036	0.0213	0.0016	0.0001	1.1892
Wisconsin	3.9511	133.3974	2.6634	0.5577	0.0354	0.0180	0.0481	0.0013	0.0067	140.6790
Wyoming	1.0899	1.5363	0.8355	0.0031	0.0970	0.0025	0.0405	0.0014	0.0104	3.6166

+ Does not exceed 0.00005 kt.

^a Accounts for CH₄ reductions due to capture and destruction of CH₄ at facilities using anaerobic digesters.

^b Disaggregated animal type (E.g., Market Swine and Breeding Swine animal types, versus “Swine”) methane emissions were not estimated by state for the current (1990 through 2023) Inventory. Disaggregated animal types will be estimated for the next (1990 through 2024) Inventory.

Table A-169: Methane Emissions by State from Livestock Manure Management for 2023 (MMT CO₂ Eq.)^{a,b}

State	Beef Cattle ^b	Dairy Cattle ^b	Swine ^b	Poultry ^b	Sheep	Goats	Horses	Mules and Asses	American Bison	Total
Alabama	0.0214	0.0064	0.0119	0.3780	0.0004	0.0002	0.0011	0.0001	+	0.4194
Alaska	0.0004	0.0001	0.0001	+	+	+	+	+	+	0.0007
Arizona	0.0472	0.5129	0.0707	0.0144	0.0010	0.0002	0.0020	+	+	0.6484
Arkansas	0.0301	0.0107	0.0614	0.1952	0.0003	0.0001	0.0009	0.0001	+	0.2989
California	0.1096	6.7848	0.0360	0.0754	0.0061	0.0005	0.0018	0.0001	+	7.0143
Colorado	0.2014	0.6251	0.1377	0.0251	0.0035	0.0002	0.0025	0.0001	0.0003	0.9960
Connecticut	0.0002	0.0749	0.0003	0.0071	0.0001	+	0.0002	+	+	0.0827
Delaware	0.0001	0.0105	0.0010	0.0316	+	+	0.0001	+	+	0.0432
Florida	0.0270	0.3665	0.0022	0.1189	0.0003	0.0003	0.0019	0.0001	+	0.5173
Georgia	0.0155	0.3180	0.0195	0.4504	0.0004	0.0003	0.0010	0.0001	+	0.8052
Hawaii	0.0028	0.0020	0.0030	0.0004	0.0002	0.0001	0.0001	+	+	0.0087

Idaho	0.0399	3.1295	0.0050	0.0098	0.0019	0.0001	0.0010	+	0.0010	3.1883
Illinois	0.1580	0.2940	1.6602	0.0074	0.0006	0.0001	0.0007	0.0001	+	2.1212
Indiana	0.0410	0.4868	1.4007	0.0583	0.0007	0.0002	0.0017	+	+	1.9894
Iowa	0.2794	0.9821	6.2025	0.0547	0.0019	0.0004	0.0011	+	0.0001	7.5222
Kansas	1.1379	1.0273	0.9836	0.0033	0.0008	0.0002	0.0009	+	0.0001	3.1542
Kentucky	0.0317	0.1143	0.1792	0.0484	0.0008	0.0002	0.0028	0.0001	0.0001	0.3775
Louisiana	0.0143	0.0214	0.0011	0.0547	0.0002	0.0001	0.0009	0.0001	+	0.0927
Maine	0.0004	0.0727	0.0003	0.0055	0.0002	+	0.0001	+	+	0.0793
Maryland	0.0020	0.1358	0.0053	0.0377	0.0002	0.0001	0.0008	+	+	0.1818
Massachusetts	0.0003	0.0108	0.0009	0.0002	0.0002	+	0.0003	+	+	0.0126
Michigan	0.0567	1.8456	0.3199	0.0261	0.0011	0.0001	0.0012	+	0.0001	2.2508
Minnesota	0.1391	1.2731	1.9965	0.0398	0.0014	0.0001	0.0008	+	0.0001	3.4509
Mississippi	0.0157	0.0131	0.0834	0.2241	0.0002	0.0001	0.0007	0.0001	+	0.3374
Missouri	0.0692	0.1761	1.2385	0.0676	0.0012	0.0002	0.0016	0.0001	+	1.5544
Montana	0.0513	0.0341	0.0467	0.0090	0.0016	0.0001	0.0017	+	0.0007	0.1451
Nebraska	0.3268	0.3187	1.3173	0.0100	0.0009	0.0001	0.0010	+	0.0008	1.9756
Nevada	0.0088	0.1968	0.0001	0.0000	0.0005	+	0.0002	+	+	0.2063
New Hampshire	0.0002	0.0295	0.0004	0.0006	0.0001	+	0.0001	+	+	0.0310
New Jersey	0.0003	0.0118	0.0012	0.0151	0.0002	+	0.0006	+	+	0.0292
New Mexico	0.0174	0.9753	0.0002	0.0009	0.0007	0.0001	0.0010	+	0.0001	0.9960
New York	0.0058	2.4097	0.0068	0.0157	0.0010	0.0001	0.0014	+	+	2.4406
North Carolina	0.0119	0.1381	4.2302	0.3664	0.0006	0.0002	0.0011	0.0001	+	4.7486
North Dakota	0.0453	0.0651	0.0363	0.0013	0.0007	+	0.0004	+	0.0004	0.1495
Ohio	0.0778	0.8635	0.8269	0.0574	0.0017	0.0002	0.0023	0.0001	+	1.8300
Oklahoma	0.1191	0.1144	1.2521	0.0713	0.0009	0.0004	0.0029	0.0002	+	1.5614
Oregon	0.0292	0.2392	0.0018	0.0097	0.0012	0.0002	0.0017	+	0.0001	0.2831
Pennsylvania	0.0124	1.1848	0.3770	0.0921	0.0012	0.0002	0.0017	0.0001	+	1.6694
Rhode Island	0.0000	0.0012	0.0002	0.0001	+	+	+	+	+	0.0016
South Carolina	0.0052	0.0307	0.0810	0.0859	0.0002	0.0002	0.0010	0.0001	+	0.2041
South Dakota	0.2081	0.8889	0.6244	0.0043	0.0028	0.0001	0.0011	+	0.0007	1.7304
Tennessee	0.0287	0.0736	0.1354	0.0389	0.0009	0.0004	0.0024	0.0002	+	0.2807
Texas	0.5752	1.8411	0.5363	0.1966	0.0071	0.0031	0.0083	0.0012	0.0003	3.1691
Utah	0.0139	0.2663	0.1847	0.0445	0.0022	0.0001	0.0014	+	+	0.5132
Vermont	0.0007	0.3503	0.0004	0.0004	0.0002	+	0.0002	+	+	0.3521
Virginia	0.0208	0.1902	0.1236	0.0453	0.0009	0.0002	0.0013	0.0001	+	0.3824
Washington	0.0278	1.1628	0.0028	0.0127	0.0004	0.0001	0.0012	+	+	1.2079
West Virginia	0.0064	0.0096	0.0003	0.0159	0.0004	0.0001	0.0006	+	+	0.0333
Wisconsin	0.1106	3.7351	0.0746	0.0156	0.0010	0.0005	0.0013	+	0.0002	3.9390
Wyoming	0.0305	0.0430	0.0234	0.0001	0.0027	0.0001	0.0011	+	0.0003	0.1013

+ Does not exceed 0.00005 MMT CO₂ Eq.

^a Accounts for CH₄ reductions due to capture and destruction of CH₄ at facilities using anaerobic digesters.

^b Disaggregated animal type (E.g., Market Swine and Breeding Swine animal types, versus “Swine”) methane emissions were not estimated by state for the current (1990 through 2023) *Inventory*. Disaggregated animal types will be estimated for the next (1990 through 2024) *Inventory*.

Table A-170: Total (Direct and Indirect) Nitrous Oxide Emissions by State from Livestock Manure Management for 2023 (kt)^a

State	Beef Cattle ^a	Dairy Cattle	Dairy Heifer	Swine ^a	Poultry ^a	Sheep	Goats	Horses	Mules and Asses	American Bison	Total
Alabama	0.0132	0.0020	0.0017	0.0023	0.8202	0.0070	0.0016	0.0037	0.0004	NA	0.8522
Alaska	0.0001	0.0001	0.0002	0.0001	+	0.0001	+	0.0001	+	NA	0.0008
Arizona	0.4670	0.4636	0.2430	0.0132	0.0182	0.0112	0.0016	0.0067	0.0001	NA	1.2245
Arkansas	0.0145	0.0033	0.0019	0.0132	0.7020	0.0056	0.0010	0.0031	0.0003	NA	0.7449
California	0.9773	3.0264	1.5192	0.0081	0.2408	0.0725	0.0041	0.0059	0.0002	NA	5.8542
Colorado	1.9690	0.4929	0.2526	0.0564	0.0194	0.0480	0.0020	0.0089	0.0002	NA	2.8493
Connecticut	0.0002	0.0241	0.0114	0.0001	0.0176	0.0022	0.0002	0.0006	+	NA	0.0563
Delaware	0.0003	0.0034	0.0014	0.0002	0.1721	0.0005	+	0.0002	+	NA	0.1783
Florida	0.0085	0.0725	0.0420	0.0004	0.0975	0.0070	0.0023	0.0063	0.0005	NA	0.2367
Georgia	0.0106	0.0631	0.0241	0.0040	0.9368	0.0071	0.0022	0.0035	0.0005	NA	1.0517
Hawaii	0.0017	0.0007	0.0022	0.0005	0.0010	0.0025	0.0006	0.0004	+	NA	0.0097
Idaho	0.5583	1.1755	0.7745	0.0019	0.0049	0.0257	0.0012	0.0037	0.0001	NA	2.5458
Illinois	0.1980	0.1037	0.0803	0.4968	0.0486	0.0176	0.0013	0.0025	0.0002	NA	0.9490
Indiana	0.1537	0.2459	0.1065	0.4062	0.3366	0.0199	0.0014	0.0061	0.0002	NA	1.2764
Iowa	1.8502	0.3055	0.2252	2.1513	0.3414	0.0532	0.0035	0.0041	0.0001	NA	4.9342
Kansas	3.5286	0.2199	0.3300	0.2041	0.0188	0.0216	0.0018	0.0033	0.0002	NA	4.3282
Kentucky	0.0266	0.0360	0.0197	0.0422	0.1822	0.0228	0.0018	0.0102	0.0005	NA	0.3419
Louisiana	0.0033	0.0061	0.0018	0.0002	0.1391	0.0033	0.0006	0.0029	0.0003	NA	0.1574
Maine	0.0012	0.0309	0.0147	0.0001	0.0162	0.0050	0.0002	0.0005	+	NA	0.0687
Maryland	0.0114	0.0474	0.0299	0.0015	0.1657	0.0067	0.0006	0.0028	0.0001	NA	0.2659
Massachusetts	0.0003	0.0106	0.0061	0.0003	0.0010	0.0049	0.0002	0.0009	0.0001	NA	0.0244
Michigan	0.2332	0.6845	0.3093	0.1125	0.1372	0.0289	0.0010	0.0042	0.0002	NA	1.5110
Minnesota	0.5388	0.6481	0.3972	0.7219	0.1910	0.0372	0.0013	0.0029	0.0001	NA	2.5383
Mississippi	0.0147	0.0048	0.0033	0.0152	0.4508	0.0048	0.0012	0.0023	0.0003	NA	0.4972
Missouri	0.1602	0.0734	0.0523	0.2971	0.3391	0.0322	0.0016	0.0056	0.0005	NA	0.9619
Montana	0.0776	0.0145	0.0083	0.0191	0.0091	0.0212	0.0006	0.0062	0.0001	NA	0.1568
Nebraska	4.7153	0.0781	0.0608	0.3259	0.0573	0.0243	0.0010	0.0034	0.0001	NA	5.2661
Nevada	0.0054	0.0406	0.0200	+	0.0001	0.0067	0.0002	0.0006	+	NA	0.0736

New												
Hampshire	0.0002	0.0126	0.0069	0.0002	0.0017	0.0031	0.0001	0.0005	+	NA	0.0253	
New Jersey	0.0002	0.0046	0.0031	0.0003	0.0109	0.0051	0.0004	0.0020	0.0001	NA	0.0267	
New Mexico	0.0213	0.7078	0.2530	0.0001	0.0009	0.0100	0.0013	0.0038	0.0001	NA	0.9982	
New York	0.0271	0.8143	0.3725	0.0025	0.0410	0.0309	0.0008	0.0049	0.0001	NA	1.2940	
North Carolina	0.0073	0.0321	0.0098	0.8230	0.8457	0.0112	0.0016	0.0037	0.0005	NA	1.7347	
North Dakota	0.0449	0.0196	0.0149	0.0142	0.0046	0.0206	0.0003	0.0014	+	NA	0.1205	
Ohio	0.1924	0.3193	0.2123	0.2567	0.3299	0.0487	0.0022	0.0084	0.0003	NA	1.3701	
Oklahoma	0.5488	0.0779	0.0419	0.2010	0.1587	0.0172	0.0034	0.0096	0.0007	NA	1.0590	
Oregon	0.2181	0.1935	0.0989	0.0005	0.0246	0.0183	0.0019	0.0060	0.0002	NA	0.5618	
Pennsylvania	0.0902	0.5078	0.2036	0.1261	0.3128	0.0371	0.0018	0.0059	0.0004	NA	1.2856	
Rhode Island	+	0.0005	0.0005	0.0001	0.0004	0.0007	+	0.0002	+	NA	0.0024	
South Carolina	0.0017	0.0067	0.0035	0.0175	0.1969	0.0036	0.0014	0.0033	0.0003	NA	0.2349	
South Dakota	0.6196	0.2188	0.0785	0.1944	0.0211	0.0781	0.0006	0.0038	0.0001	NA	1.2149	
Tennessee	0.0308	0.0209	0.0121	0.0286	0.1231	0.0189	0.0034	0.0081	0.0008	NA	0.2465	
Texas	5.0161	1.5118	0.4956	0.1145	0.6364	0.0782	0.0258	0.0277	0.0041	NA	7.9081	
Utah	0.0347	0.2104	0.1203	0.0786	0.0569	0.0301	0.0008	0.0049	+	NA	0.5368	
Vermont	0.0012	0.1482	0.0596	0.0001	0.0013	0.0065	0.0003	0.0006	+	NA	0.2178	
Virginia	0.0198	0.0572	0.0224	0.0276	0.2515	0.0278	0.0015	0.0046	0.0003	NA	0.4127	
Washington	0.3959	0.4441	0.2441	0.0011	0.0443	0.0063	0.0010	0.0043	0.0001	NA	1.1411	
West Virginia	0.0063	0.0047	0.0023	0.0001	0.0645	0.0124	0.0009	0.0021	0.0002	NA	0.0932	
Wisconsin	0.3929	1.8911	1.2142	0.0300	0.0868	0.0272	0.0045	0.0048	0.0001	NA	3.6515	
Wyoming	0.1170	0.0123	0.0091	0.0092	0.0002	0.0368	0.0006	0.0041	0.0001	NA	0.1894	

+ Does not exceed 0.00005 kt.

NA Not Applicable

^a Disaggregated animal type (E.g., Market Swine and Breeding Swine animal types, versus “Swine”) methane emissions were not estimated by state for the current (1990 through 2023) Inventory. Disaggregated animal types will be estimated for the next (1990 through 2024) *Inventory*.

Table A-171: Total (Direct and Indirect) Nitrous Oxide Emissions by State from Livestock Manure Management for 2023 (MMT CO₂ Eq.)^a

State	Beef Cattle ^a	Dairy Cow	Dairy Heifer	Swine ^a	Poultry ^a	Sheep	Goats	Horses	Mules and Asses	American Bison	Total
Alabama	0.0035	0.0005	0.0005	0.0006	0.2174	0.0019	0.0004	0.0010	0.0001	NA	0.2258
Alaska	+	+	0.0001	+	+	+	+	+	+	NA	0.0002
Arizona	0.1237	0.1229	0.0644	0.0035	0.0048	0.0030	0.0004	0.0018	+	NA	0.3245
Arkansas	0.0038	0.0009	0.0005	0.0035	0.1860	0.0015	0.0003	0.0008	0.0001	NA	0.1974
California	0.2590	0.8020	0.4026	0.0021	0.0638	0.0192	0.0010	0.0016	0.0001	NA	1.5514
Colorado	0.5218	0.1306	0.0670	0.0149	0.0051	0.0127	0.0005	0.0023	0.0001	NA	0.7551
Connecticut	0.0001	0.0064	0.0030	+	0.0047	0.0006	0.0001	0.0001	+	NA	0.0149
Delaware	0.0001	0.0009	0.0004	0.0001	0.0456	0.0001	+	0.0001	+	NA	0.0472
Florida	0.0022	0.0192	0.0111	0.0001	0.0258	0.0019	0.0006	0.0017	0.0001	NA	0.0627
Georgia	0.0028	0.0167	0.0064	0.0011	0.2482	0.0019	0.0005	0.0009	0.0001	NA	0.2787
Hawaii	0.0005	0.0002	0.0006	0.0001	0.0003	0.0007	0.0002	0.0001	+	NA	0.0026
Idaho	0.1479	0.3115	0.2053	0.0005	0.0013	0.0068	0.0003	0.0010	+	NA	0.6746
Illinois	0.0525	0.0275	0.0213	0.1317	0.0129	0.0047	0.0003	0.0007	0.0001	NA	0.2515
Indiana	0.0407	0.0652	0.0282	0.1076	0.0892	0.0053	0.0003	0.0016	+	NA	0.3383
Iowa	0.4903	0.0810	0.0597	0.5701	0.0905	0.0141	0.0008	0.0011	+	NA	1.3076
Kansas	0.9351	0.0583	0.0874	0.0541	0.0050	0.0057	0.0004	0.0009	+	NA	1.1470
Kentucky	0.0070	0.0095	0.0052	0.0112	0.0483	0.0060	0.0004	0.0027	0.0001	NA	0.0906
Louisiana	0.0009	0.0016	0.0005	0.0001	0.0369	0.0009	0.0002	0.0008	0.0001	NA	0.0417
Maine	0.0003	0.0082	0.0039	+	0.0043	0.0013	+	0.0001	+	NA	0.0182
Maryland	0.0030	0.0126	0.0079	0.0004	0.0439	0.0018	0.0001	0.0007	+	NA	0.0705
Massachusetts	0.0001	0.0028	0.0016	0.0001	0.0003	0.0013	0.0001	0.0002	+	NA	0.0065
Michigan	0.0618	0.1814	0.0820	0.0298	0.0363	0.0077	0.0002	0.0011	+	NA	0.4004
Minnesota	0.1428	0.1718	0.1052	0.1913	0.0506	0.0099	0.0003	0.0008	+	NA	0.6727
Mississippi	0.0039	0.0013	0.0009	0.0040	0.1195	0.0013	0.0003	0.0006	0.0001	NA	0.1318
Missouri	0.0424	0.0194	0.0139	0.0787	0.0899	0.0085	0.0004	0.0015	0.0001	NA	0.2549
Montana	0.0206	0.0038	0.0022	0.0051	0.0024	0.0056	0.0001	0.0017	+	NA	0.0416
Nebraska	1.2496	0.0207	0.0161	0.0864	0.0152	0.0064	0.0003	0.0009	+	NA	1.3955
Nevada	0.0014	0.0108	0.0053	+	+	0.0018	+	0.0002	+	NA	0.0195
New Hampshire	+	0.0033	0.0018	+	0.0005	0.0008	+	0.0001	+	NA	0.0067
New Jersey	+	0.0012	0.0008	0.0001	0.0029	0.0013	0.0001	0.0005	+	NA	0.0071
New Mexico	0.0056	0.1876	0.0671	+	0.0002	0.0027	0.0003	0.0010	+	NA	0.2645
New York	0.0072	0.2158	0.0987	0.0007	0.0109	0.0082	0.0002	0.0013	+	NA	0.3429
North Carolina	0.0019	0.0085	0.0026	0.2181	0.2241	0.0030	0.0004	0.0010	0.0001	NA	0.4597

North Dakota	0.0119	0.0052	0.0039	0.0038	0.0012	0.0055	0.0001	0.0004	+	NA	0.0319
Ohio	0.0510	0.0846	0.0562	0.0680	0.0874	0.0129	0.0005	0.0022	0.0001	NA	0.3631
Oklahoma	0.1454	0.0206	0.0111	0.0533	0.0421	0.0046	0.0008	0.0026	0.0002	NA	0.2806
Oregon	0.0578	0.0513	0.0262	0.0001	0.0065	0.0048	0.0005	0.0016	+	NA	0.1489
Pennsylvania	0.0239	0.1346	0.0540	0.0334	0.0829	0.0098	0.0004	0.0016	0.0001	NA	0.3407
Rhode Island	+	0.0001	0.0001	+	0.0001	0.0002	+	+	+	NA	0.0006
South Carolina	0.0005	0.0018	0.0009	0.0046	0.0522	0.0010	0.0003	0.0009	0.0001	NA	0.0623
South Dakota	0.1642	0.0580	0.0208	0.0515	0.0056	0.0207	0.0002	0.0010	+	NA	0.3220
Tennessee	0.0082	0.0055	0.0032	0.0076	0.0326	0.0050	0.0008	0.0021	0.0002	NA	0.0653
Texas	1.3293	0.4006	0.1313	0.0303	0.1686	0.0207	0.0063	0.0074	0.0011	NA	2.0956
Utah	0.0092	0.0558	0.0319	0.0208	0.0151	0.0080	0.0002	0.0013	+	NA	0.1422
Vermont	0.0003	0.0393	0.0158	+	0.0004	0.0017	0.0001	0.0001	+	NA	0.0577
Virginia	0.0052	0.0152	0.0059	0.0073	0.0667	0.0074	0.0004	0.0012	0.0001	NA	0.1094
Washington	0.1049	0.1177	0.0647	0.0003	0.0117	0.0017	0.0003	0.0011	+	NA	0.3024
West Virginia	0.0017	0.0012	0.0006	+	0.0171	0.0033	0.0002	0.0006	+	NA	0.0247
Wisconsin	0.1041	0.5012	0.3218	0.0079	0.0230	0.0072	0.0011	0.0013	+	NA	0.9676
Wyoming	0.0310	0.0033	0.0024	0.0024	0.0001	0.0098	0.0002	0.0011	+	NA	0.0502

+ Does not exceed 0.00005 MMT CO₂ Eq.

NA Not Applicable

^a Disaggregated animal type (E.g., Market Swine and Breeding Swine animal types, versus “Swine”) methane emissions were not estimated by state for the current (1990 through 2023) Inventory. Disaggregated animal types will be estimated for the next (1990 through 2024) *Inventory*.

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3.13. Methodologies for Estimating Soil Organic C Stock Changes, Soil N₂O Emissions, and CH₄ Emissions and from Agricultural Lands (Cropland and Grassland)

This annex provides a detailed description of Tier 1, 2, and 3 methods that are used to estimate soil organic carbon stock changes for cropland remaining cropland, land converted to cropland, grassland remaining grassland and land converted to grassland; direct N₂O emissions from cropland and grassland soils; indirect N₂O emissions associated with volatilization, leaching, and runoff of nitrogen from croplands and grasslands; and CH₄ emissions from rice cultivation.

Nitrous oxide (N₂O) is produced in soils through the microbial processes of nitrification and denitrification.¹¹² Management influences these processes by modifying the availability of mineral nitrogen (N), which is a key control on the N₂O emissions rates (Mosier et al. 1998; Paustian et al. 2016). Emissions can occur directly in the soil where the nitrogen is made available or can be transported to another location following volatilization, leaching, or runoff, and then converted into N₂O. Management practices influence soil organic carbon stocks in agricultural soils by modifying crop and forage production and microbial decomposition (Paustian et al. 1997; Paustian et al. 2016). CH₄ emissions from rice cultivation occur under flooded conditions through the process of methanogenesis, and is influenced by water management practices, organic amendments and cultivar choice (Sanchis et al. 2014). This annex provides the underlying methodologies for these three emission sources because there is considerable overlap in the methods with most emissions estimated using the DayCent ecosystem model.

A combination of Tier 1, 2, and 3 approaches are used to estimate soil organic carbon stock changes, direct and indirect soil N₂O emissions in agricultural croplands and grasslands in agricultural croplands and grasslands, and CH₄ emissions from rice cultivation. The methodologies used to estimate soil organic carbon stock changes include:

- 1) A Tier 3 method using the DayCent ecosystem model to estimate soil organic carbon stock changes in mineral soils on non-federal lands that have less than 35 percent coarse fragments by volume and are used to produce alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, lentils, oats, onions, peanuts, peas, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, sweet potatoes, tobacco, tomatoes, and wheat, as well as non-federal grasslands and land use change between grassland and cropland (with the crops listed above and less than 35 percent coarse fragments);
- 2) Tier 2 methods with country-specific factors for estimating mineral soil organic carbon stock changes for mineral soils that are very gravelly, cobbly, or shaley (greater than 35 percent coarse fragments by volume), are used to produce crops or have land use changes to cropland and grassland (other than the conversions between cropland and grassland that are not simulated with DayCent);
- 3) Tier 2 methods with country-specific factors for estimating mineral soil organic carbon stock changes on federal lands;
- 4) Tier 2 methods with country-specific factors for estimating losses of carbon from organic soils that are drained for agricultural production; and
- 5) Tier 2 methods for estimating additional changes in mineral soil organic carbon stocks due to additions of biosolids (i.e., municipal sewage sludge) to soils.

The methodologies used to estimate soil N₂O emissions include:

- 1) A Tier 3 method using the DayCent ecosystem model to estimate direct emissions from mineral soils that have less than 35 percent coarse fragments by volume and are used to produce alfalfa hay, barley, corn,

¹¹² Nitrification and denitrification are driven by the activity of microorganisms in soils. Nitrification is the aerobic microbial oxidation of ammonium (NH₄⁺) to nitrate (NO₃⁻), and denitrification is the anaerobic microbial reduction of nitrate to N₂. Nitrous oxide is a gaseous intermediate product in the reaction sequence of nitrification and denitrification.

cotton, dry beans, grass hay, grass-clover hay, lentils, oats, onions, peanuts, peas, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, sweet potatoes, tobacco, tomatoes, and wheat, as well as non-federal grasslands and land use change between grassland and cropland (with the crops listed above and less than 35 percent coarse fragments);

- 2) A combination of the Tier 1 and 3 methods to estimate indirect N₂O emissions associated with management of cropland and grassland simulated with DayCent;
- 3) A Tier 1 method to estimate direct and indirect N₂O emissions from mineral soils that are not simulated with DayCent, including very gravelly, cobbly, or shaley soils (greater than 35 percent coarse fragments by volume); mineral soils with less than 35 percent coarse fragments that are used to produce crops that are not simulated by DayCent; crops that are rotated with the crops that are not simulated with DayCent; Pasture/Range/Paddock (PRP) manure nitrogen deposited on federal grasslands; and land application of biosolids (i.e., treated sewage sludge) to soils; and
- 4) A Tier 1 method to estimate direct N₂O emissions due to partial or complete drainage of organic soils in croplands and grasslands.

The methodologies used to estimate soil CH₄ emissions from rice cultivation include:

- 1) A Tier 3 method using the DayCent ecosystem model to estimate CH₄ emissions from mineral soils that have less than 35 percent coarse fragments by volume and rice grown continuously or in rotation with crops that are simulated with DayCent, including alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, lentils, oats, onions, peanuts, peas, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, sweet potatoes, tobacco, tomatoes, and wheat; and
- 2) A Tier 1 method to estimate CH₄ emissions from all other soils used to produce rice that are not estimated with the Tier 3 method, including rice grown on organic soils (i.e., *Histosols*), mineral soils with very gravelly, cobbly, or shaley soils (greater than 35 percent coarse fragments by volume), and rice grown in rotation with crops that are not simulated by DayCent.

The Tier 3 approach is applied to most agricultural lands in the United States for estimation of soil carbon stock changes, direct soil N₂O emissions, and CH₄ emissions from rice cultivation for most agricultural lands. This approach has the following advantages over the IPCC Tier 1 and 2 approaches:

- 1) It utilizes observed weather data at sub-county scales enabling quantification of inter-annual variability in N₂O emissions and carbon stock changes, and CH₄ emissions at finer spatial scales, as opposed to a single emission factor for the entire country for soil N₂O from agricultural soils and CH₄ emissions from rice cultivation, or a broad climate region classification for soil organic carbon stock changes;
- 2) The model uses a more detailed characterization of spatially-mapped soil properties that influence soil nitrogen dynamics, as opposed to the broad soil taxonomic classifications of the IPCC methodology;
- 3) The simulation approach provides a more detailed representation of management influences and their interactions than are represented by a discrete factor-based approach in the Tier 1 and 2 methods;
- 4) The legacy effects of past management can be addressed with the Tier 3 approach such as land use change from decades prior to the inventory time period that can have ongoing effects on soil organic carbon stocks, and the ongoing effects of N fertilization that may continue to stimulate N₂O emissions in years after the application; and
- 5) Soil N₂O, CH₄ emissions and carbon stock changes are estimated on a more continuous, daily basis as a function of the interaction of climate, soil, and land management, compared with the linear rate changes that are estimated with the Tier 1 and 2 methods.

More information is provided about the model structure and evaluation of the Tier 3 method at the end of this annex (See section Tier 3 Model Description, Parameterization and Evaluation, below).

Splicing methods are used to fill gaps in the time series for the emission sources and are not described in this annex. Specifically, the splicing methods are applied when there are gaps in the activity data at the end of the time

series and the Tier 1, 2 and 3 methods cannot be applied. The splicing methods are described in Box 6-6 in the Cropland Remaining Cropland section and Box 5-4 of Chapter 5.4 Agricultural Soil Management.

***Inventory* Compilation Steps**

There are five steps involved in this *Inventory* to estimate the following sources: a) soil organic carbon stock changes for cropland remaining cropland, land converted to cropland, grassland remaining grassland and land converted to grassland; b) direct N₂O emissions from croplands and grassland, c) indirect N₂O emissions from volatilization, leaching, and runoff from croplands and grasslands; and d) CH₄ emissions from rice cultivation. First, the activity data are compiled from a combination of land-use, crop, and grassland management surveys, as well as expert knowledge. In the second, third, and fourth steps, soil organic carbon stock changes, direct and indirect soil N₂O emissions, and CH₄ emissions are estimated using Tier 1, 2 and 3 methods. In the fifth step, total emissions are calculated by summing all components for soil organic carbon stock changes, N₂O emissions, and CH₄ emissions. The remainder of this annex describes the methods underlying each step.

Step 1: Derive Activity Data

This step describes how the activity data are derived to estimate soil organic carbon stock changes, direct and indirect soil N₂O emissions, and CH₄ emissions from rice cultivation. The activity data requirements include: (1) land base and history data, (2) crop-specific mineral nitrogen fertilizer rates and timing,¹¹³ (3) crop-specific manure amendment nitrogen rates and timing, (4) other nitrogen inputs, (5) tillage practices, (6) cover crop management, (7) planting and harvesting dates for crops, (8) irrigation and water management data, (9) Enhanced Vegetation Index (EVI), (10) daily weather data, and (11) edaphic characteristics.¹¹⁴

Step 1a: Activity Data for the Agricultural Land Base and Histories

The U.S. Department of Agriculture's 2017 National Resources *Inventory* (NRI) (USDA-NRCS 2020) provides the basis for identifying the U.S. agricultural land base on non-federal lands, and classifying parcels into cropland remaining cropland, land converted to cropland, grassland remaining grassland, and land converted to grassland.¹¹⁵ The NRI program have data available from 1979 through 2017 (USDA-NRCS 2018a) that was extended through 2020 using the USDA-NASS Crop Data Layer (CDL) (USDA-NASS 2021, Johnson and Mueller 2010), and data provided in the National Land Cover Dataset (NLCD) (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015). The time series will be further extended as new data are released by the USDA NRI program, CDL, and NLCD. USDA-NRCS does not compile data on federal lands through the NRI program so the land use data are extracted from the NLCD for NRI survey locations in federal lands.

The NRI has a stratified multi-stage sampling design, where primary sample units are stratified on the basis of county and township boundaries defined by the U.S. Public Land Survey (Nusser and Goebel 1997). Within a primary sample unit, typically a 160-acre (64.75 ha) square quarter-section, three sample locations are selected according to a restricted randomization procedure. Each sample location in the survey is assigned an area weight (expansion factor) (Nusser and Goebel 1997). The survey weight are an approximation of the amount of area with the land use and land use change history that is the same as the survey location. The NRI uses a sampling approach, and therefore there is some uncertainty associated with scaling the survey location data to a region or the country using the weights. In general, the uncertainty declines at larger scales because of a larger sample size, such as states compared to smaller county units. An extensive amount of soils, land-use, and land management data have been collected through the survey (Nusser et al. 1998). Primary sources for data include aerial photography as well as field visits and county office records.

¹¹³ No data are currently available at the national scale to distinguish the type of fertilizer applied or timing of applications rates. It is a planned improvement to address variation in these practices in future inventories, such as application of enhanced efficiency fertilizers.

¹¹⁴ Edaphic characteristics include such factors as soil texture and pH.

¹¹⁵ Note that the *Inventory* does not currently include estimates of N₂O emissions for federal grasslands with the exception of soil N₂O from PRP manure nitrogen, i.e., manure deposited directly onto pasture, range or paddock by grazing livestock.

For this *Inventory*, NRI survey data are used to inform land use and crop histories for most years between 1979 and 2017, with the exception of 1983, 1988, 1993, and 2017 to 2020. For 1983, 1988, and 1993, the time series is gap-filled using an automated set of rules so that cropping sequences are filled with the most likely crop type given the historical cropping pattern at each NRI survey location. Grassland data are reported on 5-year increments prior to 1998, but it is assumed that the land use is also grassland between the years of data collection (see Easter et al. 2008 for more information). For 2018 to 2020, the time series is extended with the crop data provided in USDA-NASS CDL and NLCD. CDL data have a 30 to 58 m spatial resolution, depending on the year, and NLCD has a 30m spatial resolution. NRI survey locations are overlaid on the CDL and NLCD in a geographic information system, and the crop types and land use are extracted to extend the crop and land use histories, in addition to the full land use histories on federal lands for the inventory analysis.

NRI survey locations are included in the land base for the agricultural emissions inventory if they are identified as cropland or grassland between 1990 and 2017 (See Section 6.1 Representation of the U.S. Land Base for more information about areas in each land use and land use change category).¹¹⁶ The NRI data are harmonized with the Forest *Inventory* and Analysis Dataset, and in this process, the land use and land use change data are modified to address differences in forest land remaining forest land, land converted to forest land and forest land converted to other land uses between the two national surveys (See Section 6.1 for more information on the U.S. land representation). Through this process, an annual average of 604,090 survey locations in this NRI are designated as agricultural land on non-federal and federal lands in the conterminous United States and Hawaii.

For each year, land parcels are subdivided into cropland remaining cropland, land converted to cropland, grassland remaining grassland, and land converted to grassland. Land parcels under crop management in a specific year are classified as cropland remaining cropland if the parcel has been used as cropland for at least 20 years.¹¹⁷ Similarly, land parcels under grassland management in a specific year of the inventory are classified as grassland remaining grassland if they have been designated as grassland for at least 20 years. Otherwise, land parcels are classified as land converted to cropland or land converted to grassland based on the most recent use in the inventory time period. Lands are retained in the land-use change categories (i.e., land converted to cropland and land converted to grassland) for 20 years as recommended by the IPCC (2006). Lands converted into cropland and grassland are further subdivided into the specific land use conversions (e.g., forest land converted to cropland).

The Tier 3 method using the DayCent model is applied to estimate soil organic carbon stock changes and N₂O emissions for 364,333 NRI survey locations that occur on mineral soils. Parcels of land that are not simulated with DayCent are allocated to the Tier 2 approach for estimating soil organic carbon stock change, and a Tier 1 method (IPCC 2006) to estimate soil N₂O emissions¹¹⁸ (Table A-172). The use of the Tier 1 and 2 methods is consistent with the IPCC (2006) decision-tree for methodological selection as more detailed or finer resolution data are not available/the DayCent model is not parameterized to utilize higher-tier methods, as described throughout this Annex 3.13. The land base for the Tier 1 and 2 methods includes an annual average of 239,757 survey locations and is comprised of (1) land parcels occurring on organic soils; (2) land parcels that include non-agricultural uses such as forest or settlements in one or more years of the inventory; (3) land parcels on mineral soils that are very gravelly, cobbly, or shaley (i.e., classified as soils that have greater than 35 percent of soil volume comprised of gravel, cobbles, or shale); or (4) land parcels that are used to produce some of the vegetable crops and perennial/horticultural crops, which are either grown continuously or in rotation with other crops.

¹¹⁶ Land use for 2021 to 2023 has not been incorporated into this *Inventory* analysis, but will be updated in a future *Inventory*.

¹¹⁷ NRI points are classified according to land-use history records starting in 1979 when the NRI survey began, and consequently the classifications are based on less than 20 years from 1990 to 1998.

¹¹⁸ The Tier 1 method for soil N₂O does not require land area data with the exception of emissions from drainage and cultivation of organic soils, so in practice the Tier 1 method is only dependent on the amount of N input to mineral soils and not the actual land area.

**Table A-172: Total Cropland and Grassland Area Estimated with Tiers 1/2 and 3
Inventory Approaches (Million Hectares)**

Year	Land Areas (million ha)				
	Tier 1/2	Mineral Tier 3	Total	Organic Tier 1/2	Total ¹¹⁹
1990	138.78	323.28	462.06	1.41	463.47
1991	138.08	323.58	461.66	1.40	463.06
1992	137.37	323.87	461.24	1.39	462.63
1993	136.54	324.34	460.89	1.40	462.28
1994	135.76	324.76	460.52	1.39	461.91
1995	134.66	325.23	459.89	1.38	461.27
1996	133.67	325.73	459.40	1.38	460.77
1997	132.66	326.23	458.88	1.38	460.26
1998	131.79	326.71	458.50	1.37	459.87
1999	130.75	327.21	457.96	1.35	459.31
2000	130.22	327.55	457.77	1.36	459.13
2001	129.55	327.86	457.41	1.36	458.77
2002	128.88	328.17	457.04	1.36	458.40
2003	128.25	328.15	456.40	1.34	457.74
2004	127.74	328.14	455.87	1.35	457.23
2005	127.16	328.13	455.30	1.35	456.65
2006	126.60	328.16	454.76	1.35	456.11
2007	126.09	328.17	454.26	1.34	455.60
2008	125.73	328.10	453.83	1.34	455.17
2009	125.34	328.14	453.47	1.33	454.81
2010	125.03	328.04	453.06	1.33	454.40
2011	124.60	328.05	452.65	1.34	453.99
2012	124.21	328.06	452.26	1.33	453.60
2013	124.03	327.80	451.82	1.33	453.15
2014	123.76	327.54	451.30	1.32	452.62
2015	123.53	327.47	451.01	1.32	452.32
2016	122.96	327.25	450.21	1.31	451.52
2017	122.95	327.25	450.20	1.31	451.51
2018	122.91	326.76	449.67	1.30	450.96
2019	122.92	326.93	449.85	1.29	451.15
2020	123.07	325.97	449.03	1.30	450.33

Note: In the current *Inventory*, land use and management data have been incorporated through 2020. Additional data will be incorporated in the future to extend the time series of the land use data.

NRI survey locations on mineral soils are classified into specific crop categories, continuous pasture/rangeland, and other non-agricultural uses for the Tier 2 inventory analysis for soil organic carbon (Table A-173). NRI locations are assigned to IPCC input categories (low, medium, high, and high with organic amendments) according to the classification provided in IPCC (2006). For croplands on federal lands, information on specific crop systems is not available, so all croplands are assumed to be medium input. In addition, NRI differentiates between improved and unimproved grassland, where improvements include irrigation and inter-seeding of legumes. Grasslands on federal lands (as identified with the NLCD) are classified according to rangeland condition (nominal, moderately

¹¹⁹ The current *Inventory* includes lands from all privately-owned and federal grasslands and croplands in the conterminous United States and Hawaii, but does not include the croplands and grasslands in Alaska. This leads to a discrepancy between the total area in this table, which is included in the estimation, compared to the total managed land area in Section 6.1 Representation of the U.S. Land Base. See Planned Improvement sections in cropland remaining cropland and agricultural soil management for more information about filling these gaps in the future so that emissions and removals will be estimated for all managed land.

degraded and severely degraded) in areas where information is available. For lands managed for livestock grazing by the Bureau of Land Management (BLM), IPCC rangeland condition classes are interpreted at the state-level from the Rangeland *Inventory*, Monitoring and Evaluation Report (BLM 2014). In order to estimate uncertainties, NRI land-use data are based on replicate weights that allow for proper variance estimates that correctly account for the complex sampling design. In particular, the variance estimates account for spatial or temporal dependencies. For example, dependencies in land use result from the likelihood that current use is correlated with past use. These dependencies occur because as an area of a land use/management category increases, the area of another land use/management category must decline.

Table A-173: Total Land Areas by Land-Use and Management System for the Tier 2 Mineral Soil Organic Carbon Approach (Million Hectares)

Land Areas (million hectares)													
Land-Use/Management System	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Cropland Systems	24.58	24.27	23.93	23.44	22.90	22.49	22.06	21.59	20.87	20.32	19.95	19.65	19.35
Conservation Reserve Program	2.35	2.58	2.72	2.58	2.40	2.29	2.17	2.17	1.78	1.74	1.70	1.70	1.61
High Input Cropping Systems, Full Tillage	1.76	1.53	1.50	1.37	1.49	1.44	1.39	1.33	1.28	1.24	1.31	1.26	1.11
High Input Cropping Systems, Reduced Tillage	0.14	0.15	0.14	0.14	0.16	0.17	0.17	0.17	0.17	0.19	0.20	0.19	0.17
High Input Cropping Systems, No Tillage	0.06	0.08	0.08	0.09	0.09	0.10	0.12	0.11	0.12	0.13	0.15	0.15	0.14
High Input Cropping Systems with Manure, Full Tillage	0.72	0.60	0.57	0.54	0.50	0.48	0.40	0.39	0.37	0.35	0.32	0.29	0.27
High Input Cropping Systems with Manure, Reduced Tillage	0.06	0.08	0.08	0.08	0.07	0.07	0.08	0.08	0.07	0.06	0.06	0.07	0.07
High Input Cropping Systems with Manure, No Tillage	0.07	0.11	0.11	0.10	0.09	0.09	0.11	0.11	0.10	0.10	0.09	0.09	0.09
Medium Input Cropping Systems, Full Tillage	6.16	5.30	4.89	4.76	4.66	4.61	4.09	3.64	3.41	3.26	3.17	2.99	2.68
Medium Input Cropping Systems, Reduced Tillage	0.43	0.69	0.66	0.62	0.57	0.53	0.67	0.64	0.60	0.58	0.54	0.61	0.60
Medium Input Cropping Systems, No Tillage	0.38	0.70	0.67	0.63	0.59	0.56	0.79	0.76	0.71	0.66	0.64	0.75	0.74
Low Input Cropping Systems, Full Tillage	8.06	7.97	7.94	7.92	7.85	7.85	7.73	7.75	7.78	7.69	7.66	7.44	7.41
Low Input Cropping Systems, Reduced Tillage	0.13	0.19	0.19	0.18	0.18	0.17	0.24	0.22	0.22	0.19	0.20	0.22	0.22
Low Input Cropping Systems, No Tillage	0.05	0.10	0.10	0.10	0.09	0.10	0.18	0.18	0.16	0.15	0.15	0.23	0.21
Hay with Legumes or Irrigation	1.43	1.44	1.43	1.42	1.32	1.24	1.17	1.18	1.12	1.04	0.97	0.88	0.99
Hay with Legumes or Irrigation and Manure	0.43	0.41	0.44	0.48	0.45	0.43	0.43	0.44	0.45	0.43	0.40	0.39	0.48
Hay, Unimproved	0.01	0.01	0.02	0.01	0.01	0.01	0.00	0.01	0.06	0.04	0.01	0.01	0.03

Pasture with Legumes or Irrigation in Rotation	0.02	0.01	0.01	0.01	0.02	0.01	0.00	0.00	0.03	0.03	0.01	0.01	0.01
Pasture with Legumes or Irrigation and Manure, in Rotation	0.00	0.00	0.00	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rice	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.05	0.06	0.06
Perennials	2.27	2.27	2.35	2.39	2.31	2.28	2.26	2.36	2.40	2.40	2.33	2.30	2.45
Grassland Systems	114.22	113.82	113.45	113.12	112.89	112.20	111.64	111.09	110.94	110.44	110.29	109.92	109.54
Pasture with Legumes or Irrigation	3.45	3.32	3.11	3.06	3.11	2.99	2.69	2.26	2.37	2.30	2.12	2.03	1.95
Pasture with Legumes or Irrigation and Manure	0.14	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.11	0.11	0.10	0.09	0.09
Rangelands and Unimproved Pasture	78.37	78.06	78.01	78.09	77.87	77.18	76.29	76.23	75.62	75.14	75.73	75.35	76.30
Rangelands and Unimproved Pasture, Moderately Degraded	23.60	23.75	23.85	23.72	23.75	23.88	24.31	24.20	24.97	24.96	24.30	24.44	23.43
Rangelands and Unimproved Pasture, Severely Degraded	8.66	8.56	8.35	8.12	8.02	8.01	8.22	8.27	7.87	7.93	8.04	8.02	7.78
Total	138.80	138.09	137.38	136.57	135.79	134.69	133.70	132.68	131.81	130.77	130.24	129.57	128.89

Land-Use/Management System	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Cropland Systems	19.06	18.70	18.53	18.29	18.13	17.95	17.74	17.64	17.48	17.40	17.36	17.28	17.14
Conservation Reserve Program	1.44	1.23	1.31	1.34	1.27	1.23	1.08	1.11	1.02	0.88	0.88	0.78	0.79
High Input Cropping Systems, Full Tillage	1.06	1.04	1.01	0.90	0.91	0.92	0.96	0.93	1.00	0.93	0.92	0.87	0.77
High Input Cropping Systems, Reduced Tillage	0.19	0.19	0.20	0.19	0.20	0.24	0.23	0.26	0.20	0.21	0.23	0.24	0.21
High Input Cropping Systems, No Tillage	0.15	0.16	0.16	0.14	0.13	0.13	0.14	0.15	0.15	0.14	0.15	0.15	0.14
High Input Cropping Systems with Manure, Full Tillage	0.26	0.25	0.24	0.22	0.24	0.24	0.25	0.26	0.28	0.29	0.31	0.31	0.30
High Input Cropping Systems with Manure, Reduced Tillage	0.07	0.07	0.08	0.07	0.08	0.08	0.09	0.08	0.09	0.09	0.09	0.08	0.08
High Input Cropping Systems with Manure, No Tillage	0.08	0.08	0.08	0.08	0.08	0.08	0.09	0.10	0.10	0.11	0.11	0.11	0.10
Medium Input Cropping Systems, Full Tillage	2.66	2.71	2.53	2.41	2.41	2.37	2.45	2.37	2.35	2.39	2.34	2.33	2.26
Medium Input Cropping Systems, Reduced Tillage	0.59	0.60	0.56	0.59	0.59	0.56	0.55	0.52	0.48	0.48	0.47	0.45	0.45

Medium Input Cropping Systems, No Tillage	0.71	0.69	0.65	0.65	0.66	0.65	0.65	0.62	0.64	0.65	0.65	0.64	0.63
Low Input Cropping Systems, Full Tillage	7.45	7.36	7.39	7.34	7.27	7.24	7.16	7.15	7.03	7.09	7.07	7.16	7.21
Low Input Cropping Systems, Reduced Tillage	0.21	0.19	0.19	0.23	0.20	0.19	0.18	0.18	0.21	0.19	0.16	0.16	0.16
Low Input Cropping Systems, No Tillage	0.21	0.19	0.20	0.28	0.27	0.25	0.24	0.23	0.29	0.29	0.28	0.28	0.27
Hay with Legumes or Irrigation	0.96	0.92	0.95	0.94	0.94	0.92	0.87	0.85	0.82	0.82	0.83	0.83	0.82
Hay with Legumes or Irrigation and Manure	0.44	0.42	0.39	0.40	0.38	0.34	0.32	0.33	0.30	0.30	0.31	0.29	0.28
Hay, Unimproved	0.03	0.04	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Pasture with Legumes or Irrigation in Rotation	0.02	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.00	0.01	0.01
Pasture with Legumes or Irrigation and Manure, in Rotation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0	0.00	0	0.00
Rice	0.04	0.04	0.03	0.03	0.03	0.03	0.02	0.03	0.02	0.02	0.02	0.02	0.01
Perennials	2.46	2.49	2.50	2.45	2.45	2.45	2.42	2.44	2.46	2.50	2.53	2.56	2.61
Grassland Systems	109.20	109.06	108.66	108.33	107.97	107.79	107.61	107.40	107.14	106.82	106.69	106.48	106.38
Pasture with Legumes or Irrigation	1.84	1.88	1.81	1.75	1.71	1.65	1.66	1.61	1.55	1.49	1.42	1.45	1.39
Pasture with Legumes or Irrigation and Manure	0.08	0.09	0.08	0.08	0.06	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.05
Rangelands and Unimproved Pasture	76.55	75.69	75.41	75.30	74.97	74.90	74.72	74.71	74.69	74.41	74.44	74.03	74.39
Rangelands and Unimproved Pasture, Moderately Degraded	22.91	22.93	22.95	22.84	22.93	22.92	22.93	22.86	22.75	22.57	22.49	22.32	22.29
Rangelands and Unimproved Pasture, Severely Degraded	7.82	8.47	8.41	8.36	8.29	8.25	8.23	8.17	8.09	8.29	8.30	8.64	8.26
Total	128.26	127.76	127.19	126.62	126.10	125.74	125.35	125.04	124.62	124.21	124.05	123.77	123.52

Land-Use/Management System	2016	2017	2018	2019	2020
Cropland Systems	17.05	16.92	16.86	16.77	16.69
Conservation Reserve Program	0.74	0.70	0.32	0.34	0.33
High Input Cropping Systems, Full Tillage	0.85	0.82	0.92	1.30	1.41

High Input Cropping Systems, Reduced Tillage	0.14	0.16	0.16	0.16	0.17
High Input Cropping Systems, No Tillage	0.15	0.14	0.16	0.20	0.21
High Input Cropping Systems with Manure, Full Tillage	0.31	0.30	0.30	0.28	0.27
High Input Cropping Systems with Manure, Reduced Tillage	0.07	0.07	0.08	0.08	0.07
High Input Cropping Systems with Manure, No Tillage	0.11	0.10	0.11	0.11	0.10
Medium Input Cropping Systems, Full Tillage	2.38	2.25	2.62	2.95	3.11
Medium Input Cropping Systems, Reduced Tillage	0.36	0.36	0.37	0.37	0.38
Medium Input Cropping Systems, No Tillage	0.62	0.60	0.63	0.62	0.63
Low Input Cropping Systems, Full Tillage	7.01	7.03	7.37	6.64	6.46
Low Input Cropping Systems, Reduced Tillage	0.18	0.18	0.21	0.21	0.19
Low Input Cropping Systems, No Tillage	0.38	0.38	0.40	0.37	0.34
Hay with Legumes or Irrigation	0.81	0.81	0.72	0.72	0.71
Hay with Legumes or Irrigation and Manure	0.28	0.29	0.22	0.23	0.20
Hay, Unimproved	0.02	0.03	0.01	0.00	0
Pasture with Legumes or Irrigation in Rotation	0.01	0.04	0.00	0.00	0
Pasture with Legumes or Irrigation and Manure, in Rotation	0.00	0.00	0.00	0.00	0
Rice	0.02	0.02	0.01	0.01	0.01
Perennials	2.62	2.64	2.24	2.18	2.10
Grassland Systems	105.91	106.02	106.02	106.12	106.28
Pasture with Legumes or Irrigation	1.35	1.29	1.32	1.34	1.39
Pasture with Legumes or Irrigation and Manure	0.04	0.04	0.04	0.04	0.04
Rangelands and Unimproved Pasture	74.06	73.97	74.01	74.13	74.31
Rangelands and Unimproved Pasture, Moderately Degraded	22.19	22.36	22.32	22.28	22.24
Rangelands and Unimproved Pasture, Severely Degraded	8.26	8.35	8.33	8.32	8.30
Total	122.96	122.93	122.88	122.89	122.97

Note: In the current *Inventory*, land use and management data have been incorporated through 2020. Additional data will be incorporated in the future to extend the time series of the land use data. Totals may not sum due to independent rounding.

Organic soils are categorized into land-use systems based on drainage (IPCC 2006) (Table A-174). Undrained soils are treated as having no loss of organic carbon or soil N₂O emissions. Drained soils are subdivided into those used for cultivated cropland, which are assumed to have high drainage and relatively large losses of carbon, and those used for managed pasture, which are assumed to have less drainage with smaller losses of carbon. N₂O emissions are assumed to be similar for both drained croplands and grasslands.

Table A-174: Total Land Areas for Drained Organic Soils by Land Management Category and Climate Region (Million Hectares)

IPCC Land-Use Category for Organic Soils	Land Areas (million ha)													
	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Cold Temperate														
Cultivated Cropland (high drainage)	0.36	0.36	0.34	0.34	0.32	0.32	0.32	0.32	0.32	0.31	0.31	0.30	0.30	0.30
Managed Pasture (low drainage)	0.36	0.36	0.37	0.37	0.39	0.38	0.37	0.38	0.37	0.36	0.37	0.38	0.38	0.37
Undrained	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Total	0.74	0.74	0.74	0.74	0.73	0.72	0.72	0.72	0.71	0.70	0.70	0.70	0.70	0.69
Warm Temperate														
Cultivated Cropland (high drainage)	0.21	0.20	0.20	0.20	0.19	0.19	0.19	0.19	0.18	0.18	0.18	0.18	0.19	0.19
Managed Pasture (low drainage)	0.05	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.07
Undrained	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00
Total	0.27	0.26	0.26	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.26
Tropical														
Cultivated Cropland (high drainage)	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.16	0.16	0.24	0.24	0.23
Managed Pasture (low drainage)	0.18	0.17	0.17	0.18	0.18	0.18	0.18	0.18	0.17	0.17	0.18	0.16	0.17	0.15
Undrained	0	0.00	0	0.00	0.00	0.00	0.00	0	0.00	0.07	0.08	0.00	0.00	0.00
Total	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.39

IPCC Land-Use Category for Organic Soils	Land Areas (million ha)											
	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Cold Temperature												
Cultivated Cropland (high drainage)	0.30	0.30	0.30	0.30	0.29	0.28	0.28	0.29	0.29	0.29	0.29	0.29
Managed Pasture (low drainage)	0.39	0.39	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.41	0.41	0.41
Undrained	0.02	0.02	0.02	0.01	0.01	0.02	0.01	0.02	0.02	0.01	0.01	0.00
Total	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.70	0.70
Warm Temperate												
Cultivated Cropland (high drainage)	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Managed Pasture (low drainage)	0.07	0.07	0.07	0.06	0.06	0.06	0.06	0.07	0.06	0.06	0.06	0.06
Undrained	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Total	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.25
Tropical												
Cultivated Cropland (high drainage)	0.24	0.23	0.23	0.22	0.22	0.21	0.21	0.22	0.22	0.22	0.21	0.21

Managed Pasture (low drainage)	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Undrained	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0	0.00	0	0.00
Total	0.39	0.39	0.38	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.36	0.36

IPCC Land-Use Category for Organic Soils		Land Areas (million ha)				
		2016	2017	2018	2019	2020
Cold Temperate						
Cultivated Cropland (high drainage)	0.29	0.29	0.29	0.29	0.29	0.29
Managed Pasture (low drainage)	0.41	0.41	0.40	0.40	0.41	0.41
Undrained	0.01	0.00	0.00	0.01	0.00	0.00
Total	0.70	0.70	0.69	0.69	0.70	0.70
Warm Temperate						
Cultivated Cropland (high drainage)	0.19	0.19	0.19	0.19	0.19	0.19
Managed Pasture (low drainage)	0.06	0.06	0.06	0.06	0.06	0.06
Undrained	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.25	0.25	0.25	0.25	0.26	0.26
Tropical						
Cultivated Cropland (high drainage)	0.21	0.21	0.20	0.20	0.20	0.20
Managed Pasture (low drainage)	0.15	0.15	0.15	0.15	0.14	0.14
Undrained	0	0.00	0.00	0	0.00	0.00
Total	0.36	0.35	0.35	0.35	0.34	0.34

Note: In the current *Inventory*, land use and management data have been incorporated through 2020. Additional data will be incorporated in the future to extend the time series of the land use data.

The harvested area for rice cultivation is estimated from the NRI based on survey locations classified as rice (Table A-175). Ratoon crops occur in the Southeastern United States with a second season of rice during the year, including Louisiana (LSU 2015 for years 2000 through 2020) and Texas (TAMU 2015 for years 1993 through 2020), averaging 32 percent and 48 percent of rice acres planted, respectively. Florida also has a large fraction of area with ratoon crops (45 percent), but ratoon cropping is uncommon in Arkansas occurring on a relatively small fraction of fields estimated at about 1 percent. These values are used to approximate the level of ratoon cropping by randomly assigning the practice to a subset of NRI survey locations in each state. No data are available for ratoon crops in Missouri or Mississippi, and so the amount of ratooning is assumed similar to Arkansas. Ratoon rice crops are not grown in California.

Table A-175: Total Rice Harvested Area Estimated with Tier 1 and 3 *Inventory* Approaches (Million Hectares)

Year	Land Areas (Million Hectares)		
	Tier 1	Tier 3	Total
1990	0.28	1.51	1.78
1991	0.27	1.54	1.81
1992	0.28	1.68	1.96
1993	0.27	1.57	1.85
1994	0.27	1.53	1.80
1995	0.26	1.55	1.81
1996	0.27	1.52	1.78
1997	0.26	1.47	1.73
1998	0.31	1.47	1.78

1999	0.39	1.38	1.78
2000	0.43	1.47	1.90
2001	0.31	1.35	1.65
2002	0.26	1.54	1.80
2003	0.25	1.38	1.64
2004	0.22	1.44	1.66
2005	0.22	1.60	1.82
2006	0.20	1.29	1.49
2007	0.24	1.33	1.58
2008	0.19	1.25	1.43
2009	0.25	1.53	1.78
2010	0.22	1.58	1.80
2011	0.23	1.29	1.51
2012	0.23	1.19	1.41
2013	0.23	1.33	1.56
2014	0.23	1.40	1.63
2015	0.21	1.46	1.67
2016	0.25	1.45	1.69
2017	0.18	1.20	1.38
2018	0.23	1.37	1.60
2019	0.21	1.12	1.34
2020	0.22	1.41	1.63

Step 1b: Obtain Management Activity Data to estimate Soil Organic Carbon Stock Changes, Soil N₂O Emissions and Rice Cultivation CH₄ Emissions from Mineral Soils

The USDA-NRCS Conservation Effects and Assessment Project (CEAP) provides data on a variety of cropland management activities, and is used to inform the inventory analysis about tillage practices, synthetic mineral fertilization, manure amendments, cover cropping management, as well as planting and harvest dates (USDA-NRCS 2022; USDA-NRCS 2018; USDA-NRCS 2012). CEAP data are collected at a subset of NRI survey locations, and provide management information from approximately 2003 to 2006 and 2013 to 2016. The CEAP data includes additional information from NRI locations such as time of planting and harvest; amount, type and time of fertilization; implement type and timing of soil cultivation events; and type and timing of cover crop planting and termination practices.

These data are combined with other datasets in an imputation analysis to generate a time series from 1950 to 2020. For several management practices, we use gradient boosted regression (Friedman, J.H. 2001) to predict management activity data on NRI survey locations. Gradient boosted regression is a machine learning technique that combines predictions from multiple weak prediction models and outperforms many complicated machine learning algorithms. The algorithm makes predictions at specific NRI survey locations or at state or regional levels. The final imputation product includes 6 complete imputations of the management activity data in order to capture the uncertainty. The sections below provide additional information for each of the management practices.

Planting Date: CEAP data on planting dates are used to train gradient boosted regression models and predict initial planting dates on NRI survey locations. The CEAP data were grouped by crop, year, and, in the case of small grains, winter and spring growing seasons. Then predictive mean matching (Little 1988, van Buuren 2012) is used to select the final planting date for each NRI survey location from the original dates in the CEAP survey. The predictive mean matching ensures that the final imputed planting dates were consistent with those reported by farmers.

Synthetic and Manure Nitrogen Fertilizer Applications: Data on synthetic mineral nitrogen fertilizer rates are imputed based on crop-specific fertilizer rates in the USDA-NRCS CEAP products and fertilizer trends based on USDA-Economic Research Service (ERS) data. The ERS crop management data had been collected in Cropping Practices Surveys through 1995 (USDA-ERS 1997), and are now compiled as part of Agricultural Resource Management Surveys (ARMS), which started in 1996 (USDA-ERS 2020). In these surveys, data on inorganic nitrogen fertilization rates are collected for crops in the high production states and for a subset of low production states. Additional data on fertilization practices are compiled from other surveys and datasets produced by USDA (USDA 1954, 1957, 1964, 1966; USDA-NASS 1992, 1999, 2004). These data are used to build a time series of mineral

fertilizer application rates for specific crops and states from 1950 to 2020. These data are then used to inform the imputation product in combination with the USDA CEAP surveys, as described previously.

Fertilizer sales data are used to check and adjust synthetic mineral fertilizer amounts that are simulated with DayCent. The total amount of synthetic fertilizer used on-farms (cropland and grazing land application) has been estimated by the USGS from 1990 through 2012 on a county scale from fertilizer sales data (Brakebill and Gronberg 2017). For 2013 through 2017, county-level fertilizer used on-farms is adjusted based on annual fluctuations in total U.S. fertilizer sales (AAPFCO 2013 through 2022).¹²⁰ The time series is extended through 2020 using a linear regression model with moving-average (ARMA) errors (Brockwell and Davis 2016), which is a type of extrapolation method (IPCC 2006). The resulting data are used to check the simulated synthetic fertilizer inputs in the DayCent simulations at the state scale. Specifically, the simulated amounts of mineral fertilizer application for each state and year are compared to the sales data. If the simulated amounts exceed the sales data in a year, then the simulated N₂O emissions are reduced based on the amount of simulated fertilizer that exceeded the sales data relative to the total application of fertilizer in the DayCent simulations for the state. For example, if the simulated amount exceeded the sales data by 3 percent, then the emissions associated with synthetic mineral fertilization¹²¹ is reduced by 3 percent (the same adjustments are also made for leaching and volatilization losses of nitrogen that are used to estimate indirect N₂O emissions). This method ensures that the simulated amount of N₂O emissions and indirect nitrogen losses from synthetic mineral fertilization using bottom-up data from the ARMS and CEAP surveys are adjusted so that they are consistent with the top-down sales data. The bottom-up data from CEAP and ARMS will be further investigated in the future to evaluate the discrepancies with the sales data, and potentially improve these datasets to attain greater consistency.

The available manure for application to soils from 1990 to 2020 is estimated using methods described in the manure management section (Section 5.2) and annex (Annex 3.12), along with other data sources to estimate manure amounts from 1950 to 1990 (Haines et al. 2018; Kellogg et al. 2000). It is assumed that all available manure is applied to soils in cropland and grazing lands. Application rates at individual NRI survey locations are imputed from 1950 to 2020 using the methods described at the beginning of the Step 1b section. Similar to synthetic mineral fertilization in DayCent, total amount of manure available for application to soils is used to check and adjust the simulated amounts of manure application to soils in the DayCent simulations. There were no cases in this *Inventory* in which the amount of manure amendments in DayCent simulations exceeded the available manure for application to soils. The resulting amounts of synthetic and manure fertilizer application data are found in Table A-176.

PRP Manure Nitrogen: Another key source of nitrogen for grasslands is PRP manure nitrogen (i.e., manure deposited by grazing livestock on pasture, range or paddock). The total amount of PRP manure nitrogen is estimated using methods described in the manure management section (Section 5.2) and annex (Annex 3.12). Nitrogen from PRP animal waste deposited on non-federal grasslands in a county is estimated by multiplying the total PRP nitrogen (based on animal type and population data in a county) by the fraction of non-federal grassland area in the county. PRP manure nitrogen input rates for the Tier 3 DayCent simulations are estimated by dividing the total PRP manure nitrogen amount by the land area associated with non-federal grasslands in the county from the NRI survey data. During the simulations, the PRP nitrogen input is subdivided equally between urine and solid manure (i.e., 50:50 split), and carbon is also added with the solids using C:N ratios estimated from livestock-specific data on manure chemical content in the Agricultural Waste Management Field Handbook (USDA-NRCS 1996). Total PRP manure nitrogen added to soils is found in Table A-176.

Residue Nitrogen Inputs: Crop residue nitrogen, fixation by legumes, and nitrogen residue inputs from senesced grass litter are included as sources of nitrogen to the soil, and these sources of nitrogen are estimated in the DayCent simulations as a function of vegetation type, weather, and soil properties. That is, the model accounts for the contribution of nitrogen from crop residues to the soil profile based on simulating the growth of the crop and

¹²⁰ The fertilizer consumption data in AAPFCO are recorded in “fertilizer year” totals (i.e., July to June), but are converted to calendar year totals. This is done by assuming that approximately 35 percent of fertilizer usage occurred from July to December and 65 percent from January to June (TVA 1992b).

¹²¹ See Step 2A for the approach that is used to disaggregate N₂O emissions from DayCent into the sources of nitrogen inputs (e.g., mineral fertilizer inputs).

senescence. This includes the total nitrogen inputs of above- and below-ground nitrogen and fixed nitrogen in residues that are not harvested or burned (DayCent simulations assume that 3 percent of non-harvested above ground residues for crops are burned),¹²² and the resulting amounts can be found in Table A-176.

Other Nitrogen Inputs: Other nitrogen inputs are estimated within the DayCent simulation, and thus input data are not required, including mineralization from decomposition of soil organic matter and asymbiotic fixation of nitrogen from the atmosphere. Mineralization of soil organic matter will also include the effect of land use change on this process as recommended by the IPCC (2006). The influence of additional inputs of nitrogen are estimated in the simulations so that there is full estimation of all emissions from managed lands, as recommended by the IPCC (2006). The simulated nitrogen input from soil organic matter mineralization and asymbiotic nitrogen fixation are provided in Table A-176.

Tillage Practices: Tillage practices are grouped into three categories: full, reduced, and no-tillage. Full tillage is defined as multiple tillage operations every year, including significant soil inversion (e.g., plowing, deep disking) and low surface residue coverage. This definition corresponds to the intensive tillage and “reduced” tillage systems as defined by CTIC (2004). No-till is defined as not disturbing the soil except through the use of fertilizer and seed drills and where no-till is applied to all crops in the rotation. The remainder of the cultivated area is classified as reduced tillage, including mulch tillage and ridge tillage as defined by CTIC and intermittent no-till. The specific tillage implements and applications used for different crops, rotations, and regions are derived from the 1995 Cropping Practices Survey by the Economic Research Service (USDA-ERS 1997).

Tillage practices are estimated for each cropping system based on data from the Conservation Technology Information Center for 1989 to 2004 (CTIC 2004); USDA-NRCS CEAP survey (USDA-NRCS 2018b) and OptIS Data Product¹²³ from 2008 to 2020 (Hagen et al. 2020). The percentage of the land base managed with reduced till is assumed to decrease linearly from the late 1980s to 1975, and from late 1980s to 1980 for no-till. While CEAP and OptIS programs are providing data at the field scale, CTIC compiles data on cropland area under tillage management classes by major crop species and year at the county scale. The CTIC survey involves aggregate area, and therefore they do not fully characterize tillage practices as they are applied within a management sequence (e.g., crop rotation). This is particularly true for area estimates of cropland under no-till. These estimates include a relatively high proportion of “intermittent” no-till, where no-till in one year may be followed by tillage in a subsequent year, leading to no-till practices that are not continuous in time. Estimates of the area under continuous no-till for CTIC have been provided by experts at CTIC to account for intermittent tillage activity and its impact on soil organic carbon (Towery 2001).

Tillage data are further processed to impute a tillage management system for each NRI survey location over the time series from 1975 to 2020. First, the trend in the percentages for each tillage system is modeled for each CEAP region, state and crop group using CEAP, CTIC, and OptIS data products. With the modeled target percentages, we impute a tillage management system for every NRI survey location in the “base block” of 2016-2020 for each CEAP region, state and crop group by random sampling with restrictions of the modeled predictions. Once the base block is imputed, tillage systems for remaining five-year time blocks are imputed backward in time using trending information described above. The trending information from one-time block to the next is reflected in the imputations by first constructing the 3x3 transition probability matrix, **M**, between the two blocks. Let **a** denote the vector of proportions in the current time block (already imputed) and let **b** denote the vector of desired proportions in the target time block (to be imputed) based on the trending information. The rows of **M** correspond to the tillage type (no-till, reduced till, or conventional till) in the target time block and the columns of **M** correspond to the tillage type in the current time block. The elements of **M** are constrained so that (a) each column is a probability distribution (all elements between 0 and 1 and column sums to 1); (b) **Ma=b**; and (c) the diagonal elements of **M** are as large as possible. The last constraint implies as much temporal continuity as possible at a location, subject to overall trends. The solution for **M** is obtained by a mathematical optimization technique known as linear programming. Once **M** is obtained, it is used for imputing the tillage system as follows: determine the column that corresponds to the tillage system (imputed or real) of the current block, and use the probabilities in that column to

¹²² Another improvement is to reconcile the amount of crop residues burned with the field burning of agricultural residues source category (Section 5.5).

¹²³ OptIS data on tillage practices provided by Regrow Agriculture, Inc.

randomly select the tillage system for the target block. Repeat the construction of **M** and the imputation block by block backward in time to 1975. All cropland is assumed to be managed with full till prior to 1975.

Cover Crops: Cover crop data from 2000 to 2020 are based on USDA CEAP data (USDA-NRCS 2018, 2022), USDA Census of Agriculture (USDA-NASS 2012, 2017) and the OptIS data product¹²⁴ (Hagen et al. 2020). Cover crops percentages are modeled by state and crop from 2000 to 2020. NRI locations are assigned cover crop management based on random selection of locations for the base year 2020 constrained by the predicted percentages. For years before 2020 to 2000, a similar technique as in the tillage system imputation is implemented to maintain the trending and temporal continuity in assignment of cover crop management to individual NRI locations subject to overall trends.

The management activity datasets do not provide information on cover crop management prior to 2000. To address this gap, it is assumed that cover crop management was minimal prior to 1990 and the percentage of locations with cover crop management increased linearly over the decade to the levels estimated from the cover crop management data in 2000.

Irrigation: NRI (USDA-NRCS 2020) provides irrigation data starting in 1979 and differentiates between irrigated and non-irrigated land, but does not provide more detailed information on the type and intensity of irrigation. Hence, irrigation is modeled by assuming that water is applied to the level of field capacity on the day after the soil drains to 60 percent of field capacity in the DayCent model simulation. To the extend the time series to 1950, the amount of NRI survey locations with irrigation are scaled backward in time from 1979 to 1950 using historical data on irrigation management (Haines et al. 2018).

Daily Weather Data: Daily maximum/minimum temperature and precipitation data are based on gridded weather data from the PRISM Climate Group (2022). Computer-generated weather data are used to drive the DayCent model simulations because weather station data do not exist near all NRI points. The PRISM product uses interpolation algorithms to derive weather patterns for areas between the existing network of weather stations (Daly et al. 1998). PRISM weather data are available for the United States starting in the year 1981 at a 4 km resolution. Each NRI survey location is assigned the PRISM weather data for the grid cell containing the survey location.

Enhanced Vegetation Index: The Enhanced Vegetation Index (EVI) from the MODIS vegetation products, (MOD13Q1 and MYD13Q1) is an input to DayCent for estimating net primary production using the NASA-CASA production algorithm (Potter et al. 1993, 2007). MODIS imagery is collected on a nominal 8 day-time frequency when combining the two products. A best approximation of the daily time series of EVI data is derived using a smoothing process based on the Savitzky-Golay Filter (Savitzky and Golay 1964) after pre-screening for outliers and for cloud-free, high quality data as identified in the MODIS data product quality layer. The NASA-CASA production algorithm is only used for the following crops, including corn, soybeans, sorghum, cotton, wheat, and other close-grown crops such as barley and oats.¹²⁵

The MODIS EVI products have a 250 m spatial resolution, and some pixels in images have mixed land uses and crop types at this resolution, which is problematic for estimating NPP associated with a specific crop at an NRI survey location. Therefore, a threshold of 90 percent purity in an individual pixel is the cutoff for estimating NPP using the EVI data derived from the imagery (i.e., pixels with less than 90 percent purity for a crop are assumed to generate bias in the resulting NPP estimates). The USDA-NASS Crop Data Layer (CDL) (Johnson and Mueller 2010) is used to determine the purity levels of the EVI data. CDL data have a 30 to 58 m spatial resolution, depending on the year. The level of purity for individual pixels in the MODIS EVI products is determined by aggregating the crop cover data in CDL to the 250 m resolution of the EVI data. In this step, the percent cover of individual crops is determined for the 250 m EVI pixels. Pixels that do not meet a 90 percent purity level for any crop are eliminated from the dataset. The nearest pixel with at least 90 percent purity for a crop is assigned to the NRI survey location based on a 10 km buffer surrounding the survey location. EVI data are not assigned to a survey location if there are no pixels with at least 90 percent purity within the 10 km buffer. In addition, CDL does not provide full coverage for crops across the conterminous United States until 2009 so it is not possible to evaluate purity for the entire

¹²⁴ OptIS data on cover crop management provided by Regrow Agriculture, Inc.

¹²⁵ Additional crops and grassland will be used with the NASA-CASA method in the future, as a planned improvement.

cropland area prior to 2009, and therefore some NRI locations are not simulated with the NASA-CASA algorithm until 2009. In cases where EVI data are not available, production is simulated with a single value for the maximum daily NPP, which is reduced if there is water, temperature or nutrient stress affecting plant growth.

Water Management for Rice Cultivation: Rice crop production in the United States is mostly managed with continuous flooding, but does include a minor amount of land with mid-season drainage or alternate wet-dry periods (Hardke 2015; UCCE 2015; Hollier 1999; Way et al. 2014). However, continuous flooding is applied to all rice cultivation areas in the inventory because water management data are not available. Winter flooding is another key practice associated with water management in rice fields. Winter flooding occurs on 34 percent of rice fields in California (Miller et al. 2010; Fleskes et al. 2005), and approximately 21 percent of the fields in Arkansas (Wilson and Branson 2005 and 2006; Wilson and Runsick 2007 and 2008; Wilson et al. 2009 and 2010; Hardke and Wilson 2013 and 2014; Hardke 2015). No data are available on winter flooding for Texas, Louisiana, Florida, Missouri, or Mississippi. For these states, the average amount of flooding is assumed to be similar to Arkansas. In addition, the amount of winter flooding is assumed to be relatively constant over the *Inventory* time period.

Organic Amendments for Rice Cultivation: Rice straw is not typically harvested from fields in the United States. The carbon input from rice straw is simulated directly within the DayCent model for the Tier 3 method under the assumption that no straw is harvested.

Soil Properties: Soil texture and drainage capacity (i.e., hydric vs. non-hydric soil characterization) are the main soil variables used as inputs to the DayCent model. Texture is one of the main controls on soil carbon turnover and stabilization in the model, which uses particle size fractions of sand (50-2,000 μm), silt (2-50 μm), and clay (<2 μm) as inputs. Hydric conditions in soils are associated with poor drainage, and hence have a high-water table for part of the year in their native (pre-cultivation) condition. Non-hydric soils are moderately to well-drained.¹²⁶ Poorly drained soils can be subject to anaerobic (lack of oxygen) conditions if water inputs (precipitation and irrigation) exceed water losses from drainage and evapotranspiration. Depending on moisture conditions, hydric soils can range from fully aerobic to completely anaerobic, varying over the year. Decomposition rates are modified according to a linear function that varies from 0.3 under completely anaerobic conditions to 1.0 under fully aerobic conditions (default parameters in DayCent).¹²⁷ Other soil characteristics needed in the simulation, such as field capacity and wilting-point water contents, are estimated from soil texture data using a standardized hydraulic properties calculator (Saxton et al. 1986). Soil input data are derived from Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2020). The data are based on field measurements collected as part of soil survey and mapping. Each NRI survey location is assigned the dominant soil component in the polygon containing the point from the SSURGO data product.

Step 1c: Obtain Additional Management Activity Data for the Tier 1 Method to Estimate Soil N₂O Emissions from Mineral Soils

Synthetic Nitrogen Fertilizer: A process-of-elimination approach is used to estimate synthetic nitrogen fertilizer additions to crops in the Tier 1 method. The total amount of synthetic fertilizer used on-farms has been estimated using USGS and AAPFCO datasets, as discussed in Step 1b (Brakebill and Gronberg 2017; AAPFCO 2013 through 2022). The amount of nitrogen applied to crops in the Tier 1 method (i.e., not simulated by DayCent) is assumed to be the remainder of the fertilizer that is used on farms after subtracting the amount applied to crops and non-federal grasslands simulated by DayCent. The differences are aggregated to the national level, and PDFs are derived based on uncertainties in the amount of nitrogen applied to crops and non-federal grasslands for the Tier 3 method. Total fertilizer application to crops in the Tier 1 method is found in Table A-176.

Managed Livestock Manure and Other Organic Fertilizers: Managed manure nitrogen that is not applied to crops and grassland simulated by DayCent is assumed to be applied to other crops that are included in the Tier 1 method. The total amount of manure available for application to soils has been estimated with methods described in the manure management section (Section 5.2) and annex (Annex 3.12). Managed manure nitrogen applied to

¹²⁶ Artificial drainage (e.g., ditch- or tile-drainage) is simulated as a management variable.

¹²⁷ Hydric soils are primarily subject to anaerobic conditions outside the plant growing season, such as late winter or early spring prior to planting. Soils that are flooded during much of the year are typically classified as organic soils (e.g., peat), which are not simulated with the DayCent model.

croplands for the Tier 1 method is calculated using a process of elimination approach. Specifically, the amount of managed manure nitrogen that is amended to soils for the Tier 1 method is the difference between total managed manure nitrogen available for application to soils and the amount applied in the DayCent model simulations. The fate of manure available for application to soils is summarized in Table A-176.

Estimates of total national annual nitrogen additions from other commercial organic fertilizers are derived from organic fertilizer statistics (TVA 1991 through 1994; AAPFCO 1995 through 2022).¹²⁸ Commercial organic fertilizers include dried blood, tankage, compost, and other organic materials, which are recorded in mass units of fertilizer. These data are converted to mass units of nitrogen by multiplying the consumption values by the average organic fertilizer nitrogen content of commercial organic fertilizers, which range between 2.3 to 4.2 percent across the time series (TVA 1991 through 1994; AAPFCO 1995 through 2022). There is potential for double-counting nitrogen applications to soils for dried manure and biosolids (i.e., treated sewage sludge) that are included as commercial fertilizers because these nitrogen inputs are already addressed in the manure dataset (See manure management Section 5.2 and Annex 3.12) and biosolids (See Biosolids below) that are estimated for this *Inventory*. Therefore, to avoid double-counting, the amounts of dried manure and biosolids in other commercial organic fertilizer, which are provided in the reports¹²⁹ (TVA 1991 through 1994; AAPFCO 1995 through 2022), are subtracted from the total commercial organic fertilizer before estimating emissions. The PDFs are derived for the organic fertilizer applications assuming a default ± 50 percent uncertainty. Annual consumption of other organic fertilizers is presented in Table A-176.

PRP Manure Nitrogen: Soil N₂O emissions from PRP manure nitrogen deposited on federal grasslands are estimated with a Tier 1 method. PRP manure nitrogen data are derived using methods described in the manure management section (Section 5.2) and Annex 3.12. PRP nitrogen deposited on federal grasslands is calculated using a process of elimination approach. Specifically, the amount of PRP nitrogen included in the DayCent model simulations of non-federal grasslands is subtracted from total PRP nitrogen and the difference is assumed to be deposited on federal grasslands. The total PRP manure nitrogen added to soils is found in Table A-176.

Biosolids (i.e., Treated Sewage Sludge) Amendments: Biosolids are generated from the treatment of raw sewage in public or private wastewater treatment works and are typically used as a soil amendment, or are sent to waste disposal facilities, such as landfills. In this *Inventory*, all biosolids that are amended to agricultural soils are assumed to be applied to grasslands¹³⁰. Estimates of the amounts of biosolids nitrogen applied to agricultural lands are derived from national data on biosolids generation, disposition, and nitrogen content. Total biosolids generation data for 1990 through 2004, in dry mass units, are obtained from AAPFCO (1995 through 2004). Biosolids generation data for 2018 are obtained from NEBRA (2022). Values for 2005 through 2017 are interpolated. Values for 2019 through 2023 are not available so a “least squares line” statistical extrapolation using the previous 29 years of data to impute an approximate value. Refer to Annex 3.15 for additional details. The total sludge generation estimates are then converted to units of nitrogen by applying an average nitrogen content (the nitrogen content of biosolids used in estimating the total nitrogen applied from biosolids is assumed to be 3.9 percent) (AAPFCO 2000), and disaggregated into use and disposal practices using historical data in EPA (1993) and NEBRA (2007 and 2022). The use and disposal practices are agricultural land application, other land application, surface disposal, incineration, landfilling, ocean dumping (ended in 1992), and other disposal methods. The resulting estimates of biosolids nitrogen applied to agricultural land are used to estimate N₂O emissions from agricultural soil management; the estimates of biosolids nitrogen applied to other land and surface-disposed are used in

¹²⁸ Similar to the data for synthetic fertilizers described above, the organic fertilizer consumption data are recorded in “fertilizer year” totals, (i.e., July to June), but are converted to calendar year totals. This is done by assuming that approximately 35 percent of fertilizer usage occurred from July to December and 65 percent from January to June (TVA 1992b).

¹²⁹ The amount of reported dried manure and biosolids in other organic fertilizers must be converted into units of nitrogen. While the amounts of dried manure and biosolids are provided in each report (TVA 1991 through 1994; AAPFCO 1995 through 2022), the nitrogen contents of dried manure and biosolids are only provided in AAPFCO (2000). The values are 0.5 and 6.0 percent for dried manure and biosolids, respectively.

¹³⁰ A portion of biosolids may be applied to croplands, but there is no national dataset to disaggregate the amounts between cropland and grassland.

estimating N₂O fluxes from soils in settlements remaining settlements (see Section 6.9 of the Land Use, Land-Use Change, and Forestry chapter). Biosolids disposal data are provided in Table A-176.

Residue Nitrogen Inputs: Soil N₂O emissions for residue nitrogen inputs from croplands that are not simulated by DayCent are estimated with a Tier 1 method. Annual crop production statistics for all major commodity and specialty crops are taken from U.S. Department of Agriculture crop production reports (USDA-NASS 2024). Total production for each crop is converted to tons of dry matter product using the residue dry matter fractions. Dry matter yield is then converted to tons of above- and below-ground biomass nitrogen. Above-ground biomass is calculated by using linear equations to estimate above-ground biomass given dry matter crop yields, and below-ground biomass is calculated by multiplying above-ground biomass by the below-to-above-ground biomass ratio. Nitrogen inputs are estimated by multiplying above- and below-ground biomass by respective nitrogen concentrations and by the portion of cropland that is not simulated by DayCent. All ratios and equations used to calculate residue nitrogen inputs are from IPCC (2006) and Williams (2006). PDFs are derived assuming a ±50 percent uncertainty in the yield estimates (USDA-NASS does not provide uncertainty), along with uncertainties provided by the IPCC (2006) for dry matter fractions, above-ground residue, ratio of below-ground to above-ground biomass, and residue nitrogen fractions. The resulting annual residue nitrogen inputs are presented in Table A-176.

Table A-176: Sources of Soil Nitrogen (kt N)

N Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
1. Synthetic Fertilizer N: Cropland	9,817	10,008	10,092	9,989	11,150	10,306	10,874	10,862	10,827	10,982
2. Synthetic Fertilizer N: Grassland	6	4	10	37	18	5	7	8	66	8
3. Managed Manure N: Cropland	2,447	2,479	2,488	2,477	2,541	2,577	2,572	2,595	2,617	2,624
4. Managed Manure N: Grassland	+	+	+	+	+	+	+	+	+	+
5. Pasture, Range, & Paddock Manure N	4,094	4,101	4,262	4,352	4,424	4,526	4,493	4,391	4,348	4,287
6. N from Crop Residue Decomposition ^a	5,528	5,652	5,340	5,726	5,533	5,862	5,691	5,587	5,599	6,262
7. N from Grass Residue Decomposition ^a	10,788	10,694	10,999	11,065	10,596	11,266	11,001	11,022	10,513	11,737
8. Min. SOM / Asymbiotic N-Fixation: Cropland ^b	10,029	9,611	9,204	10,071	9,338	10,012	9,363	9,454	10,605	9,784
9. Min. SOM / Asymbiotic N-Fixation: Grassland ^b	15,122	15,638	15,422	15,443	14,852	15,309	15,555	15,930	15,953	14,959
10. Treated Sewage Sludge N: Grassland	52	56	60	63	66	69	72	76	79	81
11. Other Organic Amendments: Cropland ^c	4	8	6	5	8	10	13	14	12	11
Total	57,887	58,251	57,882	59,228	58,527	59,942	59,642	59,940	60,619	60,735

N Source	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
1. Synthetic Fertilizer N: Cropland	10,791	10,070	10,546	10,611	11,310	10,726	10,464	11,502	10,937	9,948
2. Synthetic Fertilizer N: Grassland	24	21	22	15	57	16	8	7	18	11
3. Managed Manure N: Cropland	2,663	2,654	2,692	2,700	2,624	2,657	2,733	2,754	2,730	2,703
4. Managed Manure N: Grassland	+	+	+	+	+	+	+	+	+	+
5. Pasture, Range, & Paddock Manure N	4,195	4,192	4,200	4,208	4,163	4,216	4,272	4,164	4,126	4,095
6. N from Crop Residue Decomposition ^a	6,013	5,977	5,824	6,028	5,699	5,797	5,781	5,713	5,639	5,754
7. N from Grass Residue Decomposition ^a	10,953	11,308	11,082	11,405	10,814	11,441	11,181	11,504	11,434	10,981
8. Min. SOM / Asymbiotic N-Fixation: Cropland ^b	9,795	10,478	10,174	10,215	10,791	10,480	10,207	10,703	10,575	10,952
9. Min. SOM / Asymbiotic N-Fixation: Grassland ^b	14,646	15,080	15,322	15,449	17,064	16,096	15,767	16,635	16,112	16,328
10. Treated Sewage Sludge N: Grassland	84	86	89	92	94	94	94	93	93	93
11. Other Organic Amendments: Cropland ^c	9	7	8	8	9	10	12	15	12	10
Total	59,172	59,874	59,960	60,731	62,626	61,531	60,520	63,091	61,675	60,874

N Source	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
1. Synthetic Fertilizer N: Cropland	10,793	11,264	11,909	11,911	11,714	11,494	11,395	11,510	11,305	11,249
2. Synthetic Fertilizer N: Grassland	1	10	10	5	4	7	3	1	5	7
3. Managed Manure N: Cropland	2,691	2,718	2,747	2,724	2,716	2,777	2,839	2,908	2,950	2,984

4. Managed Manure N: Grassland	+	+	+	+	+	+	+	+	+	+
5. Pasture, Range, & Paddock Manure N	4,046	3,951	3,868	3,827	3,768	3,849	3,982	4,053	4,052	4,049
6. N from Crop Residue Decomposition ^a	6,252	6,136	5,935	5,954	6,103	5,809	5,810	5,966	6,364	5,802
7. N from Grass Residue Decomposition ^a	11,309	10,918	11,370	10,668	10,737	10,330	10,669	10,963	10,510	10,757
8. Min. SOM / Asymbiotic N-Fixation: Cropland ^b	11,742	10,386	9,649	11,329	11,702	12,189	12,404	11,738	12,768	12,294
9. Min. SOM / Asymbiotic N-Fixation: Grassland ^b	16,642	14,934	14,266	16,508	16,349	16,778	16,716	16,038	16,735	16,528
10. Treated Sewage Sludge N: Grassland	93	92	92	92	91	91	91	90	90	90
11. Other Organic Amendments: Cropland ^c	10	12	13	13	11	12	20	22	16	14
Total	63,580	60,420	59,859	63,029	63,194	63,335	63,928	63,289	64,796	63,774

N Source	2020
1. Synthetic Fertilizer N: Cropland	11,209
2. Synthetic Fertilizer N: Grassland	6
3. Managed Manure N: Cropland	2,997
4. Managed Manure N: Grassland	+
5. Pasture, Range, & Paddock Manure N	4,003
6. N from Crop Residue Decomposition ^a	6,531
7. N from Grass Residue Decomposition ^a	11,149
8. Min. SOM / Asymbiotic N-Fixation: Cropland ^b	11,179
9. Min. SOM / Asymbiotic N-Fixation: Grassland ^b	14,605
10. Treated Sewage Sludge N: Grassland	89
11. Other Organic Amendments: Cropland ^c	13
Total	61,781

+ Does not exceed 0.5 kt

^a Residue nitrogen inputs include unharvested fixed nitrogen from legumes as well as crop and grass residue nitrogen.

^b Mineralization of soil organic matter and the asymbiotic fixation of nitrogen gas.

^c Includes dried blood, tannage, compost, other. Excludes dried manure and bio-solids (i.e., treated sewage sludge) used as commercial fertilizer to avoid double counting.

Note: Most activity data were not compiled for 2021 to 2023 and used in this *Inventory*, and so a data splicing method was used to estimate emissions. Additional activity data will be collected, and the Tier 1 and 3 methods will be applied in a future *Inventory* to recalculate the part of the time series that is estimated with the data splicing methods.

Step 1d: Additional Management Activity Data for Tier 2 Method to estimate Soil Organic Carbon Stock Changes in Mineral Soils

Biosolids (i.e., Treated Sewage Sludge) Amendments: Biosolids are generated from the treatment of raw sewage in public or private wastewater treatment facilities and are typically used as soil amendments or are sent for waste disposal to landfills. In this *Inventory*, all biosolids that are amended to agricultural soils are assumed to be applied to grasslands¹³¹. See section on biosolids in Step 1c for more information about the methods used to derive biosolid nitrogen estimates. The total amount of biosolid nitrogen is given in Table A-176. Biosolid nitrogen is assumed to be applied at the assimilative capacity provided in Kellogg et al. (2000), which is the amount of nutrients taken up by a crop and removed at harvest representing the recommended application rate for manure amendments. Future inventories may be revised to reflect the assimilative capacity of grasslands, but there is

¹³¹ Note that there are no data available on the location of biosolid amendments and so all biosolids are applied to grasslands (future *Inventories* will incorporate new information when it is available to separate amendments between croplands and grasslands).

insufficient information to approximate the capacity in this *Inventory*. Total biosolid nitrogen available for application is divided by the assimilative capacity to estimate the total land area over which biosolids have been applied. The resulting estimates are used for the estimation of soil organic carbon stock changes associated with application of biosolids.

Wetland Reserve: Wetlands enrolled in the Conservation Reserve Program have been restored in the Northern Prairie Pothole Region through the Partners for Wildlife Program funded by the U.S. Fish and Wildlife Service (USFWS 2010). The area of restored wetlands is estimated from contract agreements (Euliss and Gleason 2002). While the contracts provide reasonable estimates of the amount of land restored in the region, they do not provide the information necessary to estimate uncertainty. Consequently, a ± 50 percent range is used to construct the PDFs for the uncertainty analysis.

Step 1e: Additional Activity Data for Indirect N₂O Emissions

A portion of the nitrogen that is applied as synthetic fertilizer, livestock manure, and biosolids (i.e., treated sewage sludge) volatilizes as NH₃ and NO_x. In turn, the volatilized nitrogen is eventually returned to soils or water bodies through atmospheric deposition, thereby increasing nitrogen availability and enhancing N₂O production. Additional nitrogen is also lost from soils through leaching of mostly NO₃⁻ as water percolates through a soil profile and through runoff with overland water flow. Nitrogen losses from leaching and runoff enter groundwater and waterways, from which a portion is emitted as N₂O. Consistent with the IPCC guidelines (2006), indirect emissions are not estimated for leaching and runoff of nitrogen in semi- arid and arid regions. Semi-arid and arid regions in the United States occur in areas where the precipitation water input does not exceed 80 percent of the potential evapotranspiration (Note: Irrigated systems are always assumed to have leaching of nitrogen even in drier climates).

Using the DayCent model with the Tier 3 method and nitrogen sources contributing to indirect emissions described in IPCC (2006) guidelines, volatilization and leaching/surface run-off of nitrogen from soils is estimated in the simulations for crops and non-federal grasslands. DayCent simulates the processes leading to these losses of nitrogen based on environmental conditions (i.e., weather patterns and soil characteristics), management impacts (e.g., plowing, irrigation, harvest), and soil nitrogen availability (Del Grosso et al. 2005, 2008a; David et al. 2009). The DayCent model accounts for losses of nitrogen from all anthropogenic activity, not just the inputs of nitrogen from synthetic mineral fertilization and organic amendments¹³², which are addressed in the Tier 1 method. In addition, DayCent is a mass balance model and ensures that all nitrogen inputs are tracked through the flows in the ecosystem with no double counting of losses. Volatilized losses of nitrogen are summed for each day in the annual cycle to provide an estimate of the amount of nitrogen subject to indirect N₂O emissions. For non-arid regions, the daily losses of nitrogen through leaching and runoff in overland flow are summed for the annual cycle to provide an estimate of the amount of nitrogen subject to indirect N₂O emissions. Uncertainty in the estimates is derived from the variability in the fertilizer and organic amendment activity data, in addition to uncertainty in the DayCent model predictions.

The activity data to estimate the indirect N₂O emissions from volatilization, runoff and leaching in the Tier 1 method are based on the synthetic fertilizer, livestock manure, residue nitrogen inputs, biosolids nitrogen, and other nitrogen inputs in the calculation of direct emissions from agricultural mineral soils. These data are provided in Table A-176. To estimate volatilized nitrogen losses, the amount of synthetic fertilizers, manure, and biosolids are multiplied by the fraction subject to gaseous losses using the respective default values of 0.1 kg N/kg N added as mineral fertilizers and 0.2 kg N/kg N added as manure (IPCC 2006). Uncertainty in the volatilized nitrogen ranges from 0.03-0.3 kg NH₃-N+NO_x-N/kg N for synthetic fertilizer and 0.05-0.5 kg NH₃-N+NO_x-N/kg N for organic amendments (IPCC 2006). To estimate leaching/runoff losses of nitrogen from land areas that are not included in the DayCent simulations, the nitrogen additions from synthetic and manure, biosolids, and above- and below-ground crop residues, are multiplied by the fraction subject to leaching/runoff losses of 0.3 kg N/kg N applied, with an uncertainty from 0.1–0.8 kg NO₃-N/kg N (IPCC 2006). As noted above, leaching is assumed to be an insignificant source of indirect N₂O emissions if the amount of precipitation does not exceed 80 percent of the potential

¹³² The amount of volatilization and leaching are reduced if the simulated amount of synthetic mineral fertilization in DayCent exceeds the amount mineral fertilizer sales. See subsection on Synthetic and Manure Nitrogen Fertilizer Applications in Step 1b for more information.

evapotranspiration (Note: Irrigated systems are always assumed to have leaching of nitrogen even in drier climates). PDFs are derived for each of the nitrogen inputs in the same manner as direct N₂O emissions, discussed in Steps 1a and 1c.

Volatilized nitrogen is summed for losses from croplands and grasslands. Similarly, the annual amounts of nitrogen lost from soil profiles through leaching and surface runoff are summed to obtain the total losses for this pathway.

Step 1f: Additional Activity Data for Estimating CH₄ Emissions from Rice Cultivation with the Tier 1 Method

For the Tier 1 method, residues amounts are needed to estimate CH₄ emissions from rice cultivation, along with the water management data, which has been described in Step 1b. The residues are assumed to be left on the field for more than 30 days prior to cultivation and flooding for the next crop, with the exception of ratoon crops, which are assumed to have residues on the field for less than 30 days prior to the second crop in the season. To estimate the amount of rice residue, crop yield data (except rice in Florida) are compiled from USDA NASS QuickStats (USDA 2015). Rice yield data are not collected by USDA for Florida, and so are derived based on NRI crop areas and average primary and ratoon rice yields from Deren (2002). Relative proportions of ratoon crops are derived from information in several publications (Schueneman 1997, 1999, 2000, 2001; Deren 2002; Kirstein 2003, 2004, 2006; Cantens 2004, 2005; Gonzalez 2007 through 2014). The yields are multiplied by residue: crop product ratios from Strehler and Stützel (1987) to estimate rice residue input amounts for the Tier 1 method.

Step 2: Estimate Soil Organic Carbon Stock Changes, Soil N₂O Emissions, and CH₄ Emissions from Rice Cultivation for Mineral Soils

In this step, soil organic carbon stock changes, direct N₂O emissions, and CH₄ emissions from rice cultivation are estimated for cropland and grasslands. The DayCent process-based model is used for the croplands and non-federal grasslands included in the Tier 3 method. A Tier 2 method is used to estimate soil organic carbon stock changes for crop types, grasslands and soil types that are not simulated by DayCent. A Tier 1 methodology is used to estimate N₂O emissions from crops that are not simulated by DayCent, PRP manure nitrogen deposition on federal grasslands, and CH₄ emissions from rice cultivation.

Step 2a: Estimate Soil Organic Carbon Stock Changes, Soil N₂O Emissions, and CH₄ emissions for Crops and Non-Federal Grassland with the Tier 3 DayCent Model

Crops that are simulated with DayCent include alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, lentils, oats, onions, peanuts, peas, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, sweet potatoes, tobacco, tomatoes, and wheat, which combined represent approximately 85 percent of total cropland in the United States. The DayCent simulations also include the majority of non-federal grasslands in the United States.

The methodology description is divided into two sub-steps. First, the DayCent model is used to establish the initial conditions and carbon stocks for 1979, which is the first year of the NRI survey. In the second sub-step, DayCent is used to simulate changes in soil organic carbon stocks, direct soil N₂O emissions, leaching, runoff and volatilization losses of N contributing to indirect N₂O emissions, and CH₄ emissions from rice cultivation based on the land-use and management histories recorded in the NRI (USDA-NRCS 2020).

Simulate Initial Conditions (Pre-NRI Conditions): The purpose of the DayCent model initialization is to estimate the most accurate stock for the pre-NRI history, and the distribution of organic carbon among the pools represented in the model (e.g., structural and metabolic litter pools, in addition to active, slow, and passive soil organic matter pools). Each pool has a different turnover rate (representing the heterogeneous nature of soil organic matter), and the amount of carbon in each pool at any point in time influences the forward trajectory of total soil organic carbon storage and soil nitrogen dynamics that influence soil N₂O emissions. There is currently no national set of soil carbon measurements subdivided by the pools that can be used for establishing initial conditions in the model. Sensitivity analysis of the soil organic carbon algorithms showed that the rate of change of soil organic matter is relatively insensitive to the *amount* of total soil organic carbon but is highly sensitive to the relative *distribution* of carbon among different pools (Parton et al. 1987). By simulating the historical land use prior to the inventory period, initial pool distributions are estimated in an unbiased way.

The first step involves running the model to a steady-state condition (e.g., equilibrium) under native vegetation, historical climate data based on the PRISM product (PRISM Climate Group 2022), and the soil characteristics for the NRI survey locations. Native vegetation is represented at the MLRA level for pre-settlement time periods in the United States. The model simulates pre-settlement conditions until a steady-state condition is achieved.

The second step is to simulate the period of time from European settlement and expansion of agriculture to the beginning of the NRI survey, representing the influence of historic land-use change and management, particularly the conversion of native vegetation to agricultural uses. This encompasses a varying time period from land conversion (depending on historical settlement patterns) to 1979. The information on historical cropping practices used for DayCent simulations has been gathered from a variety of sources, ranging from the historical accounts of farming practices reported in the literature (e.g., Miner 1998) to national level databases (e.g., NASS 2004). A detailed description of the data sources and assumptions used in constructing the base history scenarios of agricultural practices can be found in Williams and Paustian (2005), along with the imputed data for tillage, mineral fertilization, and irrigation histories, as described in Step 2b.

NRI History Simulations: After model initialization, DayCent is used to simulate the NRI land use and management histories from 1979 through 2020. The simulations estimate the influence of soil management on soil organic carbon stocks, direct soil N₂O emissions, and losses of nitrogen from the profile through leaching/runoff and volatilization. These simulations are also used to estimate CH₄ emissions from rice cultivation. The NRI histories, supplemented with CDL and NLCD data, identify the land use and land use change histories for the NRI survey locations, as well as cropping patterns and irrigation history (see Step 1a for description of the NRI data). The input data for the model simulations also include the PRISM weather dataset and SSURGO soils data, synthetic nitrogen fertilizer rates, managed manure amendments to cropland and grassland, manure deposition on grasslands (i.e., PRP), tillage histories, cover crop usage, and EVI data (See Step 1b for description of the inputs). There are six simulations for each NRI survey location based on the imputation product in order to capture the uncertainty in the management activity data derived by combining data from the CEAP survey, ARMS, Census of Agriculture, OpTIS data product, CTIC survey and related data. See Step 1b for more information. The simulation system incorporates a dedicated MySQL database server and a parallel processing computer cluster. Input/output operations are managed by a run control system.

Evaluating uncertainty is an integral part of the analysis and includes three components: (1) uncertainty in the management activity data inputs (input uncertainty); (2) uncertainty in the model formulation and parameterization (structural uncertainty); and (3) uncertainty in the land-use and management system areas (scaling uncertainty) (Ogle et al. 2010; Del Grosso et al. 2010; Ogle et al. 2023). For the first component, the uncertainty is based on the six imputations underlying the data product combining CEAP survey, ARMS, OpTIS data product, Census of Agriculture and CTIC survey data. See Step 1b for discussion about the imputation product. The second component deals with uncertainty inherent in model formulation and parameterization. This component is the largest source of uncertainty in the Tier 3 model-based inventory analysis, accounting for more than 80 percent of the overall uncertainty in the final estimates (Ogle et al. 2010; Del Grosso et al. 2010). An empirically based procedure is applied to develop a structural uncertainty estimator from the relationship between modeled results and field measurements from agricultural experiments (Ogle et al. 2007). The inputs to the model are essentially known in the simulations for the long-term experiments, and, therefore, the analysis is designed to evaluate uncertainties associated with the model structure (i.e., model algorithms and parameterization).

The empirical relationship between field measurements and modeled emissions/stock changes are statistically analyzed using linear-mixed effect modeling techniques. The modeled emissions are treated as a fixed effect in the statistical models. The resulting relationships are used to make an adjustment to modeled values if there are biases due to significant mismatches between the modeled and measured values. Several other variables are tested in these models including soil characteristics, geographic location (i.e., state), and management practices (e.g., tillage practices, fertilizer rates, crop type, cover crop usage, irrigation). Random effects are included in all of these models to capture the dependence in time series and data collected from the same site, which are needed to estimate appropriate standard deviations for parameter coefficients. See the Tier 3 Model Description, Parameterization and Evaluation Section, below, for more information about model evaluation, including graphs illustrating the relationships between modeled and measured values.

The third element is the uncertainty associated with scaling the DayCent results for each NRI survey location to the entire land base, using the survey weights provided with the NRI dataset. The survey weights represent the number of hectares associated with the land-use and management history for a particular survey location. The scaling

uncertainty is due to the complex sampling design that selects the locations for NRI, and this uncertainty is properly reflected in the replicate weights. The empirical variance computed from the replicate weights is an estimate of the scaling uncertainty associated with the NRI sampling design.

Uncertainty in the DayCent model estimates is quantified with two variance components (Ogle et al., 2010). The first variance component quantifies the uncertainty in management activity data, model structure and parameterization. To assess this uncertainty, carbon and nitrogen dynamics at each NRI survey location are simulated six times using the imputation product and other model driver data. Uncertainty in parameterization and model algorithms are determined using a structural uncertainty estimator derived from fitting a linear mixed-effect model (Ogle et al. 2007, 2010, 2023). The data are combined in a Monte Carlo stochastic simulation with 1,000 iterations. In each iteration, there is a random selection of management activity data from the imputation product and a random draw of parameter values for the uncertainty estimator (Ogle et al. 2010). Note that parameter values for the statistical equations (i.e., fixed effects) are selected from their joint probability distribution, along with random error associated with the time series and data collected from the same site, and the residual/unexplained error. The randomly selected parameter values and associated management information are then used as input into the linear mixed-effect model, and adjusted values are computed for each emissions/stock change estimate that was produced by DayCent. The results are used to compute the first variance component (V_1) according to the following equation:

$$V_1 = \frac{\sum_{i=1}^m \left(\theta_i - m^{-1} \sum_{i=1}^m \theta_i \right)^2}{m - 1}$$

where m is the number of Monte Carlo iterations (i.e., 1000), and θ is the emissions/stock change estimate for each iteration i .

The second variance component quantifies uncertainty in scaling from the NRI survey to the entire land base and is computed with the NRI replicate weights. Specifically, the second variance component (V_2) is estimated using the following formula:

$$V_2 = \left(\frac{28}{29} \right) \sum_{l=1}^{29} \left(\sum_{k \in s_h} w_k^{(l)} f_k - \sum_{k \in s_h} w_k f_k \right)^2$$

where k represents an NRI point, s_h is the set of NRI points in stratum h , $w_k^{(l)}$ represents the l^{th} replicate weight (area in ha) for NRI point k ($l = 1, \dots, 29$), and f_k represents the mean rate of change (g/ha) in soil organic carbon for the k^{th} point in the Monte Carlo analysis. The total variance is calculated by summing V_1 and V_2 .

For soil N_2O , DayCent cannot distinguish among the original sources of nitrogen after the mineral nitrogen enters the soil pools, and therefore it is not possible to determine which management activity led to specific N_2O emissions. This means, for example, that N_2O emissions from applied synthetic fertilizer cannot be separated from emissions due to other nitrogen inputs, such as crop residues. It is desirable, however, to report emissions associated with specific sources of nitrogen inputs. Thus, for each NRI survey location, the nitrogen inputs in a simulation are determined for anthropogenic practices discussed in IPCC (2006), including synthetic mineral nitrogen fertilization, organic amendments, and crop residue nitrogen added to soils (including nitrogen-fixing crops). The percentage of nitrogen input for anthropogenic practices is divided by the total nitrogen input, and this proportion is used to determine the amount of N_2O emissions assigned to each of the nitrogen sources. For example, if 70 percent of the mineral nitrogen made available in the soil is due to synthetic mineral fertilization, then 70 percent of the N_2O emissions are assigned to this practice.

A portion of soil N_2O emissions is reported under “other N inputs,” which includes mineralization due to decomposition of soil organic matter and litter, as well as asymbiotic nitrogen fixation from the atmosphere. Mineralization of soil organic matter is significant source of nitrogen, but is typically less than half of the amount of nitrogen made available in cropland soils compared to application of synthetic fertilizers and manure amendments. Mineralization of soil organic matter accounts for the majority of available nitrogen in grassland soils. Asymbiotic nitrogen fixation by soil bacteria is a minor source of nitrogen, typically not exceeding 10 percent of total nitrogen inputs. Accounting for the influence of “other N inputs” is necessary because the processes leading to these inputs of nitrogen are influenced by management.

This attribution of N₂O emissions to the individual nitrogen sources is required for reporting emissions based on national inventory reporting standards. However, this method is a simplification of reality to allow partitioning of N₂O emissions, as it assumes that all nitrogen inputs have an identical chance of being converted to N₂O. It is important to realize that sources such as synthetic fertilization may have a larger impact on N₂O emissions than would be suggested by the associated level of nitrogen input for this source (Delgado et al. 2009). Further research will be needed to improve upon this attribution method, however.

For the land base that is simulated with the DayCent model, direct soil N₂O emissions are provided in Table A-180 and Table A-181.

Step 2b: Soil N₂O Emissions from Agricultural Lands on Mineral Soils Approximated with the Tier 1 Approach

To estimate direct N₂O emissions from nitrogen additions to crops in the Tier 1 method, the amount of nitrogen in applied synthetic fertilizer, manure, and other commercial organic fertilizers (i.e., dried blood, tankage, compost, and other) is added to nitrogen inputs from crop residues, and the resulting annual totals are multiplied by the IPCC default emission factor of 0.01 kg N₂O-N/kg N (IPCC 2006). The uncertainty is determined based on simple error propagation methods (IPCC 2006). The uncertainty in the default emission factor ranges from 0.3–3.0 kg N₂O-N/kg N (IPCC 2006). For flooded rice soils, the IPCC default emission factor is 0.003 kg N₂O-N/kg N and the uncertainty range is 0.000–0.006 kg N₂O-N/kg N (IPCC 2006).¹³³ Uncertainties in the emission factor and fertilizer additions are combined with uncertainty in the equations used to calculate residue nitrogen additions from above- and below-ground biomass dry matter and nitrogen concentration to derive overall uncertainty.

The Tier 1 method is also used to estimate emissions from manure nitrogen deposited by livestock on federal lands (i.e., PRP manure nitrogen), and from biosolids (i.e., treated sewage sludge) application to grasslands. These two sources of nitrogen inputs to soils are multiplied by the IPCC (2006) default emission factors (0.01 kg N₂O-N/kg N for sludge and horse, sheep, and goat manure, and 0.02 kg N₂O-N/kg N for cattle, swine, and poultry manure) to estimate N₂O emissions. The uncertainty is determined based on the simple error propagation methods provided by the IPCC (2006) with uncertainty in the default emission factor ranging from 0.007 to 0.06 kg N₂O-N/kg N (IPCC 2006).

The results for direct soil N₂O emissions using the Tier 1 method are provided in Table A-180 and Table A-181.

Step 2c: Soil CH₄ Emissions from Agricultural Lands Approximated with the Tier 1 Approach

To estimate CH₄ emissions from rice cultivation for the Tier 1 method, an adjusted daily emission factor is calculated using the default baseline emission factor of 1.30 kg CH₄ ha⁻¹ d⁻¹ (ranging 0.8–2.2 kg CH₄ ha⁻¹ d⁻¹) multiplied by a scaling factor for the cultivation water regime, pre-cultivation water regime and a scaling factor for organic amendments (IPCC 2006). The water regime during cultivation is continuously flooded for rice production in the United States and so the scaling factor is always 1 (ranging from 0.79 to 1.26). The pre-season water regime varies based on the proportion of land with winter flooding; land that does not have winter flooding is assigned a value of 0.68 (ranging from 0.58 to 0.80) and areas with winter flooding are assigned a value of 1 (ranging from 0.88 to 1.14). Organic amendments are estimated based on the amount of rice straw and multiplied by 1 (ranging 0.97 to 1.04) for rice straw residue incorporated greater than 30 days before cultivation, and by 0.29 (0.2 to 0.4) for rice straw residue incorporated greater than 30 days before cultivation. The adjusted daily emission factor is multiplied by the cultivation period and harvested area to estimate the total CH₄ emissions. The uncertainty is propagated through the calculation using an Approach 2 method with a Monte Carlo analysis (IPCC 2006), combining uncertainties associated with the adjusted daily emission factor and the harvested areas derived from the USDA NRI survey data.

The results for rice CH₄ emissions using the Tier 1 method are provided in Table A-177 and Table A-178.

¹³³ Due to lack of data, uncertainties are not addressed for managed manure nitrogen production, PRP manure nitrogen production, other commercial organic fertilizer amendments, indirect losses of nitrogen in the DayCent simulations, and biosolids (i.e., treated sewage sludge), but these sources of uncertainty will be included in future Inventories.

Step 2d: Soil Organic Carbon Stock Changes in Agricultural Lands on Mineral Soils Approximated with the Tier 2 Approach

Mineral soil organic carbon stock values are derived for crop rotations that were not simulated by DayCent and land converted from non-agricultural land uses to cropland or grassland from 1990 through 2020, based on the land-use and management activity data in conjunction with appropriate reference carbon stocks, land-use change, management, input, and wetland restoration factors. Each quantity in the inventory calculations has uncertainty that is quantified in PDFs, including the land use and management activity data based on the six imputations in the data product combining CEAP, ARMS, Census of Agriculture, CTIC data and other related datasets (See Step 1b for more information); reference carbon stocks and stock change factors; and the replicated weights from the NRI survey. Uncertainty is estimated using two variance components (Ogle et al. 2010), as described in the section, Step 2a. In this case, a Monte Carlo Analysis is used to quantify uncertainty in soil organic carbon stock changes for the inventory period based on random selection of values from management data, reference carbon stocks and stock change factors. Input values are randomly selected from PDFs in an iterative process to estimate soil organic carbon change for 1,000 iterations in the analysis. This result is used to compute the first variance component. The second variance component is computed with the NRI replicate weights using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). The two variance components are combined to produce a 95% confidence interval using simple error propagation methods provided by the IPCC (2006).

Derive Mineral Soil Organic Carbon Stock Change Factors: Stock change factors representative of U.S. conditions are estimated from published studies (Ogle et al. 2003; Ogle et al. 2006). The numerical factors quantify the impact of changing land use and management on soil organic carbon storage in mineral soils, including tillage practices, cropping rotation or intensification, and land conversions between cultivated and native conditions (including set-asides in the Conservation Reserve Program). Studies from the United States and Canada are used in this analysis under the assumption that they would best represent management impacts for the *Inventory*.

The IPCC inventory methodology for agricultural soils divides climate into eight distinct zones based upon average annual temperature, average annual precipitation, and the length of the dry season (IPCC 2006). Seven of these climate zones occur in the conterminous United States and Hawaii (Eve et al. 2001). Climate zones are classified using the IPCC climate map (IPCC 2006).

Soils are classified into one of seven mineral soil types based upon texture, morphology, and ability to store organic matter (IPCC 2006). Reference carbon stocks, representing estimates from conventionally managed cropland, are computed for each of the mineral soil types across the various climate zones, based on pedon (i.e., soil) data from the National Soil Survey Characterization Database (NRCS 1997) (Table A-177). These stocks are used in conjunction with management factors to estimate the change in soil organic carbon stocks that result from management and land-use activity. PDFs, which represent the variability in the stock estimates, are constructed as normal densities based on the mean and variance from the pedon data. Pedon locations are clumped in various parts of the country, which reduces the statistical independence of individual pedon estimates. To account for this lack of independence, samples from each climate by soil zone are tested for spatial autocorrelation using the Moran's I test, and variance terms are inflated by 10 percent for all zones with significant p-values.

Table A-177: U.S. Soil Groupings Based on the IPCC Categories and Dominant Taxonomic Soil, and Reference Carbon Stocks (Metric Tons C/ha)

IPCC Inventory Soil Categories	USDA Taxonomic Soil Orders	Reference Carbon Stock in Climate Regions					
		Cold Temperate, Dry	Cold Temperate, Moist	Warm Temperate, Dry	Warm Temperate, Moist	Tropical, Dry	Tropical, Moist
High Clay Activity Mineral Soils	Vertisols, Mollisols, Inceptisols, Aridisols, and high base status Alfisols	42 (n = 133)	65 (n = 526)	37 (n = 203)	51 (n = 424)	42 (n = 26)	57 (n = 12)
Low Clay Activity Mineral Soils	Ultisols, Oxisols, acidic Alfisols, and many Entisols	45 (n = 37)	52 (n = 113)	25 (n = 86)	40 (n = 300)	39 (n = 13)	47 (n = 7)
Sandy Soils	Any soils with greater than 70 percent sand and less than 8 percent clay (often Entisols)	24 (n = 5)	40 (n = 43)	16 (n = 19)	30 (n = 102)	33 (n = 186)	50 (n = 18)
Volcanic Soils	Andisols	124 (n = 12)	114 (n = 2)	124 (n = 12)	124 (n = 12)	124 (n = 12)	128 (n = 9)
Spodic Soils	Spodosols	86 (n = 20)	74 (n = 13)	86 (n = 20)	107 (n = 7)	86 (n = 20)	86 (n = 20)
Aquic Soils	Soils with Aquic suborder	86 (n = 4)	89 (n = 161)	48 (n = 26)	51 (n = 300)	63 (n = 503)	48 (n = 12)

Notes: Carbon stocks are for the top 30 cm of the soil profile, and are estimated from pedon data available in the National Soil Survey Characterization database (NRCS 1997); sample size provided in parentheses (i.e., 'n' values refer to sample size).

To estimate the stock change factors for land use, management and input, studies had to report soil organic carbon stocks (or information to compute stocks), depth of sampling, and the number of years since a management change to be included in the analysis. The data are analyzed using linear mixed-effect models, accounting for both fixed and random effects. Fixed effects included depth, number of years since a management change, climate, and the type of management change (e.g., reduced tillage vs. no-till). For depth increments, the data are not aggregated for the carbon stock measurements; each depth increment (e.g., 0-5 cm, 5-10 cm, and 10-30 cm) is included as a separate observation in the dataset. Similarly, time-series data are not aggregated in these datasets. Linear regression models assume that the underlying data are independent observations, but this is not the case with data from the same experimental site, or plot in a time series. These data are more related to each other than data from other sites (i.e., not independent). Consequently, random effects are needed to account for the dependence in time-series data and the dependence among data points representing different depth increments from the same study. Factors are estimated for the effect of management practices at 20 years for the top 30 cm of the soil (Table A-178). Variance is calculated for each of the country-specific factor values, and used to construct PDFs with a normal density. In the IPCC method, factor values are given for improved grassland, high input cropland with organic amendments, and for wetland rice, each of which influences carbon stock changes in soils. Specifically, higher stocks are associated with increased productivity and carbon inputs on improved grassland with both medium and high input.¹³⁴ Organic amendments in annual cropping systems also increase soil organic carbon stocks due to greater carbon inputs, while high soil organic carbon stocks in rice cultivation are associated with reduced decomposition due to periodic flooding. There are insufficient field studies to derive factor values for these systems from the published literature, and, thus, the factor values from IPCC (2006) are used under the assumption that they would best approximate the impacts, given the lack of data to derive country-specific factors. A measure of uncertainty is provided for these factors in IPCC (2006), which is used to construct PDFs.

¹³⁴ Improved grasslands are identified in the NRI as grasslands that are irrigated or seeded with legumes, in addition to those reclassified as improved with manure amendments.

Table A-178: Soil Organic Carbon Stock Change Factors for the United States and the IPCC Default Values Associated with Management Impacts on Mineral Soils

	U.S. Factor				
	IPCC default	Warm Moist Climate	Warm Dry Climate	Cool Moist Climate	Cool Dry Climate
Land-Use Change Factors					
Cultivated ^a	1	1	1	1	1
General Uncult ^{a,b} (n=251)	1.4	1.42±0.06	1.37±0.05	1.24±0.06	1.20±0.06
Set-Aside ^a (n=142)	1.25	1.31±0.06	1.26±0.04	1.14±0.06	1.10±0.05
Improved Grassland Factors					
Medium Input	1.1	1.14±0.06	1.14±0.06	1.14±0.06	1.14±0.06
High Input	NA	1.11±0.04	1.11±0.04	1.11±0.04	1.11±0.04
Wetland Rice Production					
Factor ^b	1.1	1.1	1.1	1.1	1.1
Tillage Factors					
Conv. Till	1	1	1	1	1
Red. Till (n=93)	1.05	1.08±0.03	1.01±0.03	1.08±0.03	1.01±0.03
No-till (n=212)	1.1	1.13±0.02	1.05±0.03	1.13±0.02	1.05±0.03
Cropland Input Factors					
Low (n=85)	0.9	0.94±0.01	0.94±0.01	0.94±0.01	0.94±0.01
Medium	1	1	1	1	1
High (n=22)	1.1	1.07±0.02	1.07±0.02	1.07±0.02	1.07±0.02
High with amendment ^b	1.2	1.38±0.06	1.34±0.08	1.38±0.06	1.34±0.08

Note: The “n” values refer to sample size.

NA (Not Applicable)

^aFactors in the IPCC documentation (IPCC 2006) are converted to represent changes in soil organic carbon storage from a cultivated condition rather than a native condition.

^bU.S.-specific factors are not estimated for grassland improvements, rice production, or high input with amendment because of few studies addressing the impact of legume mixtures, irrigation, or manure applications for crop and grassland in the United States, or the impact of wetland rice production in the United States. Factors provided in IPCC (2006) are used as the best estimates of these impacts.

Wetland restoration management also influences soil organic carbon storage in mineral soils, because restoration leads to higher water tables and inundation of the soil for at least part of the year. A stock change factor is estimated assessing the difference in soil organic carbon storage between restored and unrestored wetlands enrolled in the Conservation Reserve Program (Euliss and Gleason 2002), which represents an initial increase of carbon in the restored soils over the first 10 years (Table A-179). A PDF with a normal density is constructed from these data based on results from a linear regression model. Following the initial increase of carbon, natural erosion and deposition leads to additional accretion of carbon in these wetlands. The mass accumulation rate of organic carbon is estimated using annual sedimentation rates (cm/yr) in combination with percent organic carbon, and soil bulk density (g/cm³) (Euliss and Gleason 2002). Procedures for calculation of mass accumulation rate are described in Dean and Gorham (1998). The resulting rates and standard deviations are used to construct PDFs with a normal density (Table A-179).

Table A-179: Rate and standard deviation for the Initial Increase and Subsequent Annual Mass Accumulation Rate (Mg C/ha-yr) in Soil Organic Carbon Following Wetland Restoration of Conservation Reserve Program

Variable	Value
Factor (Initial Increase—First 10 Years)	1.22±0.18
Mass Accumulation (After Initial 10 Years)	0.79±0.05

Note: Mass accumulation rate represents additional gains in carbon for mineral soils after the first 10 years (Euliss and Gleason 2002).

Estimate Annual Changes in Mineral Soil Organic Carbon Stocks: In accordance with IPCC methodology, annual changes in mineral soil organic carbon are calculated by subtracting the beginning stock from the ending stock and

then dividing by 20.¹³⁵ For this analysis, stocks are estimated for each year and difference between years is the stock change. From the final distribution of 1,000 values, the median is used as the estimate of soil organic carbon stock change and a 95 percent confidence interval is generated based on the simulated values at the 2.5 and 97.5 percentiles in the distribution.

Soil organic carbon stock changes using the Tier 2 method are provided in Table A-182 and Table A-184.

Step 2e: Estimate Additional Changes in Soil Organic Carbon Stocks Due to Biosolids (i.e., Treated Sewage Sludge) Amendments

There are two additional land use and management activities occurring on mineral soils of U.S. agricultural lands that are not estimated in Steps 2a and 2b. The first activity involves the application of biosolids to agricultural lands. Minimal data exist on where and how much biosolids are applied to U.S. agricultural soils. However, national estimates of mineral soil land area receiving biosolids can be approximated based on biosolids nitrogen production data, and the assumption that amendments are applied at a rate equivalent to the assimilative capacity from Kellogg et al. (2000). In this *Inventory*, it is assumed that biosolids for agricultural land application to soils is only used as an amendment in grassland. The impact of organic amendments on soil organic carbon is calculated as 0.38 metric tonnes C/ha-yr. This rate is based on the IPCC default method and country-specific factors, by calculating the effect of converting nominal, medium-input grassland to high input improved grassland. The assumptions for this estimation are as follows: a) the reference carbon stock is 50 metric tonnes C/ha, which represents a mid-range value of reference carbon stocks for the cropland soils in the United States,¹³⁶ b) the land use factor for grassland of 1.4 and 1.11 for high input improved grassland are representative of typical conditions, and c) the change in stocks are occurring over a 20 year (default value) time period (i.e., $[50 \times 1.4 \times 1.11 - 50 \times 1.4] / 20 = 0.38$). A ± 50 percent uncertainty is attached to these estimates due to limited information on application and the rate of change in soil organic carbon stock change with amendments of biosolids.

The influence of biosolids (i.e., treated sewage sludge) on soil organic carbon stocks is provided in and Table A-184.

Table A-180: Direct Soil N₂O Emissions from Mineral Soils in Cropland (MMT CO₂ Eq.)

Land Use Category	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Cropland Mineral Soil Emission	171.4	163.7	160.3	172.9	175.9	170.4	178.2	168.1	169.4	173.2
Tier 3 Cropland	151.4	144.8	140.5	153.0	153.9	149.7	155.6	147.8	148.0	149.2
Inorganic N Fertilizer Application	51.7	51.8	50.2	52.1	57.3	50.8	55.1	54.4	50.6	50.0
Managed Manure Additions	4.1	3.8	4.1	4.0	4.0	3.8	4.2	4.7	4.4	3.9
Crop Residue N	30.8	30.3	28.8	32.4	31.6	32.6	33.7	30.4	29.5	34.9
Min. SOM / Asymbiotic N-Fixation ^a	64.8	58.9	57.5	64.5	60.9	62.5	62.6	58.3	63.5	60.5
Tier 1 Cropland	20.0	18.9	19.8	19.9	22.0	20.7	22.6	20.4	21.4	24.0
Inorganic N Fertilizer Application	9.3	8.2	9.2	9.4	11.0	9.8	11.8	10.1	10.8	13.1
Managed Manure Additions	7.3	7.5	7.5	7.5	7.8	8.0	7.9	7.3	7.5	8.1
Other Organic Amendments ^b	+	+	+	+	+	+	0.1	0.1	0.1	+
Crop Residue N	3.3	3.1	3.2	2.9	3.2	2.9	2.9	2.9	2.9	2.8
Implied Emission Factor for Croplands ^c (kt N ₂ O-N/kt N)	0.015	0.014	0.014	0.015	0.015	0.015	0.015	0.014	0.014	0.014

Land Use Category	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Cropland Mineral Soil Emission	168.6	177.5	179.5	180.5	180.7	177.3	175.5	184.0	181.2	179.3
Tier 3 Cropland	149.4	157.8	159.7	161.1	159.6	158.2	154.6	164.0	160.9	163.6
Inorganic N Fertilizer Application	54.6	51.5	53.7	55.1	54.8	54.4	52.0	57.5	54.2	54.7
Managed Manure Additions	4.7	5.7	7.1	6.2	5.9	6.1	5.6	7.1	7.6	7.3
Crop Residue N	32.1	33.9	33.7	34.7	31.6	32.4	32.9	32.4	31.9	32.8
Min. SOM / Asymbiotic N-Fixation ^a	58.0	66.7	65.2	65.2	67.3	65.3	64.2	67.1	67.3	68.9
Tier 1 Cropland	19.2	19.7	19.8	19.4	21.1	19.1	20.8	20.0	20.2	15.7

¹³⁵ The difference in carbon stocks is divided by 20 because the stock change factors represent change over a 20-year time period.

¹³⁶ Reference carbon stocks are based on cropland soils for the Tier 2 method applied in this *Inventory*.

Inorganic N Fertilizer Application	8.9	10.0	10.8	9.8	11.8	9.9	11.0	11.1	11.7	7.2
Managed Manure Additions	7.5	6.9	6.3	6.9	6.6	6.6	7.3	6.3	6.1	6.0
Other Organic Amendments ^b	+	+	+	+	+	+	0.1	0.1	+	+
Crop Residue N	2.8	2.8	2.6	2.7	2.7	2.6	2.5	2.5	2.4	2.5
Implied Emission Factor for Croplands ^c (kt N ₂ O-N/kt N)	0.014	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015

Land Use Category	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Cropland Mineral Soil Emission	181.9	185.7	176.1	200.2	206.7	195.6	186.7	192.7	205.9	190.6
Tier 3 Cropland	164.3	165.5	158.1	180.1	187.3	176.3	169.5	173.4	187.7	169.9
Inorganic N Fertilizer Application	52.8	55.9	60.4	62.0	63.4	58.3	58.1	58.9	61.5	54.7
Managed Manure Additions	7.5	8.2	7.9	8.5	8.7	8.1	7.8	8.1	8.1	7.8
Crop Residue N	33.9	35.9	32.4	35.0	36.8	32.9	30.5	33.8	36.7	31.7
Min. SOM / Asymbiotic N-Fixation ^a	70.1	65.5	57.3	74.6	78.5	76.9	73.0	72.6	81.3	75.7
Tier 1 Cropland	17.6	20.2	18.0	20.1	19.4	19.3	17.2	19.3	18.2	20.6
Inorganic N Fertilizer Application	9.6	12.2	9.9	12.1	11.2	10.9	8.5	10.2	8.8	11.0
Managed Manure Additions	5.6	5.6	5.7	5.6	5.6	5.9	6.0	6.3	6.5	6.8
Other Organic Amendments ^b	+	+	0.1	0.1	+	0.1	0.1	0.1	0.1	0.1
Crop Residue N	2.4	2.3	2.3	2.4	2.6	2.5	2.6	2.7	2.8	2.8
Implied Emission Factor for Croplands ^c (kt N ₂ O-N/kt N)	0.014	0.015	0.014	0.015	0.016	0.015	0.014	0.015	0.015	0.014

Land Use Category	2020
Total Cropland Mineral Soil Emission	179.6
Tier 3 Cropland	160.5
Inorganic N Fertilizer Application	53.8
Managed Manure Additions	7.6
Crop Residue N	34.7
Min. SOM / Asymbiotic N-Fixation ^a	64.3
Tier 1 Cropland	19.1
Inorganic N Fertilizer Application	9.4
Managed Manure Additions	6.7
Other Organic Amendments ^b	0.1
Crop Residue N	2.9
Implied Emission Factor for Croplands ^c (kt N ₂ O-N/kt N)	0.014

+ Does not exceed 0.05 MMT CO₂ Eq.

^aMineralization of soil organic matter and the asymbiotic fixation of nitrogen gas.

^bIncludes dried blood, tankage, compost, other. Excludes dried manure and bio-solids (i.e., treated sewage sludge) used as commercial fertilizer to avoid double counting.

^cAnnual Implied Emission Factor (kt N₂O-N/kt N) is calculated by dividing total estimated emissions by total activity data for N applied.

Note: Emissions for 2021 to 2023 are mostly estimated with a data splicing method as described in the agricultural soil management section of the *Inventory*. Additional activity data will be collected, and the Tier 1 and 3 methods will be applied in a future *Inventory* to recalculate the part of the time series that is estimated with the data splicing methods.

Table A-181: Direct Soil N₂O Emissions from Mineral Soils in Grassland (MMT CO₂ Eq.)

Land Use Change Category	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Grassland Mineral Soil Emission	81.7	80.6	79.4	81.0	80.0	81.6	83.4	82.9	83.8	79.6
Tier 3 Grassland	73.0	72.1	70.6	72.2	71.2	72.7	74.7	74.6	75.7	71.7
Inorganic N Fertilizer Application	+	+	+	0.1	+	+	+	+	0.2	+
Managed Manure Additions	+	+	+	+	+	+	+	+	+	+
Pasture, Range, & Paddock N Deposition	7.0	6.9	6.9	7.3	7.7	7.7	7.9	7.6	7.9	7.4
Grass Residue N	27.1	26.2	26.3	27.1	26.3	27.6	27.5	27.3	26.7	28.2
Min. SOM / Asymbiotic N-Fixation ^a	38.9	39.0	37.3	37.7	37.1	37.5	39.3	39.8	40.9	36.2
Tier 1 Grassland	8.7	8.6	8.8	8.8	8.9	8.9	8.6	8.3	8.1	7.9

Pasture, Range, & Paddock N Deposition	8.5	8.3	8.6	8.6	8.6	8.6	8.3	8.0	7.8	7.5
Treated Sewage Sludge Additions	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Implied Emission Factor for Grassland ^b (kt N ₂ O-N/kt N)	0.007	0.007	0.006	0.006	0.007	0.006	0.007	0.007	0.007	0.006

Land Use Change Category	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Grassland Mineral Soil Emission	77.5	81.7	82.4	81.7	85.5	83.0	83.0	82.9	82.1	84.3
Tier 3 Grassland	69.8	74.2	75.0	74.4	78.3	75.7	75.8	76.0	75.3	77.5
Inorganic N Fertilizer Application	0.1	+	0.1	+	0.1	+	+	+	+	+
Managed Manure Additions	+	+	+	+	+	+	+	+	+	+
Pasture, Range, & Paddock N Deposition	7.4	7.7	7.8	7.6	7.6	7.5	7.8	7.4	7.4	7.7
Grass Residue N	26.4	28.5	27.9	28.4	27.1	28.4	28.1	28.0	28.2	28.3
Min. SOM / Asymbiotic N-Fixation ^a	36.0	37.9	39.1	38.4	43.5	39.8	39.9	40.5	39.6	41.5
Tier 1 Grassland	7.6	7.5	7.4	7.3	7.2	7.3	7.3	6.9	6.9	6.8
Pasture, Range, & Paddock N Deposition	7.3	7.1	7.0	6.9	6.8	6.9	6.9	6.5	6.5	6.4
Treated Sewage Sludge Additions	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Implied Emission Factor for Grassland ^b (kt N ₂ O-N/kt N)	0.006	0.007	0.007	0.006	0.007	0.006	0.007	0.006	0.006	0.007

Land Use Change Category	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Grassland Mineral Soil Emission	84.8	80.2	76.6	86.3	86.0	85.6	84.5	83.7	87.6	85.6
Tier 3 Grassland	78.1	73.7	70.3	80.0	79.8	79.4	78.1	77.3	81.0	79.1
Inorganic N Fertilizer Application	+	+	+	+	+	+	+	+	+	+
Managed Manure Additions	+	+	+	+	+	+	+	+	+	+
Pasture, Range, & Paddock N Deposition	7.5	7.5	7.0	7.4	7.4	7.5	7.5	7.6	8.2	7.8
Grass Residue N	28.6	28.2	27.8	28.5	28.7	27.1	27.3	28.4	28.0	28.3
Min. SOM / Asymbiotic N-Fixation ^a	42.0	38.0	35.5	44.1	43.8	44.7	43.3	41.2	44.8	42.9
Tier 1 Grassland	6.7	6.5	6.3	6.3	6.2	6.2	6.4	6.4	6.5	6.5
Pasture, Range, & Paddock N Deposition	6.3	6.1	6.0	5.9	5.8	5.9	6.0	6.1	6.2	6.1
Treated Sewage Sludge Additions	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Implied Emission Factor for Grassland ^b (kt N ₂ O-N/kt N)	0.007	0.007	0.006	0.007	0.007	0.007	0.007	0.007	0.007	0.007

Land Use Change Category	2020
Total Grassland Mineral Soil Emission	78.5
Tier 3 Grassland	71.8
Inorganic N Fertilizer Application	+
Managed Manure Additions	+
Pasture, Range, & Paddock N Deposition	7.4
Grass Residue N	28.2
Min. SOM / Asymbiotic N-Fixation ^a	36.2
Tier 1 Grassland	6.7
Pasture, Range, & Paddock N Deposition	6.3
Treated Sewage Sludge Additions	0.4
Implied Emission Factor for Grassland ^b (kt N ₂ O-N/kt N)	0.007

+ Does not exceed 0.05 MMT CO₂ Eq.

^aMineralization of soil organic matter and the asymbiotic fixation of nitrogen gas.

^bAnnual Implied Emission Factors (kt N₂O-N/kt N) are calculated by dividing total estimated emissions by total activity data for N applied.

Note: Emissions for 2021 to 2023 are mostly estimated with a data splicing method as described in the agricultural soil management section of the *Inventory*. Additional activity data will be collected, and the Tier 1 and 3 methods will be applied in a future *Inventory* to recalculate the part of the time series that is estimated with the data splicing methods.

Table A-182: Annual Change in Soil Organic Carbon Stocks in Croplands (MMT CO₂ Eq./yr)

Land Use Change Category	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Cropland Soil Organic C Stock Change	-16.0	-27.7	-38.5	-27.6	-34.9	-29.7	-51.9	-48.4	-45.8	-41.2
Cropland Remaining Cropland (CRC)	-39.2	-52.2	-59.5	-45.9	-53.1	-49.8	-69.6	-66.5	-61.3	-59.1
Tier 2	-1.6	-2.9	-3.6	-3.6	-3.1	-3.1	-2.9	-4.0	-3.4	-3.8
Tier 3	-37.6	-49.3	-55.9	-42.3	-50.0	-46.7	-66.8	-62.5	-57.9	-55.3
Grassland Converted to Cropland (GCC)	24.6	26.1	22.8	20.3	20.2	22.1	19.8	20.4	17.8	20.2
Tier 2	3.1	3.3	3.1	3.0	3.3	3.6	3.9	3.8	3.9	3.8
Tier 3	21.5	22.8	19.7	17.3	16.9	18.5	15.9	16.6	14.0	16.4
Forest Converted to Cropland (FCC) (Tier 2 Only)	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Other Lands Converted to Cropland (OCC) (Tier 2 Only)	-1.9	-2.1	-2.2	-2.4	-2.5	-2.5	-2.6	-2.7	-2.7	-2.8
Settlements Converted to Cropland (SCC) (Tier 2 Only)	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.2	-0.2
Wetlands Converted to Cropland (WCC) (Tier 2 Only)	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3

Land Use Change Category	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Cropland Soil Organic C Stock Change	-50.3	-53.5	-56.1	-46.6	-52.6	-50.5	-49.0	-46.1	-56.0	-36.7
Cropland Remaining Cropland (CRC)	-64.7	-66.1	-68.3	-59.1	-64.1	-61.8	-58.3	-56.6	-63.4	-45.0
Tier 2	-3.2	-3.5	-5.2	-4.6	-4.2	-4.4	-3.6	-3.6	-3.3	-3.5
Tier 3	-61.5	-62.5	-63.0	-54.5	-59.9	-57.5	-54.6	-53.0	-60.0	-41.5
Grassland Converted to Cropland (GCC)	17.2	15.3	14.8	15.0	13.9	13.7	11.6	12.6	9.4	10.2
Tier 2	3.9	4.1	3.9	3.7	3.8	3.8	3.6	3.7	3.6	3.5
Tier 3	13.2	11.2	10.9	11.3	10.1	9.9	8.0	8.9	5.8	6.7
Forest Converted to Cropland (FCC) (Tier 2 Only)	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1
Other Lands Converted to Cropland (OCC) (Tier 2 Only)	-3.1	-3.1	-3.0	-2.8	-2.7	-2.6	-2.6	-2.3	-2.2	-2.1
Settlements Converted to Cropland (SCC) (Tier 2 Only)	-0.2	-0.2	-0.2	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
Wetlands Converted to Cropland (WCC) (Tier 2 Only)	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2

Land Use Change Category	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Cropland Soil Organic C Stock Change	-39.6	-61.1	-47.7	-35.0	-42.7	-43.0	-40.6	-37.8	-38.0	-39.9
Cropland Remaining Cropland (CRC)	-49.2	-67.8	-56.4	-45.3	-51.6	-53.3	-51.6	-47.8	-47.1	-48.5
Tier 2	-3.8	-3.2	-3.0	-3.8	-4.1	-4.5	-4.3	-4.2	0.2	-1.7
Tier 3	-45.5	-64.6	-53.4	-41.5	-47.6	-48.8	-47.3	-43.6	-47.4	-46.8
Grassland Converted to Cropland (GCC)	11.6	8.6	10.6	12.2	10.7	12.0	12.8	11.8	10.7	10.1
Tier 2	3.5	3.6	3.6	3.5	3.4	3.3	3.2	3.0	3.0	2.7
Tier 3	8.1	5.0	7.0	8.7	7.3	8.7	9.6	8.8	7.7	7.4
Forest Converted to Cropland (FCC) (Tier 2 Only)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Other Lands Converted to Cropland (OCC) (Tier 2 Only)	-2.1	-2.1	-2.1	-2.0	-1.9	-1.9	-1.9	-1.9	-1.7	-1.6
Settlements Converted to Cropland (SCC) (Tier 2 Only)	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2

Wetlands Converted to Cropland (WCC) (Tier 2 Only)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2

Land Use Change Category	2020
Total Cropland Soil Organic C Stock Change	-31.3
Cropland Remaining Cropland (CRC)	-38.2
Tier 2	-1.9
Tier 3	-36.3
Grassland Converted to Cropland (GCC)	8.0
Tier 2	2.5
Tier 3	5.5
Forest Converted to Cropland (FCC) (Tier 2 Only)	0.1
Other Lands Converted to Cropland (OCC) (Tier 2 Only)	-1.2
Settlements Converted to Cropland (SCC) (Tier 2 Only)	-0.2
Wetlands Converted to Cropland (WCC) (Tier 2 Only)	0.2

Note: Emissions for 2021 to 2023 are mostly estimated with a data splicing method as described in the cropland remaining croplands section of the *Inventory*. Additional activity data will be collected, and the Tier 1 and 3 methods will be applied in a future *Inventory* to recalculate the part of the time series that is estimated with the data splicing methods.

Table A-183: Annual Change in Soil Organic Carbon Stocks in Grasslands (MMT CO₂ Eq./yr)

Land Use Change Category	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Grassland Soil Organic C Stock Change	4.1	6.5	2.3	0.2	-18.6	-6.2	-17.3	4.1	-14.2	-2.3
Grassland Remaining Grassland (GRG)	18.6	21.4	17.8	17.6	1.3	13.4	3.8	25.5	11.1	22.2
Tier 2	-0.2	-0.3	-0.5	-0.3	-0.0	-0.0	0.0	-0.0	0.0	0.1
Tier 3	19.5	22.3	18.9	18.6	2.1	14.2	4.6	26.4	12.0	23.1
Treated Sewage Sludge Additions	-0.6	-0.6	-0.7	-0.7	-0.8	-0.8	-0.8	-0.9	-0.9	-0.9
Cropland Converted to Grassland (CCG)	-10.4	-10.6	-10.9	-11.9	-13.5	-12.9	-14.1	-14.2	-17.6	-16.6
Tier 2	-3.9	-3.8	-3.8	-4.1	-4.4	-4.3	-4.2	-4.0	-4.7	-4.7
Tier 3	-6.6	-6.7	-7.1	-7.9	-9.1	-8.6	-10.0	-10.2	-12.9	-11.9
Forest Converted to Grassland (FCG) (Tier 2 Only)	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
Other Lands Converted to Grassland (OCG) (Tier 2 Only)	-3.8	-4.0	-4.3	-5.2	-6.1	-6.4	-6.6	-6.9	-7.3	-7.5
Settlements Converted to Grassland (SCG) (Tier 2 Only)	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.3	-0.3
Wetlands Converted to Grassland (WCG) (Tier 2 Only)	+	+	+	+	+	+	+	+	+	+

Land Use Change Category	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Grassland Soil Organic C Stock Change	-34.9	-18.3	-15.3	-17.4	-15.1	-9.4	-26.2	-9.8	-23.4	-18.8
Grassland Remaining Grassland (GRG)	-7.2	9.9	13.3	10.8	13.8	18.6	3.0	18.1	4.6	7.5
Tier 2	-0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2
Tier 3	-6.2	10.9	14.3	11.7	14.7	19.5	3.9	19.1	5.5	8.4
Treated Sewage Sludge Additions	-1.0	-1.0	-1.0	-1.0	-1.1	-1.1	-1.1	-1.1	-1.1	-1.1
Cropland Converted to Grassland (CCG)	-18.5	-18.5	-18.9	-18.5	-19.2	-18.1	-19.4	-18.0	-18.0	-16.2
Tier 2	-4.8	-4.7	-4.6	-4.4	-4.3	-4.1	-3.9	-3.6	-3.5	-3.1
Tier 3	-13.8	-13.8	-14.2	-14.1	-14.8	-14.0	-15.4	-14.4	-14.5	-13.1
Forest Converted to Grassland (FCG) (Tier 2 Only)	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1

Other Lands Converted to Grassland (OCG) (Tier 2 Only)	-8.7	-9.3	-9.3	-9.3	-9.3	-9.4	-9.4	-9.4	-9.5	-9.6
Settlements Converted to Grassland (SCG) (Tier 2 Only)	-0.3	-0.3	-0.4	-0.3	-0.3	-0.3	-0.4	-0.4	-0.4	-0.4
Wetlands Converted to Grassland (WCG) (Tier 2 Only)	-+	-+	-+	-+	-+	-+	-+	-+	-+	-+

Land Use Change Category	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Grassland Soil Organic C Stock Change	-5.0	-20.1	-23.6	-7.3	-1.0	-8.5	11.7	-1.7	-0.4	-0.1
Grassland Remaining Grassland (GRG)	21.6	6.2	4.4	19.3	23.4	18.5	36.1	22.4	22.0	22.0
Tier 2	0.2	0.2	0.1	0.1	0.1	0.1	0.0	0.0	0.1	0.1
Tier 3	22.4	7.1	5.4	20.2	24.4	19.5	37.1	23.4	22.9	22.9
Treated Sewage Sludge Additions	-1.1	-1.1	-1.1	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
Cropland Converted to Grassland (CCG)	-16.6	-16.1	-15.0	-14.4	-12.9	-14.7	-12.7	-13.0	-11.7	-11.1
Tier 2	-3.1	-2.9	-2.9	-2.7	-2.2	-2.2	-2.1	-2.2	-1.9	-2.0
Tier 3	-13.5	-13.1	-12.1	-11.7	-10.7	-12.5	-10.6	-10.8	-9.8	-9.1
Forest Converted to Grassland (FCG) (Tier 2 Only)	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
Other Lands Converted to Grassland (OCG) (Tier 2 Only)	-9.6	-9.7	-12.4	-11.5	-10.9	-11.8	-11.0	-10.5	-10.1	-10.4
Settlements Converted to Grassland (SCG) (Tier 2 Only)	-0.4	-0.4	-0.5	-0.6	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
Wetlands Converted to Grassland (WCG) (Tier 2 Only)	-+	-+	-+	-+	-+	-+	-+	-+	-+	-+

Land Use Change Category	2020
Total Grassland Soil Organic C Stock Change	-9.4
Grassland Remaining Grassland (GRG)	9.3
Tier 2	0.1
Tier 3	10.2
Treated Sewage Sludge Additions	-1.0
Cropland Converted to Grassland (CCG)	-10.1
Tier 2	-1.8
Tier 3	-8.3
Forest Converted to Grassland (FCG) (Tier 2 Only)	-0.1
Other Lands Converted to Grassland (OCG) (Tier 2 Only)	-8.1
Settlements Converted to Grassland (SCG) (Tier 2 Only)	-0.4
Wetlands Converted to Grassland (WCG) (Tier 2 Only)	-+

+ Does not exceed 0.05 MMT CO₂ Eq.

Note: Emissions for 2021 to 2023 are mostly estimated with a data splicing method as described in the cropland remaining croplands section of the *Inventory*. Additional activity data will be collected, and the Tier 1 and 3 methods will be applied in a future *Inventory* to recalculate the part of the time series that is estimated with the data splicing methods.

Table A-184: Methane Emissions from Rice Cultivation (MMT CO₂ Eq.)

Approach	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Rice Methane Emission	18.9	19.5	19.0	19.1	18.1	19.1	19.7	17.9	20.4	19.0
Tier 1	3.0	3.0	3.0	2.9	3.0	2.8	2.9	2.9	3.3	4.2
Tier 3	15.9	16.5	16.0	16.2	15.1	16.3	16.8	15.0	17.2	14.8

Approach	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009

Total Rice Methane Emission	22.4	19.0	21.5	17.9	17.6	20.6	18.0	18.5	16.4	19.6
Tier 1	5.2	3.9	3.3	3.1	2.7	2.7	2.5	3.0	2.4	3.2
Tier 3	17.3	15.1	18.2	14.8	14.9	17.8	15.5	15.5	14.0	16.4

Approach	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Rice Methane Emission	21.5	19.4	17.7	18.1	17.6	19.6	19.9	16.7	19.9	15.6
Tier 1	2.8	2.9	3.0	3.0	3.1	2.8	3.2	2.4	3.0	2.6
Tier 3	18.7	16.5	14.7	15.0	14.5	16.8	16.7	14.3	16.9	13.0

Approach	2020
Total Rice Methane Emission	18.6
Tier 1	2.9
Tier 3	15.7

+ Does not exceed 0.05 MMT CO₂ Eq.

Emissions for 2021 to 2023 are mostly estimated with a data splicing method as described in the cropland remaining croplands section of the *Inventory*. Additional activity data will be collected, and the Tier 1 and 3 methods will be applied in a future *Inventory* to recalculate the part of the time series that is estimated with the data splicing methods.

Step 3: Estimate Soil Organic Carbon Stock Changes and Direct N₂O Emissions from Organic Soils

In this step, soil organic carbon losses and direct N₂O emissions are estimated for organic soils that are drained for agricultural production in croplands and grasslands.

Step 3a: Direct N₂O Emissions Due to Drainage of Organic Soils in Cropland and Grassland

To estimate annual N₂O emissions from drainage of organic soils in cropland and grassland, the area of drained organic soils for temperate regions is multiplied by the IPCC (2006) default emission factor for temperate soils and the corresponding area in sub-tropical regions is multiplied by the average (12 kg N₂O-N/ha cultivated) of IPCC (2006) default emission factors for temperate (8 kg N₂O-N/ha cultivated) and tropical (16 kg N₂O-N/ha cultivated) organic soils. The uncertainty is determined based on simple error propagation methods (IPCC 2006), including uncertainty in the default emission factor ranging from 2–24 kg N₂O-N/ha (IPCC 2006). Table A-185 lists the direct N₂O emissions associated with drainage of organic soils in cropland and grassland.

Table A-185: Direct Soil N₂O Emissions from Drainage of Organic Soils (MMT CO₂ Eq.)

Land Use	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Organic Soil Emissions	6.1	6.0	6.0	6.0	6.0	6.0	5.9	6.0	5.9	5.9
Cropland	3.5	3.5	3.4	3.4	3.3	3.3	3.3	3.3	3.3	3.3
Grassland	2.6	2.5	2.6	2.6	2.7	2.6	2.6	2.6	2.6	2.5

Land Use	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Organic Soil Emission	5.9	5.9	5.9	5.8	5.8	5.8	5.8	5.7	5.7	5.7
Cropland	3.3	3.3	3.3	3.3	3.3	3.3	3.2	3.2	3.1	3.1
Grassland	2.6	2.6	2.6	2.5	2.5	2.5	2.6	2.5	2.5	2.6

Land Use	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Organic Soil Emission	5.7	5.7	5.7	5.7	5.6	5.6	5.6	5.5	5.5	5.5
Cropland	3.1	3.1	3.1	3.1	3.1	3.0	3.0	3.0	3.0	3.0
Grassland	2.6	2.6	2.5	2.6	2.6	2.6	2.6	2.5	2.5	2.5

Land Use	2020
Total Organic Soil Emission	5.5
Cropland	2.9
Grassland	2.5

Note: Emissions for 2021 to 2023 are estimated with a data splicing method as described in the agricultural soil management section of the *Inventory*. Additional activity data will be collected, and the Tier 1 method will be applied in a future *Inventory* to recalculate the part of the time series that is estimated with the data splicing methods.

Step 3b: Soil Organic Carbon Stock Changes Due to Drainage of Organic Soils in Cropland and Grassland

Change in soil organic carbon stocks due to drainage of organic soils in cropland and grassland are estimated annually from 1990 through 2020, based on the land-use and management activity data in conjunction with appropriate emission factors. The activity data are based on annual data from 1990 through 2020 from the NRI. Organic soil emission factors that are representative of U.S. conditions have been estimated from published studies (Ogle et al. 2003), based on subsidence studies in the United States and Canada (Table A-186). PDFs are constructed as normal densities based on the mean carbon loss rates and associated variances. Uncertainty is estimated using two variance components (Ogle et al. 2010), as described in the section, Step 2a for the first variance component, input values are randomly selected from PDFs in a Monte Carlo analysis to estimate soil organic carbon change for 1,000 iterations. The second variance component is computed with the NRI replicate weights using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). The two variance components are combined to produce a 95% confidence interval using simple error propagation methods provided by the IPCC (2006). Losses of soil organic carbon from drainage of cropland and grassland soils are provided in Table A-187 for croplands and Table A-188 for grasslands.

Table A-186: Carbon Loss Rates for Organic Soils Under Agricultural Management in the United States, and IPCC Default Rates (Metric Ton C/ha-yr)

Region	Cropland		Grassland	
	IPCC	U.S. Revised	IPCC	U.S. Revised
Cold Temperate, Dry & Cold Temperate, Moist	1	11.2±2.5	0.25	2.8±0.5 ^a
Warm Temperate, Dry & Warm Temperate, Moist	10	14.0±2.5	2.5	3.5±0.8 ^a
Tropical, Dry & Tropical, Moist	1	14.3±2.5	0.25	2.8±0.5 ^a

^aThere are not enough data available to estimate a U.S. value for carbon losses from grassland. Consequently, estimates are 25 percent of the values for cropland, which is an assumption that is used for the IPCC default organic soil carbon losses on grassland.

Table A-187: Soil Organic Carbon Stock Changes due to Drainage of Organic Soils in Cropland (MMT CO₂ Eq.)

Land Use Category	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Cropland Soil Organic C Stock Change	37.3	36.7	35.9	35.7	35.0	35.1	35.0	35.0	34.8	30.8
Cropland Remaining Cropland (CRC)	34.2	33.6	32.8	32.3	31.7	31.6	31.5	31.5	31.0	26.9
Grassland Converted to Cropland (GCC)	2.4	2.4	2.4	2.6	2.5	2.7	2.7	2.6	3.0	3.1
Forest Converted to Cropland (FCC)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Other Lands Converted to Cropland (OCC)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Settlements Converted to Cropland (SCC)	+	+	+	+	+	+	+	+	+	+
Wetlands Converted to Cropland (WCC)	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.6

Land Use Category	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Cropland Soil Organic C Stock Change	30.5	34.5	34.4	34.2	34.2	34.1	33.7	33.3	33.1	32.6
Cropland Remaining Cropland (CRC)	26.7	30.3	30.2	30.1	30.3	30.2	30.0	29.6	29.6	29.4
Grassland Converted to Cropland (GCC)	3.1	3.6	3.6	3.5	3.3	3.3	3.1	3.2	3.0	2.7
Forest Converted to Cropland (FCC)	0.1	0.1	0.1	0.1	+	+	+	+	+	+
Other Lands Converted to Cropland (OCC)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Settlements Converted to Cropland (SCC)	+	+	+	+	+	+	+	+	+	+
Wetlands Converted to Cropland (WCC)	0.5	0.4	0.4	0.3	0.4	0.5	0.5	0.4	0.4	0.3

Land Use Category	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Cropland Soil Organic C Stock Change	32.6	32.8	33.1	32.9	32.8	32.6	32.5	32.4	32.4	32.0
Cropland Remaining Cropland (CRC)	29.3	29.3	29.3	29.3	29.3	29.3	29.1	29.0	29.3	29.1
Grassland Converted to Cropland (GCC)	2.7	3.0	3.3	3.2	3.2	3.1	3.1	3.1	2.7	2.7
Forest Converted to Cropland (FCC)	+	+	+	+	+	+	+	+	+	+

Other Lands Converted to Cropland (OCC)	+	+	+	+	+	+	+	+	+	+
Settlements Converted to Cropland (SCC)	+	+	+	+	+	+	+	0.1	+	+
Wetlands Converted to Cropland (WCC)	0.4	0.4	0.4	0.3	0.2	0.2	0.2	0.2	0.2	0.2

Land Use Category	2020
Total Cropland Soil Organic C Stock Change	32.0
Cropland Remaining Cropland (CRC)	29.4
Grassland Converted to Cropland (GCC)	2.4
Forest Converted to Cropland (FCC)	+
Other Lands Converted to Cropland (OCC)	0
Settlements Converted to Cropland (SCC)	+
Wetlands Converted to Cropland (WCC)	0.2

+ Does not exceed 0.05 MMT CO₂ Eq.

Note: Emissions for 2021 to 2023 are estimated with a data splicing method as described in the cropland remaining croplands section of the *Inventory*. Additional activity data will be collected, and the Tier 2 method will be applied in a future *Inventory* to recalculate the part of the time series that is estimated with the data splicing methods.

Table A-188: Soil Organic Carbon Stock Changes due to Drainage of Organic Soils in Grasslands (MMT CO₂ Eq.)

Land Use Category	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Grassland Soil Organic C Stock Change	6.7	6.7	6.8	6.9	7.0	6.9	6.8	6.9	6.8	6.7
Grassland Remaining Grassland (GRG)	6.1	6.0	6.0	6.0	5.9	5.8	5.8	5.8	5.6	5.4
Cropland Converted to Grassland (CCG)	0.6	0.6	0.7	0.8	0.9	0.9	0.8	0.9	1.1	1.0
Forest Converted to Grassland (FCG)	+	+	+	+	+	+	+	+	+	+
Other Lands Converted to Grassland (OCG)	+	+	+	+	+	+	+	+	+	+
Settlements Converted to Grassland (SCG)	0	0	0	0	+	+	+	+	+	+
Wetlands Converted to Grassland (WCG)	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2

Land Use Category	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Grassland Soil Organic C Stock Change	6.8	6.8	6.9	6.7	6.8	6.9	6.9	6.9	6.9	7.0
Grassland Remaining Grassland (GRG)	5.5	5.3	5.2	5.1	5.1	5.1	5.1	5.0	5.1	5.1
Cropland Converted to Grassland (CCG)	1.0	1.2	1.3	1.3	1.4	1.4	1.5	1.5	1.4	1.5
Forest Converted to Grassland (FCG)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Other Lands Converted to Grassland (OCG)	+	+	+	+	+	+	+	+	+	+
Settlements Converted to Grassland (SCG)	+	+	+	+	+	+	+	+	+	+
Wetlands Converted to Grassland (WCG)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3

Land Use Category	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Grassland Soil Organic C Stock Change	7.0	7.0	6.9	6.9	6.9	6.9	6.9	6.9	6.8	6.8
Grassland Remaining Grassland (GRG)	5.1	5.1	5.0	5.1	5.2	5.2	5.2	5.1	5.3	5.3
Cropland Converted to Grassland (CCG)	1.5	1.4	1.4	1.4	1.3	1.3	1.3	1.3	1.1	1.1
Forest Converted to Grassland (FCG)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Other Lands Converted to Grassland (OCG)	+	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Settlements Converted to Grassland (SCG)	+	+	+	+	+	+	+	+	+	+
Wetlands Converted to Grassland (WCG)	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2

Land Use Category	2020
Total Grassland Soil Organic C Stock Change	6.9
Grassland Remaining Grassland (GRG)	5.5
Cropland Converted to Grassland (CCG)	1.0
Forest Converted to Grassland (FCG)	0.1
Other Lands Converted to Grassland (OCG)	0.1
Settlements Converted to Grassland (SCG)	+

Wetlands Converted to Grassland (WCG) 0.2

+ Does not exceed 0.05 MMT CO₂ Eq.

Note: Emissions for 2021 to 2023 are estimated with a data splicing method as described in the grassland remaining grassland section of the *Inventory*. Additional activity data will be collected, and the Tier 2 method will be applied in a future *Inventory* to recalculate the part of the time series that is estimated with the data splicing methods.

Step 4: Estimate Indirect Soil N₂O Emissions for Croplands and Grasslands

In this step, soil N₂O emissions are estimated for the two indirect emission pathways (N₂O emissions due to volatilization, and N₂O emissions due to leaching and runoff of N), which are summed to yield total indirect N₂O emissions from croplands and grasslands.

Step 4a: Indirect Soil N₂O Emissions Due to Volatilization

Indirect emissions from volatilization of nitrogen inputs from synthetic fertilizer, manure amendments, and PRP manure, are calculated according to the amount of mineral nitrogen that is volatilized from the soil profile and later emitted as soil N₂O following atmospheric deposition. See Step 1d for additional information about the methods used to compute nitrogen losses due to volatilization. The estimated nitrogen volatilized is multiplied by the IPCC default emission factor of 0.01 kg N₂O-N/kg N (IPCC 2006) to estimate total indirect soil N₂O emissions from volatilization. The uncertainty is estimated using simple error propagation methods (IPCC 2006), by combining uncertainties in the amount of nitrogen volatilized, with uncertainty in the default emission factor ranging from 0.002–0.05 kg N₂O-N/kg N (IPCC 2006). See the following peer-reviewed publications on the use of DayCent for estimating the nitrogen losses that lead to indirect soil N₂O emissions: Del Grosso et al. (2001; 2005; 2008b; 2010; 2011), Delgado et al. (2009) and Scheer et al. (2013). The estimates and implied emission factors are provided in Table A-189 and for cropland and grassland, respectively.

Step 4b: Indirect Soil N₂O Emissions Due to Leaching and Runoff

The amounts of mineral nitrogen from synthetic fertilizers, manure amendments, PRP manure, crop residue, nitrogen mineralization, asymbiotic fixation that is transported from the soil profile in water flows are used to calculate indirect emissions from leaching of mineral nitrogen from soils and losses in runoff associated with overland flow. See Step 1d for additional information about the methods used to estimate nitrogen losses from soils due to leaching and runoff in overland water flows. The total amount of nitrogen transported from soil profiles through leaching and surface runoff is multiplied by the IPCC default emission factor of 0.0075 kg N₂O-N/kg N (IPCC 2006) to estimate emissions for this source. The uncertainty is quantified based on simple error propagation methods (IPCC 2006), including uncertainty in the default emission factor ranging from 0.0005 to 0.025 kg N₂O-N/kg N (IPCC 2006). The emission estimates are provided in Table A-189 and Table A-190 for cropland and grassland, respectively.

Table A-189: Indirect Soil N₂O Emissions for Cropland from Volatilization and Atmospheric Deposition, and from Leaching and Runoff (MMT CO₂ Eq.)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Cropland Indirect Emissions	23.6	21.5	23.2	25.7	20.8	23.4	23.4	22.0	25.2	23.5
Volatilization & Atmospheric Deposition	6.6	6.3	6.1	6.4	6.8	6.7	6.8	6.6	7.0	7.1
Leaching & Runoff	17.0	15.2	17.1	19.3	14.1	16.7	16.5	15.4	18.2	16.4
	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Volatilization Implied Emission Factor	0	0	0	0	0	0	0	0	0	0
	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007
Leaching & Runoff Implied Emission Factor	5	5	5	5	5	5	5	5	5	5

Source	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Cropland Indirect Emissions	21.4	23.9	21.7	22.6	25.6	22.4	23.5	24.7	25.3	24.1
Volatilization & Atmospheric Deposition	7.0	6.9	6.9	6.9	7.2	7.0	7.1	6.9	6.9	6.6
Leaching & Runoff	14.4	17.1	14.8	15.7	18.5	15.4	16.4	17.8	18.4	17.5
	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Volatilization Implied Emission Factor	0	0	0	0	0	0	0	0	0	0
	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007
Leaching & Runoff Implied Emission Factor	5	5	5	5	5	5	5	5	5	5

Source	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Cropland Indirect Emissions	24.8	24.3	19.4	26.5	26.5	28.8	25.0	26.4	28.2	28.0
Volatilization & Atmospheric Deposition	7.0	7.0	6.6	7.2	7.5	7.4	7.4	7.4	7.9	7.1
Leaching & Runoff	17.8	17.4	12.8	19.3	19.0	21.4	17.6	18.9	20.3	20.9
Volatilization Implied Emission Factor	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
Leaching & Runoff Implied Emission Factor	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075

Source	2020
Total Cropland Indirect Emissions	23.3
Volatilization & Atmospheric Deposition	7.5
Leaching & Runoff	15.8
Volatilization Implied Emission Factor	0.0100
Leaching & Runoff Implied Emission Factor	0.0075

Note: Emissions for 2021 to 2023 are estimated with a data splicing method as described in the agricultural soil management section of the *Inventory*. Additional activity data will be collected, and the Tier 1 method will be applied in a future *Inventory* to recalculate the part of the time series that is estimated with the data splicing methods.

Table A-190: Indirect Soil N₂O Emissions for Grassland from Volatilization and Atmospheric Deposition, and from Leaching and Runoff (MMT CO₂ Eq.)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Grassland Indirect Emissions	6.4	6.3	6.4	6.6	6.3	6.4	6.3	6.4	7.0	6.2
Volatilization & Atmospheric Deposition	3.4	3.4	3.4	3.3	3.4	3.5	3.5	3.4	3.5	3.3
Leaching & Runoff	2.9	2.9	3.0	3.3	2.9	3.0	2.8	3.0	3.5	2.9
Volatilization Implied Emission Factor	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
Leaching & Runoff Implied Emission Factor	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075

Source	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Grassland Indirect Emissions	5.7	6.6	6.4	6.1	6.8	6.2	6.2	6.7	6.6	6.6
Volatilization & Atmospheric Deposition	3.1	3.3	3.4	3.4	3.5	3.4	3.5	3.3	3.3	3.3
Leaching & Runoff	2.5	3.3	3.0	2.7	3.3	2.7	2.8	3.3	3.2	3.2
Volatilization Implied Emission Factor	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
Leaching & Runoff Implied Emission Factor	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075

Source	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Grassland Indirect Emissions	6.3	6.2	5.7	6.6	6.0	6.8	6.2	6.3	7.1	6.8
Volatilization & Atmospheric Deposition	3.3	3.1	3.1	3.4	3.4	3.3	3.4	3.3	3.4	3.2
Leaching & Runoff	3.0	3.1	2.6	3.2	2.6	3.5	2.9	3.0	3.7	3.6
Volatilization Implied Emission Factor	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
Leaching & Runoff Implied Emission Factor	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075

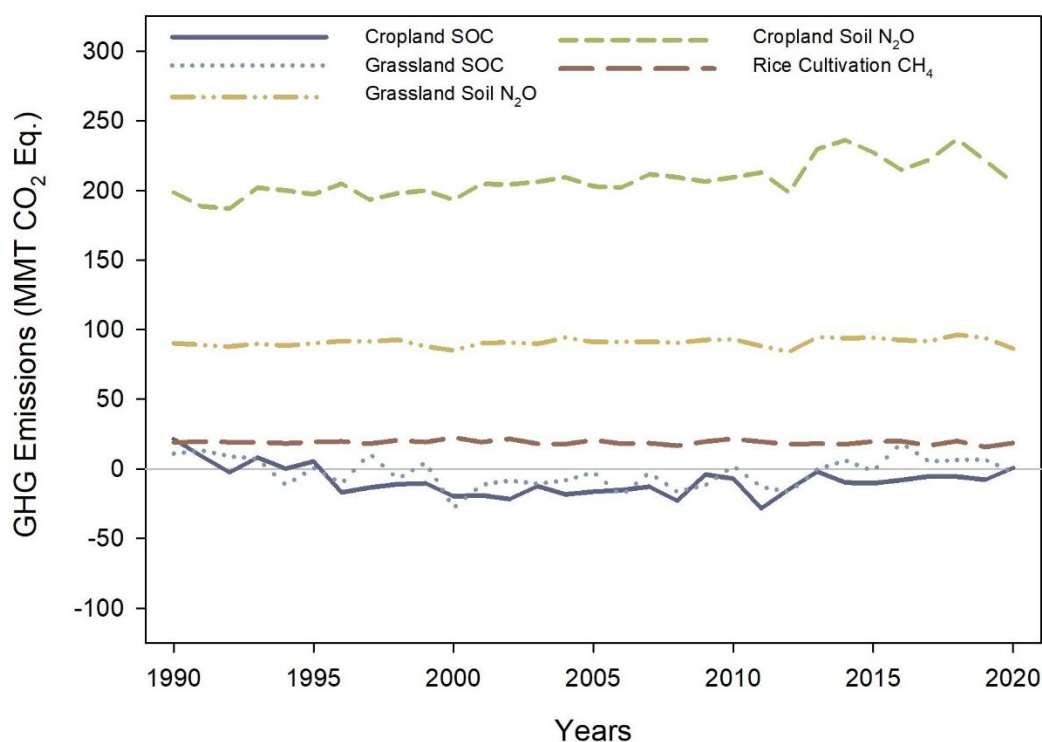
Source	2020
Total Grassland Indirect Emissions	6.2
Volatilization & Atmospheric Deposition	3.1
Leaching & Runoff	3.1
Volatilization Implied Emission Factor	0.0100
Leaching & Runoff Implied Emission Factor	0.0075

Note: Emissions for 2021 to 2023 are estimated with a data splicing method as described in the agricultural soil management section of the *Inventory*. Additional activity data will be collected, and the Tier 1 method will be applied in a future *Inventory* to recalculate the part of the time series that is estimated with the data splicing methods.

Step 5: Estimate Total Emissions for U.S. Agricultural Soils

Total N₂O emissions are estimated by summing total direct and indirect emissions for croplands and grasslands with organic and mineral soils based on the Tier 1 and 3 methods. Total soil organic carbon stock changes are estimated by summing changes in mineral and organic soils for cropland remaining cropland, land converted to cropland, grassland remaining grassland, and land converted to grassland based on the Tier 2 and 3 methods. Total rice CH₄ emissions are estimated by summing results from the Tier 1 and 3 methods. The results are provided in Figure A-8. In general, N₂O emissions from agricultural soil management have been relatively stable for grasslands and increasing slightly for croplands from 1990 to 2020, while CH₄ emissions from rice cultivation have been relatively stable. Agricultural soil organic carbon stocks have increased for most years in croplands and grasslands leading to sequestration of carbon in soils.

Figure A-8: Greenhouse Gas Emissions and Removals for Cropland & Grassland



Direct and indirect simulated emissions of soil N₂O vary regionally in croplands and grasslands as a function of N input, other management practices, weather, and soil type. The top-5 highest total N₂O emissions for 2020¹³⁷ occur in Illinois, Iowa, Kansas, Nebraska, and Texas (Table A-173). These areas are in the Midwestern Corn Belt region, which is the largest crop producing region in the country, and/or have a large population of grazing livestock with high levels of PRP manure nitrogen inputs. The states with largest increases in soil organic carbon stocks in 2020 include Illinois, Iowa, Kansas, Missouri, and Nebraska (Table A-191). These states tend to have larger amounts of land conversion to grassland and/or more conservation practices such as enrollment in Conservation Reserve Program or adoption of conservation tillage. For rice cultivation, the states with highest CH₄ emissions are Arkansas, California, Louisiana and Texas (Table A-191). These states also have the largest areas of rice cultivation, and Louisiana and Texas have a relatively large proportion of fields with a second ratoon crop each year. Ratoon crops extend the period of flooding, and with the residues left from the initial rice crop, there are

¹³⁷ The emissions data at the state scale are available for 1990 to 2020 from application of the inventory methods described in this annex. A data splicing method has been applied to estimate emissions at the national scale for 2021 to 2023. Therefore, the final year of emissions data at the state scale is 2020.

additional CH₄ emissions compared to non-ratoon rice management systems.

Table A-191: Total Soil N₂O Emissions (Direct and Indirect), Soil Organic Carbon Stock Changes and Rice CH₄ Emissions from Agricultural Lands by State in 2020 (MMT CO₂ Eq.)

State	N ₂ O Emissions		Soil Organic C Stock Change		Rice CH ₄	Total Emissions
	Croplands	Grasslands	Croplands	Grasslands		
AL	1.37	0.96	-0.38	-0.62	NO	1.33
AKa	+	0.01	NE	NE	NO	0.01
AZ	0.74	2.92	-0.09	0.57	NO	4.13
AR	4.67	1.22	-0.18	-0.48	6.82	12.05
CA	5.72	2.39	0.52	-0.26	3.62	11.99
CO	3.60	3.66	-0.50	-0.86	NO	5.89
CT	0.08	0.02	-0.01	-0.04	NO	0.05
DE	0.26	0.02	-0.24	-0.02	NO	0.02
DCb	+	+	NE	NE	NO	+
FL	2.04	2.14	10.70	0.45	+	15.33
GA	1.93	0.75	0.02	-0.34	NO	2.36
HIa	0.04	0.36	0.20	0.37	NO	0.97
ID	3.61	1.43	-0.44	0.19	NO	4.79
IL	15.38	0.78	-1.64	-0.73	+	13.79
IN	7.93	0.52	1.76	-0.35	NO	9.86
IA	18.62	1.48	-3.01	-3.07	NO	14.02
KS	14.12	4.25	-3.91	-2.52	NO	11.94
KY	2.95	1.53	-1.16	-0.71	+	2.60
LA	3.41	0.89	0.75	-0.22	3.65	8.49
ME	0.18	0.05	-0.05	-0.06	NO	0.13
MD	0.63	0.14	-0.69	-0.11	NO	-0.02
MA	0.10	0.04	0.22	-0.03	NO	0.33
MI	4.04	0.80	2.24	0.05	NO	7.13
MN	13.33	1.84	6.31	1.12	+	22.59
MS	3.23	0.79	0.37	-0.25	0.60	4.74
MO	8.46	2.65	-1.13	-1.53	0.96	9.40
MT	5.33	6.55	-0.89	8.79	NO	19.78
NE	13.46	3.96	-3.52	-2.56	NO	11.34
NV	0.22	0.85	0.01	0.07	NO	1.15
NH	0.04	0.03	0.01	-0.02	NO	0.07
NJ	0.20	0.05	0.03	-0.09	NO	0.19
NM	0.79	4.57	0.02	2.60	NO	7.98
NY	2.21	0.78	-0.62	-0.31	+	2.05
NC	2.85	0.55	1.04	-0.41	NO	4.03
ND	11.92	2.26	-1.03	-0.45	NO	12.70
OH	6.13	0.64	-0.84	-0.67	NO	5.26
OK	3.62	4.32	-0.09	-1.26	NO	6.59
OR	1.99	1.58	+	0.77	NO	4.35
PA	2.14	0.62	-1.78	-0.59	NO	0.39
RI	0.01	0.01	0.01	+	NO	0.03
SC	1.02	0.30	-0.30	-0.12	NO	0.90
SD	10.89	4.52	-1.82	-0.47	NO	13.12
TN	2.31	1.23	-1.08	-0.52	+	1.95
TX	10.79	14.04	1.70	1.39	2.93	30.85
UT	0.72	1.19	0.06	0.13	NO	2.10
VT	0.30	0.10	-0.06	-0.06	NO	0.28
VA	1.20	0.90	-0.94	-0.39	NO	0.77
WA	3.15	1.08	0.06	0.19	NO	4.49
WV	0.22	0.36	-0.15	-0.27	NO	0.16
WI	6.54	1.33	1.45	-0.11	NO	9.21
WY	1.32	3.72	-0.25	1.35	NO	6.14

+ Does not exceed 0.05 MMT CO₂ Eq.

^a N₂O emissions are not reported for Alaska and Hawaii except from managed and unmanaged manure and biosolids applications, which are estimated with the Tier 1 method.

^b N₂O emissions are not reported for Washington, DC except from biosolids applications that are estimated with the Tier 1 method.

Note: NE means that emissions are not estimated for the state. NO means that emissions are not observed for the state.

Tier 3 Model Description, Parameterization and Evaluation

The DayCent ecosystem model (Parton et al. 1998; Del Grosso et al. 2001, 2011) simulates biogeochemical carbon and nitrogen fluxes between the atmosphere, vegetation, and soil. The model is consistent with the approaches laid out in the *2006 IPCC Guidelines* but provides a more complete estimation of soil N₂O emissions than IPCC Tier 1 or 2 methods by accounting for a broader suite of environmental drivers that influence emissions and carbon stock changes. These drivers include soil characteristics, weather patterns, crop and forage characteristics, and management practices. The DayCent model utilizes the soil carbon modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. Carbon and nitrogen dynamics are linked in plant-soil systems through biogeochemical processes of microbial decomposition and plant production (McGill and Cole 1981). Coupling the three source categories (i.e., agricultural soil organic carbon, rice CH₄ and soil N₂O) in a single inventory analysis ensures that there is a consistent treatment of the processes and interactions between carbon and nitrogen cycling in soils, and ensuring conservation of mass. For example, plant growth is controlled by nutrient availability, water, and temperature stress. Plant growth, along with residue management, determines carbon inputs to soils and influences carbon stock changes. Removal of soil mineral nitrogen by microbial organisms influences the amount of production and carbon inputs, while plant uptake of nitrogen influences availability of nitrogen for microbial processes of nitrification and denitrification that generate N₂O emissions. Nutrient supply is a function of external nutrient additions as well as litter and soil organic matter (SOM) decomposition rates, and increasing decomposition can lead to a reduction in soil organic carbon stocks due to microbial decomposition, and greater N₂O emissions by enhancing mineral nitrogen availability in soils.

The DayCent process-based simulation model (daily time-step version of the Century model) has been selected for the Tier 3 approach based on the following criteria:

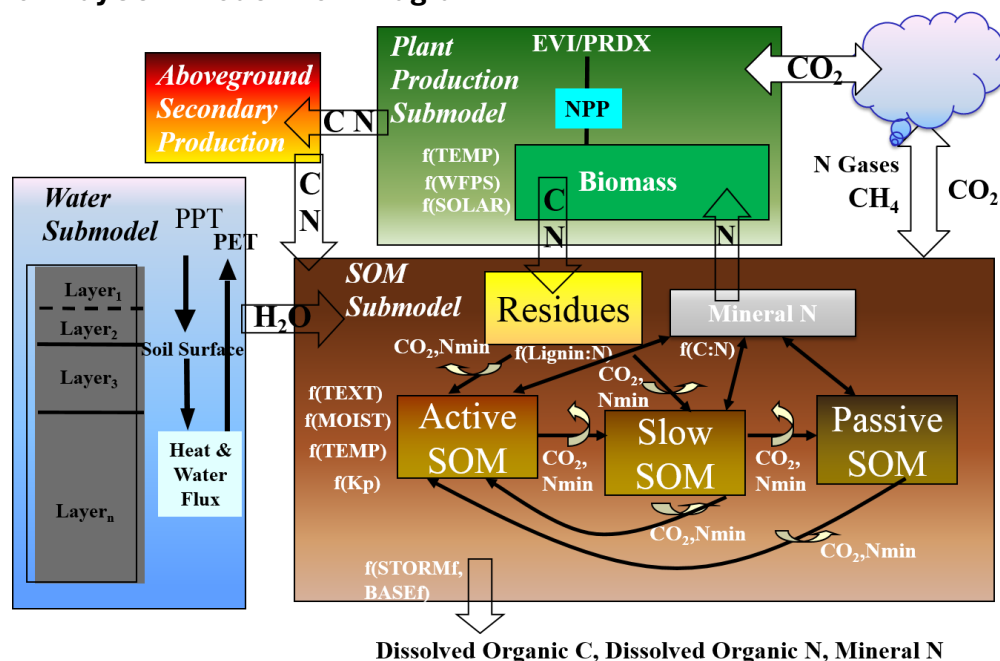
- 1) The model has been developed in the United States and extensively tested for U.S. conditions (e.g., Parton et al. 1987, 1993). In addition, the model has been widely used by researchers and agencies in many other parts of the world for simulating soil carbon dynamics at local, regional and national scales (e.g., Brazil, Canada, India, Jordan, Kenya, Mexico), soil N₂O emissions (e.g., Canada, China, Ireland, New Zealand) (Abdalla et al. 2010; Li et al. 2005; Smith et al. 2008; Stehfest and Muller 2004; Cheng et al. 2014), and CH₄ emissions (Cheng et al. 2013).
- 2) The model is designed to simulate management practices that influence soil carbon dynamics, CH₄ emissions and direct N₂O emissions, with the exception of cultivated organic soils; cobbly, gravelly, or shaley soils; and crops that have not been parameterized for DayCent simulations (e.g., some vegetables, perennial/horticultural crops, and crops that are rotated with these crops). For these latter cases, an IPCC Tier 2 method has been used to estimate soil organic carbon stock changes, and an IPCC Tier 1 method is used to estimate CH₄ and N₂O emissions. The model can also be used to estimate the amount of nitrate leaching and runoff, as well as volatilization of ammonia and nitrogen oxides, which are subject to indirect N₂O emissions.
- 3) Much of the data needed for the model is available from existing national databases. The exceptions are management of federal grasslands and amendments of biosolids (i.e., treated sewage sludge) to soils, which are not known at a sufficient resolution or detail to use the Tier 3 model. Soil N₂O emissions and carbon stock changes associated with these practices are addressed with Tier 1 and 2 methods, respectively.

DayCent Model Description

Key processes simulated by DayCent include (1) plant growth; (2) organic matter formation and decomposition; (3) soil water and temperature regimes by layer; (4) nitrification and denitrification processes; and (5) methanogenesis (Figure A-9). Each submodel is described below.

- 1) The plant-growth submodel simulates carbon assimilation through photosynthesis; nitrogen uptake; dry matter production; partitioning of carbon within the crop or forage; senescence; and mortality. The primary function of the growth submodel is to estimate the amount, type, and timing of organic matter inputs to soil, and to represent the influence of the plant on soil water, temperature, and N balance. Yield and removal of harvested biomass are also simulated. Separate submodels are designed to simulate herbaceous plants (i.e., agricultural crops and grasses) and woody vegetation (i.e., trees and scrub). Maximum daily net primary production (NPP) is estimated using the NASA-CASA production algorithm (Potter et al. 1993, 2007) and MODIS Enhanced Vegetation Index (EVI) products, MOD13Q1 and MYD13Q1. The NASA-CASA production algorithm is only used for the following major crops: corn, soybeans, sorghum, cotton, wheat, and other close-grown crops such as barley and oats.¹³⁸ Model evaluation has shown that the NASA-CASA algorithm improves the precision of NPP estimates by using the EVI products to inform the production model. The r^2 is 83 percent for the NASA-CASA algorithm and 64 percent for the single parameter value approach. See Figure A-10. Other regions and crops are simulated with a single value for the maximum daily NPP, instead of the more dynamic NASA-CASA algorithm. The maximum daily NPP rate is modified by air temperature and available water to capture temperature and moisture stress, and then production is further subject to nutrient limitations (i.e., nitrogen).

Figure A-9: DayCent Model Flow Diagram



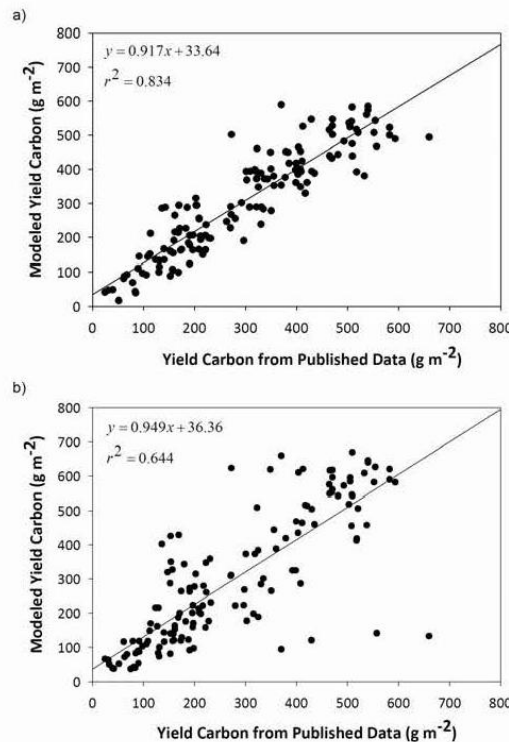
- 2) Dynamics of soil organic carbon and nitrogen (Figure A-9) are simulated for the surface and belowground litter pools and soil organic matter in the top 30 cm of the soil profile; mineral nitrogen dynamics are simulated through the whole soil profile. Organic carbon and nitrogen stocks are represented by two plant litter pools (metabolic and structural) and three soil organic matter (SOM) pools (active, slow, and passive). The metabolic litter pool represents the easily decomposable constituents of plant residues, while the structural

¹³⁸ It is a planned improvement to estimate NPP for additional crops and grass forage with the NASA-CASA method in the future.

litter pool is composed of more recalcitrant, ligno-cellulose plant materials. The three SOM pools represent a gradient in decomposability, from active SOM (representing microbial biomass and associated metabolites) having a rapid turnover (months to years), to passive SOM (representing highly processed, humified, condensed decomposition products), which is highly recalcitrant, with mean residence times on the order of several hundred years. The slow pool represents decomposition products of intermediate stability, having a mean residence time on the order of decades and is the fraction that tends to be influenced the most by land use and management activity. Soil texture influences turnover rates of the slow and passive pools. The clay and silt-sized mineral fraction of the soil provides physical protection from microbial decomposition, leading to enhanced SOM stabilization in finely textured soils. Soil temperature and moisture, tillage disturbance, aeration, and other factors influence decomposition and loss of carbon from the soil organic matter pools.

- 3) The soil-water module simulates water flows and changes in soil water availability, which influences both plant growth, decomposition and nutrient cycling. Soil moisture content is simulated through a multi-layer profile based on precipitation, snow accumulation and melting, interception, soil and canopy evaporation, transpiration, soil water movement, runoff, and drainage.

Figure A-10: Modeled versus measured net primary production



Part a) presents results of the NASA-CASA algorithm ($r^2 = 83\%$) and part b) presents the results of a single parameter value for maximum net primary production ($r^2 = 64\%$).

- 4) Soil mineral nitrogen dynamics are modeled based on nitrogen inputs from fertilizer inputs (synthetic and organic), residue nitrogen inputs, soil organic matter mineralization in addition to symbiotic and asymbiotic nitrogen fixation. Mineral nitrogen is available for plant and microbial uptake and is largely controlled by the specified stoichiometric limits for these organisms (i.e., C:N ratios). Mineral and organic nitrogen losses are simulated with leaching and runoff, and nitrogen can be volatilized and lost from the soil through ammonia volatilization, nitrification and denitrification. Soil N_2O emissions occur through nitrification and denitrification. Denitrification is a function of soil NO_3^- concentration, water filled pore space (WFPS), heterotrophic (i.e., microbial) respiration, and texture. Nitrification is controlled by soil ammonium (NH_4^+) concentration, water filled pore space, temperature, and pH (See Box A-2 for more information).

- 5) Methanogenesis is modeled under anaerobic conditions and is controlled by carbon substrate availability, temperature, and redox potential (Cheng et al. 2013). Carbon substrate supply is determined by decomposition of residues and soil organic matter, in addition to root exudation. The transport of CH₄ to the atmosphere occurs through the rice plant and via ebullition (i.e., bubbles). CH₄ can be oxidized (methanotrophy) as it moves through a flooded soil and the oxidation rates are higher as the plants mature and in soils with more clay (Sass et al. 1994).

The model allows for a variety of management options to be simulated, including different crop types, crop sequences (e.g., rotation), cover crops, tillage practices, fertilization, organic matter addition (e.g., manure amendments), harvest events (with variable residue removal), drainage, flooding, irrigation, burning, and grazing intensity. An input “schedule” file is used to simulate the timing of management activities and temporal trends; schedules can be organized into discrete time blocks to define a repeated sequence of events (e.g., a crop rotation or a frequency of disturbance such as a burning cycle for perennial grassland). Management options can be specified for any day of a year within a scheduling block, where management codes point to operation-specific parameter files (referred to as *.100 files), which contain the information used to simulate management effects. User-specified management activities can be defined by adding to or editing the contents of the *.100 files. Additional details of the model formulation are given in Parton et al. (1987, 1988, 1994, 1998), Del Grosso et al. (2001, 2011), Cheng et al. (2013) and Methereil et al. (1993), and archived copies of the model source code are available.

Box A-2: DayCent Model Simulation of Nitrogen Gas losses and Nitrate Leaching

The DayCent model simulates the two biogeochemical processes, nitrification and denitrification, that result in N₂O and NO_x emissions from soils (Del Grosso et al. 2000, Parton et al. 2001). Nitrification is calculated for the top 15 cm of soil (where nitrification mostly occurs) while denitrification is calculated for the entire soil profile (accounting for denitrification near the surface and subsurface as nitrate leaches through the profile). The equations and key parameters controlling N₂O emissions from nitrification and denitrification are described below.

Nitrification is controlled by soil ammonium (NH₄⁺) concentration, temperature (t), Water Filled Pore Space (WFPS) and pH according to the following equation:

Equation A-42: Soil Nitrification Rate

$$\text{Nit} = \text{NH}_4^+ \times K_{\max} \times F(t) \times F(\text{WFPS}) \times F(\text{pH})$$

where,

Nit	=	the soil nitrification rate (g N/m ² /day)
NH ₄ ⁺	=	the model-derived soil ammonium concentration (g N/m ²)
K _{max}	=	the maximum fraction of NH ₄ ⁺ nitrified (K _{max} = 0.10/day)
F(t)	=	the effect of soil temperature on nitrification (Figure A-11a)
F(WFPS)	=	the effect of soil water content and soil texture on nitrification (Figure A-11b)
F(pH)	=	the effect of soil pH on nitrification (Figure A-11c)

The current parameterization used in the model assumes that 1.2 percent of nitrified nitrogen is converted to N₂O.

The model assumes that denitrification rates are controlled by the availability of soil NO₃⁻ (electron acceptor), labile carbon compounds (electron donor) and oxygen (competing electron acceptor). Heterotrophic soil respiration is used as a proxy for labile carbon availability, while oxygen availability is a function of soil physical properties that influence gas diffusivity, soil WFPS, and oxygen demand. The model selects the minimum of the NO₃⁻ and CO₂ functions to establish a maximum potential denitrification rate. These rates vary for particular levels of electron acceptor and carbon substrate, and account for limitations of oxygen availability to estimate daily denitrification rates according to the following equation:

Equation A-43: Soil Denitrification Rate

$$\text{Den} = \min[F(\text{CO}_2), F(\text{NO}_3)] \times F(\text{WFPS})$$

where,

Den	=	the soil denitrification rate (g N/g soil/day)
$F(\text{NO}_3)$	=	a function relating N gas flux to nitrate levels Figure A-12a)
$F(\text{CO}_2)$	=	a function relating N gas flux to soil respiration (Figure A-12b)
$F(\text{WFPS})$	=	a dimensionless multiplier (Figure A-12c)

The x inflection point of $F(\text{WFPS})$ is a function of respiration and soil gas diffusivity at field capacity (D_{FC}):

Equation A-44: Inflection Point Calculation

$$x_{\text{inflection}} = 0.90 - M(\text{CO}_2)$$

where,

M	=	a multiplier that is a function of D_{FC} . In technical terms, the inflection point is the domain where either $F(\text{WFPS})$ is not differentiable or its derivative is 0. In this case, the inflection point can be interpreted as the WFPS value at which denitrification reaches half of its maximum rate.

Respiration has a much stronger effect on the water curve in clay soils with low D_{FC} than in loam or sandy soils with high D_{FC} (Figure A-11). The model assumes that microsites in fine-textured soils can become anaerobic at relatively low water contents when oxygen demand is high. After calculating total nitrogen gas flux, the ratio of $\text{N}_2/\text{N}_2\text{O}$ is estimated so that total nitrogen gas emissions can be partitioned between N_2O and N_2 :

Equation A-45: Ratio of Nitrogen Gas (N_2) to Nitrous Oxide

$$R_{\text{N}_2/\text{N}_2\text{O}} = F_r(\text{NO}_3/\text{CO}_2) \times F_r(\text{WFPS}).$$

where,

$R_{\text{N}_2/\text{N}_2\text{O}}$	=	the ratio of $\text{N}_2/\text{N}_2\text{O}$
$F_r(\text{NO}_3/\text{CO}_2)$	=	a function estimating the impact of the availability of electron donor relative to substrate
$F_r(\text{WFPS})$	=	a multiplier to account for the effect of soil water on $\text{N}_2:\text{N}_2\text{O}$.

For $F_r(\text{NO}_3/\text{CO}_2)$, as the ratio of electron donor to substrate increases, a higher portion of nitrogen gas is assumed to be in the form of N_2O . For $F_r(\text{WFPS})$, as WFPS increases, a higher portion of nitrogen gas is assumed to be in the form of N_2 .

After calculating and summing N_2O emissions from nitrification and denitrification, NO_x emissions are calculated using a $\text{NO}_x/\text{N}_2\text{O}$ ratio function based on soil gas diffusivity. The $\text{NO}_x/\text{N}_2\text{O}$ ratio is high (maximum of about 17) when soil gas diffusivity is high and decreases to a minimum of approximately 0.28 as diffusivity decreases.

Ammonia volatilization is simulated less mechanistically than the other nitrogen gas losses. A soil texture specific portion of nitrogen excreted from animals ranging from 15-30 percent is assumed to be volatilized with more volatilization as soil texture becomes coarser. In addition, a plant specific portion ranging from 2-15 percent of harvested or senesced biomass nitrogen is assumed to be volatilized.

A portion of the nitrate is assumed to be dissolved and flows with water between soil layers during saturated and unsaturated water movement. The portion of nitrate that flows from the upper layer to the lower layer increases with increasing sand content and with water flow volume so most movement occurs during saturated flow events triggered by precipitation or irrigation. The amount of nitrate leaching for estimating indirect N_2O emissions is based on the nitrate that flows through the entire profile in the model simulation. In addition to sand content, leaching rates are influenced by soil depth, plant nitrogen demand, precipitation event size, and other factors.

Figure A-11: Effect of Soil Temperature (a), Water-Filled Pore Space (b), and pH (c) on Nitrification Rates

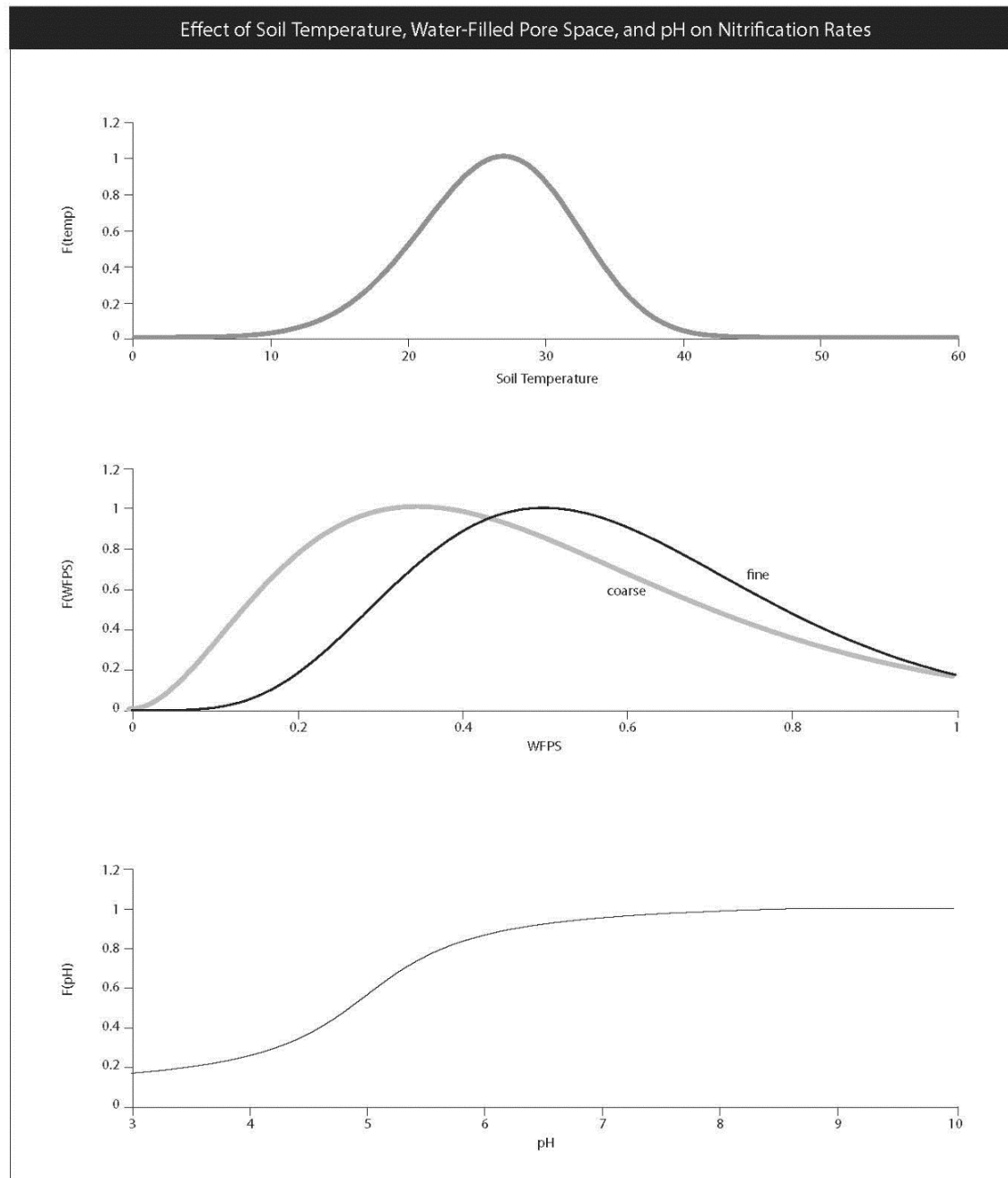
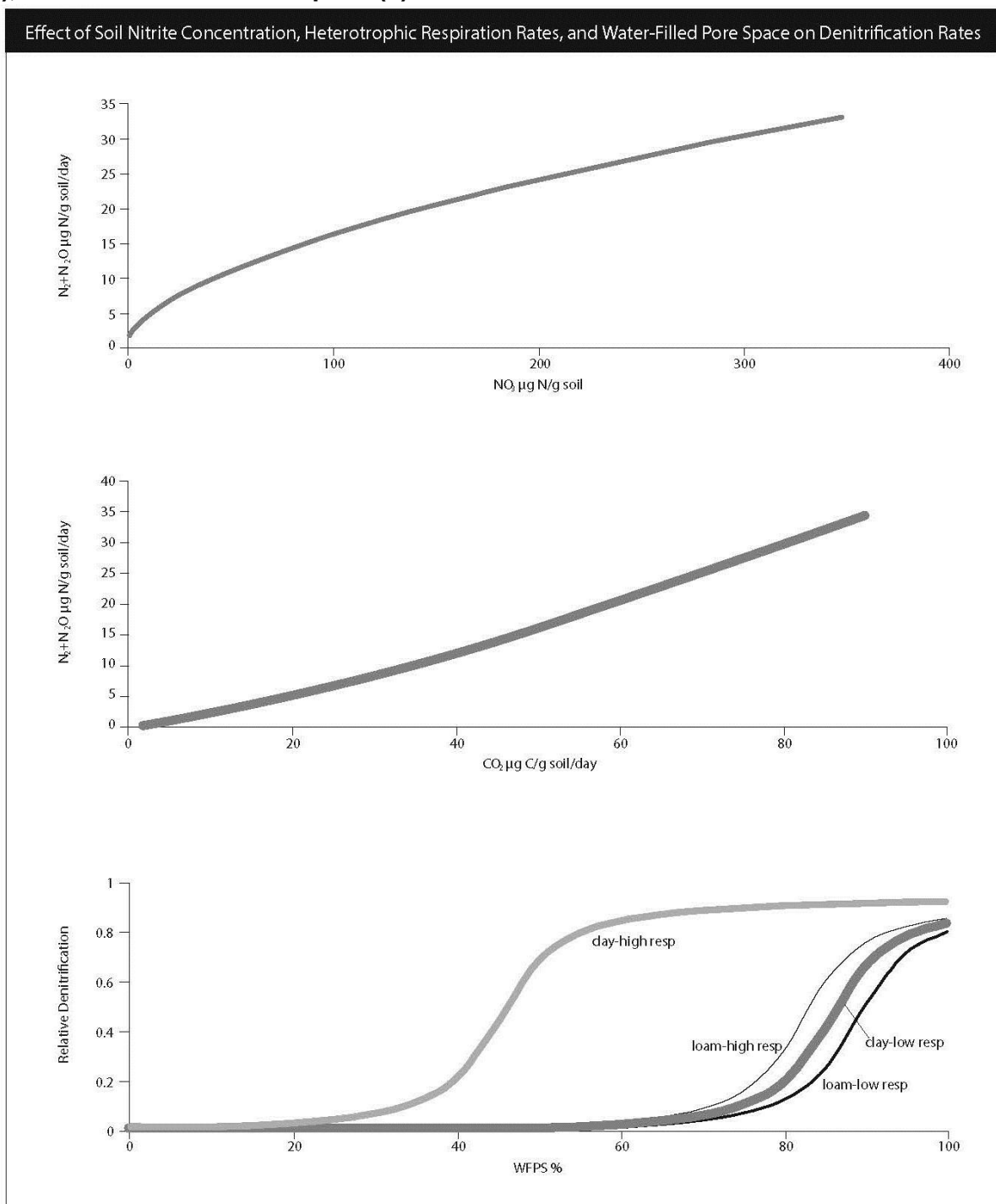


Figure A-12: Effect of Soil Nitrite Concentration (a), Heterotrophic Respiration Rates (b), and Water-Filled Pore Space (c) on Denitrification Rates



Pulses of N_2O emissions can occur during freeze-thaw events in soils of cold climates, and these events can contribute a substantial portion of annual emissions in northern temperate and boreal regions (Butterbach-Bahl et al. 2017; Wagner-Riddle et al. 2017; Del Grosso et al. 2022). The mechanisms responsible for this phenomenon are not entirely understood but the general hypotheses include accumulation of substrates while the soil is frozen that drives denitrification as the soil thaws; impacts on soil gas diffusivity and O_2 availability in pores during freeze-thaw events that influence denitrification rates; and differing temperature sensitivities of the enzymatic processes that

control the amounts of N₂ and N₂O gases released during denitrification (Congreves et al. 2018). The denitrification routine in DayCent was amended so that periods of thawing of frozen soils in the 2-5 cm layer during the late winter/spring will trigger a pulse of N₂O emissions (Del Grosso et al. 2022). Specifically, the soil water content and microbial respiration controls on denitrification are relaxed for approximately 3 days upon melting and N₂O from denitrification is amplified by an amount proportional to cumulative freezing degree days during the winter season. DayCent was evaluated using annual high frequency N₂O data collected at research sites in eastern and western Canada (Wagner-Riddle et al. 2017) and fluxes derived from atmospheric data (Nevison et al. 2017). The results showed less bias with a better match to observed patterns of late winter/spring emissions than the previous version of the DayCent model (Del Grosso et al. 2022).

DayCent Model Parameterization

DayCent has been widely applied and calibrated over the years through manual parameterization (e.g., Parton et al. 1998; Del Grosso et al. 2001). However, manual approaches do not necessarily provide the best calibration for a process-based model, and so there is an effort underway to re-parameterize DayCent with Bayesian calibration methods. There are three steps to this calibration method: a) conduct a sensitivity analysis to identify the most influential parameters, b) conduct the Bayesian calibration with the most sensitive parameters, and 3) evaluate the results with independent data. First, the framework uses a global sensitivity analysis to evaluate the importance of parameters given their full parameter space and potential interactions with other parameters (Saltelli et al. 2008). This approach is considered more robust for ranking parameter importance rather than a local sensitivity analysis that focuses on the effect of varying one parameter, generally within a small area of the overall parameter space. The Sobol method is used to conduct the global sensitivity analysis (Sobol 2001), which is appropriate for the complexity in the DayCent model (Saltelli 2002). Second, the model is calibrated using Bayesian logic with the Sampling Importance Resampling (SIR) method (Rubin 1987, Rubin 1988). A set of prior parameter distributions are developed based on the knowledge of the inventory compilers and information in the published literature. The model is then applied in a Monte Carlo analysis by randomly selecting values from the prior parameter distributions using a Latin Hypercube Sampling (LHS) approach. The LHS approach for selecting parameters allows for values that are used in the simulations to be distributed throughout the entire domain of the prior parameter distributions. The posterior distribution is approximated from the results generated by the Monte Carlo analysis using a likelihood function and weighting parameters based on the level of mismatch between modeled and measured emissions or soil organic carbon stock changes. If the data are informative, the likelihood will update the prior parameter distribution based on the weighting and lead to more resolved joint posterior parameter distribution. Third, the model is applied to simulate experimental sites that are not used in the Bayesian calibration, and the results are evaluated relative to the model application with the prior parameter distributions. If the model has been improved through the calibration process, then the results should have less bias and/or variance than the model application with the prior parameter distributions.

This Bayesian calibration model framework has initially been applied to calibrate DayCent for modeling soil organic carbon stock changes to a 30 cm depth (Gurung et al. 2020). The analysis reduced uncertainty in model predictions by a factor of 6.6. See Gurung et al. (2020) for more detail about this application. We anticipate expanding the calibration to other model processes in the near future, and eventually using the joint posterior parameter distribution to quantify uncertainty in model predictions. In this *Inventory*, the *maximum a posterior* value for each parameter from the posterior distribution has been used to simulate soil organic carbon stock changes.

DayCent Model Evaluation

DayCent has been applied to sites that are independent from model calibration to evaluate the model for estimating greenhouse gas emissions in the United States inventory. Moreover, these analyses are used to quantify uncertainty with an empirical approach as discussed in Step 2a of this annex (Ogle et al. 2007). The model was tested and shown to capture the general trends in carbon storage across 1406 observations from 69 long-term experiment sites and 145 NRI soil monitoring network sites (Spencer et al. 2011) (Figure A-13). Some bias and imprecision occur in predictions of soil organic carbon, which is reflected in the uncertainty associated with DayCent model results. Regardless, the Tier 3 approach has considerably less uncertainty than Tier 1 and 2 methods (Del Grosso et al. 2010; Figure A-14).

Figure A-13: Comparisons of Results from DayCent Model and Measurements of Soil Organic Carbon Stocks

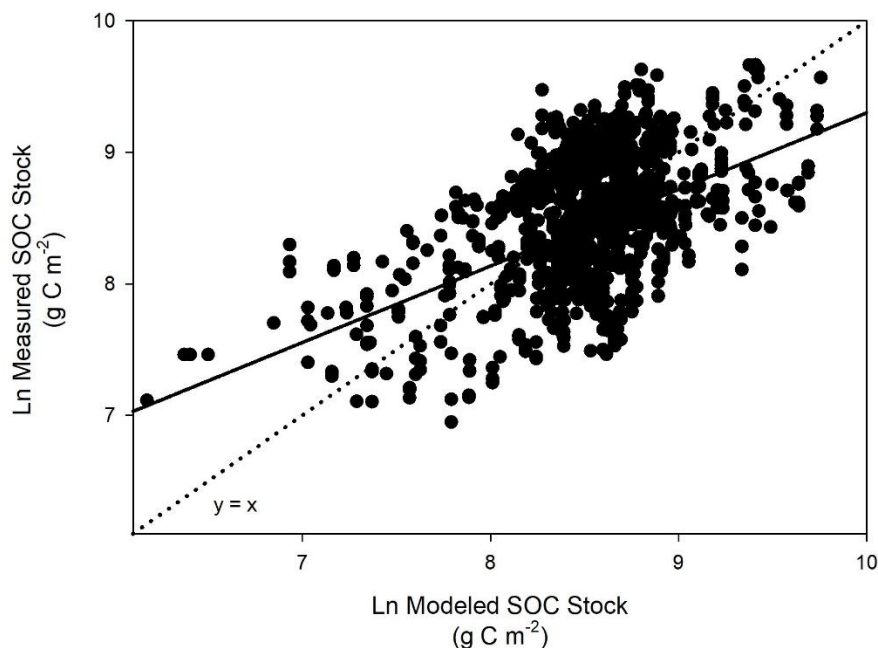
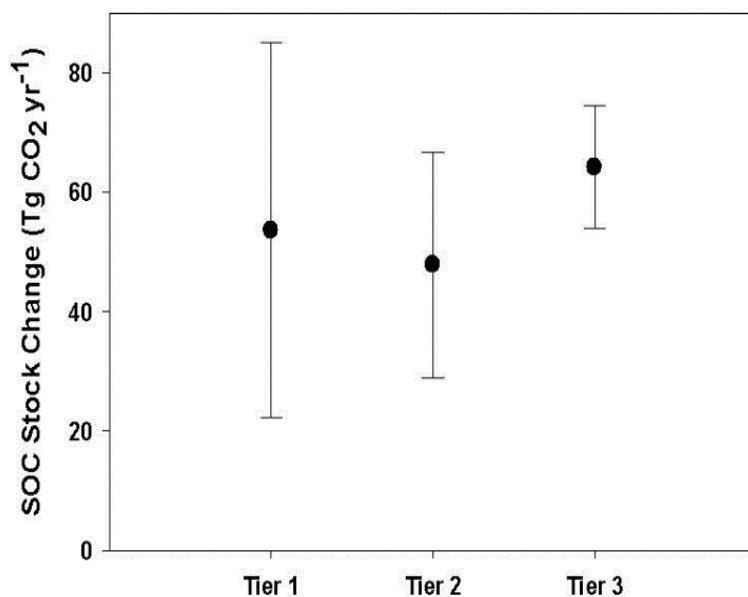


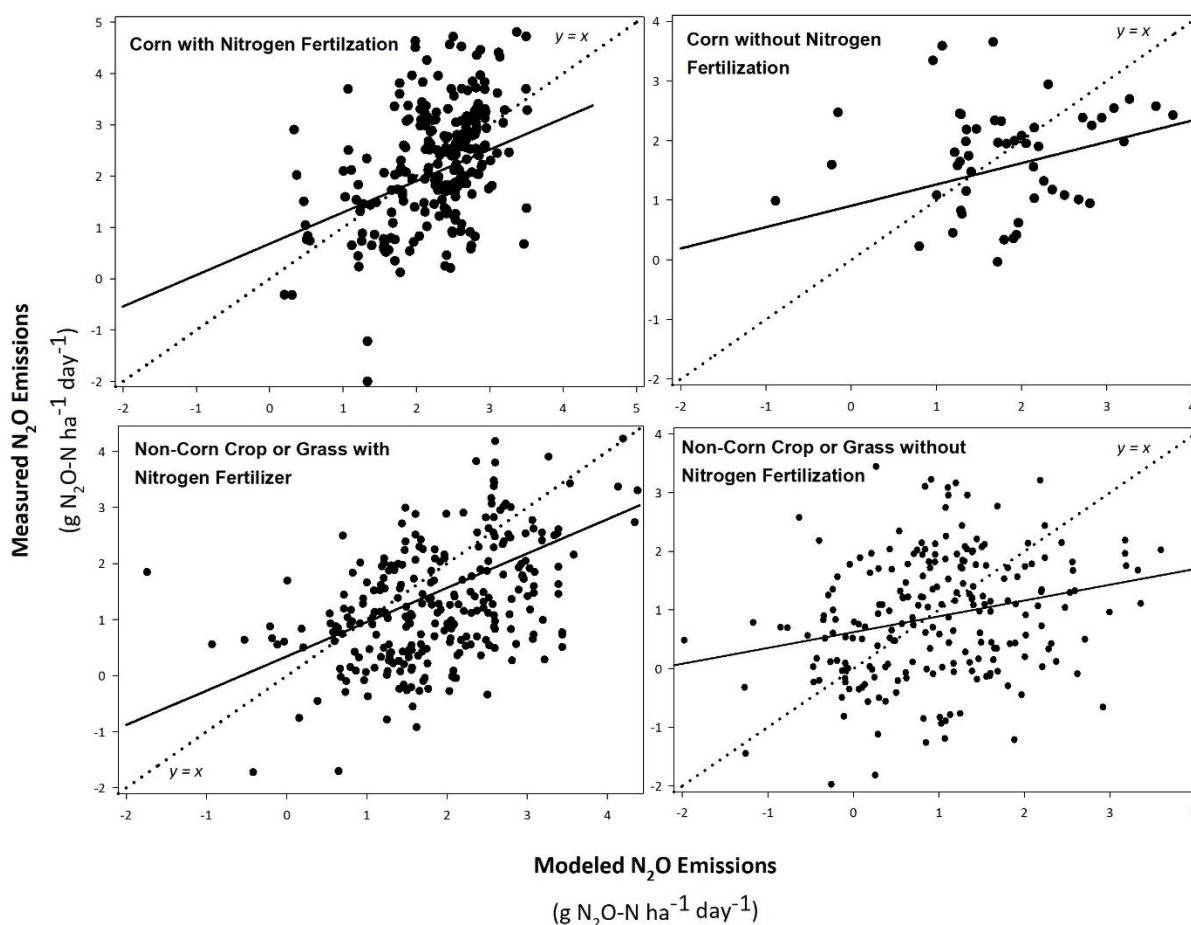
Figure A-14: Comparison of Estimated Soil Organic Carbon Stock Changes and Uncertainties using Tier 1 (IPCC 2006), Tier 2 (Ogle et al. 2003, 2006) and Tier 3 Methods



DayCent model results have also been compared to trace gas N₂O fluxes for native and managed systems including 76 experimental sites with about 857 observations (Figure A-14). In general, the model simulates reasonable patterns for the emissions, but there are some biases and imprecision in the predictions, which is reflected in the uncertainty associated with DayCent model results. Comparisons with measured data showed that DayCent estimated N₂O emissions more accurately and precisely than the IPCC Tier 1 methodology (IPCC 2006) with higher r^2 values and a fitted line closer to a perfect 1:1 relationship between measured and modeled

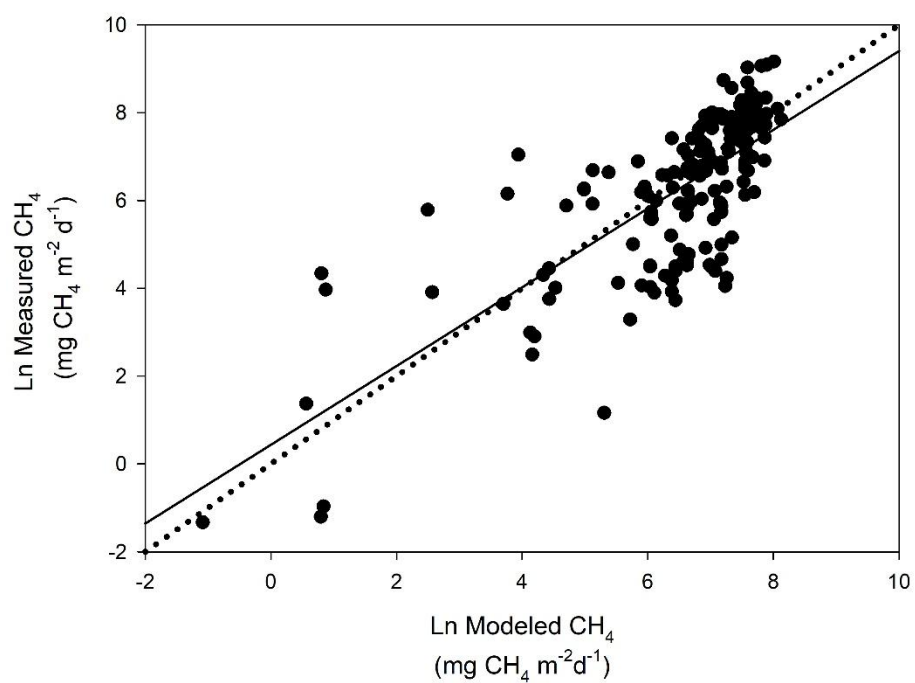
N₂O emissions (Del Grosso et al. 2005, 2008b). This is not surprising, since DayCent includes site-specific factors (climate, soil properties, and previous management) that influence N₂O emissions. Furthermore, DayCent also simulated NO₃⁻ leaching (root mean square error = 20 percent) more accurately than IPCC Tier 1 methodology (root mean square error = 69 percent) (Del Grosso et al. 2005). Volatilization of N gases that contribute to indirect soil N₂O emissions is the only component that has not been thoroughly tested, which is due to a lack of measurement data.

Figure A-15: Comparisons of Results from the DayCent Model and Measurements of Soil Nitrous Oxide Emissions



DayCent predictions of soil CH₄ emissions have also been compared to experimental measurements from sites in California, Texas, Arkansas, and Louisiana (Figure A-16). There are 17 long-term experiments with data on CH₄ emissions from rice cultivation, representing 238 treatment observations. In general, the model estimates CH₄ emissions with no apparent bias, but there is a lack of precision, which is addressed in the uncertainty analysis.

Figure A-16: Comparisons of Results from DayCent Model and Measurements of Soil Methane Emissions from Rice Cultivation



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3.14. Methodology for Estimating Net Carbon Stock Changes in Forest Ecosystems and Harvested Wood Products for Forest Land Remaining Forest Land and Land Converted to Forest Land as well as Non-CO₂ Emissions from Forest Fires

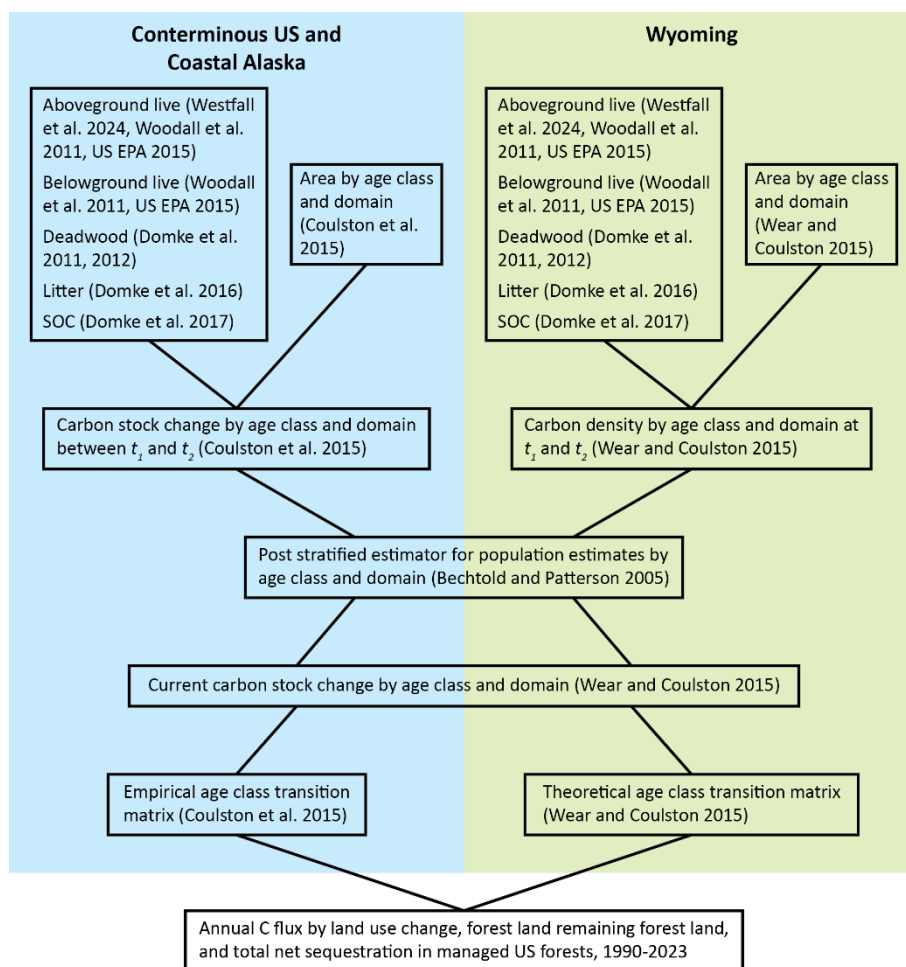
This annex expands on the methodology used to estimate net changes in carbon (C) stocks in forest ecosystems and harvested wood products for forest land remaining forest land and land converted to forest land as well as non-CO₂ emissions from forest fires. Full details of the carbon conversion factors and procedures may be found in the cited references. For details on the methods used to estimate changes in mineral soil carbon stocks in the land converted to forest land section please refer to Annex 3.13.

Carbon stocks and net stock change in forest ecosystems

The inventory-based methodologies for estimating forest carbon stocks are based on a combination of approaches (Woodall et al 2015a) and are consistent with the IPCC (2003, 2006) stock-difference (used for the conterminous United States and coastal southeast and southcentral Alaska) and gain-loss (used for interior Alaska, Hawaii, and the U.S. Territories) methods. Estimates of ecosystem carbon are based on data from the network of periodic and annual nationwide forest inventory (NFI) plots established and measured by the Forest Inventory and Analysis (FIA) program within the USDA Forest Service; either direct measurements or variables from the NFI are the basis for estimating metric tons of carbon per hectare in forest ecosystem carbon pools (i.e., above- and belowground biomass, dead wood, litter, and soil organic carbon (SOC)). For the conterminous United States and coastal Alaska, plot-level estimates are used to inform land area (by use) and stand age transition matrices across time which can be summed annually for an estimate of forest carbon stock change for forest land remaining forest land and land converted to forest land. A general description of the land use and stand age transition matrices that are informed by the annual NFI of the United States and were used in the estimation framework to compile estimates for the conterminous United States and coastal Alaska in this *Inventory* are described in Coulston et al. (2015). The annual NFI data in the conterminous United States and coastal Alaska allows for empirical estimation of the net change in forest ecosystem carbon stocks within the estimation framework. In contrast, Wyoming has a lack of remeasurement data within the NFI, so theoretical age transition matrices were developed (Figure A-17). The incorporation of all managed forest land in Alaska was facilitated by an analysis to determine the managed land base in Alaska (Ogle et al. 2018), the expansion of the NFI into interior Alaska beginning in 2014, and a myriad of publicly available data products that provided information necessary for prediction of carbon stocks and fluxes on plots that have yet to be measured as part of the NFI.

The following sections of this annex describe the estimation system used this year (Figure A-17), including the methods for estimating individual pools of forest ecosystem carbon in addition to the approaches used to inform land use and stand age transitions.

Figure A-17: Flowchart of the inputs necessary in the estimation framework, including the methods for estimating individual pools of forest carbon in the conterminous United States and Coastal Alaska



Note: An empirical age class transition matrix was used in Coastal Alaska and every state in the conterminous United States with the exception of Wyoming where a theoretical age class transition matrix was used due to a lack of remeasurements in the annual NFI.

Forest Land Definition

The definition of forest land within the United States and used for this *Inventory* is defined in Oswalt et al. (2019) as “Land at least 120 feet (37 meters) wide and at least 1 acre (0.4 hectare) in size with at least 10 percent cover (or equivalent stocking) by live trees including land that formerly had such tree cover and that will be naturally or artificially regenerated. Trees are woody plants having a more or less erect perennial stem(s) capable of achieving at least 3 inches (7.6 cm) in diameter at breast height (dbh), or 5 inches (12.7 cm) diameter at root collar, and a height of 16.4 feet (5 meters) at maturity in situ. The definition here includes all areas recently having such conditions and currently regenerating or capable of attaining such condition in the near future. Forest land also includes transition zones, such as areas between forest and non-forest lands that have at least 10 percent cover (or equivalent stocking) with live trees and forest areas adjacent to urban and built-up lands. Unimproved roads and trails, streams, and clearings in forest areas are classified as forest if they are less than 120 feet (36.6 meters) wide or an acre (0.4 hectare) in size. Forest land does not include land that is predominantly under agricultural or urban land use.” Timberland is productive forest land, which is on unreserved land and is producing or capable of producing crops of industrial wood. This is an important subclass of forest land because timberland is the primary

source of carbon incorporated into harvested wood products. Productivity for timberland is at a minimum rate of 20 cubic feet per acre (1.4 cubic meters per hectare) per year of industrial wood (Woudenberg and Farrenkopf 1995). There are about 208 million hectares of timberland in the conterminous United States, which represents 67 percent of all forest lands over the same area (Oswalt et al. 2019).

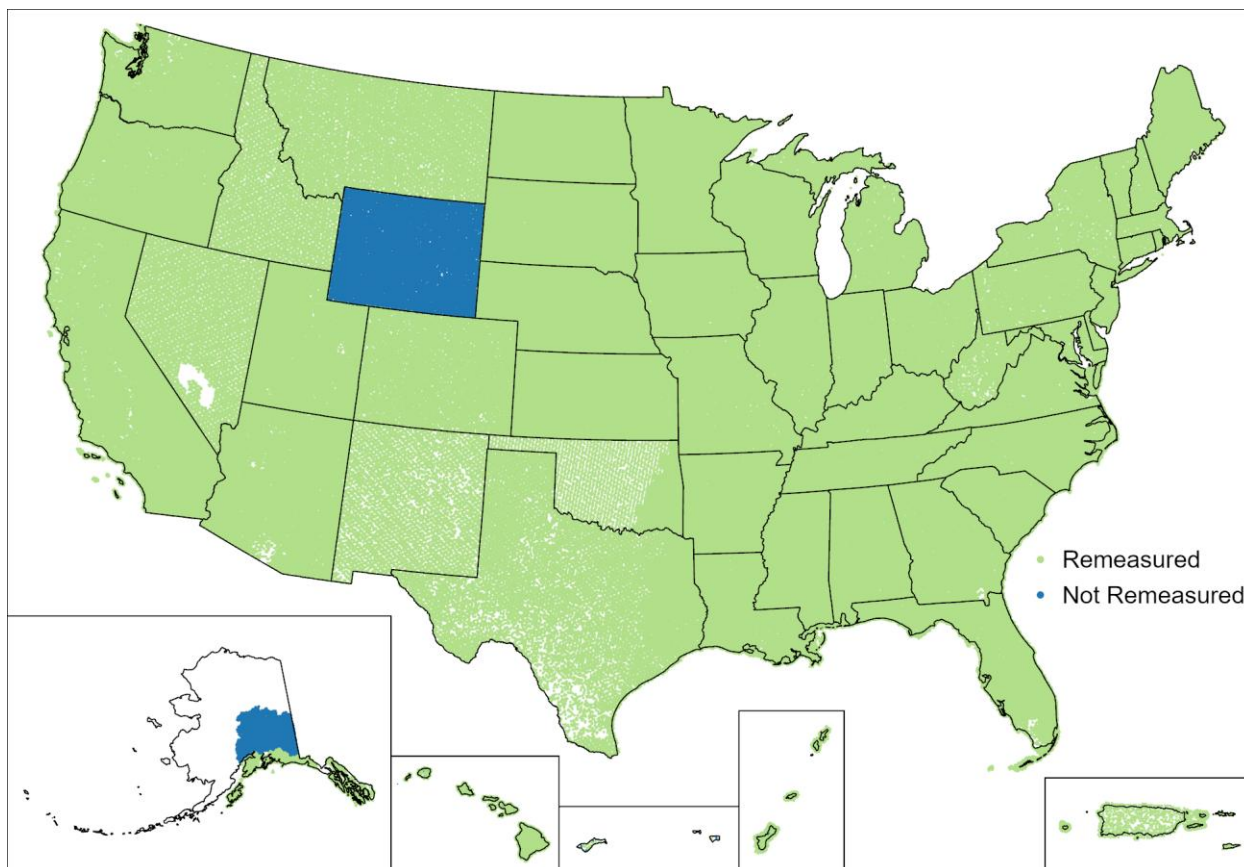
Forest Inventory Data

The estimates of forest carbon stocks are based on data from the annual NFI. NFI data were obtained from the USDA Forest Service FIA Program (Frayer and Furnival 1999; USDA Forest Service 2024a; USDA Forest Service 2024b). NFI data include remote sensing information and a collection of field measurements at sample locations called plots. Tree measurements include diameter at breast height (dbh), tree height, species, and variables describing tree form and condition. On a subset of plots, additional measurements or samples are taken on downed dead wood, litter, and soil variables. The technical advances needed to estimate carbon stocks from these data are ongoing (Woodall et al. 2015a) with the latest research incorporated on an annual basis (see Domke et al. 2022, Westfall et al. 2024). The field protocols are thoroughly documented and available for download from the USDA Forest Service (2024c). Bechtold and Patterson (2005) provide the estimation procedures for NFI population estimation. The data are freely available for download at USDA Forest Service (2024b) as the FIA Database (FIADB) Version 9.2 (USDA Forest Service 2024b; USDA Forest Service 2024c); these are the primary sources of NFI data used to estimate forest carbon stocks. In addition to the field sampling component, fine-scale remotely sensed imagery (National Agriculture Imagery Program) (NAIP 2015; Woodall et al. 2015b) is used to assign the land use at each sample location which has a nominal spatial resolution (raster cell size) of 1 m². Prior to field measurement of each year's collection of annual plots due for measurement (i.e., panel), each sample location in the panel (i.e., systematic distribution of plots within each state each year) is photo-interpreted manually to classify the land use. Annual NFI data are available for the temperate oceanic ecoregion of Alaska (southeast and south central) from 2004 to present as well as for interior Alaska from a pilot inventory in 2014 which became operational in 2016. Agroforestry systems are not currently accounted for in this *Inventory* since they are not explicitly inventoried by either of the two primary national natural resource inventory programs: the FIA program of the USDA Forest Service and the National Resources Inventory (NRI) of the USDA Natural Resources Conservation Service (Perry et al. 2005). The majority of these tree-based practices do not meet the size and definitions for forests within each of these resource inventories.

A national plot design and annualized sampling (USDA Forest Service 2024a) were introduced by FIA with most new annual NFIs beginning after 1998. These annual NFIs are used in combination with periodic NFIs for most of the U.S. Territories in the compilation of estimates for this *Inventory*. The annual NFIs involve the sampling of all forest land including reserved and lower productivity lands. All conterminous states in the U.S., coastal Alaska, and most of Puerto Rico and the U.S. Virgin Islands have annualized NFI data available with substantial remeasurement (with the exception of Wyoming; Figure A-18). Annualized sampling means that a spatially representative portion of plots throughout the state are sampled each year, with the goal of measuring all plots once every 5 to 10 years, depending on the region of the U.S. The full unique set of data with all measured plots, such that each plot has been measured one time, is called a cycle. Sampling is designed such that partial inventory cycles provide usable, unbiased samples of forest inventory within the state, but with higher sampling uncertainty than the full cycle. After all plots have been measured once, the sequence continues with remeasurement of the first year's plots, starting the next new cycle. Most eastern states have completed three or four cycles of the annualized NFI (with 5–7-year remeasurements), and most western states are on their second annual cycle (with 10-year remeasurement). Annually updated estimates of forest carbon stocks are affected by the redundancy in the data used to generate the annual updates of carbon stock. For example, a typical annual inventory update for an eastern state will include new data from remeasurement on 20 percent of plots; data from the remaining 80 percent of plots is identical to that included in the previous year's annual update. The interpretation and use of the annual inventory data can affect trend estimates of carbon stocks and stock changes (e.g., estimates based on 60 percent of an inventory cycle will be different than estimates with a complete (100 percent) cycle). In general, the carbon stock and stock change estimates use annual NFI summaries (updates) with unique sets of plot-level data (that is, without redundant sets); the most-recent annual update (i.e., 2023) is the exception because it is included in stock change calculations in order to include the most recent available data for each state. The specific inventories used in this report are listed in Table A-192 and this list can be compared with the full set of summaries available for download (USDA Forest Service 2024b).

Similar methods are used in the periodic NFIs available for Hawaii (USDA Forest Service 2022a), and the Pacific Islands of American Samoa, Guam, Northern Mariana Islands (USDA Forest Service 2022b). However, in most cases, only aboveground live biomass carbon estimates are available in the periodic NFIs so IPCC (2019) defaults and country-specific estimates were used to supplement periodic NFI data. The IPCC (2019) defaults were used in this *Inventory* where necessary because they are more contemporary than the IPCC (2006) defaults and provide more specific information for the ecological zones relevant to the Pacific Islands.

Figure A-18: Annual and Periodic FIA plots (remeasured and not remeasured) across the United States



Note: Due to the vast number of plots (where land use is measured even if no forest is present) they appear as spatially contiguous when displayed at the scale and resolution presented in this figure.

It should be noted that as the FIA program explores expansion of its vegetation inventory beyond the forest land use to other land uses (e.g., woodlands and urban areas), subsequent inventory observations will need to be delineated between forest and other land uses as opposed to a strict forest land use inventory. The forest carbon estimates provided here represent carbon stocks and stock change on managed forest lands (IPCC 2006, see Section 6.1 Representation of the U.S. Land Base), which is how all forest lands are classified. In some cases, there are NFI plots that do not meet the height component of the definition of forest land (Coulston et al. 2016). These plots are identified as “woodlands” (i.e., not forest land use) and were removed from the forest estimates and classified as grassland.¹³⁹ Note that minor differences (approximately 2 percent less forest land area in the conterminous United States) in identifying and classifying woodland as “forest” versus “woodland” exist between the current Resources Planning Act Assessment (RPA) data (Oswalt et al. 2019) and the FIADB (USDA Forest Service 2024b) due to a refined modelling approach developed specifically for *Inventory* reporting (Coulston et al.

¹³⁹ See the Grassland Remaining Grassland and Land Converted to Grassland sections for details.

2016). Plots in the coastal region of the conterminous United States were also evaluated using the National Land Cover Database (NLCD) and the Coastal Change Analysis Program data products to ensure that land areas were completely accounted for in this region and also that they were not included in both the wetlands category and the forest land category. This resulted in several NFI plots or subplots being removed from the forest land compilation.

Table A-192: Specific Annual Forest Inventories by State Used in Development of Forest Carbon Stock and Stock Change Estimate

Remeasurement States and Territories			Split Evaluation States/Territories and Periodic Inventories ¹		
State/Territory	Time 1 Year Range	Time 2 Year Range	State/Territory	Time 1 Year Range	Time 2 Year Range
Alabama	2006 - 2017	2015 - 2023	American Samoa	2001, 2012	
Alaska (Coastal)	2004 - 2008	2015 - 2019	Guam	2002, 2013	
Arizona	2001 - 2009	2011 - 2019	Hawaii	2010, 2019	
Arkansas	2013 - 2018	2019 - 2023	Northern Mariana Islands	2004, 2015	
California	2002 - 2011	2012 - 2021	Puerto Rico (Mona Island)	2008, 2013	
Colorado	2002 - 2009	2012 - 2019	Wyoming	2000	2011 - 2020
Connecticut	2009 - 2014	2015 - 2021			
Delaware	2009 - 2014	2015 - 2021			
Florida	2011 - 2018	2016 - 2021	Alaska (Interior)	2014, 2016 - 2023	
Georgia	2011 - 2019	2016 - 2022			
Idaho	2004 - 2009	2014 - 2019			
Illinois	2010 - 2015	2016 - 2022			
Indiana	2009 - 2014	2015 - 2021			
Iowa	2010 - 2015	2016 - 2022			
Kansas	2009 - 2014	2015 - 2021			
Kentucky	2006 - 2014	2014 - 2020			
Louisiana	2001 - 2014	2015 - 2021			
Maine	2013 - 2017	2018 - 2022			
Maryland	2009 - 2014	2015 - 2021			
Massachusetts	2009 - 2014	2015 - 2021			
Michigan	2009 - 2014	2015 - 2021			
Minnesota	2012 - 2016	2017 - 2021			
Mississippi	2009 - 2019	2017 - 2022			
Missouri	2009 - 2014	2015 - 2021			
Montana	2003 - 2009	2013 - 2019			
Nebraska	2009 - 2014	2015 - 2021			
Nevada	2004 - 2009	2014 - 2019			
New Hampshire	2009 - 2015	2015 - 2021			
New Jersey	2011 - 2016	2017 - 2021			
New Mexico	2005 - 2009	2015 - 2019			
New York	2009 - 2014	2015 - 2021			
North Carolina	2009 - 2019	2016 - 2022			
North Dakota	2010 - 2015	2016 - 2022			
Ohio	2010 - 2015	2016 - 2022			
Oklahoma	2009 - 2016	2017 - 2021			
Oregon	2001 - 2010	2011 - 2020			
Pennsylvania	2009 - 2014	2015 - 2021			
Puerto Rico (Mainland,	2011 - 2014	2016 - 2019			

Vieques, Culebra)		
Rhode Island	2010 - 2015	2016 - 2022
South Carolina	2012 - 2019	2017 - 2022
South Dakota	2009 - 2014	2015 - 2021
Tennessee	2005 - 2014	2014 - 2020
Texas (East)	2009 - 2018	2015 - 2022
Texas (West)	2004 - 2013	2014 - 2020
Utah	2000 - 2009	2010 - 2019
Vermont	2010 - 2015	2016 - 2022
Virginia	2012 - 2020	2017 - 2023
Washington	2002 - 2010	2012 - 2020
West Virginia	2009 - 2014	2015 - 2021
Wisconsin	2009 - 2014	2015 - 2021
U.S. Virgin Islands	2009	2014

¹ Plots in interior Alaska have not been split but are included in this column to conserve space in the table.

Note: Remeasured annual plots represent a complete inventory cycle between measurements of the same plots while split annual cycle plots represent a single inventory cycle of plots that are split where remeasurements have yet to occur.

Estimating Forest Inventory Plot-Level Carbon-Density

For each inventory plot in each state, field data from the FIA program are used alone or in combination with auxiliary information (e.g., climate, surficial geology, elevation) to predict carbon density for each forest ecosystem carbon pool (i.e., aboveground and belowground biomass, dead wood, litter, SOC). In the past, most of the conversion factors and models used for inventory-based forest carbon estimates (Smith et al. 2010; Heath et al. 2011) were initially developed as an extension of the forest carbon simulation model FORCARB (Heath et al. 2010). The conversion factors and model coefficients were usually categorized by region and forest type. Thus, region and type are specifically defined for each set of estimates. More recently, the coarse approaches of the past have been updated with empirical information regarding carbon variables for individual forest carbon pools such as dead wood and litter (e.g., Domke et al. 2013 and Domke et al. 2016). Factors are applied to the forest inventory data at the scale of NFI plots which are a systematic sample of all forest attributes and land uses within each state. The results are estimates of carbon density (T per hectare) for each forest ecosystem carbon pool. Carbon density for live trees, standing dead trees, understory vegetation, downed dead wood, litter, and SOC are estimated. All non-soil carbon pools except litter and downed dead wood can be separated into aboveground and belowground components. The live tree and understory carbon pools are combined into the aboveground and belowground biomass pools in this *Inventory*. Similarly, standing dead trees and downed dead wood are pooled as dead wood in this *Inventory*. Carbon stocks and fluxes for forest land remaining forest land and land converted to forest land are reported in forest ecosystem carbon pools following IPCC (2006).

Live tree carbon pools

Live tree carbon pools include aboveground and belowground (coarse root) biomass of live trees with dbh of at least 2.54 cm at 1.37 m above the forest floor. Separate estimates are made for above- and below-ground biomass components. The NSVB models have been implemented in the FIA program and associated public database (USDA Forest Service 2024b) along with a national standardization of tree defects and new carbon fractions. These volume, biomass, and carbon estimates cover timber tree species in the conterminous United States and coastal Alaska. All other trees (i.e., trees that are woodland species and trees within Pacific and Caribbean Islands) use regional models for volume and biomass, with updated carbon fractions (when available). While NSVB did not directly update models for trees that are considered woodland species or trees within the Pacific (USDA Forest Service 2022a,b) and Caribbean Islands (collectively referred to hereafter as ‘non-NSVB trees’), volume, biomass, and carbon estimates for these trees have also changed. For non-NSVB trees, the standardization of tree defects and how variables are reported (i.e., whether models for total-stem or merchantable-bole volumes are available) may be reflected as differences in volume estimates. Additionally, biomass estimates for non-NSVB trees are based on regional biomass models and no longer are adjusted as they were under the CRM. Finally, updates to

carbon fractions (when available) and calculation of aboveground biomass are reflected in aboveground and belowground biomass carbon estimates. If inventory plots included data on individual trees, a new method was implemented to estimate aboveground biomass carbon (Westfall et al. 2024).

Understory vegetation

Understory vegetation is a minor component of total forest ecosystem biomass. Understory vegetation is defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. In this *Inventory*, it is assumed that 10 percent of understory carbon mass is belowground. This general root-to-shoot ratio (0.11) is near the lower range of temperate forest values provided in IPCC (2006) and was selected based on two general assumptions: ratios are likely to be lower for light-limited understory vegetation as compared with larger trees, and a greater proportion of all root mass will be less than 2 mm diameter.

Estimates of carbon density are based on information in Birdsey (1996), which was applied to FIA permanent plots. These were fit to the model below:

Equation A-46: Ratio of Understory Carbon Density to Live Tree Carbon Density

$$\text{Ratio} = e^{(A - B \times \ln(\text{live tree C density}))} \quad (1)$$

Where “e” = exponential function, “A” and “B” are model coefficients and “ln(live tree C density)” = log base e. In this model, the ratio is the ratio of understory C density (T C/ha) to live tree carbon density (above- and below-ground) according to Jenkins et al. (2003) and expressed in T C/ha. An additional coefficient is provided as a maximum ratio; that is, any estimate predicted from the model that is greater than the maximum ratio is set equal to the maximum ratio. A full set of coefficients are in Table A-193. Regions and forest types are the same classifications described in Smith et al. (2003). As an example, the basic calculation for understory carbon in aspen-birch forests in the Northeast is:

Equation A-47: Understory Carbon Density

$$\text{Understory (T C/ha)} = (\text{live tree C density}) \times e^{(0.855 - 1.03 \times \ln(\text{tree C density}))} \quad (2)$$

This calculation is followed by three possible modifications. First, the maximum value for the ratio is set to 2.02 (see value in Table A-193 column “maximum ratio”); this also applies to stands with zero tree carbon, which is undefined in the above model. Second, the minimum ratio is set to 0.005 (Birdsey 1996). Third, nonstocked (i.e., currently lacking tree cover but still in the forest land use) and pinyon/juniper forest types (see Table A-193) are set to coefficient A, which is a carbon density (T C/ha) for these types only.

Table A-193: Coefficients for Estimating the Ratio of Carbon Density of Understory Vegetation (above- and belowground, T C/ha) by Region and Forest Type^a

Region ^b	Forest Type ^b	A	B	Maximum ratio ^c
NE	Aspen-Birch	0.855	1.032	2.023
	MBB/Other Hardwood	0.892	1.079	2.076
	Oak-Hickory	0.842	1.053	2.057
	Oak-Pine	1.960	1.235	4.203
	Other Pine	2.149	1.268	4.191
	Spruce-Fir	0.825	1.121	2.140
	White-Red-Jack Pine	1.000	1.116	2.098
	Nonstocked	2.020	2.020	2.060
NLS	Aspen-Birch	0.777	1.018	2.023
	Lowland Hardwood	0.650	0.997	2.037
	Maple-Beech-Birch	0.863	1.120	2.129
	Oak-Hickory	0.965	1.091	2.072
	Pine	0.740	1.014	2.046
	Spruce-Fir	1.656	1.318	2.136
	Nonstocked	1.928	1.928	2.117
NPS	Conifer	1.189	1.190	2.114
	Lowland Hardwood	1.370	1.177	2.055
	Maple-Beech-Birch	1.126	1.201	2.130

	Oak-Hickory	1.139	1.138	2.072
	Oak-Pine	2.014	1.215	4.185
	Nonstocked	2.052	2.052	2.072
PSW	Douglas-fir	2.084	1.201	4.626
	Fir-Spruce	1.983	1.268	4.806
	Hardwoods	1.571	1.038	4.745
	Other Conifer	4.032	1.785	4.768
	Pinyon-Juniper	4.430	4.430	4.820
	Redwood	2.513	1.312	4.698
	Nonstocked	4.431	4.431	4.626
PWE	Douglas-fir	1.544	1.064	4.626
	Fir-Spruce	1.583	1.156	4.806
	Hardwoods	1.900	1.133	4.745
	Lodgepole Pine	1.790	1.257	4.823
	Pinyon-Juniper	2.708	2.708	4.820
	Ponderosa Pine	1.768	1.213	4.768
	Nonstocked	4.315	4.315	4.626
PWW	Douglas-fir	1.727	1.108	4.609
	Fir-Spruce	1.770	1.164	4.807
	Other Conifer	2.874	1.534	4.768
	Other Hardwoods	2.157	1.220	4.745
	Red Alder	2.094	1.230	4.745
	Western Hemlock	2.081	1.218	4.693
	Nonstocked	4.401	4.401	4.589
RMN	Douglas-fir	2.342	1.360	4.731
	Fir-Spruce	2.129	1.315	4.749
	Hardwoods	1.860	1.110	4.745
	Lodgepole Pine	2.571	1.500	4.773
	Other Conifer	2.614	1.518	4.821
	Pinyon-Juniper	2.708	2.708	4.820
	Ponderosa Pine	2.099	1.344	4.776
RMS	Nonstocked	4.430	4.430	4.773
	Douglas-fir	5.145	2.232	4.829
	Fir-Spruce	2.861	1.568	4.822
	Hardwoods	1.858	1.110	4.745
	Lodgepole Pine	3.305	1.737	4.797
	Other Conifer	2.134	1.382	4.821
	Pinyon-Juniper	2.757	2.757	4.820
SC	Ponderosa Pine	3.214	1.732	4.820
	Nonstocked	4.243	4.243	4.797
	Bottomland			
	Hardwood	0.917	1.109	1.842
	Misc. Conifer	1.601	1.129	4.191
	Natural Pine	2.166	1.260	4.161
	Oak-Pine	1.903	1.190	4.173
SE	Planted Pine	1.489	1.037	4.124
	Upland Hardwood	2.089	1.235	4.170
	Nonstocked	4.044	4.044	4.170
	Bottomland			
	Hardwood	0.834	1.089	1.842
	Misc. Conifer	1.601	1.129	4.191
	Natural Pine	1.752	1.155	4.178
	Oak-Pine	1.642	1.117	4.195
	Planted Pine	1.470	1.036	4.141
	Upland Hardwood	1.903	1.191	4.182
	Nonstocked	4.033	4.033	4.182

^a Prediction of ratio of understory carbon to live tree carbon is based on the model: $\text{Ratio} = \exp(A - B \times \ln(\text{tree\_C\_density}))$, where “ratio” is the ratio of understory carbon density to live tree (above-and below- ground) carbon density, and “tree_C_density” is live tree (above-and below- ground) carbon density in T C/ha. Note that this ratio is multiplied by tree carbon density on each plot to produce understory vegetation.

^b Regions and types as defined in Smith et al. (2003).

^c Maximum ratio: any estimate predicted from the model that is greater than the maximum ratio is set equal to the maximum ratio.

Dead Wood

The standing dead tree estimates are primarily based on plot-level measurements (Westfall et al. 2024, Woodall et al. 2011). This carbon pool includes aboveground and belowground (coarse root) mass and includes trees of at least 2.54 cm dbh. Calculations follow the basic methods applied to live trees (Westfall et al. 2024) with additional modifications to account for decay (Harmon et al. 2011). Carbon fractions by decay class and hardwood and softwood are used for standing dead trees (Westfall et al. 2024).

Downed dead wood, inclusive of logging residue, are sampled on a subset of NFI plots. Despite a reduced sample intensity, a single down woody material population estimate (Woodall et al. 2010; Domke et al. 2013; Woodall et al. 2013) per state is now incorporated into these empirical downed dead wood estimates. Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. It also includes stumps and roots of harvested trees. Ratio estimates of downed dead wood to live tree biomass were calculated using the NSVB modeling framework (Westfall et al. 2024) developed using FORCARB2 simulations and applied at the plot level (Smith et al. 2004). Estimates for downed dead wood correspond to the region and forest type classifications described in Smith et al. (2003). A full set of ratios is provided in Table A-194. An additional component of downed dead wood is a regional average estimate of logging residue based on Smith et al. (2006) applied at the plot level. These are based on a regional average carbon density at age zero and first order decay; initial densities and decay coefficients are provided in Table A-195. These amounts are added to explicitly account for downed dead wood following harvest. The sum of these two components is then adjusted by the ratio of population totals; that is, the ratio of plot-based to modeled estimates (Domke et al. 2013). An example of this 3-part calculation for downed dead wood in a 25-year-old naturally regenerated loblolly pine forest with 82.99 T C/ha in live trees (Jenkins et al. 2003) in Louisiana is as follows:

First, an initial estimate from live tree carbon density and Table A-194 (SC, Natural Pine).

Equation A-48: Carbon Density of Downed Dead Wood

$$\text{C density} = 82.99 \times 0.068 = 5.67 \text{ (T C/ha)}$$

Second, an average logging residue from age and Table A-194 (SC, softwood)

Equation A-49: Logging Residue Carbon Density

$$\text{C density} = 5.5 \times e(-25/17.9) = 1.37 \text{ (T C/ha)}$$

Third, adjust the sum by the downed dead wood ratio plot-to-model for Louisiana, which was $27.6/31.1 = 0.886$

Equation A-50: Adjusted Carbon Density of Downed Dead Wood

$$\text{C density} = (5.67 + 1.37) \times 0.886 = 6.24 \text{ (T C/ha)}$$

Table A-194: Ratio for Estimating Downed Dead Wood by Region and Forest Type

Region ^a	Forest type ^a	Ratio ^b
NE	Aspen-Birch	0.078
	MBB/Other Hardwood	0.071
	Oak-Hickory	0.068
	Oak-Pine	0.061
	Other Pine	0.065
	Spruce-Fir	0.092
	White-Red-Jack Pine	0.055

	Nonstocked	0.019
NLS	Aspen-Birch	0.081
	Lowland Hardwood	0.061
	Maple-Beech-Birch	0.076
	Oak-Hickory	0.077
	Pine	0.072
	Spruce-Fir	0.087
	Nonstocked	0.027
NPS	Conifer	0.073
	Lowland Hardwood	0.069
	Maple-Beech-Birch	0.063
	Oak-Hickory	0.068
	Oak-Pine	0.069
	Nonstocked	0.026
PSW	Douglas-fir	0.091
	Fir-Spruce	0.109
	Hardwoods	0.042
	Other Conifer	0.100
	Pinyon-Juniper	0.031
	Redwood	0.108
	Nonstocked	0.022
PWE	Douglas-fir	0.103
	Fir-Spruce	0.106
	Hardwoods	0.027
	Lodgepole Pine	0.093
	Pinyon-Juniper	0.032
	Ponderosa Pine	0.103
	Nonstocked	0.024
PWW	Douglas-fir	0.100
	Fir-Spruce	0.090
	Other Conifer	0.073
	Other Hardwoods	0.062
	Red Alder	0.095
	Western Hemlock	0.099
	Nonstocked	0.020
RMN	Douglas-fir	0.062
	Fir-Spruce	0.100
	Hardwoods	0.112
	Lodgepole Pine	0.058
	Other Conifer	0.060
	Pinyon-Juniper	0.030
	Ponderosa Pine	0.087
	Nonstocked	0.018
RMS	Douglas-fir	0.077
	Fir-Spruce	0.079
	Hardwoods	0.064
	Lodgepole Pine	0.098
	Other Conifer	0.060
	Pinyon-Juniper	0.030
	Ponderosa Pine	0.082
	Nonstocked	0.020
SC	Bottomland Hardwood	0.063
	Misc. Conifer	0.068
	Natural Pine	0.068
	Oak-Pine	0.072
	Planted Pine	0.077

	Upland Hardwood	0.067
	Nonstocked	0.013
	Bottomland Hardwood	0.064
	Misc. Conifer	0.081
	Natural Pine	0.081
SE	Oak-Pine	0.063
	Planted Pine	0.075
	Upland Hardwood	0.059
	Nonstocked	0.012

^a Regions and types as defined in Smith et al. (2003).

^b The ratio is multiplied by the live tree carbon density on a plot to produce downed dead wood carbon density (T C/ha).

Table A-195: Coefficients for Estimating Logging Residue Component of Downed Dead Wood

Region ^a	Forest Type Group ^b (softwood/ hardwood)	Initial C Density (T/ha)	Decay Coefficient
Alaska	hardwood	6.9	12.1
Alaska	softwood	8.6	32.3
NE	hardwood	13.9	12.1
NE	softwood	12.1	17.9
NLS	hardwood	9.1	12.1
NLS	softwood	7.2	17.9
NPS	hardwood	9.6	12.1
NPS	softwood	6.4	17.9
PSW	hardwood	9.8	12.1
PSW	softwood	17.5	32.3
PWE	hardwood	3.3	12.1
PWE	softwood	9.5	32.3
PWW	hardwood	18.1	12.1
PWW	softwood	23.6	32.3
RMN	hardwood	7.2	43.5
RMN	softwood	9.0	18.1
RMS	hardwood	5.1	43.5
RMS	softwood	3.7	18.1
SC	hardwood	4.2	8.9
SC	softwood	5.5	17.9
SE	hardwood	6.4	8.9
SE	softwood	7.3	17.9

^a Regions are defined in Smith et al. (2003) with the addition of coastal Alaska.

^b Forest types are according to majority hardwood or softwood species.

Litter carbon

Carbon in the litter layer is currently sampled on a subset of the NFI plots. Litter carbon is the pool of organic carbon (including material known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. Because litter attributes are only collected on a subset of NFI plots, a model (3) was developed to predict carbon density based on plot/site variables for plots that lacked litter information (Domke et al. 2016):

Equation A-51: Litter Carbon density

$$P(\text{FFCFull}) = f(\text{lat}, \text{lon}, \text{elev}, \text{fortypgrp}, \text{above}, \text{ppt}, \text{tmax}, \text{gmi}) + u \quad (3)$$

where,

lat	=	latitude,
lon	=	longitude,
elev	=	elevation,
fortypgrp	=	forest type group,
above	=	aboveground live tree C (trees ≥ 2.54 cm dbh),
ppt	=	mean annual precipitation,
tmax	=	average maximum temperature,
gmi	=	the ratio of precipitation to potential evapotranspiration,
u	=	the uncertainty in the prediction resulting from the sample-based estimates of the model parameters and observed residual variability around this prediction.

Due to data limitations in certain regions and inventory periods, a series of reduced non-parametric models, which did not include climate variables, were used rather than replacing missing variables with imputation techniques. Database records used to compile estimates for this report were grouped by variable availability and the approaches described herein were applied. Litter carbon predictions are expressed as density ($T \text{ ha}^{-1}$).

Soil organic carbon

This section provides a summary of the methodology used to predict SOC for this report. A complete description of the approach is in Domke et al. (2017). The data used to develop the modeling framework to predict SOC on forest land came from the NFI and the International Soil Carbon Network. Since 2001, the FIA program has collected soil samples on every 16th base intensity plot (approximately every 2,428 ha) distributed approximately every 38,848 ha, where at least one forested condition exists (Woodall et al. 2010). On fully forested plots, mineral and organic soils were sampled adjacent to subplot 2 by taking a single core at each location from two layers: 0 to 10.16 cm and 10.16 to 20.32 cm. The texture of each soil layer was estimated in the field, and physical and chemical properties were determined in the laboratory (U.S. Forest Service 2011). For this analysis, estimates of SOC from the NFI were calculated following O'Neill et al. (2005):

Equation A-52: Total mass of mineral and organic soil carbon

$$\sum SOC_{FIA\_TOTAL} = C_i \cdot BD_i \cdot t_i \cdot ucf \quad (4)$$

where,

$\sum SOC_{FIA\_TOTAL}$	=	total mass (Mg C ha ⁻¹) of the mineral and organic soil C over all <i>i</i> th layers,
C_i	=	percent organic C in the <i>i</i> th layer,
BD_i	=	bulk density calculated as weight per unit volume of soil (g·cm ⁻³) at the <i>i</i> th soil layer,
t_i	=	thickness (cm) of the <i>i</i> th soil layer (either 0 to 10.16 cm or 10.16 to 20.32 cm), and
ucf	=	unit conversion factor (100).

The SOC_{FIA_TOTAL} estimates from each plot were assigned by forest condition on each plot, resulting in 3,667 profiles with SOC layer observations at 0 to 10.16 and 10.16 to 20.32 cm depths. Since the United States has historically reported SOC estimates to a depth of 100 cm (Heath et al. 2011, USEPA 2015), International Soil Carbon Monitoring Network (ISCN) data from forests in the United States were harmonized with the FIA soil layer observations to develop model functions of SOC by soil order to a depth of 100 cm. All observations used from the ISCN were contributed by the Natural Resources Conservation Service. A total of 16,504 soil layers from 2,037 profiles were used from ISCN land uses defined as deciduous, evergreen, or mixed forest. The FIA-ISCN harmonized dataset used for model selection and prediction included a total of 5,704 profiles with 23,838 layer observations at depths ranging from 0 to 1,148 cm. The modeling framework developed to predict SOC for this report was built around strategic-level forest and soil inventory information and auxiliary variables available for all FIA plots in the United States. The first phase of the new estimation approach involved fitting models using the midpoint of each soil layer from the harmonized dataset and SOC estimates at those midpoints. Several linear and nonlinear models were evaluated, and a log-log model provided the optimal fit to the harmonized data:

Equation A-53: Soil organic carbon at midpoint depth

$$\log_{10} SOC_i = I + \log_{10} Depth \quad (5)$$

where,

$$\begin{aligned}
 \log_{10} SOC_i &= \text{SOC density (Mg C ha}^{-1} \text{ cm depth}^{-1}) \text{ at the midpoint depth,} \\
 I &= \text{intercept,} \\
 \log_{10} D_{epth} &= \text{profile midpoint depth (cm).}
 \end{aligned}$$

The model was validated by partitioning the complete harmonized dataset multiple times into training and testing groups and then repeating this step for each soil order to evaluate model performance by soil order. Extra sum of squares F tests were used to evaluate whether there were statistically significant differences between the model coefficients from the model fit to the complete harmonized dataset and models fit to subsets of the data by soil order. Model coefficients for each soil order were used to predict SOC for the 20.32 to 100 cm layer for all FIA plots with soil profile observations. Next, the SOC layer observations from the FIA and predictions over the 100 cm profile for each FIA plot were summed:

Equation A-54: Total soil organic carbon density

$$SOC_{100} = SOC_{FIA\_TOTAL} + SOC_{20-100} \quad (6)$$

where,

$$\begin{aligned}
 SOC_{100} &= \text{total estimated SOC density from 0-100 cm for each forest condition with a soil sample in the FIA database,} \\
 SOC_{FIA\_TOTAL} &\text{as previously defined in model (4), } SOC_{20-100} \\
 &= \text{predicted SOC from 20.32 to 100 cm from model (5).}
 \end{aligned}$$

In the second phase of the modeling framework, SOC_{100} estimates for FIA plots were used to predict SOC for plots lacking SOC_{100} estimates using a non-parametric model; this particular machine learning tool used bootstrap aggregating (i.e., bagging) to develop models to improve prediction (Breimen 2001). It also relies on random variable selection to develop a forest of uncorrelated regression trees. These trees recognize the relationship between a dependent variable, in this case SOC_{100} , and a set of predictor variables. All relevant predictor variables—those that may influence the formation, accumulation, and loss of SOC—from annual inventories collected on all base intensity plots and auxiliary climate, soil, and topographic variables obtained from the PRISM climate group (Northwest Alliance 2015), Natural Resources Conservation Service (NRCS 2015), and U.S. Geological Survey (Danielson and Gesch 2011), respectively, were included in the analysis. Due to regional differences in sampling protocols, many of the predictor variables included in the variable selection process were not available for all base intensity plots. To avoid problems with data limitations, pruning was used to reduce the models to the minimum number of relevant predictors (including both continuous and categorical variables) without substantial loss in explanatory power or increase in root mean squared error (RMSE). The general form of the full non-parametric models were:

Equation A-55: Predicted soil organic carbon

$$P(SOC) = f(lat, lon, elev, fortypgrp, ppt, tmax, gmi, order, surfgeo) \quad (7)$$

where,

$$\begin{aligned}
 P(SOC) &= \text{predicted soil organic carbon per hectare to a depth of 100 cm} \\
 lat &= \text{latitude,} \\
 lon &= \text{longitude,} \\
 elev &= \text{elevation,} \\
 fortypgrp &= \text{forest type group,} \\
 ppt &= \text{mean annual precipitation,} \\
 tmax &= \text{average maximum temperature,} \\
 gmi &= \text{the ratio of precipitation to potential evapotranspiration,} \\
 order &= \text{soil order,} \\
 surfgeo &= \text{surficial geological description}
 \end{aligned}$$

Compilation of population estimates using NFI plot data

Methods for the conterminous United States and Coastal Alaska

The estimation framework is fundamentally driven by the annual NFI. Unfortunately, the annual NFI does not extend to 1990 and the periodic data from the NFI are not consistent (e.g., different plot design) with the annual NFI

necessitating the adoption of a system to predict the annual carbon parameters back to 1990. To facilitate the carbon prediction parameters, the estimation framework is comprised of a forest dynamics module (age transition matrices) and a land-use dynamics module (land area transition matrices). The forest dynamics module assesses forest uptake, forest aging, and disturbance effects (e.g., disturbances such as wind, fire, and floods identified by foresters on inventory plots). The land use dynamics module assesses carbon stock transfers associated with afforestation and deforestation (e.g., Woodall et al. 2015b). Both modules are developed from land use area statistics and carbon stock change or carbon stock transfer by age class. The required inputs are estimated from more than 625,000 forest and non-forest observations in the NFI database (U.S. Forest Service 2024a-c). Model predictions for before or after the annual NFI period are constructed from the estimation framework using only the annual observations. This modeling framework includes opportunities for user-defined scenarios to evaluate the impacts of land-use change and disturbance rates on future carbon stocks and stock changes. As annual NFIs have largely completed at least one cycle and have been remeasured, age and area transition matrices can be empirically informed. In contrast, as annual inventories in Wyoming are still undergoing their first complete cycle, they are still in the process of being remeasured, and as a result theoretical transition matrices need to be developed.

Wear and Coulston (2015) and Coulston et al. (2015) provide the framework for the model. The overall objective is to estimate unmeasured historical changes and future changes in forest carbon parameters consistent with annual NFI estimates. For most regions, forest conditions are observed at time t_0 and at a subsequent time $t_1 = t_0 + s$, where s is the time step (time measured in years) and is indexed by discrete (5 year) forest age classes. The inventory from t_0 is then predicted back to the year 1990 and projected from t_1 to 2023. This prediction approach requires simulating changes in the age-class distribution resulting from forest aging and disturbance events and then applying carbon density estimates for each age class. For all states in the conterminous United States (except for Wyoming), age class transition matrices are estimated from observed changes in age classes between t_0 and t_1 . In Wyoming, only one inventory was available (t_0) so transition matrices were obtained from theory but informed by the condition of the observed inventory to predict from t_0 to 1990 and predict from t_0 to 2023.

Theoretical Age Transition Matrices

Without any mortality-inducing disturbance, a projection of forest conditions would proceed by increasing all forest ages by the length of the time step until all forest resided in a terminal age class where the forest is retained indefinitely (this is, by assumption, where forest carbon per unit area reaches a stable maximum). For the most basic case, disturbances (e.g., wildfire or timber harvesting) can reset some of the forest to the first age class. Disturbance can also alter the age class in more subtle ways. If a portion of trees in a multiple-age forest dies, the trees comprising the average age calculation change, thereby shifting the average age higher or lower (generally by one age class).

With n age classes, the age transition matrix ($\mathbf{T}$) is an $n \times n$ matrix, and each element ($\mathbf{T}_{qr}$) defines the proportion of forest area in class q transitioning to class r during the time step (s). The values of the elements of $\mathbf{T}$ depend on a number of factors, including forest disturbances such as harvests, fire, storms, and the value of s , especially relative to the span of the age classes. For example, holding area fixed, allowing for no mortality, defining the time step s equivalent to the span of age classes, and defining five age classes results in,

Equation A-56: Example age transition matrix

$$\mathbf{T} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 \end{pmatrix} \quad (8)$$

where all forest area progresses to the next age class and forests within the terminal age class are retained forever. With this version of $\mathbf{T}$, after five time steps all forests would be in the terminal age class. Relaxing these assumptions changes the structure of $\mathbf{T}$. If all disturbances, including harvesting and fire, that result in stand regeneration are accounted for and stochastic elements in forest aging are allowed, $\mathbf{T}$ defines a traditional Lefkovitch matrix population model (e.g., Caswell 2001) and becomes,

$$\mathbf{T} = \begin{pmatrix} 1 - t_1 - d_1 & d_2 & d_3 & d_4 & d_5 \\ t_1 & 1 - t_2 - d_2 & 0 & 0 & 0 \\ 0 & t_2 & 1 - t_3 - d_3 & 0 & 0 \\ 0 & 0 & t_3 & 1 - t_4 - d_4 & 0 \\ 0 & 0 & 0 & t_4 & 1 - d_5 \end{pmatrix} \quad (9)$$

where t_q is the proportion of forest of age class q transitioning to age class $q+1$, d_q is the proportion of age class q that experiences a stand-replacing disturbance, and $(1 - t_q - d_q)$ is the proportion retained within age class q ($\mathbf{T}_{qr}$).

Projections and Backcast for Wyoming

Projections of forest carbon in Wyoming are based on a life stage model:

Equation A-57: Carbon Stock Change

$$\Delta C_t = C_{t+m} - C_t = (\mathbf{F}_t \mathbf{T} - \mathbf{F}_t) \cdot \mathbf{Den} + \mathbf{L}_t \cdot \mathbf{Den} \quad (10)$$

In this framework $\mathbf{T}$ is an age transition matrix that shifts the age distribution of the forest $\mathbf{F}$. The difference in forest area by age class between time t and $t+s$ is $\mathbf{F}_t \mathbf{T} - \mathbf{F}_t$. This quantity is multiplied by carbon density by age class ($\mathbf{Den}$) to estimate carbon stock change of forest remaining forest between t and $t+s$. Land-use change is accounted for by the addition of $\mathbf{L}_t \cdot \mathbf{Den}$, where $\mathbf{L}_t$ identifies the age distribution of net land shifts into or out of forests. A query of the forest inventory databases provides estimates of $\mathbf{F}$ and $\mathbf{Den}$, while inventory observations and modeling assumptions are used to estimate $\mathbf{T}$. By expanding $\mathbf{Den}$ to a matrix of carbon contained in all the constituent pools of forest carbon, projections for all pools are generated.

Land-use change is incorporated as a $1 \times n$ vector $\mathbf{L}$, with positive entries indicating increased forest area and negative entries indicating loss of forest area, which provides insights of net change only. Implementing a forest area change requires some information and assumptions about the distribution of the change across age classes (the n dimension of $\mathbf{L}$). In the eastern states, projections are based on the projection of observed gross area changes by age class. In western states, total forest area changes are applied using rules. When net gains are positive, the area is added to the youngest forest age class; when negative, area is subtracted from all age classes in proportion to the area in each age class category.

Backcasting forest carbon inventories generally involve the same concepts as forecasting. An initial age class distribution is shifted at regular time steps backwards through time, using a transition matrix ($\mathbf{B}$):

Equation A-58: Backcasting Age Class Distribution

$$\mathbf{F}_{t-s} = \mathbf{F}_t \cdot \mathbf{B} \quad (11)$$

$\mathbf{B}$ is constructed based on similar logic used for creating $\mathbf{T}$. The matrix cannot simply be derived as the inverse of $\mathbf{T}$ ($\mathbf{F}_{t-s} = \mathbf{F}_t \mathbf{T}^{-1}$) because of the accumulating final age class (i.e., $\mathbf{T}$ does not contain enough information to determine the proportion of the final age class derived from the $n-1$ age class and the proportion that is retained in age class n from the previous time step).¹⁴⁰ However, $\mathbf{B}$ can be constructed using observed changes from the inventory and assumptions about transition/accumulation including nonstationary elements of the transition model:

¹⁴⁰ Simulation experiments show that a population that evolves as a function of $\mathbf{T}$ can be precisely predicted using $\mathbf{T}^{-1}$. However, applying the inverse to a population that is not consistent with the long-run outcomes of the transition model can result in predictions of negative areas within some stage age classes.

Equation A-59: Age Transition Model

$$\mathbf{B} = \begin{pmatrix} 1 - \sum_q d_q & b_2 & 0 & 0 & 0 \\ d_1 & 1 - b_2 & b_3 & 0 & 0 \\ d_2 & 0 & 1 - b_3 & b_4 & 0 \\ d_3 & 0 & 0 & 1 - b_4 & b_r \\ d_4 & 0 & 0 & 0 & 1 - b_r \end{pmatrix} \quad (12)$$

Forest area changes need to be accounted for in the backcasts as well:

Equation A-60: Forest Area Change

$$\mathbf{F}_{t-s} = \mathbf{F}_t \mathbf{B} - \mathbf{L}_t \quad (13)$$

Where $\mathbf{L}_t$ is the forest area change between t_1 and t_0 as previously defined.

In Wyoming, the theoretical life-stage models described by matrices (9) and (10) were applied. The disturbance factors (d) in both $\mathbf{T}$ and $\mathbf{B}$ are obtained from the current NFI by assuming that the area of forest in age class 1 resulted from disturbance in the previous period, the area in age class 2 resulted from disturbance in the period before that, and so on. The source of disturbed forest was assumed to be proportional to the area of forest in each age class. For projections ($\mathbf{T}$), the average of implied disturbance for the previous two periods was applied. For the backcast ($\mathbf{B}$), the disturbance frequencies implied by the age class distribution for each time step are moved. For areas with empirical transition matrices, change in forest area ($\mathbf{L}_t$) was backcasted/projected using the change in forest area observed for the period t_0 to t_1 .

Projections and backcast for the Conterminous United States (excluding Wyoming) and coastal Alaska

For all states in the conterminous United States (with the exception of Wyoming) and coastal Alaska remeasured plots were available. When remeasured data are available, the previously described approach is extended to estimate change more directly; in this case $\Delta C_t = F_t \times \delta C$, where ΔC is net stock change by pool within the analysis area, F is as previously defined, and δC is an $n \times cp$ matrix of per unit area forest carbon stock change per year by pool (cp) arrayed by forest age class. Inter-period forest carbon dynamics are previously described, and the age transition matrix (T) is estimated from the observed data directly. Forest carbon change at the end of the next period is defined as: $\Delta C_{t+s} = F_t \times T \times \delta C$. Land-use change and disturbances such as cutting, fire, weather, insects, and diseases were incorporated by generalizing to account for the change vectors and undisturbed forest remaining as undisturbed forest:

Equation A-61: Land Use Change and Disturbance

$$\Delta C_{t+s} = \sum_{d \in L} (A_{td} \cdot T_d \cdot \delta C_d) \quad (14)$$

Where A_{td} = area by age class of each mutually exclusive land category in L which includes d disturbances at time t .

$L = (FF, NFF, FNF, Fcut, Ffire, Fweather, Fid)$ where FF =undisturbed forest remaining as undisturbed forest, NFF =nonforest to forest conversion, FNF =forest to nonforest conversion, $Fcut$ =cut forest remaining as forest, $Ffire$ =forest remaining as forest disturbed by fire, $Fweather$ =forest remaining as forest disturbed by weather, and Fid =forest remaining as forest disturbed by insects and diseases. In the case of land transfers (FNF and NFF), T_d is an $n \times n$ identity matrix and δC_d is a carbon stock transfer rate by age. Paired measurements for all plots in the inventory provide direct estimates of all elements of δC , T_d , and A_{td} matrices.

Predictions are developed by specifying either F_{t+s} or A_{t+sd} for either a future or a past state. To move the system forward, T is specified so that the age transition probabilities are set up as the probability between a time 0 and a time 1 transition. To move the system backward, T is replaced by B so that the age transition probabilities are for transitions from time 1 to time 0. Forecasts were developed by assuming the observed land-use transitions and disturbance rates would continue for the next 5 years. Predictions moving back in time were developed using a Markov Chain process for land-use transitions and observed disturbance rates for fire, weather, and insects.

Historical forest cutting was incorporated by using the relationship between the area of forest cutting estimated from the inventory plots and the volume of roundwood production from the Timber Products Output program (U.S. Forest Service 2024d). This relationship allowed for the modification of F_{cut} such that it followed trends described by Oswalt et al. (2019).

Methods for Interior Alaska

Inventory and sampling

In 2014, a pilot inventory was established in the Tanana Valley State Forest and Tetlin National Wildlife Refuge in Interior Alaska. This pilot inventory was a collaboration between the USDA Forest Service, FIA program, the National Aeronautical and Space Administration (NASA), and many other federal, state, and local partners. This effort resulted in the establishment of 98 field plots which were measured during the summer of 2014 and integrated with NASA's Goddard LiDAR/Hyperspectral/Thermal (G-LiHT) imaging system. Given the remote nature of Interior Alaska forest, the NFI plots in the pilot campaign were sampled at a lower intensity than base NFI plots (1 plot per 2403 ha) in the conterminous United States and coastal Alaska. Several plot-level protocols were also adapted to accommodate the unique conditions of forests in this region (see Pattison et al. 2018 for details on plot design and sampling protocols). The pilot field campaign became operational in 2016 and plots measured on a 1/5 intensity (1 plot per 12013 ha) from 2014, 2016 to 2023 from the Interior Alaska NFI were used ($n = 1206$).

A spatially balanced sampling design was used to identify field sample locations across interior Alaska following standard FIA procedures with a tessellation of hexagons and one sample plot selected per hexagon – 1/5 intensity in interior Alaska (Bechtold and Patterson 2005). The sampling locations were classified as forest or non-forest using the NLCD from 2016 in conjunction with the LANDFIRE Existing Vegetation Type (EVT) 2016 data product (LANDFIRE 2021). The EVT data was used only on plots that intersected with the 'Woody Wetlands' NLCD land cover category to determine whether the primary vegetation type was trees or shrubs. It is important to note that this is different from the process for classifying NFI plots into land cover and land-use categories in the conterminous United States where high resolution areal imagery is used. Since the fine-scale remotely sensed imagery (National Agriculture Imagery Program; NAIP 2015) used in the conterminous United States were not available for Alaska and given that the NLCD has been used to classify land use categories in Alaska in the Representation of the U.S. Land Base in this *Inventory*, the NLCD and LANDFIRE EVT was the most consistent and credible option for classification. Next, the forest land was further classified as managed or unmanaged following the definition in the Representation of the U.S. Land Base and using similar procedures (see Ogle et al. 2018 for details on the managed land layer for the United States).

While only a subset of the total NFI sample was available at the time of this *Inventory*, all NFI plot locations within the sampling frame were used in this analysis. Auxiliary climate, soil, structural, disturbance, and topographic variables were harmonized with each plot location and year of occurrence (if relevant and available) over the entire time series (1990 to 2023).

Prediction

The harmonized data were used to predict plot-level parameters using non-parametric random forests (RF) for regression, a machine learning tool that uses bootstrap aggregating (i.e., bagging) to develop models to improve prediction (Breiman 2001). The RF analysis relies on random variable selection to develop a forest of uncorrelated regression trees. These trees uncover the relationship between a dependent variable (e.g., live aboveground biomass carbon) and a set of predictor variables. The RF analysis included predictor variables ($n > 100$) that may influence carbon stocks within each forest ecosystem pool at each plot location over the entire time series. To avoid problems with data limitations over the time series, variable pruning was used to reduce the RF models to the minimum number of relevant predictors without substantial loss in explanatory power or increase in root mean squared error (RMSE; see Domke et al. 2017). The harmonized dataset used to develop the RF models for each plot-level parameter were partitioned 10 times into training (70 percent) and testing (30 percent) groups and the results were evaluated graphically and with a variety of statistical metrics including Spearman's rank correlation, equivalence tests (Wellek 2003), as well as RMSE. All analyses were conducted using R statistical software (R Core Team 2018).

The RF predictions of carbon stocks for the year 2016 were used as a baseline for plots that have not yet been measured. Next, simple linear regression was used to predict average annual gains/losses by forest ecosystem carbon pool using the chronosequence of plot measurements available at the time of this *Inventory*. These predicted gains/losses were applied over the time series from the year of measurement or the 2016 base year in

the case of plots that have not yet been measured. Since the RF predictions of carbon stocks and the predicted gains/losses were obtained from empirical measurements on NFI plots that may have been disturbed at some point over the time series, the predictions inherently incorporate gains/losses associated with natural disturbance and harvesting. That said, there was no evidence of fire disturbance on the plots that have been measured to date. To account for carbon losses associated with fire, carbon stock predictions for plots that have not been measured but were within a fire perimeter, using the same geospatial layers described in the Emissions from Forest Fires section, during the *Inventory* period were adjusted to account for area burned (see Table A-211) and the IPCC (Table 2.6, IPCC 2006) default combustion factor for boreal forests was applied to all live, dead, and litter biomass carbon stocks in the year of the disturbance. The plot-level predictions in each year were then multiplied by the area they represent within the sampling frame to compile population estimates over the time series for this *Inventory*.

Methods for Hawaii and the U.S. Territories

To implement the gain-loss approach in Hawaii and the U.S. Territories, a combination of Tier 1 and Tier 2 methods were applied. All forest land conditions were observed on annual and periodic NFI plots from 2001 to 2019 (see Table A-184 for specific inventories included for each Island). Plot-level data from the NFI were harmonized with data describing ecological zone (FAO 2010), soil attributes (Johnson and Kern 2003, Deenik and McClellan, 2007, IPCC 2019), and dead wood and litter carbon stocks (Oswalt et al. 2008; IPCC 2019). Only estimates of carbon stocks in live trees were consistently available in the NFI for Hawaii and the U.S. Territories for each inventory. These estimates were used to obtain average annual carbon stock change estimates for above and belowground live trees which were applied to each forest plot to capture growth, harvest removals, and mortality. The carbon stocks and annual stock change estimates were compared with country-specific estimates (Oswalt et al. 2008; Selmann et al. 2017), and IPCC (2019) default estimates to ensure they were consistent with other sources. There were limited data available on disturbances and management activities on NFI plots over the time series so Tier 1 methods were applied for dead wood and litter. It was assumed that the average transfer rate into dead wood and litter is equivalent to the average transfer rate out of dead organic matter so there are no net carbon stock changes included for these pools in the time series (IPCC 2006). Similarly, given data limitations on forest soils and changes on NFI plots over the time series, a Tier 1 approach was also used for soil carbon with country-specific estimates (Johnson and Kern 2003) and IPCC (2019) defaults used to estimate soil carbon stocks with no net carbon stock change reported.

Forest Land Remaining Forest Land Area Estimates

Forest land area estimates in Section 6.2 Forest Land Remaining Forest Land (Category 4A1) of this *Inventory* are compiled using NFI data. Forest land area estimates obtained from these data are also used as part of section 6.1 Representation of the U.S. Land Base (Category 4.1). The forest land area estimates in section 6.2 include Hawaii and the U.S. Territories compiled using different methods than in Section 6.1. The National Land Cover Dataset is used in addition to NFI estimates in Section 6.1 Representation of the U.S. Land Base and forest land in Hawaii are included in that section, but do not include U.S. Territories. Also, it is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation, this prevents harmonization of forest land in Wyoming with the NFI/NLCD method used in Section 6.1 Representation of the U.S. Land Base (Category 4.1). These issues result in small differences in the managed forest land area in Sections 6.1 and 6.2 of this *Inventory* (Table A-205). There are also other factors contributing to the small differences such as harmonization of aspatial and spatial data across all land-use categories in Section 6.1 over the entire *Inventory* time series.

Carbon in Harvested Wood Products

Estimates of the Harvested Wood Product (HWP) contribution to forest carbon emissions and removals (hereafter called “HWP Contribution”) are based on methods described in Skog (2008) using the WOODCARB II model and the U.S. forest products module (Ince et al. 2011) and many data sources (Table A-196). These methods are based on IPCC (2006) guidance for estimating HWP carbon. The 2006 IPCC *Guidelines for National Inventories* provide methods to quantify the HWP Contribution using one of several different accounting approaches: production, stock change, and atmospheric flow, as well as a default method. The various approaches are described below. The approaches differ in how HWP Contribution is allocated based on production or consumption as well as what processes (atmospheric fluxes or stock changes) are emphasized.

- **Production approach:** Accounts for the net changes in carbon stocks in forests and in the wood products pool, but attributes both to the producing country.
- **Stock-change approach:** Accounts for changes in the product pool within the boundaries of the consuming country.
- **Atmospheric-flow approach:** Accounts for net emissions or removals of carbon to and from the atmosphere within national boundaries. Carbon removal due to forest growth is accounted for in the producing country while carbon emissions to the atmosphere from oxidation of wood products are accounted for in the consuming country.
- **Default approach:** Assumes no change in carbon stocks in HWP. IPCC (2006) requests that such an assumption be justified if used.

Table A-196: WOODCARB II inputs, including sources for the data and most recent update.

Harvest wood product	Category	Source(s)	Updated
Softwood			
Lumber	Production Imports Exports	American Forest and Paper Association; USDA, Foreign Agricultural Service; U.S. International Trade Commission; USDC, Bureau of the Census; Western Wood Products Association	Current
Plywood	Production Imports Exports	American Plywood Association, The Engineered Wood Association; USDA, Foreign Agricultural Service; U.S. International Trade Commission	Current
Veneer	Production Imports Exports	American Plywood Association, The Engineered Wood Association; USDA, Foreign Agricultural Service; U.S. International Trade Commission	Current
Other structural panel	Production Imports Exports	American Plywood Association, The Engineered Wood Association; USDA, Foreign Agricultural Service	Current
Pulpwood-based products	Production Imports Exports	American Plywood Association, The Engineered Wood Association; Composite Panel Association; American Forest and Paper Association; U.S. International Trade Commission; USDA, Foreign Agricultural Service; American Pulpwood Association; United Nations Food and Agriculture Organization	Current
Other industrial products	Production and consumption	USDA, Forest Service; U.S. International Trade Commission	2006
Logs	Imports Exports	Western Wood Products Association; U.S. International Trade Commission	Current
Pulpwood chips	Imports Exports	American Forest and Paper Association; American Pulpwood Association	Current
Fuelwood	Production and consumption	USDA, Forest Service; U.S. International Trade Commission	2006
Hardwood			
Lumber	Production Imports Exports	American Forest and Paper Association; USDA, Foreign Agricultural Service; U.S. International Trade Commission; USDC, Bureau of the Census; Western Wood Products Association	Current
Plywood	Production Imports Exports	American Plywood Association, The Engineered Wood Association; USDA, Foreign Agricultural Service; U.S. International Trade Commission	Current

Veneer	Production Imports Exports	American Plywood Association, The Engineered Wood Association; USDA, Foreign Agricultural Service; U.S. International Trade Commission	Current
Other structural panel	Production Imports Exports	American Plywood Association, The Engineered Wood Association; USDA, Foreign Agricultural Service	Current
Pulpwood-based products	Production Imports Exports	American Plywood Association, The Engineered Wood Association; Composite Panel Association; American Forest and Paper Association; U.S. International Trade Commission; USDA, Foreign Agricultural Service; American Pulpwood Association; United Nations Food and Agriculture Organization	Current
Other industrial products	Production and consumption	USDA, Forest Service; U.S. International Trade Commission	2006
Logs	Imports Exports	Western Wood Products Association; U.S. International Trade Commission	Current
Pulpwood chips	Imports Exports	American Forest and Paper Association; American Pulpwood Association	Current
Fuelwood	Production and consumption	USDA, Forest Service; U.S. International Trade Commission	2006
Total			
Paper and board	Production Imports Exports		Current 2020 American Forest and Paper Association 2020
Wood pulp	Production Imports Exports	United Nations Food and Agriculture Organization; American Forest and Paper Association	Current
Recovered paper	Consumption	American Forest and Paper Association	Current
Other fibrous	Consumption	American Forest and Paper Association	Current
Recyclable paper for molded pulp, insulation, and other uses		American Forest and Paper Association	2021
Recyclable paper	Imports Exports	American Forest and Paper Association	2020
Particleboard	Production	Composite Panel Association	Current
Medium-density fiberboard	Production	Composite Panel Association	Current
Particleboard and medium-density fiberboard	Imports Exports	U.S. International Trade Commission; USDA, Foreign Agricultural Service	Current
Insulating board	Production Imports Exports	American Forest and Paper Association; North American Fiberboard Association	1994
Hardboard	Production Imports Exports	American Forest and Paper Association; U.S. International Trade Commission; Composite Panel Association; U.S. Department of Agriculture, Foreign Agricultural Service	Current
Recovered fiber pulp	Imports Exports	United Nations Food and Agriculture Organization	Current

The United States uses the production accounting approach (as in previous years) to report HWP Contribution (Table A-197) but estimates for all three approaches are provided in Table A-198. Annual estimates of change are calculated by tracking the additions to (i.e., transfers of harvested wood from the forest ecosystem) and losses from (i.e., the decay of) the pool of products held in end uses (i.e., products in use such as housing or publications) and the pool of products held in solid waste disposal sites (SWDS).

Estimates of five HWP variables that can be used to calculate HWP contribution for the stock change and atmospheric flow approaches for imports and exports are provided in Table A-199 The HWP variables estimated are:

- (1A) Annual change of carbon in wood and paper products in use in the United States,
- (1B) Annual change of carbon in wood and paper products in SWDS in the United States,
- (2A) Annual change of carbon in wood and paper products in use in the United States and other countries where the wood came from trees harvested in the United States,
- (2B) Annual change of carbon in wood and paper products in SWDS in the United States and other countries where the wood came from trees harvested in the United States,
- (3) Carbon in imports of wood, pulp, and paper to the United States,
- (4) Carbon in exports of wood, pulp, and paper from the United States, and
- (5) Carbon in annual harvest of wood from forests in the United States. The sum of these variables yield estimates for HWP contribution under the production accounting approach.

Table A-197: Harvested Wood Products from Wood Harvested in the United States—Annual Additions of Carbon to Stocks and Total Stocks under the Production Approach

Net C additions per year (MMT C per year)				Total C stocks (MMT C)		
Year	Total	Products in use	Products in SWDS	Total	Products in use	Products in SWDS
		Total	Total			
1990	(33.8)	(14.9)	(18.8)	1,895	1,249	646
1991	(33.8)	(16.3)	(17.4)	1,929	1,264	665
1992	(32.9)	(15.0)	(17.9)	1,963	1,280	683
1993	(33.4)	(15.9)	(17.5)	1,996	1,295	701
1994	(32.3)	(15.1)	(17.2)	2,029	1,311	718
1995	(30.6)	(14.1)	(16.5)	2,061	1,326	735
1996	(32.0)	(14.7)	(17.3)	2,092	1,340	752
1997	(31.1)	(13.4)	(17.7)	2,124	1,355	769
1998	(32.5)	(14.1)	(18.4)	2,155	1,368	787
1999	(30.8)	(12.8)	(18.0)	2,188	1,382	805
2000	(25.5)	(8.7)	(16.8)	2,218	1,395	823
2001	(26.8)	(9.6)	(17.2)	2,244	1,404	840
2002	(25.6)	(9.4)	(16.2)	2,271	1,413	857
2003	(28.4)	(12.1)	(16.3)	2,296	1,423	873
2004	(28.7)	(12.4)	(16.4)	2,325	1,435	890
2005	(28.9)	(11.6)	(17.3)	2,353	1,447	906
2006	(27.3)	(10.0)	(17.4)	2,382	1,459	923
2007	(20.8)	(3.7)	(17.1)	2,410	1,469	941
2008	(14.8)	1.8	(16.7)	2,430	1,473	958
2009	(16.6)	(0.0)	(16.6)	2,445	1,471	974
2010	(18.8)	(2.0)	(16.8)	2,462	1,471	991
2011	(19.4)	(2.4)	(17.0)	2,481	1,473	1,008
2012	(20.8)	(3.7)	(17.1)	2,500	1,475	1,025
2013	(22.5)	(5.3)	(17.3)	2,521	1,479	1,042
2014	(23.4)	(6.1)	(17.4)	2,543	1,484	1,059
2015	(24.9)	(7.4)	(17.5)	2,567	1,490	1,076
2016	(26.1)	(8.4)	(17.7)	2,592	1,498	1,094
2017	(27.3)	(9.4)	(17.8)	2,618	1,506	1,112
2018	(25.6)	(7.8)	(17.8)	2,645	1,516	1,130
2019	(23.7)	(6.2)	(17.5)	2,671	1,523	1,147
2020	(26.4)	(8.8)	(17.6)	2,694	1,530	1,165
2021	(25.8)	(8.3)	(17.5)	2,721	1,538	1,182

2022	(25.3)	(7.9)	(17.4)	2,747	1,547	1,200
2023	(24.8)	(7.5)	(17.3)	2,772	1,555	1,217

Note: Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere).

Table A-198: Comparison of Net Annual Change in Harvested Wood Products Carbon Stocks Using Alternative Accounting Approaches (MMT CO₂ Eq.)

<i>Inventory Year</i>	Stock-Change Approach	Atmospheric Flow Approach	Production Approach
1990	(117)	(131)	(124)
1991	(120)	(132)	(124)
1992	(127)	(128)	(121)
1993	(130)	(130)	(122)
1994	(126)	(128)	(118)
1995	(122)	(122)	(112)
1996	(131)	(127)	(117)
1997	(137)	(123)	(114)
1998	(147)	(127)	(119)
1999	(141)	(120)	(113)
2000	(125)	(100)	(93)
2001	(131)	(103)	(98)
2002	(126)	(98)	(94)
2003	(143)	(108)	(104)
2004	(142)	(110)	(105)
2005	(136)	(112)	(106)
2006	(113)	(110)	(100)
2007	(72)	(88)	(76)
2008	(42)	(70)	(54)
2009	(48)	(80)	(61)
2010	(51)	(92)	(69)
2011	(59)	(95)	(71)
2012	(72)	(103)	(76)
2013	(86)	(109)	(83)
2014	(93)	(113)	(86)
2015	(101)	(119)	(91)
2016	(105)	(123)	(96)
2017	(110)	(129)	(100)
2018	(108)	(125)	(94)
2019	(106)	(117)	(87)
2020	(128)	(138)	(97)
2021	(129)	(137)	(95)
2022	(131)	(133)	(93)
2023	(133)	(133)	(91)

Note: Parentheses indicate net carbon sequestration (i.e., a net removal of carbon from the atmosphere).

Table A-199: Harvested Wood Products Sectoral Background Data

	1A	1B	2A	2B	3	4	5	6	7	8
					Annual Imports of wood, and paper products plus wood fuel, pulp, recovered paper, roundwood/ chips	Annual Exports of wood, and paper products plus wood fuel, pulp, recovered paper, roundwood/ chips	Annual Domestic Harvest	Annual release of C to the atmosphere from HWP consumption (from fuelwood and products in use and products in SWDS)	Annual release of C to the atmosphere from HWP (including firewood) where wood came from domestic harvest (from products in use and products in SWDS)	HWP Contribution to AFOLU CO ₂ emissions/removals
<i>Inventory year</i>	Annual Change in stock of HWP in use from consumption	Annual Change in stock of HWP in SWDS from consumption	Annual Change in stock of HWP in use produced from domestic harvest	Annual Change in stock of HWP in SWDS produced from domestic harvest	PIM	PEX	H	↑CHWP DC	↑CHWP DH	
	ΔCHWP IU DC	ΔCHWP SWDS DC	ΔC HWP IU DH	ΔCHWP SWDS DH						
						MMT C/yr				MMT CO ₂ /yr
1990	13.2	18.6	14.9	18.8	11.6	15.6	144.4	108.6	110.7	(123.8)
1995	17.0	16.3	14.1	16.5	16.7	16.7	134.5	101.1	103.9	(112.2)
2000	16.5	17.6	8.7	16.8	22.1	15.3	127.9	100.5	102.4	(93.4)
2005	18.7	18.6	11.6	17.3	25.5	18.8	120.1	89.6	91.2	(106.0)
2010	(2.1)	16.1	2.0	16.8	13.8	25.0	102.7	77.5	83.9	(69.1)
2019	11.5	17.4	6.2	17.5	15.9	18.8	124.4	92.5	100.7	(86.9)
2020	16.9	17.9	8.8	17.6	17.0	19.7	125.9	88.3	99.5	(96.8)
2021	17.1	18.1	8.3	17.5	17.6	19.7	125.0	87.7	99.2	(94.7)
2022	17.4	18.3	7.9	17.4	19.1	19.7	124.1	87.8	98.8	(92.8)
2023	17.7	18.5	7.5	17.3	19.7	19.7	123.2	87.0	98.4	(90.9)

Note: Parentheses indicate net carbon sequestration (i.e., a net removal of carbon from the atmosphere).

Annual estimates of variables 1A, 1B, 2A and 2B were calculated by tracking the additions to and losses from the pool of products held in end uses (e.g., products in uses such as housing or publications) and the pool of products held in SWDS. In the case of variables 2A and 2B, the pools include products exported and held in other countries and the pools in the United States exclude products made from wood harvested in other countries. Solidwood products added to pools include lumber and panels. End-use categories for solidwood include single and multifamily housing, alteration and repair of housing, and other end uses. There is one product category and one end-use category for paper. Additions to and losses from pools are tracked beginning in 1900, with the exception that additions of softwood lumber to housing begins in 1800. Solidwood and paper product production and trade data are from USDA Forest Service and other sources (Hair and Ulrich 1963; Hair 1958; USDC Bureau of Census 1976; Ulrich, 1985, 1989; Steer 1948; AF&PA 2006a, 2006b; Howard 2003, 2007; Howard and Jones 2016; Howard and Liang 2019; AF&PA 2021; AF&PA 2023; FAO 2023).

The rate of transfers or losses from products in use and the rate of decay of products in SWDS are specified by first order (exponential) decay curves with given half-lives (e.g., the time at which half of amount placed in use will have been discarded from use). Half-lives for products in use, determined after calibration of the model to meet two criteria, are shown in Table A-200. The first criterion is that the WOODCARB II model estimate of carbon in houses standing in 2001 needed to match an independent estimate of carbon in housing based on U.S. Census and USDA Forest Service survey data. The second criterion is that the WOODCARB II model estimate of wood and paper being discarded to SWDS needed to match EPA estimates of discards over the period 1990 to 2000. This calibration strongly influences the estimate of variable 1A, and to a lesser extent variable 2A. The calibration also determines the amounts going to SWDS. In addition, WOODCARB II landfill decay rates have been validated by making sure that estimates of methane emissions from landfills based on EPA data are reasonable in comparison to methane estimates based on WOODCARB II landfill decay rates.

Decay parameters for products in SWDS are shown in Table A-201. Estimates of 1B and 2B also reflect the change over time in the fraction of products discarded to SWDS (versus burning or recycling) and the fraction of SWDS that are sanitary landfills versus dumps.

Variables 2A and 2B are used to estimate HWP Contribution under the production accounting approach. A key assumption for estimating these variables is that products exported from the United States and held in pools in other countries have the same half-lives for products in use, the same percentage of discarded products going to SWDS, and the same decay rates in SWDS. Summaries of net fluxes and stocks for harvested wood in products and SWDS are in Table A-199. The decline in net additions to HWP carbon stocks continued through 2009 from the recent high point in 2006. This is due to sharp declines in U.S. production of solidwood and paper products in 2009 primarily due to the decline in housing construction. The low level of gross additions to solidwood and paper products in use in 2009 was exceeded by discards from uses. The result is a net reduction in the amount of HWP carbon that is held in products in use during 2009. For 2009 additions to landfills still exceeded emissions from landfills and the net additions to landfills have remained relatively stable. Overall, there were net carbon additions to HWP in use and in landfills combined.

Table A-200: Half-life of Solidwood and Paper Products in End-Uses

Parameter	Value	Units
Half-life of wood in single family housing 1920 and before	78.0	Years
Half-life of wood in single family housing 1920–1939	78.0	Years
Half-life of wood in single family housing 1940–1959	80.0	Years
Half-life of wood in single family housing 1960–1979	81.9	Years
Half-life of wood in single family housing 1980 +	83.9	Years
Ratio of multifamily half-life to single family half life	0.61	NA
Ratio of repair and alterations half-life to single family half-life	0.30	NA
Half-life for other solidwood product in end uses	38.0	Years
Half-life of paper in end uses	2.54	Years

Source: Skog, K.E. (2008) "Sequestration of C in harvested wood products for the U.S." *Forest Products Journal* 58:56–72. Note that "NA" refers to not applicable.

Table A-201: Parameters Determining Decay of Wood and Paper in SWDS

Parameter	Value	Units
Percentage of wood and paper in dumps that is subject to decay	100	Percent
Percentage of wood in landfills that is subject to decay	23	Percent
Percentage of paper in landfills that is subject to decay	56	Percent
Half-life of wood in landfills / dumps (portion subject to decay)	29	Years
Half-life of paper in landfills/ dumps (portion subject to decay)	14.5	Years

Source: Skog, K.E. (2008) "Sequestration of C in harvested wood products for the U.S." *Forest Products Journal* 58:56–72.

Table A-202: Net CO₂ Flux from Forest Pools in Forest Land Remaining Forest Land and Harvested Wood Pools (MMT CO₂ Eq.)

Carbon Pool	1990	1995	2000	2005	2010	2019	2020	2021	2022	2023
Forest	(931.1)	(923.5)	(900.6)	(843.9)	(850.7)	(790.2)	(829.6)	(813.2)	(749.6)	(789.1)
Aboveground										
Biomass	(605.4)	(593.2)	(578.7)	(554.3)	(541.5)	(512.8)	(519.4)	(510.1)	(487.3)	(493.4)
Belowground										
Biomass	(117.3)	(114.6)	(111.9)	(107.6)	(105.2)	(101.1)	(101.4)	(99.8)	(95.9)	(96.4)
Dead Wood	(210.1)	(210.2)	(208.7)	(203.5)	(205.7)	(202.2)	(205.4)	(203.3)	(197.5)	(199.7)
Litter	(3.3)	(10.4)	(5.7)	17.9	(0.9)	25.6	(3.9)	(0.5)	30.6	(0.0)
Soil (Mineral)	4.9	4.7	4.2	3.2	2.1	(0.6)	(0.5)	(0.5)	(0.5)	(0.5)
Soil (Organic)	(0.7)	(0.7)	(0.6)	(0.4)	(0.2)	0.2	0.2	0.2	0.2	0.2
Drained Organic										
Soil ^a	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Harvested Wood	(123.8)	(112.2)	(93.4)	(106.0)	(69.1)	(86.9)	(96.8)	(94.7)	(92.8)	(90.9)
Products in Use	(54.8)	(51.7)	(31.9)	(42.6)	(7.4)	(22.6)	(32.3)	(30.4)	(28.8)	(27.4)
SWDS	(69.0)	(60.5)	(61.5)	(63.4)	(61.7)	(64.3)	(64.5)	(64.3)	(63.9)	(63.5)
Total Net Flux	(1,054.9)	(1,035.8)	(994.1)	(950.0)	(919.8)	(877.1)	(926.5)	(907.9)	(842.4)	(880.0)

^a These estimates include carbon stock changes from drained organic soils from both forest land remaining forest land and land converted to forest land.

Note: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table A-203: Net Carbon Flux from Forest Pools in Forest Land Remaining Forest Land and Harvested Wood Pools (MMT C)

Carbon Pool	1990	1995	2000	2005	2010	2019	2020	2021	2022	2023
Forest	(253.9)	(251.9)	(245.6)	(230.2)	(232.0)	(215.5)	(226.3)	(221.8)	(204.4)	(215.2)
Aboveground										
Biomass	(165.1)	(161.8)	(157.8)	(151.2)	(147.7)	(139.9)	(141.7)	(139.1)	(132.9)	(134.6)
Belowground										
Biomass	(32.0)	(31.3)	(30.5)	(29.4)	(28.7)	(27.6)	(27.7)	(27.2)	(26.2)	(26.3)
Dead Wood	(57.3)	(57.3)	(56.9)	(55.5)	(56.1)	(55.2)	(56.0)	(55.4)	(53.9)	(54.5)
Litter	(0.9)	(2.8)	(1.6)	4.9	(0.3)	7.0	(1.1)	(0.1)	8.4	(0.0)
Soil (Mineral)	1.3	1.3	1.2	0.9	0.6	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)
Soil (Organic)	(0.2)	(0.2)	(0.2)	(0.1)	(0.0)	0.1	0.1	0.1	0.0	0.0
Drained Organic										
Soil ^a	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Harvested Wood	(33.8)	(30.6)	(25.5)	(28.9)	(18.8)	(23.7)	(26.4)	(25.8)	(25.3)	(24.8)
Products in Use	(14.9)	(14.1)	(8.7)	(11.6)	(2.0)	(6.2)	(8.8)	(8.3)	(7.9)	(7.5)
SWDS	(18.8)	(16.5)	(16.8)	(17.3)	(16.8)	(17.5)	(17.6)	(17.5)	(17.4)	(17.3)
Total Net Flux	(287.7)	(282.5)	(271.1)	(259.1)	(250.9)	(239.2)	(252.7)	(247.6)	(229.7)	(240.0)

^a These estimates include carbon stock changes from drained organic soils from both forest land remaining forest land and land converted to forest land.

Note: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table A-204: Forest area (1,000 ha) and Carbon Stocks in Forest Land Remaining Forest Land and Harvested Wood Pools (MMT C)

	1990	1995	2000	2005	2010	2019	2020	2021	2022	2023	2024
Forest Area (1000 ha)	281,632	281,435	281,316	280,734	280,583	280,429	280,358	280,307	280,250	280,195	280,139
Carbon Pools											
Forest Ecosystem	54,984	56,256	57,504	58,693	59,861	61,932	62,148	62,374	62,596	62,801	63,016
Aboveground Biomass	12,614	13,434	14,235	15,009	15,760	17,073	17,212	17,354	17,493	17,626	17,761
Belowground Biomass	2,240	2,398	2,553	2,703	2,849	3,105	3,133	3,160	3,188	3,214	3,240
Dead Wood	2,743	3,030	3,316	3,596	3,877	4,384	4,439	4,495	4,551	4,604	4,659
Litter	3,724	3,736	3,748	3,736	3,731	3,729	3,722	3,723	3,723	3,714	3,714
Soil (Mineral)	28,132	28,126	28,119	28,114	28,110	28,108	28,108	28,108	28,108	28,108	28,108
Soil (Organic)	5,531	5,532	5,533	5,534	5,534	5,534	5,534	5,534	5,534	5,534	5,534
Harvested Wood	1,895	2,061	2,218	2,353	2,462	2,671	2,694	2,721	2,747	2,772	2,797
Products in Use	1,249	1,326	1,395	1,447	1,471	1,523	1,530	1,538	1,547	1,555	1,562
SWDS	646	735	823	906	991	1,147	1,165	1,182	1,200	1,217	1,235
Total Stock	56,879	58,318	59,722	61,046	62,323	64,603	64,842	65,095	65,343	65,573	65,813

Note: Totals may not sum due to independent rounding.

Table A-205: Forest Land Area Estimates and Differences Between Estimates in 6.1 Representation of the U.S. Land Base (Category 4.1) and 6.2 Forest Land Remaining Forest Land (Category 4A1) (kha)

Year	Forest Land (managed) - 6.1 Representation of the U.S. Land Base	Forest Land (managed) - 6.2 Forest Land Remaining Forest Land	Difference between Forest Land Areas (managed) – 6.1 and Forest Land Remaining Forest Land – 6.2 area estimates
1990	279,447	281,632	(2,185)
1995	279,220	281,435	(2,215)
2000	279,051	281,316	(2,265)
2005	278,860	280,734	(1,873)
2010	278,704	280,583	(1,879)
2019	278,557	280,429	(1,872)
2020	278,443	280,358	(1,914)
2021	278,368	280,307	(1,939)
2022	278,316	280,250	(1,935)
2023	278,268	280,195	(1,927)

Note: Parentheses indicate negative values.

Table A-206: State-level Net Carbon Flux from all Forest Pools in Forest Land Remaining Forest Land (MMT C) with Uncertainty Range Relative to Flux Estimate, 2023

State	Stock Change	Lower Bound	Lower Bound (%)	Upper Bound	Upper Bound (%)
Alabama	(15.2)	(17.0)	-12%	(13.3)	12%
Alaska	(5.0)	(12.1)	-141%	2.1	141%
Arizona	0.6	0.2	-65%	1.0	65%
Arkansas	(11.3)	(12.9)	-14%	(9.7)	14%
California	(6.1)	(14.1)	-130%	1.9	130%
Colorado	2.7	(5.8)	-317%	11.2	317%
Connecticut	(0.9)	(1.1)	-33%	(0.6)	33%
Delaware	(0.0)	(0.1)	-157%	0.0	157%
Florida	(4.2)	(4.9)	-16%	(3.6)	16%
Georgia	(9.7)	(10.2)	-5%	(9.2)	5%
Hawaii	(0.9)	(5.3)	-485%	3.5	485%
Idaho	(0.2)	(3.7)	-2090%	3.3	2090%
Illinois	(2.2)	(3.2)	-46%	(1.2)	46%
Indiana	(3.2)	(4.8)	-49%	(1.6)	49%
Iowa	(1.2)	(1.5)	-27%	(0.8)	27%
Kansas	(0.8)	(1.2)	-52%	(0.4)	52%
Kentucky	(6.6)	(8.2)	-24%	(5.0)	24%
Louisiana	(8.0)	(8.4)	-6%	(7.5)	6%
Maine	(5.0)	(8.0)	-60%	(2.0)	60%
Maryland	(1.4)	(1.9)	-38%	(0.9)	38%
Massachusetts	(1.5)	(1.8)	-25%	(1.1)	25%
Michigan	(6.0)	(9.5)	-60%	(2.4)	60%
Minnesota	(5.9)	(8.2)	-39%	(3.6)	39%
Mississippi	(15.9)	(18.8)	-18%	(13.0)	18%
Missouri	(5.0)	(7.5)	-52%	(2.4)	52%
Montana	1.8	(6.2)	-454%	9.8	454%
Nebraska	(0.3)	(0.4)	-16%	(0.3)	16%
Nevada	(0.1)	(0.3)	-459%	0.2	459%
New Hampshire	(1.8)	(2.4)	-34%	(1.2)	34%
New Jersey	(0.9)	(1.0)	-10%	(0.8)	10%

New Mexico	0.4	(1.5)	-453%	2.3	453%
New York	(10.0)	(12.3)	-23%	(7.7)	23%
North Carolina	(9.4)	(10.7)	-13%	(8.1)	13%
North Dakota	(0.1)	(0.2)	-91%	(0.0)	91%
Ohio	(3.9)	(6.0)	-53%	(1.9)	53%
Oklahoma	(3.7)	(4.3)	-17%	(3.1)	17%
Oregon	(11.5)	(13.6)	-18%	(9.4)	18%
Pennsylvania	(6.3)	(10.8)	-71%	(1.9)	71%
Rhode Island	(0.1)	(0.2)	-138%	0.0	138%
South Carolina	(5.3)	(5.8)	-10%	(4.8)	10%
South Dakota	0.4	0.1	-81%	0.7	81%
Tennessee	(9.3)	(10.8)	-16%	(7.8)	16%
Texas	(12.7)	(13.3)	-4%	(12.2)	4%
Utah	0.5	(0.9)	-279%	1.9	279%
Vermont	(1.9)	(2.6)	-38%	(1.2)	38%
Virginia	(9.2)	(11.9)	-30%	(6.5)	30%
Washington	(4.9)	(9.5)	-94%	(0.3)	94%
West Virginia	(7.8)	(9.5)	-22%	(6.0)	22%
Wisconsin	(6.8)	(7.2)	-7%	(6.3)	7%
Wyoming	0.1	(0.6)	-1063%	0.7	1063%
American Samoa	(0.0)	(0.2)	-656%	0.1	656%
Guam	(0.0)	(0.3)	-584%	0.2	584%
Northern Mariana Islands	(0.0)	(0.2)	-504%	0.2	504%
Puerto Rico	0.2	(2.3)	-1314%	2.7	1314%
U.S. Virgin Islands	(0.0)	(0.2)	-525%	0.1	525%
Total	(215.4)	(236.0)	-9.5%	(194.8)	9.5%

Note: Parentheses indicate negative values.

Land Converted to Forest Land

The following section includes a description of the methodology used to estimate stock changes in all forest carbon pools for land converted to forest land. Forest Inventory and Analysis data and IPCC (2006) defaults for reference carbon stocks were used to compile separate estimates for the five carbon storage pools within an age class transition matrix for the 20-year conversion period (where possible). The 2017 USDA National Resources Inventory (NRI) land-use survey points were classified according to land-use history records starting in 1982 when the NRI survey began. Consequently, the classifications from 1990 to 2001 were based on less than 20 years. Furthermore, the FIA data used to compile estimates of carbon sequestration in the age class transition matrix are based on 5- to 10-yr remeasurements so the exact conversion period was limited to the remeasured data over the time series. Estimates for aboveground and belowground biomass, dead wood and litter were based on data collected from the extensive array of permanent, annual forest inventory plots and associated models (e.g., live tree belowground biomass) in the United States (USDA Forest Service 2024b, 2024c). Carbon conversion factors were applied at the disaggregated level of each inventory plot and then appropriately expanded to population estimates. To ensure consistency in the land converted to forest land category where carbon stock transfers occur between land-use categories, all soil estimates are based on methods from Ogle et al. (2003, 2006) and IPCC (2006).

Live tree carbon pools

Live tree carbon pools include aboveground and belowground (coarse root) biomass of live trees with diameter at breast height (dbh) of at least 2.54 cm at 1.37 m above the forest floor. Separate estimates were made for above and belowground biomass components. If inventory plots included data on individual trees, aboveground tree carbon was based on Westfall et al. (2024). The component ratio method (CRM) which is a function of volume, species, and diameter was used to compile estimates for woodland species where diameter measurements are taken at root collar and belowground biomass carbon for all tree species (Woodall et al. 2011a). An additional component of foliage, which was not explicitly included in Woodall et al. (2011a), was added to each woodland tree following the same CRM method. Carbon is estimated by multiplying the estimated oven-dry biomass by species-specific carbon fraction (Westfall et al. 2024). Complete details are provided in Westfall et al. 2024 and Woodall et al. 2011.

Understory vegetation

Understory vegetation is a minor component of total forest ecosystem biomass. Understory vegetation is defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than one-inch dbh. In this *Inventory*, it is assumed that 10 percent of understory carbon mass is belowground. This general root-to-shoot ratio (0.11) is near the lower range of temperate forest values provided in IPCC (2006) and was selected based on two general assumptions: ratios are likely to be lower for light-limited understory vegetation as compared with larger trees, and a greater proportion of all root mass will be less than 2 mm diameter.

Estimates of carbon density are based on information in Birdsey (1996), which was applied to NFI permanent plots. See model (1) in the forest land remaining forest land section of the Annex.

In this model, the ratio is the ratio of understory carbon density (T C/ha) to live tree carbon density (above- and below-ground) according to Jenkins et al. (2003) and expressed in T C/ha. An additional coefficient is provided as a maximum ratio; that is, any estimate predicted from the model that is greater than the maximum ratio is set equal to the maximum ratio. A full set of coefficients are in Table A-193. Regions and forest types are the same classifications described in Smith et al. (2003). An example calculation for understory carbon in aspen-birch forests in the Northeast is provided in the forest land remaining forest land section of the Annex.

This calculation is followed by three possible modifications. First, the maximum value for the ratio is set to 2.02 (see value in column “maximum ratio”); this also applies to stands with zero tree carbon, which is undefined in the above model. Second, the minimum ratio is set to 0.005 (Birdsey 1996). Third, nonstocked (i.e., currently lacking tree cover but still in the forest land use) and pinyon/juniper forest types (see Table A-193) are set to coefficient A, which is a carbon density (T C/ha) for these types only.

Dead wood

The standing dead tree estimates are primarily based on plot-level measurements (Westfall et al. 2024, Woodall et al. 2011). This carbon pool includes aboveground and belowground (coarse root) mass and includes trees of at least 2.54 cm dbh. Calculations follow the basic methods applied to live trees (Westfall et al. 2024, Woodall et al. 2011) with additional modifications to account for decay and structural loss (Harmon et al. 2011). Carbon fractions by decay class and hardwood and softwood are used for standing dead trees (Westfall et al. 2024).

Downed dead wood, inclusive of logging residue, are sampled on a subset of FIA plots. Despite a reduced sample intensity, a single down woody material population estimate (Woodall et al. 2010; Domke et al. 2013; Woodall et al. 2013) per state is now incorporated into these empirical downed dead wood estimates. Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. It also includes stumps and roots of harvested trees. Ratio estimates of downed dead wood to live tree biomass were developed using FORCARB2 simulations and applied at the plot level (Smith et al. 2004). Estimates for downed dead wood correspond to the region and forest type classifications described in Smith et al. (2003). A full set of ratios is provided in Table A-194. An additional component of downed dead wood is a regional average estimate of logging residue based on Smith et al. (2006) applied at the plot level. These are based on a regional average carbon density at age zero and first order decay; initial densities and decay coefficients are provided in Table A-195. These amounts are added to explicitly account for downed dead wood following harvest. The sum of these two components are then adjusted by the ratio of population totals; that is, the ratio of plot-based to modeled estimates (Domke et al. 2013).

Litter carbon

Carbon in the litter layer is currently sampled on a subset of the NFI plots. Litter carbon is the pool of organic carbon (including material known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. Because litter attributes are only collected on a subset of NFI plots, a model (3) was developed to predict carbon density based on plot/site variables for plots that lacked litter information (Domke et al. 2016)

Soil organic carbon

A Tier 2 method is applied to estimate mineral soil carbon stock changes for land converted to forest land (Ogle et al. 2003, 2006; IPCC 2006). For this method, land is stratified by climate, soil types, land-use, and land management activity, and then assigned reference carbon levels and factors for the forest land and the previous land use. The difference between the stocks is reported as the stock change under the assumption that the change

occurs over 20 years. Reference carbon stocks have been estimated from data in the National Soil Survey Characterization Database (USDA-NRCS 1997), and U.S.-specific stock change factors have been derived from published literature (Ogle et al. 2003; Ogle et al. 2006). Land use and land use change patterns are determined from a combination of the Forest Inventory and Analysis Dataset (FIA), the 2015 National Resources Inventory (NRI) (USDA-NRCS 2018), and National Land Cover Dataset (NLCD) (Yang et al. 2018). See Annex 3.13 for more information about this method (Methodology for Estimating N₂O Emissions, CH₄ Emissions and Soil Organic Carbon Stock Changes from Agricultural Soil Management).

Table A-207 summarizes the annual change in mineral soil carbon stocks from U.S. soils that were estimated using a Tier 2 method (MMT C/year). The range is a 95 percent confidence interval estimated from the standard deviation of the NRI sampling error and uncertainty associated with the 1000 Monte Carlo simulations (See Annex 3.13).

Table A-209 summarizes the total land areas by land use/land-use change subcategory that were used to estimate soil C stock changes for mineral soils between 1990 and 2015.

Land Converted to Forest Land Area Estimates

Forest land area estimates in Section 6.3 Land Converted to Forest Land (Category 4A2) of this *Inventory* are compiled using NFI data. Forest Land area estimates obtained from these data are also used as part of Section 6.1 Representation of the U.S. Land Base (Category 4.1). The land converted to forest land area estimates in Section 6.3 do not include Hawaii or the U.S. Territories as insufficient data is available from the NFI to compile area estimates of land use conversions over the entire time series. The National Land Cover Dataset is used in addition to NRI estimates in Section 6.1 Representation of the U.S. Land Base and land converted to forest land in Hawaii is included in that section, but the U.S. Territories are not included. Also, it is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation; this prevents harmonization of forest land in Wyoming with the NRI/NLCD method used in Section 6.1 Representation of the U.S. Land Base (Category 4.1). These issues result in small differences in the managed forest Land area in Sections 6.1 and 6.3 of this *Inventory* (Table A-210). There are also other factors contributing to the small differences in area such as harmonization of aspatial and spatial data across all land-use categories in Section 6.1 over the entire *Inventory* time series.

Table A-207: Annual change in Mineral Soil C stocks from U.S. agricultural soils that were estimated using a Tier 2 method (MMT C/year)

Category	1990	1995	2000	2005	2010	2019	2020	2021	2022	2023
Cropland Converted to Forest Land	0.07 (0.04 to 0.11)	0.06 (0.02 to 0.09)	0.06 (0.02 to 0.1)	0.05 (0.02 to 0.09)	0.05 (0.01 to 0.08)	0.03 (0.01 to 0.06)	0.03 (0.01 to 0.05)	0.03 (-0.02 to 0.08)	0.03 (-0.02 to 0.08)	0.03 (-0.02 to 0.08)
Grassland Converted to Forest Land	-0.04 (-0.08 to 0)	-0.04 (-0.08 to 0)	-0.05 (-0.1 to 0)	-0.06 (-0.11 to -0.01)	-0.06 (-0.11 to -0.01)	-0.05 (-0.1 to 0)	-0.05 (-0.1 to 0)	-0.05 (-0.12 to 0.02)	-0.05 (-0.13 to 0.02)	-0.05 (-0.13 to 0.02)
Other Lands Converted to Forest Land	0.13 (0.12 to 0.15)	0.15 (0.14 to 0.17)	0.17 (0.16 to 0.19)	0.20 (0.18 to 0.23)	0.22 (0.2 to 0.24)	0.25 (0.22 to 0.27)	0.25 (0.23 to 0.27)	0.25 (-0.05 to 0.55)	0.25 (-0.06 to 0.56)	0.25 (-0.07 to 0.57)
Settlements Converted to Forest Land	0.01 (0.01 to 0.01)	0.01 (0.01 to 0.01)	0.01 (0.01 to 0.01)	0.01 (0.01 to 0.01)	0.01 (0.01 to 0.01)	0.02 (0.01 to 0.02)	0.02 (0.01 to 0.02)	0.02 (0.01 to 0.02)	0.02 (0.01 to 0.02)	0.02 (0.01 to 0.02)
Wetlands Converted to Forest Land	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)
Total Lands Converted to Forest Lands	0.17	0.17	0.19	0.21	0.22	0.24	0.24	0.24	0.24	0.24

Note: The range is a 95 percent confidence interval from 50,000 simulations (Ogle et al. 2003, 2006).

Table A-208: Annual change in Mineral Soil C stocks from Federal U.S. agricultural soils that were estimated using a Tier 2 method (MMT C/year)

Category	1990	1995	2000	2005	2010	2019	2020	2021	2022	2023
Cropland Converted to Forest Land	-0.02 (-0.04 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (-0.01 to 0.01)	0.00 (-0.01 to 0.01)	0.00 (-0.02 to 0.02)
Grassland Converted to Forest Land	-0.01 (-0.02 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (-0.01 to 0.01)	0.00 (-0.02 to 0.01)	0.00 (-0.02 to 0.02)
Other Lands Converted to Forest Land	0.07 (0.06 to 0.08)	0.01 (0 to 0.01)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.01 (-0.01 to 0.03)	0.01 (-0.03 to 0.04)	0.01 (-0.03 to 0.05)
Settlements Converted to Forest Land	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)
Wetlands Converted to Forest Land	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)	0.00 (0 to 0)

Total Lands Converted to Forest Lands	0.04	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01

Note: The range is a 95 percent confidence interval from 50,000 simulations (Ogle et al. 2003, 2006).

Table A-209: Total land areas (hectares) by land use/land-use change subcategory for mineral soils between 1990 to 2023

Conversion Land Areas (Hectares x10⁶)	1990	1995	2000	2005	2015	2016	2017	2018	2019	2020	2021	2022	2023
Cropland Converted to Forest Land	0.21	0.14	0.16	0.14	0.12	0.11	0.11	0.10	0.09	0.08	0.08	0.08	0.08
Grassland Converted to Forest Land	0.76	0.91	0.96	0.95	0.99	0.96	0.95	0.93	0.94	0.93	0.93	0.94	0.94
Other Lands Converted to Forest Land	0.07	0.05	0.05	0.07	0.09	0.10	0.11	0.10	0.10	0.10	0.09	0.09	0.09
Settlements Converted to Forest Land	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Wetlands Converted to Forest Land	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01
Total Lands Converted to Forest Lands	1.06	1.14	1.20	1.19	1.23	1.21	1.20	1.17	1.16	1.14	1.13	1.13	1.13

Note: Estimated with a Tier 2 approach and based on analysis of USDA National Resources Inventory data (USDA-NRCS 2018).

Table A-210: Land Converted to Forest Land area estimates and differences between estimates in the Representation of the U.S. Land Base (Category 4.1) and Land Converted to Forest Land (Category 4A1) (kha)

Year	1990	1995	2000	2005	2010	2018	2019	2020	2021	2022	2023
Cropland Converted to Forest Land - 6.1 Representation of the U.S. Land Base (Category 4.1)	209	140	152	141	127	100	86	77	75	74	73
Cropland Converted to Forest Land - 6.3 Land Converted to Forest Land (Category 4A2)	151	152	148	150	148	153	151	150	148	148	148
Difference between estimates	57	(11)	4	(10)	(21)	(53)	(65)	(73)	(73)	(74)	(76)
Grassland Converted to Forest Land - 6.1 Representation of the U.S. Land Base (Category 4.1)	767	917	944	951	1,004	1,016	973	973	970	973	973
Grassland Converted to Forest Land - 6.3 Land Converted to Forest Land (Category 4A2)	663	695	681	676	723	708	654	646	641	641	641
Difference between estimates	103	222	264	275	281	308	319	327	329	332	332
Other Lands Converted to Forest Land - 6.1 Representation of the U.S. Land Base (Category 4.1)	75	49	57	72	78	106	94	97	91	87	80

Other Lands Converted to Forest Land - 6.3											
Land Converted to Forest Land (Category 4A2)	31	32	31	32	32	29	31	37	38	38	38
Difference between estimates	44	18	26	40	47	77	63	60	53	49	42
Settlements Converted to Forest Land - 6.1											
Representation of the U.S. Land Base (Category 4.1)	11	19	18	18	18	21	21	20	19	20	22
Settlements Converted to Forest Land - 6.3											
Land Converted to Forest Land (Category 4A2)	170	167	163	167	167	173	172	171	171	171	171
Difference between estimates	(159)	(148)	(145)	(150)	(149)	(152)	(151)	(151)	(152)	(151)	(150)
Wetlands Converted to Forest Land - 6.1											
Representation of the U.S. Land Base (Category 4.1)	15	24	23	23	24	20	18	16	15	15	15
Wetlands Converted to Forest Land - 6.3											
Land Converted to Forest Land (Category 4A2)	50	51	51	51	51	54	53	52	51	51	51
Difference between estimates	(35)	(27)	(28)	(28)	(27)	(34)	(35)	(36)	(37)	(37)	(37)
Total	10	53	120	127	131	145	130	127	121	119	112

Uncertainty Analysis

The uncertainty analyses for total net flux of forest carbon (see Table 6-12 in the FLRFL section) are consistent with the IPCC-recommended Tier 1 methodology (IPCC 2006). Specifically, they are considered approach 1 (propagation of error [Section 3.2.3.1]) (IPCC 2006). To better understand the effects of covariance, the contributions of sampling error and modeling error were parsed out. In addition, separate analyses were produced for forest ecosystem and HWP flux.

Estimates of forest carbon stocks in the United States are based on carbon estimates assigned to each of several thousand inventory plots from a regular grid. Uncertainty in these estimates and uncertainty associated with change estimates arise from many sources including sampling error and modeling error. Here EPA focuses on these two types of error but acknowledge several other sources of error are present in the overall stock and stock change estimates. In terms of sampling-based uncertainty, design-based estimators described by Bechtold and Patterson (2005) were used to quantify the variance of carbon stock estimates. In this section EPA denotes the estimate of carbon stock at time t as C_t and the variances of the estimate of carbon stock for time t as $\text{Var}(C_t)$. These calculations follow Bechtold and Patterson (2005). The variance of stock change is then:

Equation A-62: Variance of the Carbon Stock Change

$$\text{Var}(C_{t2} - C_{t1}) = \text{Var}(C_{t2}) + \text{Var}(C_{t1}) - 2 \times \text{Cov}(C_{t2}, C_{t1}) \quad (15)$$

The uncertainty of a stock estimate associated with sampling error is $U(C_t)_s = \text{Var}(C_t)^{0.5}$. The uncertainty of a stock changes estimate associated with sampling error is $U(\Delta C)_s = \text{Var}(C_{t2} - C_{t1})^{0.5}$.

Model-based uncertainty is important because the pool-level carbon models have error. The total modeling mean-squared error (MSE_m) is approximately 1,622 (Mg/ha)². The percent modeling error at time t is

Equation A-63: Percent Modeling Error

$$\%U(C_t)_m = 100 \times \text{MSE}_m / dt \quad (16)$$

Where dt is the total carbon stock density at time t calculated as C_t / A_t where A_t is the forest area at time t .

The uncertainty of C_t from modeling error is

Equation A-64: Uncertainty of Carbon Stock Estimate at Time t

$$U(C_t)_m = C_t \times \%U(C_t)_m / 100 \quad (17)$$

The model-based uncertainty with respect to stock change is then

Equation A-65: Model-based Uncertainty of Carbon Stock Change

$$U(\Delta C)_m = (U(C_{t1})_m + U(C_{t2})_m - 2 \times \text{Cov}(U(C_{t1})_m, U(C_{t2})_m))^{0.5} \quad (18)$$

The sampling and model-based uncertainty are combined for an estimate of total uncertainty. We considered these sources of uncertainty independent and combined as follows for stock change (ΔC):

Equation A-66: Total Uncertainty of Carbon Stock Change

$$U(\Delta C) = (U(\Delta C)_m^2 + U(\Delta C)_s^2)^{0.5} \text{ and the 95 percent confidence bounds was } \pm 2 \times U(\Delta C) \quad (19)$$

The mean square error (MSE) of pool models was (MSE, [Mg C/ha]²): soil C (1143.0), litter (78.0), live tree (259.6), dead trees (101.5), understory (0.9), down dead wood (38.9), total MSE (1,621.9).

Numerous assumptions were adopted for creation of the forest ecosystem uncertainty estimates. Potential pool error correlations were ignored. Given the magnitude of the MSE for soil, including correlation among pool error would not appreciably change the modeling error contribution. Modeling error correlation between time 1 and time 2 was assumed to be 1. Because the MSE was fixed over time EPA assumed a linear relationship dependent on either the measurements at two points in time or an interpolation of measurements to arrive at annual flux estimates. Error associated with interpolation to arrive at annual flux is not included.

Uncertainty about net carbon flux in HWP is based on Skog et al. (2004) and Skog (2008). Latin hypercube sampling is the basis for the HWP Monte Carlo simulation. Estimates of the HWP variables and HWP Contribution under the production approach are subject to many sources of uncertainty. An estimate of uncertainty is provided that evaluated the effect of uncertainty in 13 sources, including production and trade data and parameters used to make the estimate. Uncertain data and parameters include data on production and trade and factors to convert them to carbon, the census-based estimate of carbon in housing in 2001, the EPA estimate of wood and paper discarded to SWDS for 1990 to 2000, the limits on decay of wood and paper in SWDS, the decay rate (half-life) of wood and paper in SWDS, the proportion of products produced in the United States made with wood harvested in the United States, and the rate of storage of wood and paper carbon in other countries that came from U.S. harvest, compared to storage in the United States.

The uncertainty about HWP and forest ecosystem net carbon flux were combined and assumed to be additive. Typically, when propagating error from two estimates the variances of the estimates are additive. However, the uncertainty around the HWP flux was approximated using a Monte Carlo approach which resulted in the lack of a variance estimate for HWP carbon flux. Therefore, EPA considered the uncertainty additive between the HWP sequestration and the forest land remaining forest land sequestration. Further, EPA assumed there was no covariance between the two estimates which is plausible as the observations used to construct each estimate are independent.

Emissions from Forest Fires

CO₂ Emissions from Forest Fires

As stated in other sections, the forest inventory approach implicitly accounts for CO₂ emissions due to disturbances. Net carbon stock change is estimated from successive carbon stock estimates. A disturbance, such as a forest fire, removes carbon from the forest. The inventory data, on which net carbon stock estimates are based, already reflects the carbon loss from such disturbances because only carbon remaining in the forest is estimated. Estimating the CO₂ emissions from a disturbance such as fire and adding those emissions to the net CO₂ change in forests would result in double-counting the loss from fire because the inventory data already reflect the loss. There is interest, however, in the size of the CO₂, CH₄, and N₂O emissions from disturbances such as fire.

Estimates of historic forest fires and associated emissions (i.e., from 1990 through the current year) provided with this report are updated each year to represent any improvements in available data or methodology. Most of this year's estimates are based on a system of country-specific models and spatially defined burn areas to simulate fire emissions (i.e., the 50 states). However, emissions estimates for Puerto Rico and Guam are based on spatially defined burn data with Tier-1 emissions factors (IPCC 2019), which represent updates of the IPCC (2006) guidance on reporting fire emissions.

Estimated annual emissions (CO₂ and non-CO₂) from forest fires over the interval from 1990 to the current inventory are calculated consistent with IPCC (2019) methodology, which is also updated relative to IPCC (2006); this includes U.S.-specific data and models on area, fuel, consumption, and emission. Area of forest burned is based on annual area of forest coincident with fires according to annual datasets from Monitoring Trends in Burn Severity (MTBS perimeters, Eidenshink et al. 2007), MODIS burned area mapping (MODIS MCD64A1 V6.1, Giglio et al. 2018), or Wildland Fire Interagency Geospatial Service interagency fire perimeters (WFIGS 2023). Annual forest fire and emissions estimates were calculated by the Wildland Fire Emissions Inventory System (WFEIS, French et al. 2011, 2014). The WFEIS calculator¹⁴¹ was used to provide annual emissions estimates by state and year for the MODIS-based burned areas and by individual fire events for the MTBS and WFIGS burned areas. Note that N₂O emissions are not included in WFEIS calculations; emissions provided here are based on the average N₂O to CO₂ ratio of 0.000166 (Larkin et al. 2014, IPCC 2019).

Forest areas within the full burn boundaries (MTBS, WFIGS, or MODIS) were based on two fuels layers within WFEIS – the Fuel Characteristic Classification System (FCCS, Prichard et al. 2019) and the North American Wildland Fuels Database (NAWFD, Prichard et al. 2019). Each delineates fuelbed classes, and forest classifications within each fire identified forest land per fire. Additionally, the National Land Cover (NLCD) images that include forest transition classes (Homer et al. 2015; Yang et al. 2018) identified forest land on the spatial burn features in order to

¹⁴¹ See <https://wfeis.mtri.org/calculator>.

compare with forest burned areas from the fuels models as a quality assurance step and to identify spatial subsets such as forests on managed land in Alaska or forests within specific states. The MTBS data do not include fires smaller than approximately 400 or 200 ha for the western or eastern United States, respectively. Fire areas and emissions reported for Alaska are reduced to only include managed land (Ogle et al. 2018); forest fires (burned area) on managed land averaged 66 percent of total Alaska forest fires(burned area) on managed and unmanaged forest land over the years 2012 through 2021.

Emissions from prescribed fires on forest land contribute to total annual emissions from forest fires. However, information on area or emissions from prescribed fires on forest land is limited. Delineation of emissions associated with prescribed fires is not available in the WFEIS calculations as applied here. The MTBS and WFIGS records identify fire origin, including many prescribed fires. Based on MTBS fire origins, we estimate that an annual average of about 15 percent of forest land within the MTBS burn perimeters were prescribed forest burns over the 10-year interval 2011-2020 (based on NLCD land cover over MTBS perimeters in the conterminous United States + Alaska). In 2020, 8 percent of the MTBS forest fires were identified as prescribed. However, note that the minimum size thresholds for MTBS reporting are likely to exclude many of the smaller controlled burns.

Statistics for all prescribed fires, but without separate forest classification, are available for the U.S. The National Interagency Fire Center¹⁴² reports 2.45 million hectares of prescribed fires in 2019 and annual reports by the National Association of State Foresters and the Coalition of Prescribed Fire Councils¹⁴³ report 4.05 million hectares of prescribed fires in 2019. In 2019, the most recent year with these prescribed burn data, 20.6 percent of MTBS forest fires (also based on forest cover as described above) were labeled as prescribed; however, also note that the WFEIS-calculated total forest area burned was 0.78 million hectares (and 20.6 percent of this is 0.16 million hectares).

The MTBS data available for this report (MTBS 2024) included fires from 1990 through 2022 for all states and Puerto Rico. The MODIS-based records include 2001 through 2023 for the 50 states. The WFIGS-based records for 2021 through 2023 included all states plus Puerto Rico and Guam. All emissions calculations were based on these burned area definitions. The WFEIS calculator provided all other parts of calculations—fuels, fire characteristics, and emissions—for the 50 states. The burn perimeters for Puerto Rico and Guam were partly allocated to forest land according to forest cover (Homer et al. 2015), with fuels, consumption, and emissions estimates made according to Tier-1 factors for secondary tropical forests (IPCC 2019).

Current uncertainty estimates provided with emissions are based on variability among the limited alternate mean estimates per state per year. That is, the three burn sources and the two fuel models can produce multiple estimates, depending on year. Two annual estimates for 1990 through 2000 are MTBS-based while estimates for subsequent years depend on availability of burned area information. Uncertainty in the MTBS or MODIS data are not currently addressed. Similarly, uncertainty in other parts of the WFEIS system, such as the Consume model (Prichard et al. 2014), are not a part of the uncertainty quantified here. Planned improvements for future analyses are to incorporate preliminary WFEIS uncertainty analyses (Prichard et al. 2019; Kennedy et al. 2020) in reported forest fire emissions. Variability in fuel loading modeled from use of the NAWFD data is available through additional calculation and download of the WFEIS calculator¹⁴⁴ as emissions based on the 25th, 50th, or 75th percentiles of fuel. These data were considered for developing uncertainty, but their use was inconsistent with the single mean values from FCCS, however the quantiles may be incorporated in future analyses. A simple Monte Carlo (Approach 2) method was employed to propagate uncertainty by state by year to country-wide totals. For additional details and analysis see Smith et al. (2024).

¹⁴² See <https://www.nifc.gov/fire-information/statistics>.

¹⁴³ See <http://www.prescribedfire.net/>.

¹⁴⁴ See <https://wfeis.mtri.org/calculator>.

Table A-211: Areas (Hectares) and Corresponding Emissions (MMT/year) Associated with Past Forest Fires^a

		1990	1995	2000	2005	2010	2015	2020	2021	2022	2023
Conterminous States (48), Hawaii, Puerto Rico, and Guam	Forest area burned (1000 ha)	127.1	108.2	786.7	376.1	345.8	886.0	2160.9	1971.3	773.5	440.5
	C emitted (MMT/yr)	3.5	2.4	20.4	8.3	6.9	24.1	70.2	64.7	20.2	12.6
	CO ₂ emitted (MMT/yr)	11.2	7.8	66.3	26.8	22.6	78.0	227.7	210.2	65.3	41.1
Alaska	Forest area burned (1000 ha)	278.4	5.7	110.0	759.8	55.4	759.8	10.5	50.8	421.9	82.5
	C emitted (MMT/yr)	12.4	0.3	6.0	39.5	2.6	41.5	0.3	2.2	18.6	4.5
	CO ₂ emitted (MMT/yr)	40.2	0.9	19.6	127.9	8.5	134.5	1.1	7.1	60.4	14.5
Conterminous States (48), Alaska, Hawaii, Puerto Rico, and Guam	CH ₄ emitted (kt/yr)	112.9	18.8	225.6	354.5	64.7	522.2	639.3	601.2	312.7	135.1
	N ₂ O emitted (kt/yr)	8.5	1.4	14.3	25.7	5.2	35.3	38.0	36.1	20.9	9.2
	CO emitted (kt/yr)	2946.9	455.6	5045.0	9188.7	1694.1	12694.0	13279.9	12731.7	7374.5	3114.4
	NO _x emitted (kt/yr)	45.4	10.6	82.5	132.3	35.6	184.8	223.0	206.3	116.6	56.4

^a These emissions have already been accounted for in the estimates of net annual changes in carbon stocks, which accounts for the amount sequestered minus any emissions, including the assumption that combusted wood may continue to decay through time.

Table A-212: Equivalence Ratios, of CH₄ and N₂O to CO₂ equivalent

Equivalence Ratios ^a	
CH ₄ to CO ₂ Eq.	28
N ₂ O to CO ₂ Eq.	265

^a Source: the IPCC *Fifth Assessment Report* (2013)

Non-CO₂ Emissions from Forest Fires

Emissions of non-CO₂ gases (CH₄, N₂O, CO, and NO_x) (Table A-211) are estimated using the same WFEIS calculator approach as described above for estimating CO₂ emissions from forest fires. Values for global warming potential (GWP) to express CH₄ and N₂O as CO₂ equivalents (Table A-212) are based on the IPCC *Fifth Assessment Report* (IPCC 2013) Estimated uncertainty follows methods described in the previous section.

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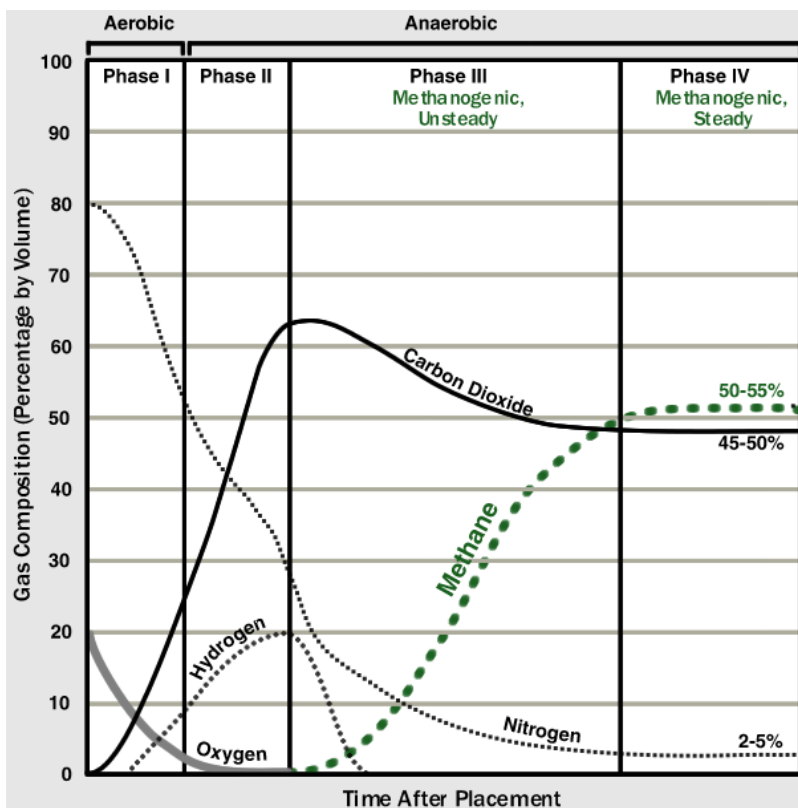
3.15. Methodology for Estimating CH₄ Emissions from Landfills

A combination of Tier 2 and 3 approaches are used to calculate emissions from MSW Landfills. A Tier 2 approach is used to calculate emissions for industrial waste landfills.

Landfill gas is a mixture of substances generated when bacteria decompose the organic materials contained in solid waste. By volume, landfill gas is about half CH₄ and half CO₂.¹⁴⁵ The amount and rate of CH₄ generation depends upon the quantity and composition of the landfilled material, as well as the surrounding landfill environment. Not all CH₄ generated within a landfill is emitted to the atmosphere. The CH₄ can be extracted and either flared or utilized for energy, thus oxidizing the CH₄ to CO₂ during combustion. Of the remaining CH₄, a portion oxidizes to CO₂ as it travels through the top layer of the landfill cover. In general, landfill-related CO₂ emissions are of biogenic origin and primarily result from the decomposition, either aerobic or anaerobic, of organic matter such as food or yard wastes.

Figure A-19 illustrates how landfill gas composition varies over time after waste is disposed in an MSW landfill when bacterial populations decompose the waste in different, often concurrent phases of waste decomposition (ATSDR 2001). Gas is generated at a stable rate in Phase IV for approximately 20 years and may be generated for 50 or more years after waste is placed in the landfill depending on management practices and waste composition (ASTDR 2001).

Figure A-19: Landfill Gas Composition Over Time



Source: ASTDR (2001)

Methane emissions from landfills are estimated using two primary methods. The first method uses the first order decay (FOD) model as described by the 2006 IPCC Guidelines to estimate CH₄ generation. The amount of CH₄

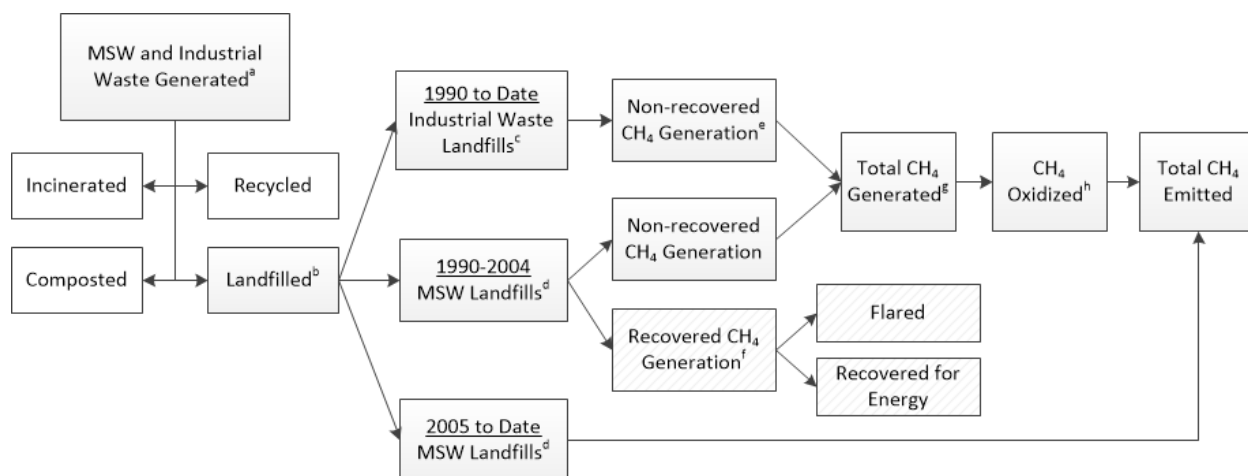
¹⁴⁵ Typically, landfill gas also contains small amounts of nitrogen, oxygen, and hydrogen, less than 1 percent nonmethane volatile organic compounds (NMVOCs), and trace amounts of inorganic compounds.

recovered and combusted from MSW landfills is subtracted from the CH₄ generation and is then adjusted with an oxidation factor. The second method used to calculate CH₄ emissions from landfills, also called the back-calculation method, is based off directly measured amounts of recovered CH₄ from the landfill gas and is expressed by Equation HH-8 in CFR Part 98.343 of the EPA's Greenhouse Gas Reporting Program (GHGRP).

The current *Inventory* methodology uses both methods to estimate CH₄ emissions across the time series. The 1990 to 2015 *Inventory* was the first *Inventory* to incorporate directly reported GHGRP net CH₄ emissions data for landfills. In previous *Inventories*, only the first order decay method was used. EPA's GHGRP requires landfills meeting or exceeding a threshold of 25,000 metric tons (MT) of CH₄ generation per year to report a variety of facility-specific information, including historical and current waste disposal quantities by year, CH₄ generation, gas collection system details, CH₄ recovery, and CH₄ emissions. EPA's GHGRP provides a consistent methodology, a broader range of values for the oxidation factor, and allows for facility-specific annual waste disposal data to be used, thus these data are considered Tier 3 (highest quality data) under the 2006 IPCC Guidelines. Using EPA's GHGRP data was a significant methodological change and required a merging of the GHGRP methodology with the *Inventory* methodology used in previous years to ensure time-series consistency.

Figure A-20 presents the CH₄ emissions process—from waste generation to emissions—in graphical format. A detailed discussion of the steps taken to compile the 1990 to 2023 *Inventory* are presented in the remainder of this Annex.

Figure A-20: Methane Emissions Resulting from Landfilling Municipal and Industrial Waste



^a MSW waste generation is not calculated because annual quantities of waste landfilled are available through secondary sources as described in figure note b.

^b Quantities of MSW landfilled for 1940 through 1988 are based on EPA 1988 and EPA 1993; 1989 through 2004 are based on *BioCycle* 2010; 2005 through 2023 are incorporated through the directly reported emissions from MSW landfills to the Greenhouse Gas Reporting Program. Quantities of industrial waste landfilled are estimated using a disposal factor and industrial production data sourced from Lockwood Post's Directory and the USDA.

^c The 2006 IPCC Guidelines – First Order Decay (FOD) Model is used for industrial waste landfills.

^d Two different methodologies are used in the time series for MSW landfills. For 1990 to 2004, the 2006 IPCC Guidelines – FOD Model is used. For 2005 to 2023, directly reported net CH₄ emissions from the GHGRP for 2010 to the current *Inventory* year are used with the addition of a scale-up factor applied to each year's emissions. The scale-up factor accounts for emissions from landfills that do not report to the GHGRP. A scale-up factor of 9 percent is applied to 2005-2016 and a scale-up factor of 11 percent is applied to 2017-2023. The GHGRP emissions from 2010 to the current *Inventory* year are also used to backcast emissions for 2005 to 2009 to merge the FOD methodology with the GHGRP methodology for time series consistency. Additional details on how the scale-up factor was developed and the backcasting approach are included in Step 4 of this Annex chapter.

^e Methane recovery from industrial waste landfills is not incorporated into the *Inventory* because it does not appear to be a common practice according to the GHGRP dataset.

^f Methane recovery data are pulled from four recovery databases: EIA 2007, flare vendor database, the landfill gas-to-energy database, and EPA (GHGRP) 2015(a). These databases are used to estimate national recovery for the *Inventory* between 1990 to 2009. CH₄ recovery estimates between 2010 to the current inventory year are calculated from GHGRP recovery amounts with a scale-up factor applied as explained in Step 3 of this Annex chapter.

^g For years 1990 to 2004, the total CH₄ generated from MSW landfills and industrial waste landfills are summed. For years 2005 to 2023, MSW landfill CH₄ generated is back-calculated from the annual net CH₄ emissions, recovery, and oxidation; CH₄ generation from industrial waste landfills are summed with the back-calculated MSW landfills CH₄ generation amounts.

^h An oxidation factor of 10 percent is applied to all CH₄ generated in years 1990 to 2004 (2006 IPCC Guidelines; Mancinelli and McKay 1985; Czepiel et al 1996). For 2005 to 2023, directly reported CH₄ emissions from the GHGRP are used for MSW landfills. Various oxidation factor percentages are included in the GHGRP dataset (0, 10, 25, and 35); an average percent of 0.14 is effectively applied between 2005 to 2009, 0.17 between 2010 to 2014, 0.20 between 2015 to 2019, 0.22 between 2020 to 2021, and 0.23 applied for 2022 and 2023.

Step 1: Estimate Annual Quantities of Solid Waste Placed in MSW Landfills for 1940 to the Present Year

Total national annual waste generation and disposal data back to 1940 are directly used to estimate CH₄ emissions for the 1990 to 2009 *Inventory* time series. The waste generation and disposal estimates are also made for the rest of the *Inventory* time series (i.e., 2010 to the current *Inventory* year) for informational purposes; these data however do not inform the annual CH₄ emission estimates for this portion of the time series. The specific steps are described below (in sections 1a and 1b), followed by a summary of a comparative analysis of datasets that contain or are used to estimate annual waste disposal (in Box A-3). Step 2 describes how the estimated annual quantities of waste landfilled are used to estimate annual CH₄ generation between 1990 to 2009, and the methodology used to estimate CH₄ generation for 2010 to the current *Inventory* year.

Step 1a. Historical Estimates: 1940 to 1988

Historical waste data, preferably from 50 years prior to the first year of the *Inventory* time series (i.e., since 1940 because the time series begins in 1990), are required for the FOD model to estimate CH₄ generation for the *Inventory* time series (IPCC 2006). 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 sources or estimated via proxy data.

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 the 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 CH₄ generation, estimates for those years were included in the FOD model for completeness in accounting for CH₄ generation rates and are based on the population in those years and the per capita rate for land disposal for the 1960s.

Step 1b. *Inventory* Time Series Estimates: 1990 to the Current *Inventory* Year

For 1989 to 2008, estimates of the annual quantity of MSW generated were developed from a survey of state agencies as reported in the State of Garbage (SOG) in America surveys (BioCycle 2001, 2004, 2006, 2010), adjusted to include U.S. Territories.¹⁴⁶ The SOG surveys collected data from state agencies and then applied 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 2006; Shin 2014). This approach assumes that all waste management methods are tracked and reported to state agencies. Survey respondents were 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 surveys have typically been adjusted to exclude non-MSW materials (e.g.,

¹⁴⁶ Since the SOG survey does not include U.S. Territories, waste landfilled in U.S. Territories was estimated using population data for the U.S. Territories (U.S. Census Bureau 2020 and 2022) and the per capita rate for waste landfilled from BioCycle (2010).

industrial and agricultural wastes, construction and demolition debris, automobile scrap, and sludge from wastewater treatment plants) that may be included in survey responses. While non-municipal solid wastes may have been disposed of in MSW landfills, they were not the primary type of waste material disposed and are typically inert. In last survey (BioCycle 2010), state agencies were asked to provide MSW-only data. Where this was not possible, they were asked to provide comments to better understand the data being reported. Methodological changes have occurred over the time frame the SOG surveys have been published, which directly impacted the fluctuating trends observed in the waste disposal data and emission estimates from 1990 to 2004 (RTI 2013).

The SOG survey is voluntary and not all states provided 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 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 U.S. 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 presented in the SOG reports 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 Waste Business Journal [WBJ]) to fill gaps for non-reporting states and survey responses.

Although some fluctuation in waste generation data reported by states to the SOG survey 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 speculated 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 SOG surveys provide state-specific landfill waste generation data used in the *Inventory* for select years – 1989 to 2000, 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.

For the *Inventory* year 2010 and later, EREF's 2016 report entitled, *MSW Management in the United States*, is used as the primary data source because BioCycle ceased preparing the SOG surveys. EREF (2016) includes state-specific landfill MSW generation and disposal data for 2010 and 2013 using a similar methodology as the SOG surveys. Waste generation data were interpolated for 2009, the year in-between the 2008 SOG survey data and the 2010 EREF data. Waste generation data were also extrapolated for 2011 and 2012 using the EREF data for 2010 and 2013. Waste generation data for 2014 and the current year were extrapolated based on the EREF 2013 data and population increases from the U.S. Census (U.S. Census Bureau 2020, 2022, 2023, and 2024). No data source on annual waste generation by state or nationally (similar to an SOG or EREF report) has been published since EREF (2016).

For each year in the time series, estimates of the quantity of waste landfilled are determined by applying a waste disposal factor to the total amount of waste generated. A waste disposal factor was determined for each year a SOG survey was published and is the ratio of the total amount of waste landfilled to the total amount of waste generated. The waste disposal factor is interpolated for the years in between the SOG surveys and EREF report and

extrapolated for years after the last year of EREF data (i.e., 2013). The applied waste disposal factor has ranged from approximately 77 percent in 1990 to 65.3 percent from 2015 to 2023.

Table A-213 shows estimates of MSW generated and landfilled, and industrial waste landfilled. A description of the data sources used to estimate industrial waste landfilled is included in Step 7. Estimates for MSW generated and landfilled are presented for various years after 2004 for informational purposes only. As described in Step 4, after 2004, the *Inventory* methodology relies on the GHGRP net reported CH₄ emissions data, replacing the need for the now discontinued SOG surveys and intermittent EREF estimates.

Table A-213: Solid Waste in MSW and Industrial Waste Landfills Contributing to CH₄ Emissions (MMT unless otherwise noted)

	1990	2005	2019	2020	2021	2022	2023
Total MSW Generated ^a	270	368	331	334	334	335	337
Percent of MSW Landfilled	77%	64%	65%	65%	65%	65%	65%
Total MSW Landfilled	205	234	214	216	216	217	218
MSW last 30 years ^b	4,876	5,992	6,537	6,548	6,559	6,582	6,609
MSW since 1940 ^c	6,808	9,925	12,935	13,150	13,366	13,583	13,801
Total Industrial Waste Production Data	198	223	209	205	204	199	197
Pulp and Paper Sector ^d	129	139	120	117	117	113	109
Food and Beverage Sector ^e	69	84	89	88	87	86	88
Percent Total Industrial Waste Landfilled	5%	5%	5%	5%	5%	5%	5%
Total Industrial Waste Landfilled	9.7	10.9	11.3	11.1	11.1	10.8	10.7
Pulp and Paper Sector ^d	6.5	6.9	6.0	5.9	5.9	5.7	5.5
Food and Beverage Sector ^e	3.3	4.0	5.3	5.3	5.2	5.2	5.3

^a This estimate represents the waste that has been in place for 30 years or less, which contributes about 90 percent of the CH₄ generation. Values are based on EPA (1993) for years 1940 to years 1988 (not presented in table), BioCycle 2001, 2004, 2006, and 2010 for years 1989 to 2009 (1981 to 2004, and 2006 to 2011 are not presented in table). Values for years 2010 to 2023 are based on EREF (2016) and annual population data from the U.S. Census Bureau (2020, 2022, 2023, and 2024).

^b This estimate is the cumulative amount of waste that has been placed in landfills for the 30 years prior to the year indicated and is the sum of the annual disposal rates used in the first order decay model. Values are based on EPA 1993; BioCycle 2001, 2004, 2006, and 2010; EREF 2016; and extrapolated data based on annual population increases U.S. Census Bureau (2020, 2022, 2023, and 2024).

^c This estimate represents the cumulative amount of waste that has been placed in landfills since 1940 to the year indicated and is the sum of the annual disposal rates used in the first order decay model. Values are based on EPA 1993; BioCycle 2001, 2004, 2006, and 2010; EREF 2016; and extrapolated data based on annual population increases U.S. Census Bureau (2020, 2022, 2023, and 2024).

^d A disposal factor of 0.050 MT/MT of product is applied to total pulp and paper production data to estimate the annual amount landfilled. See Step 7 for the references and rationale for this method. The same disposal factor is applied to every year of the time series. Production data from 1990 and 2001 are from Lockwood-Post's Directory (2002). Production data from 2002 to 2023 are from the FAOSTat database.¹⁴⁷

^e A disposal factor of 0.0486 MT/MT of product is applied to total food production data to estimate the annual amount landfilled for years 1990 to 2009. A disposal factor of 0.060 MT/MT is applied for years 2010 to present. See Step 7 for the references and rationale for this method. Food production values for 1990 to 2023 are from FAO (2023).¹⁴⁸

Notes: Totals may not sum due to independent rounding.

Box A-3: Comparison of Annual Waste Disposal Estimates Across Available Data Sources

In 2020, EPA compared the available data on estimates of total waste generated and landfilled as presented in Table A-213 for the years 2017 and 2018 and found inconsistencies between the estimates of MSW landfilled between the data sources. Data sources directly compared include the EREF-extrapolated estimate for 2017

¹⁴⁷ Available at: <http://faostat3.fao.org/home/index.html#DOWNLOAD>. Accessed on September 5, 2023.

¹⁴⁸ 2022 USDA-NASS Ag QuickStats. Available at: <http://quickstats.nass.usda.gov>.

and 2018 to the Advancing Sustainable Materials Management: Facts and Figures report (EPA (2020) Advancing Sustainable Materials Management: Facts and Figures 2018, November 2020). These inconsistencies are expected, as the data sources use two different methodologies to estimate MSW landfilled. While there are differences in the methods used between these data sources, the uncertainty factors for MSW Landfills are intended to account for these variabilities in the emission estimates for 1990 to 2004.

The EREF-extrapolated national estimate of total MSW landfilled for 2017 and 2018 is based on a bottom-up approach using information at the facility-level to estimate national MSW for the sector as a whole, while the Facts and Figures report uses a top-down (materials flow mass balance) approach to estimate the same quantity. The materials flow methodology develops post-consumer MSW generation estimates of quantities of MSW products in the marketplace (using product sales and replacement data) and assessing waste generation by component material based on product lifespans. Discarded or landfilled material is post-consumer MSW and assumed to be the calculated difference between generation and recovery through recycling and composting, other food management (e.g., anaerobic digestion), and combustion (EPA 2020). MSW typically does not include construction and demolition waste, for example, which many GHGRP-reporting facilities accept and include in their greenhouse gas reports.

As a quality check, EPA also compared the MSW landfilled estimates from the EREF-extrapolated data, the Facts and Figures report, and the estimated waste disposed by facilities reporting to EPA's GHGRP under Subpart HH (MSW Landfills) for 2017 and 2018 plus an 11 percent scale-up factor to account for landfills that do not report to Subpart HH.

On average, the EREF-extrapolated value was 39 percent less than GHGRP-based estimated waste disposal amount for the year 2017 and 41 percent less than GHGRP-based estimated waste disposal amount for the year 2018 (including a scale-up factor of 11 percent for 2017 and 2018).

The difference between the EREF-extrapolated and GHGRP-based estimates are largely assumed to be due to the difference in estimated number of facilities included in the respective sources, and because the EREF 2013 waste landfilled estimate was extrapolated to 2018 based on population growth. In 2013, EREF estimated 1,540 landfills (data collected from state agencies, individual facilities for Hawaii and Florida, and estimated using population-based estimates for Alaska, Idaho and Wyoming). In 2018, the GHGRP-based estimate includes 2,111 total facilities, including 1,136 facilities reporting to the GHGRP, and 975 assumed or confirmed operational MSW landfills identified through WBJ 2016 and LMOP 2020 that do not report to the GHGRP.

Estimates of MSW landfilled from the Facts and Figures report for the year 2017 and 2018 were, on average, 61 percent less than the GHGRP + scale-up factor waste quantity (including a scale-up factor of 11 percent and subtracting 23 percent estimate of construction and demolition waste for both years).

While this 61 percent difference is large, it is not unexpected given the Facts and Figures top-down mass balance methodology and focus on MSW (i.e., non-MSW streams are purposely excluded). The GHGRP uses a facility-specific, bottom-up approach to estimating emissions while the Facts and Figures report uses a top-down approach which incorporates many assumptions regarding production, import and export values, and estimated product life are built into the MSW generation and landfill disposal estimate at the national level. The Facts and Figures report also specifically omits certain types of waste that are explicitly included in the GHGRP reports, such as construction and demolition waste, industrial waste, biosolids (sludges), agricultural waste, and other inert wastes (EPA 2020). Construction and demolition waste that was reported under the GHGRP were excluded to the extent possible, but because the GHGRP facilities typically report a default waste composition, some construction and demolition waste may still be included in what is assumed to be the MSW quantity. Additionally, the amount of biosolids (sludges) and other non-MSW streams could not reliably be estimated and excluded from the GHGRP data and may also be contributing to the percent difference.

Step 2: Estimate CH₄ Generation at MSW Landfills

Step 2a. CH₄ Generation at MSW Landfills for 1990 to 2009

The FOD method is exclusively used for 1990 to 2009. For the FOD method, methane generation is based on nationwide MSW generation data, to which a national average disposal factor is applied; it is not landfill-specific.

The FOD method is presented below and is similar to Equation HH-6 in CFR Part 98.343 for MSW landfills, and Equation TT-6 in CFR Part 98.463 for industrial waste landfills.

Equation A-67: Net Methane Emissions from Solid Waste

$$CH_{4,\text{Solid Waste}} = [G_{CH_4,\text{MSW}} - R] - Ox$$

where,

$CH_{4,\text{Solid Waste}}$	=	Net CH_4 emissions from solid waste
$G_{CH_4,\text{MSW}}$	=	CH_4 generation from MSW or industrial waste landfills
R	=	CH_4 recovered and combusted
Ox	=	CH_4 oxidized from MSW or industrial waste landfills before release to the atmosphere

The input parameters needed for the FOD model equations are the mass of waste disposed each year (discussed under Step 1), degradable organic carbon (DOC) as a function of methane generation potential (L_0), and the decay rate constant (k). The equation below provides additional detail on the activity data and emission factors used in the $CH_{4,\text{MSW}}$ equation presented above to calculate CH_4 generation.

Equation A-68: Methane Generation from MSW Landfills

$$CH_{4,\text{MSW}} = \left[\sum_{x=S}^{T-1} \left\{ W_x \times L_0 \times \frac{16}{12} \times (e^{-k(T-x-1)} - e^{-k(T-x)}) \right\} \right]$$

where,

$CH_{4,\text{MSW}}$	=	Total CH_4 generated from MSW or industrial waste landfills
T	=	Reporting year for which emissions are calculated
x	=	Year in which waste was disposed
S	=	Start year of calculation
W_x	=	Quantity of waste disposed of in the landfill in a given year
L_0	=	Methane generation potential (100 m ³ CH_4 /Mg waste; EPA 1998, 2008)
16/12	=	conversion factor from CH_4 to C
k	=	Decay rate constant (yr ⁻¹ , see Table A-214)

The DOC is determined from the CH_4 generation potential (L_0 in m³ CH_4 /Mg waste) as shown in the following equation:

Equation A-69: Degradable Organic Carbon Fraction of Solid Waste

$$DOC = [L_0 \times 6.74 \times 10^{-4}] \div [F \times \frac{16}{12} \times DOC_f \times MCF]$$

where,

DOC	=	degradable organic carbon (fraction, kt C/kt waste),
L_0	=	CH_4 generation potential (100 m ³ CH_4 /Mg waste; EPA 1998, 2008),
6.74×10^{-4}	=	CH_4 density (Mg/m ³),
F	=	fraction of CH_4 by volume in generated landfill gas (equal to 0.5)
16/12	=	molecular weight ratio CH_4 /C,
DOC_f	=	fraction of DOC that can decompose in the anaerobic conditions in the landfill (fraction equal to 0.5 for MSW), and
MCF	=	methane correction factor for year of disposal (fraction equal to 1 for anaerobic managed sites).

DOC values can be derived for individual landfills if a good understanding of the waste composition over time is known. A default DOC value is used in the *Inventory* because waste composition data are not regularly collected for all landfills nationwide. When estimating CH_4 generation for the years 1990 to 2009, a default DOC value is

used. This DOC value is calculated from a national CH₄ generation potential¹⁴⁹ of 100 m³ CH₄/Mg waste (EPA 2008) as described below.

The DOC value used in the CH₄ generation estimates from MSW landfills for 1990 to 2009 is 0.2028, which is based on the CH₄ generation potential of 100 m³ CH₄/Mg waste (EPA 1998; EPA 2008). After EPA developed the L₀ value, RTI analyzed data from a set of 52 representative landfills across the United States in different precipitation ranges to evaluate L₀, and ultimately the national DOC value. The 2004 Chartwell Municipal Solid Waste Facility Directory confirmed that each of the 52 landfills chosen accepted or accepts both MSW and construction and demolition (C&D) waste (Chartwell 2004; RTI 2009). The values for L₀ were evaluated from landfill gas recovery data for this set of 52 landfills, which resulted in a best fit value for L₀ of 99 m³/Mg of waste (RTI 2004). This value compares favorably with a range of 50 to 162 (midrange of 106) m³/Mg presented by Peer, Thorneloe, and Epperson (1993); a range of 87 to 91 m³/Mg from a detailed analysis of 18 landfills sponsored by the Solid Waste Association of North America (SWANA 1998); and a value of 100 m³/Mg recommended in EPA's compilation of emission factors (EPA 1998; EPA 2008; based on data from 21 landfills). Based on the results from these studies, a value of 100 m³/Mg appears to be a reasonable best estimate to use in the FOD model for the national inventory for years 1990 through 2009, and is the value used to derive the DOC value of 0.2028.

In 2004, the FOD model was also applied to the gas recovery data for the 52 landfills to calculate a decay rate constant (k) directly for L₀ = 100 m³/Mg. The decay rate constant was found to increase with annual average precipitation; consequently, average values of k were developed for three precipitation ranges, shown in Table A-214 and recommended in EPA's compilation of emission factors (EPA 2008).

Table A-214: Average Values for Rate Constant (k) by Precipitation Range (yr⁻¹)

Precipitation range (inches/year)	k (yr ⁻¹)
<20	0.020
20-40	0.038
>40	0.057

These values for k show reasonable agreement with the results of other studies. For example, EPA's compilation of emission factors (EPA 1998; EPA 2008) recommends a value of 0.02 yr⁻¹ for arid areas (less than 25 inches/year of precipitation) and 0.04 yr⁻¹ for non-arid areas. The SWANA (1998) study of 18 landfills reported a range in values of k from 0.03 to 0.06 yr⁻¹ based on CH₄ recovery data collected generally in the time frame of 1986 to 1995.

Using data collected primarily for the year 2000, the distribution of waste-in-place versus precipitation was developed from over 400 landfills (RTI 2004). A distribution was also developed for population versus precipitation for comparison. The two distributions were very similar and indicated that population in areas or regions with a given precipitation range was a reasonable proxy for waste landfilled in regions with the same range of precipitation. Using U.S. Census data and rainfall data, the distributions of population versus rainfall were developed for each Census decade from 1950 through 2010. The distributions showed that the U.S. population has shifted to more arid areas over the past several decades. Consequently, the population distribution was used to apportion the waste landfilled in each decade according to the precipitation ranges developed for k, as shown in Table A-215.

¹⁴⁹ Methane generation potential (L₀) varies with the amount of organic content of the waste material. A higher L₀ occurs with a higher content of organic waste.

Table A-215: Percent of U.S. Population within Precipitation Ranges by Decade (%)

Precipitation Range (inches/year)	1950	1960	1970	1980	1990	2000
<20	10	13	14	16	19	20
20-40	40	39	37	36	34	33
>40	50	48	48	48	48	48

Notes: The precipitation range data are no longer used in the IPCC waste model (i.e., the FOD method) for 2010 and later years. Totals may not add to 100% due to independent rounding.

Source: Years 1950 through 2000 are from RTI (2004) using population data from the U.S. Census Bureau and precipitation data from the National Climatic Data Center's National Oceanic and Atmospheric Administration.

The 2006 *IPCC Guidelines* also require annual proportions of waste disposed of in managed landfills versus unmanaged and uncategorized sites prior to 1980. Based on the historical data presented by Mintz et al. (2003), a timeline was developed for the transition from the use of unmanaged and uncategorized sites for solid waste disposed to the use of managed landfills. Based on this timeline, it was estimated that 6 percent of the waste that was land disposed in 1940 was disposed of in managed landfills and 94 percent was managed in uncategorized sites. The uncategorized sites represent those sites where not enough information was available to assign a percentage to unmanaged shallow versus unmanaged deep solid waste disposal sites. Between 1940 and 1980, the fraction of waste that was land disposed transitioned towards managed landfills until 100 percent of the waste was disposed of in managed landfills in 1980. For wastes disposed of in the uncategorized sites, a methane correction factor (MCF) of 0.6 was used based on the recommended IPCC default value for uncharacterized land disposal (IPCC 2006). The recommended IPCC default value for the MCF for managed landfills of 1 (IPCC 2006) has been used for the managed landfills for the years where the first order decay methodology was used (i.e., 1990 to 2009).

Step 2b. CH₄ Generation at MSW Landfills for 2010 to Present

A different methodology is used to estimate CH₄ generation at MSW landfills between 2010 to 2023. Recent inventories prior to the 1990 through 2020 *Inventory* did not separately present CH₄ generation, CH₄ recovery, or CH₄ oxidation from MSW landfills after 2005 because the methodology switched to using the directly reported net CH₄ emissions plus a scale-up factor (discussed in Step 4) between 2005 to the current *Inventory* year. In response to various queries and comments, estimates for CH₄ generation, CH₄ recovery, and CH₄ oxidation were added to the 1990 to 2020 *Inventory* and will be updated annually.

Step 3: Estimate CH₄ Emissions Avoided from MSW Landfills

Between 1990 to 2009, the estimated landfill gas recovered per year (R) at MSW landfills is based on a combination of four databases that include recovery from flares and/or landfill gas-to-energy projects:

- 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 EPA LMOP (EPA 2016),
- the flare vendor database (contains updated sales data collected from vendors of flaring equipment), and the
- EPA's GHGRP MSW landfills database (EPA 2015a).¹⁵⁰

Between 2010 and 2023, the estimated R at MSW landfills is calculated using directly reported annual quantities of R from EPA's GHGRP (EPA 2024) plus a scale-up factor to account for recovery from MSW landfills that may not be reporting to the GHGRP. The development of the scale-up factor is detailed under Step 4a. A scale-up factor of 9

¹⁵⁰ The 2015 GHGRP dataset is used in the GHGRP MSW landfills dataset described in Step 3a. The flare database is no longer updated because the methodology changed such that the directly reported net methane emissions are used. The GHGRP dataset is available through Envirofacts <http://www.epa.gov/enviro/facts/ghg/search.html>.

percent and 11 percent is applied to the total R from EPA's GHGRP from 2010 to 2016 and 2017 to 2023, respectively. In 2022, the *Inventory* team compared the total R from EPA's GHGRP and EPA's LMOP 2021 database (EPA 2021); total R between the two databases were within a reasonable range, but higher in the LMOP 2021 database. The GHGRP data consist of mandatory, annually updated facility-specific data, while the LMOP database includes the GHGRP data in addition to voluntary, intermittent facility-specific data for facilities that do not report to the GHGRP.

Step 3a: Estimate CH₄ Emissions Avoided Through Landfill Gas-to-Energy (LFGE) and Flaring Projects for 1990 to 2009

The quantity of CH₄ avoided due to LFGE systems was estimated based on information from three sources: (1) a database developed by the EIA for the voluntary reporting of greenhouse gases (EIA 2007); (2) a database compiled by LMOP and referred to as the LFGE database for the purposes of this inventory (EPA 2016); and (3) the GHGRP MSW landfills dataset (EPA 2015a).

The EIA database includes location information for landfills with LFGE projects, estimates of CH₄ reductions, descriptions of the projects, and information on the methodology used to determine the CH₄ reductions. In general, the CH₄ reductions for each reporting year were based on the measured amount of landfill gas collected and the percent CH₄ in the gas.

For the LFGE database, data on landfill gas flow and energy generation (i.e., MW capacity) were used to estimate the total direct CH₄ emissions avoided due to the LFGE project.

The GHGRP MSW landfills database contains the most detailed data on landfills that reported under EPA's GHGRP for years 2010 through 2015, however the amount of CH₄ recovered is not specifically allocated to a flare versus a LFGE project. The allocation into flares or LFGE was performed by matching landfills to the EIA and LMOP databases for LFGE projects and to the flare database for flares. Detailed information on the landfill name, owner or operator, city, and state are available for both the EIA and LFGE databases; consequently, it was straightforward to identify landfills that were in both databases against those in EPA's GHGRP MSW landfills database. The EPA's GHGRP MSW landfills database was first introduced as a source for recovery data for the 1990 through 2013 *Inventory*. The GHGRP MSW landfills database contains facility-reported data that undergoes rigorous verification and is considered to contain the least uncertain data of the four databases. However, this database only contains a portion of the landfills in the United States (although, presumably the highest emitters since only those landfills that meet the methane generation threshold must report) and only contains data from 2010 and later. For landfills in this database, methane recovery data reported data for 2010 and later were linearly backcasted to 1990, or the date the landfill gas collection system at a facility began operation, whichever is earliest.

A destruction efficiency of 99 percent was applied to amounts of CH₄ recovered to estimate CH₄ emissions avoided for all recovery databases. This value for destruction efficiency was selected based on the range of efficiencies (86 to 99+ percent) recommended for flares in EPA's *AP-42 Compilation of Air Pollutant Emission Factors*, Draft Chapter 2.4, Table 2.4-3 (EPA 2008). A typical value of 97.7 percent was presented for the non-methane components (i.e., volatile organic compounds and non-methane organic compounds) 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 *Inventory* methodology. Other data sources supporting a 99 percent destruction efficiency include those used to establish New Source Performance Standards (NSPS) for landfills.

The same landfill may be included one or more times across these four databases before RTI data cleaning. To avoid double- or triple- counting CH₄ 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.

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 counting the recovery amounts multiple times across the different databases. In other words, the CH₄ recovery from the same landfill was not included in the total recovery from the EIA, LFGE, or flare vendor databases. While the GHGRP contains facility-reported information on MSW Landfills starting in the year 2010, EPA has backcasted GHGRP emissions to the year 2005 in order to merge the two methodologies (more information provided in Steps 4a and 4b). 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 CH₄ 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 CH₄ recovery data in the GHGRP database for that facility was backcasted to the year 2002 only.

If a landfill in the EIA database was also in the LFGE and/or the flare vendor database, the CH₄ recovery was based on the EIA data because landfill owners or operators directly reported the amount of CH₄ recovered using gas flow concentration and measurements, and because the reporting accounted for changes over time. The EIA database only includes facility-reported data through 2006; the amount of CH₄ recovered in this database for years 2007 and later were assumed to be the same as in 2006. Nearly all (93 percent) of landfills in the EIA database also report to EPA's GHGRP.

If both the flare data and LFGE recovery data were available for any of the remaining landfills (i.e., not in the EIA or EPA's GHGRP databases), then the CH₄ recovered 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 CH₄ combusted by flares using the midpoint of a flare's reported capacity. 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).

Step 3b: Estimate CH₄ Emissions Avoided Through Flaring for the Flare Database for 1990 to 2009

To avoid double counting, flares associated with landfills in EPA's GHGRP, EIA and LFGE databases were not included in the total quantity of CH₄ recovery from the flare vendor database. As with the LFGE projects, reductions from flaring landfill gas in the EIA database were based on measuring the volume of gas collected and the percent of CH₄ in the gas. The information provided by the flare vendors included information on the number of flares, flare design flow rates or flare dimensions, year of installation, and generally the city and state location of the landfill. When a range of design flare flow rates was provided by the flare vendor, the median landfill gas flow rate was used to estimate CH₄ recovered from each remaining flare (i.e., for each flare not associated with a landfill in the EIA, EPA's GHGRP, or LFGE databases). Several vendors have provided information on the size of the flare rather than the flare design gas flow rate for most years of the *Inventory*. Flares sales data have not been obtained since the 1990 to 2015 *Inventory* year, when the net CH₄ emission directly reported to EPA's GHGRP began to be used to estimate emission from MSW landfills.

To estimate a median flare gas flow rate for flares associated with these vendors, the size of the flare was matched with the size and corresponding flow rates provided by other vendors. Some flare vendors reported the maximum capacity of the flare. An analysis of flare capacity versus measured CH₄ flow rates from the EIA database showed that the flares operated at 51 percent of capacity when averaged over the time series and at 72 percent of capacity for the highest flow rate for a given year. For those cases when the flare vendor supplied maximum capacity, the actual flow was estimated as 50 percent of capacity. Total CH₄ avoided through flaring from the flare vendor database was estimated by summing the estimates of CH₄ recovered by each flare for each year.

Step 3c: Correct Overestimation of CH₄ Emissions Avoided Through Flaring for 1990 to 2009

If comprehensive data on flares were available, each LFGE project in EPA's GHGRP, EIA, and LFGE databases would have an identified flare because it is assumed that most LFGE projects have flares. However, given that the flare vendor database only covers approximately 50 to 75 percent of the flare population, an associated flare was not identified for all LFGE projects. These LFGE projects likely have flares, yet flares were unable to be identified for one of two reasons: 1) inadequate identifier information in the flare vendor data, or 2) a lack of the flare in the flare vendor database. For those projects for which a flare was not identified due to inadequate information, CH₄ avoided would be overestimated, as both the CH₄ avoided from flaring and the LFGE project would be counted. To avoid overestimating emissions avoided from flaring, the CH₄ avoided from LFGE projects with no identified flares was determined and the flaring estimate from the flare vendor database was reduced by this quantity (referred to as a flare correction factor) on a state-by-state basis. This step likely underestimates CH₄ avoided due to flaring but was applied to be conservative in the estimates of CH₄ emissions avoided.

Additional effort was undertaken to improve the methodology behind the flare correction factor for the 1990 to 2009 and 1990 to 2014 inventory years to reduce the total number of flares in the flare vendor database that were not matched to landfills and/or LFGE projects in the EIA and LFGE databases. Each flare in the flare vendor database not associated with a LFGE project in the EIA, LFGE, or EPA's GHGRP databases was investigated to determine if it could be matched. For some unmatched flares, the location information was missing or incorrectly transferred to the flare vendor database and was corrected during the review. In other instances, the landfill names were slightly different between what the flare vendor provided, and the actual landfill name as listed in the EIA, LFGE and EPA's GHGRP databases. The remaining flares did not have adequate information through the name, location, or owner to identify it to a landfill in any of the recovery databases or through an Internet search; it is these flares that are included in the flare correction factor for the current inventory year.

A large majority of the unmatched flares are associated with landfills in the LFGE database that are currently flaring but are also considering LFGE. These landfills projects considering a LFGE project are labeled as candidate, planned, or construction in the LFGE database. The flare vendor database was improved in the 1990 to 2009 inventory year to match flares with operational, shutdown as well as candidate, potential, and construction LFGE projects, thereby reducing the total number of unidentified flares in the flare vendor database, all of which are used in the flare correction factor. The results of this effort significantly decreased the number of flares used in the flare correction factor, and consequently, increased recovered flare emissions, and decreased net emissions from landfills for the 1990 through 2009 *Inventory*. The revised state-by-state flare correction factors were applied to the entire *Inventory* time series (RTI 2010).

Step 4: Estimate CH₄ Emissions from MSW Landfills for 1990 to 2009

Methane emissions from MSW Landfills between 1990 and 2004 are estimated by subtracting the total annual amount of CH₄ recovered from the estimated CH₄ generation (see Equation A-67).

Methane emissions from MSW Landfills between 2005 to 2009 are estimated via a different methodology as described in the remainder of this step. During preparation of the 1990 through 2015 *Inventory*, EPA engaged with stakeholders both within and outside of the landfill industry on the methodology used in the *Inventory*, the data submitted by facilities under EPA's GHGRP Subpart HH for MSW Landfills, and the application of this information as direct inputs to the MSW landfill methane emissions estimates in the 1990 through 2015 *Inventory*. Based on discussions with stakeholders, EPA developed several options for improving the *Inventory* through methodological changes and moved forward with using the directly reported net GHGRP methane emissions from 2010 to 2015 for MSW landfills in the 1990 through 2015 *Inventory*.

The *Inventory* methodology now uses directly reported net CH₄ emissions for the 2010 to 2023 reporting years from EPA's GHGRP to backcast 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 EPA's 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 CH₄ 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).

Including the GHGRP net emissions data was a significant methodological change from the FOD method previously described in Steps 1 to 3 and only covered a portion of the *Inventory* time series. Therefore, EPA needed to merge the previous method with the new (GHGRP) dataset to create a continuous time series and avoid any gaps or jumps in estimated emissions in the year the GHGRP net emissions are first included (i.e., 2010).

To accomplish this, EPA backcasted GHGRP net emissions to 2005 to 2009 and added a scale-up factor to account for emissions from landfills that do not report to the GHGRP. A description of how the scale-up factor was determined and why the GHGRP emissions were backcasted are included below as Step 4a and Step 4b, respectively. The methodology described in this section was determined based on the good practice guidance in Volume 1: Chapter 5 Time Series Consistency of the 2006 IPCC Guidelines. Additional details including other options considered are included in RTI (2017a) and RTI (2018).

Step 4a: Developing and Applying the Scale-up Factor for MSW Landfills for 2005 to 2009

Landfills that do not meet the reporting threshold are not required to report to the GHGRP. As a result, the GHGRP dataset is only partially complete when considering the universe of MSW landfills. In theory, national emissions from MSW landfills equals the emissions from landfills that report to the GHGRP plus emissions from landfills that do not report to the GHGRP. Therefore, for completeness, a scale-up factor had to be developed to estimate the amount of emissions from the landfills that do not report to the GHGRP. A scale-up factor of 9 percent is applied annually to the net GHGRP CH₄ emissions between 2005 to 2016.

To develop the 9 percent scale-up factor, EPA completed four main steps:

1. EPA determined the number of landfills that do not report to the GHGRP (hereafter referred to as the non-reporting landfills). Source databases included the LMOP database 2017 (EPA 2017) and the WBJ Directory 2016 (WBJ 2016). This step identified 1,544 landfills that accepted MSW between 1940 and 2016 and had never reported to the GHGRP. These landfills and the data collected were compiled into the 2016 Non-Reporting Landfills Database.
2. EPA estimated annual waste disposed and the total waste-in-place (WIP) at each non-reporting landfill as of 2016. Both databases include critical details about individual landfills to estimate annual methane emissions, including the year waste was first accepted, the year the landfill closed (as applicable), and the estimated amount of waste disposed. But not all details are included for all landfills. A total of 969 of the 1,544 landfills (63 percent) contained the critical information necessary to estimate WIP.
 - a. For 234 non-reporting landfills, there was not enough information in the source databases to estimate WIP.
 - b. For 341 of the non-reporting landfills, WIP could be estimated with assumptions that either (i) “forced” the year that waste was first accepted as 30 years prior to the landfill closure year (if a closure date was included); or (ii) “forced” a closure year of 2016 if the landfill was known to be closed and a closure year was not included in the source database.
 - c. The database was reviewed by industry and staff from LMOP at this stage to help fill data gaps and rectify discrepancies between individual landfills across the source databases, which improved the WIP estimates by landfill and overall.
3. EPA summed the total WIP for the non-reporting landfills. Using the assumptions mentioned above, the total WIP in 2016 across the non-reporting landfills was approximately 0.922 billion MT.
4. EPA calculated the scale-up factor (9 percent) by dividing the non-reporting landfills WIP (0.92 billion MT) by the sum of the GHGRP WIP and the non-reporting landfills WIP (10.0 billion MT).

Table A-216: Revised Waste-in-Place (WIP) for GHGRP Reporting and Non-Reporting Landfills in 2016

Category	Estimated WIP (Billion metric tons)	Percentage
Non-reporting facilities	0.92	9 percent (the applied scale-up factor)
GHGRP facilities	9.1	91 percent
Total	10.0	100 percent

Note: The scale-up factor is applied in each year the GHGRP reported emissions are used in the *Inventory*.

Step 4b: Backcasting GHGRP Emissions for MSW Landfills for 2005 to 2009 to Ensure Time Series Consistency

Regarding 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). Chapter 5, however, does not recommend backcasting emissions 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 becomes available for multiple years, which was the case with the GHGRP data, where directly reported net CH₄ 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 (1) the FOD method from 1990 to 2009, or (2) using the FOD method for a portion of that time series and backcasting the GHGRP emissions data to a year where emissions from the two methodologies aligned. Plotting the backcasted 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 backcast the GHGRP emissions from 2009 to 2005 only, to merge the datasets and adhere to the IPCC good practice guidance.

EPA used the Excel Forecast function to backcast net methane emissions using the GHGRP data. The forecast function is used to predict a future value by using existing values, but EPA has applied it to predict previous values. Although it is not ideal, it allowed for expeditious implementation. In the forecast function, the known values are existing x-values and y-values (i.e., the years and data for the GHGRP, 2010 to 2015). The unknown y-values are the years to be estimated (i.e., all years prior to 2009). The following Excel formula was used: =FORECAST(year to backcast, GHGRP data for 2010 to 2015, years 2010 to 2015). The forecast function is a linear regression; thus, it will not account for annual fluctuations in CH₄ emissions when used for multiple years.

An important factor in this approach is that the backcasted emissions for 2005 to 2009 are subject to change with each *Inventory* because the GHGRP dataset may change as facilities revise their annual reports. The revisions are generally minor considering the entire GHGRP dataset and EPA has not determined any revisions to the backcasting approach or scale-up factor are necessary to date.

Step 5: Estimate CH₄ Emissions from MSW Landfills for 2010 to 2016

CH₄ emissions directly reported to EPA’s GHGRP are used for 2010 to 2016. Inherent in these direct emissions are the use of various GHGRP default emission factors such as the gas collection and control system collection efficiencies (where applicable), decay rate (k), and degradable organic carbon (DOC).

Facilities reporting to Subpart HH of the GHGRP can report their k and DOC values under one of three waste type options: (1) Bulk waste option, where all waste is accounted for within one bulk k and DOC value; (2) Modified bulk waste option, where waste disposed of at the landfill can be binned into bulk MSW excluding inerts and construction and demolition waste, construction and demolition waste, and inerts; and (3) Waste Composition option, where waste disposed of can be delineated into specific waste streams (i.e., food waste, garden waste, textiles, etc.) OR where facilities report a known quantity of inert waste and consider the remaining waste as bulk MSW (using the same k and DOC value for MSW as the bulk waste option).

The GHGRP requires facilities with a gas collection and control system to report their emissions using both a forward-estimating (i.e., using a first order decay approach, accounting for soil oxidation) and a back-calculating (i.e., using methane recovery and collection efficiency data, accounting for soil oxidation) method as described in Chapter 7 of this *Inventory*. To determine collection efficiency, facilities are required to report the amount of waste-in-place (surface area and soil depth) at their landfill as categorized by one of five area types (see Table A-217).

Table A-217: Table HH-3 to Subpart HH of the EPA’s Greenhouse Gas Reporting Program, Area Types Applicable to the Calculation of Gas Collection Efficiency

Description	Landfill Gas Collection Efficiency
A1: Area with no waste-in-place	Not applicable, do not use this area in the calculation
A2: Area without active gas collection, regardless of cover type	CE2: 0%
A3: Area with daily soil cover and active gas collection	CE3: 60%
A4: Area with an intermediate soil cover, or a final soil cover not meeting the criteria for A5 below, and active gas collection	CE4: 75%
A5: Area with a final soil cover of 3 feet or thicker of clay or final cover (as approved by the relevant agency) and/or geomembrane cover system and active gas collection	CE5: 95%
Weighted average collection efficiency for landfills:	
Area weighted average collection efficiency for landfills	$CE_{ave1} = (A2 \times CE2 + A3 \times CE3 + A4 \times CE4 + A5 \times CE5) / (A2 + A3 + A4 + A5)$

If facilities are unable to bin their waste into these area types, they are instructed to use 0.75, or 75 percent as a default value. In the EPA’s original rulemaking for the GHGRP, the EPA proposed this default collection efficiency of 75 percent because it was determined to be a reasonable central-tendency default considering the availability of data such as surface monitoring under the EPA’s New Source Performance Standards for MSW Landfills (40 CFR Part 60 Subpart WWW), which suggested that gas collection efficiencies generally range from 60 to 95 percent. This 75 percent default gas collection efficiency value only applies to areas at the landfill that are under gas collection and control; for areas of the landfill that are not under gas collection and control, a gas collection efficiency of 0 percent is applied.

The 9 percent scale-up factor is applied to the net annual emissions reported to the GHGRP for 2010 to 2016 as is done for 2005 to 2009 because the GHGRP does not capture emissions from all landfills in the United States.

Step 6: Estimate CH₄ Emissions from MSW Landfills for 2017 to 2023

The same methodology described in Step 5 is used to estimate CH₄ emissions from MSW Landfills for 2017 to 2023, except the scale-up factor applied is different (11 percent instead of 9 percent). The scale-up factor was initially developed to use the GHGRP reported data and account for the remaining subset of landfills that are not required to report to the GHGRP. The EPA acknowledges there are uncertainties associated with the 9 percent scale-up factor and underlying landfill-specific data used to develop the Non-Reporting Landfills database. Specifically, the GHGRP allows facilities to off-ramp (i.e., stop reporting to the GHGRP) after meeting certain criteria; therefore, the number of facilities and WIP reported under the GHGRP will vary year to year. Nearly 200 facilities have off-ramped from the GHGRP to date, which means there is now more WIP for non-reporting landfills than there was in the 2016 scale-up factor analysis. Reassessment of the scale-up factor at regular intervals to account for changes in the GHGRP dataset and LMOP database is considered good practice and was therefore included in the Planned Improvements section for a previous (1990 through 2018) *Inventory*.

The methodology used to revise the scale-up factor largely followed that to develop the 2016 Non-Reporting Landfills Database, as summarized below, except that the scale-up factor is now a time-based threshold considering total waste disposed in the 50 years prior to 2020 (i.e., between 1970 to 2020) instead of total waste-in-place for all non-reporting landfills. This methodological change was made in response to reviewer comments on the 1990 to 2019 *Inventory*. Both a 30-year and a 50-year time-based threshold were evaluated for the scale-up factor under the knowledge that peak production of landfill gas typically occurs within 5 to 7 years after wastes are first disposed, almost all gas is produced within 20-30 years after waste is disposed, and small quantities of gas may continue to be emitted from a landfill for 50 or more years (ASTDR, 2001). EPA decided to use the 50-year threshold for the scale-up factor applied between 2017 to 2020 for three reasons: (1) because 50 years aligns with the IPCC recommendation of using 50 years of historical waste disposal data in the FOD model to estimate CH₄ generation; (2) expert knowledge that MSW landfills can generate CH₄ for up to 50 years (ASTDR, 2001); and (3) because the Non-Reporting Landfills Database cannot estimate waste disposal for several hundred landfills where

not enough data are available. The 50-year threshold for the scale-up factor is a conservative approach considering the number of assumptions and missing data in the Non-Reporting Landfills Database.

Details on the revised 2020 scale-up factor are included in RTI (2021) and the general methodology is summarized in the remainder of this Step.

1. EPA streamlined the layout of the 2016 Non-Reporting Landfills Database to remove extraneous columns, clearly present the landfill-specific data from the main sources (i.e., the 2017 LMOP Database [EPA 2017] and the WBJ Directory 2016 [WBJ 2016]), and the calculation columns that yield the start year, closure year, and WIP data used to estimate the total WIP at all non-reporting landfills. The database is hereafter referred to as the 2018 Non-Reporting Landfills Database.
2. EPA added in new or updated data for existing non-reporting landfills and added in entries for new non-reporting landfills.
 - a. Added the 194 landfills that have off-ramped from the GHGRP as of 2020 (EPA 2022) into the Non-Reporting Landfills Database.
 - b. Cross-referenced and updated the 2017 LMOP Database (EPA 2017) information with the 2021 LMOP Database (EPA 2021) information. Approximately 217 new cases or updated information from the 2021 LMOP Database were added or revised.
 - c. These revisions increased the count of non-reporting landfills from 1,544 landfills to 1,672 landfills, a net increase of 128 landfills from the 2016 Non-Reporting Landfills Database; however, only 1,069 landfills had enough information for the scale-up factor calculations.
3. EPA conducted additional quality control checks on calculations in the 2016 Non-Reporting Landfills Database and rectified identified errors, which resulted in an increase of 38,498,070 MT of waste from the 2016 Non-Reporting Landfills Database.
 - a. A formula error was identified that under-estimated the WIP for landfills with a permitted end year after 2016, especially for those landfills that had reported closure dates in 2030 or later. For example, if the start year was 1980 and the permitted closure year was 2040, the formula was estimating 50 years when, for the purposes of this exercise, the number of years should have been 36 years. Dividing the WIP by 60 years results in a lower annual waste disposal value than dividing the WIP by 36 years (2016-1980). The methodology calculates an annual disposal rate for each landfill and then applies the annual disposal rate to 2016 minus the start year.
 - b. The WIP data year was not pulled from the 2017 LMOP Database and it was assumed the WIP data were from 2016 unless otherwise noted. The WIP year is now included in the 2018 Non-Reporting Landfills Database. The WBJ Directory does not present the year the WIP data are from, thus we assumed each data point was from 2016. These assumptions underestimate the amount of WIP for a large majority of the landfills where the WIP data year is not reported.
4. EPA estimated annual waste disposed at each non-reporting landfill as of 2020. Where available, the databases include details about individual landfills, including the year waste was first accepted, the year the landfill closed (as applicable), and the estimated amount of waste disposed. When enough data were available, EPA estimated total WIP by calculating an annual waste disposal rate and multiplied that by the number of operating years up to the closure year, or 2018 (if the landfill was known or assumed to be open). EPA used a tiered methodology when a landfill with critical information was included in more than one database:
 - Tier 1: If the landfill has off-ramped from the GHGRP, use the Subpart HH WIP value (and update to include assumed waste disposed between the year the landfill off-ramped to 2020, if operational during that time frame).
 - Tier 2: If the landfill is in the 2021 LMOP Database, use the 2021 LMOP WIP value.
 - Tier 3: Otherwise, EPA used the average of the estimated WIP value that was forced or provided from the 2016 Non-reporting Landfill Database industry and LMOP reviewers.

5. Annual waste disposal was then calculated by dividing the total WIP by the number of operational years for each landfill between 1970 to 2020 (i.e., 50 years).
 - a. A total of 1,352 of the 1,672 landfills (approximately 81 percent) contained enough critical information necessary to estimate the 2020 WIP (i.e., first year of operation, either total WIP or annual waste disposal data, and either an indication the landfill was still operating or the closure date). It is important to note that the WIP and annual waste disposal data are estimates. The quality of the source data for WIP and annual waste disposed have not been individually verified by the EPA team. In the case of the GHGRP data, the annual waste disposal quantities are either estimates using defined methodologies or actual waste disposed from tipping receipts. In general, most landfills have relied on tipping receipts for the past decade, meaning that annual waste disposed several decades ago are estimates.
 - b. For 593 of the 1,672 landfills (35 percent), WIP could be estimated with assumptions that either (i) “forced” the year that waste was first accepted as 30 years prior to the landfill closure year (if a closure year was included); or (ii) forced a closure year of 2018 if the landfill was known or thought to be open and a closure year was not included in the source database. These are the same general assumptions applied in the 2016 Non-Reporting Landfills Database.
6. For 321 of the 1,672 landfills (19 percent), there was not enough information in the source databases to estimate WIP, thus no WIP data was calculated for these facilities, which underestimates the total WIP and total waste disposed between 1970 to 2020 for the non-reporting landfills. EPA summed the total waste disposed for the 50-year threshold (1970 to 2020) for the non-reporting landfills, yielding 1.33 billion MT.
7. EPA calculated the scale-up factor (11 percent) by dividing the waste disposed by non-reporting landfills (1.33 billion MT) by the sum of the reporting landfills’ waste disposed and the total of both categories (12.3 billion MT).

Table A-218: Total Waste Disposed over 50 Years (1970-2020) for GHGRP Reporting and Non-reporting Landfills in 2020

Category	Estimated Waste Disposed (billion metric tons)	Percentage
Non-reporting facilities	1.33 (the applied scale-up factor)	11 percent
GHGRP facilities	11.0	89 percent
Total	12.33	100 percent

An 11 percent scale-up factor is applied annually for 2017 to 2023 because the GHGRP does not capture emissions from all landfills in the United States. In future inventories, the scale-up factor will be reassessed to include additional facilities that off-ramp from the GHGRP, revisions to the LMOP Database, and adjust the start and end years for a 50-year threshold.

Step 7: Estimate CH₄ Generation at Industrial Waste Landfills for 1990 to the Current Inventory Year

A Tier 2 approach (IPCC 2006) is used to estimate annual emissions from industrial waste landfills. A tailored IPCC waste model, based on the FOD method and country-specific defaults, is exclusively used for 1990 to 2023. For the FOD method, methane generation is based on nationwide industrial production data from two major sectors—pulp and paper, and food and beverage manufacturing—to which a national average disposal factor is applied, separately for each sector. The methodology is not Tier 3 (i.e., it is not landfill-specific) because data for individual landfills are limited. Table A-213 presents the amount of industrial production data and estimated amount of industrial waste landfilled for select years.

The FOD method is presented is presented in Equation A-67 and is similar to Equation HH-6 in CFR Part 98.343 for MSW landfills, and Equation TT-6 in CFR Part 98.463 for industrial waste landfills.

Industrial waste landfills receive waste from factories, processing plants, and other manufacturing activities. In national inventories prior to the 1990 through 2005 inventory, CH₄ generation at industrial landfills was estimated as seven percent of the total CH₄ generation from MSW landfills, based on a study conducted by EPA (1993). In 2005, the methodology was updated and improved by using activity factors (industrial production levels) to estimate the amount of industrial waste landfilled each year, and by applying the FOD model to estimate CH₄ generation. A nationwide survey of industrial waste landfills found that most of the organic waste placed in industrial waste landfills originated from two sectors: food processing (meat, vegetables, fruits) and pulp and paper (EPA 1993). Data for annual nationwide production for the food and beverage processing and pulp and paper sectors were taken from industry and government sources for recent years and estimates were developed for production for the earlier years for which data were not available.

For the pulp and paper sector, production data published by the Lockwood-Post's Directory were used for years 1990 to 2001 and production data published by the Food and Agriculture Organization were used for years 2002 to 2023. An extrapolation based on U.S. real gross domestic product was used for years 1940 through 1964.

For the food and beverage processing sector, production data were obtained from the U.S. Department of Agriculture for the years 1990 to 2023 (ERG 2023, 2024). An extrapolation based on U.S. population was used for the years 1940 through 1989.

In addition to production data for the pulp and paper and food processing sectors, the following inputs are needed to use the FOD model for estimating CH₄ generation from industrial waste landfills: 1) quantity of waste that is disposed in industrial waste landfills (as a function of production), 2) CH₄ generation potential (L_0) from which a DOC value can be calculated, and 3) the decay rate constant (k).

Research into waste generation and disposal in landfills for the pulp and paper sector indicated that the quantity of waste landfilled was about 0.050 MT/MT (5 percent) of product. This waste disposal factor is applied to all years of the time series for the pulp and paper sector. A waste disposal factor of 0.0486 MT/MT (4.86 percent) of product (RTI 2006 using data from EPA 1993) is applied for the food processing sector between 1990 to 2009. A revised waste disposal factor of 6 percent (based on recent survey data from the food and beverage sector, see FWRA 2016) is applied to the food and beverage production data between 2010 to the current year. These waste disposal factors are applied to estimates of annual production to estimate annual waste disposal in industrial waste landfills (see Table A-213 for select years). Estimates for DOC were derived from available data (EPA, 2015b; Heath et al., 2010; NCASI, 2005; Kraft and Orender, 1993; NCASI 2008; Flores et al. 1999 as documented in RTI 2015a). The DOC value for industrial pulp and paper waste is estimated at 0.15 (L_0 of 49 m³/MT); the DOC value for industrial food waste is estimated as 0.26 (L_0 of 128 m³/MT) (RTI 2015; RTI 2014). Estimates for k were taken from the default values in the 2006 IPCC Guidelines; the value of k given for food waste with disposal in a wet temperate climate is 0.19 yr⁻¹, and the value given for paper waste is 0.06 yr⁻¹.

A literature review was conducted for the 1990 to 2010 and 1990 to 2014 inventory years with the intent of updating values for L_0 (specifically DOC) and k in the pulp and paper sector (RTI 2014). Where pulp and paper mill wastewater treatment residuals or sludge are the primary constituents of pulp and paper waste landfilled, values for k available in the literature range from 0.01/yr to 0.1/yr, while values for L_0 range from 50 m³/Mt to 200 m³/Mt.¹⁵¹ Values for these factors are highly variable and are dependent on the soil moisture content, which is generally related to rainfall amounts. At this time, sufficient data were available through EPA's GHGRP to warrant a change to the L_0 (DOC) from 99 to 49 m³/MT, but sufficient data were not obtained to warrant a change to k . EPA will consider an update to the k values for the pulp and paper sector as new data arises and will work with stakeholders to gather data and other feedback on potential changes to these values.

As with MSW landfills, a similar trend in disposal practices from unmanaged landfills, or open dumps to managed landfills was expected for industrial waste landfills; therefore, the same timeline that was developed for MSW landfills was applied to the industrial landfills to estimate the average MCF. That is, between 1940 and 1980, the fraction of waste that was land disposed transitioned from 6 percent managed landfills in 1940 and 94 percent open dumps to 100 percent managed landfills in 1980 and on. For wastes disposed of in unmanaged sites, an MCF

¹⁵¹ Sources reviewed included Heath et al. 2010; Miner 2008; Skog 2008; Upton et al. 2008; Barlaz 2006; Sonne 2006; NCASI 2005; Barlaz 1998; and Skog and Nicholson 2000.

of 0.6 was used and for wastes disposed of in managed landfills, an MCF of 1 was used, based on the recommended IPCC default values (IPCC 2006).

The parameters discussed above were used in the integrated form of the FOD model to estimate CH₄ generation from industrial waste landfills.

Step 8: Estimate CH₄ Oxidation from MSW and Industrial Waste Landfills

Step 8a: Estimate CH₄ Oxidation from Industrial Waste Landfills for 1990 to Present

A portion of the CH₄ escaping from a landfill oxidizes to CO₂ in the top layer of the soil. The amount of oxidation depends upon the characteristics of the soil and the environment. For purposes of this analysis, it was assumed that of the CH₄ generated, minus the amount of gas recovered for flaring or LFGE projects, 10 percent was oxidized in the soil (Jensen and Pipatti 2002; Mancinelli and McKay 1985; Czepiel et al 1996). The literature was reviewed in 2011 (RTI 2011) and 2017 (RTI 2017b) to provide recommendations for the most appropriate oxidation rate assumptions. It was found that oxidation values are highly variable and range from zero to over 100 percent (i.e., the landfill is considered to be an atmospheric sink by virtue of the landfill gas extraction system pulling atmospheric methane down through the cover). There is considerable uncertainty and variability surrounding estimates of the rate of oxidation because oxidation is difficult to measure and varies considerably with the presence of a gas collection system, thickness and type of the cover material, size and area of the landfill, climate, and the presence of cracks and/or fissures in the cover material through which methane can escape. IPCC (2006) notes that test results from field and laboratory studies may lead to over-estimations of oxidation in landfill cover soils because they largely determine oxidation using uniform and homogeneous soil layers. In addition, several studies note that gas escapes more readily through the side slopes of a landfill as compared to moving through the cover thus complicating the correlation between oxidation and cover type or gas recovery.

An oxidation factor of 0.10 (IPCC 2006) is applied for industrial waste landfills for the entire time series.

Step 8b: Estimate CH₄ Oxidation from MSW Landfills for 1990 to 2004

An oxidation factor of 0.10 (IPCC 2006) is applied for MSW Landfills between 1990 to 2004. A variety of oxidation factors (0.0, 0.10, 0.25, or 0.35) are applied for MSW landfills between 2005 to 2009 as described below. The oxidation factors applied for MSW landfills are based on IPCC 2006 (0.10) and scientific literature reviewed for the development of the GHGRP regulations (40 CFR Part 98). An annual weighted average of facility-reported oxidation factors from the GHGRP dataset are applied between 2005 to 2021. Between 2005 to 2009, the annual weighted average oxidation factor ranges from 11 percent to 15 percent. Between 2010 to 2016, the annual weighted average oxidation factor ranges from 17 to 21 percent; and from 2017 to 2023, the annual weighted average oxidation factor ranges from 21 to 23 percent (EPA 2024).

The annual amount of CH₄ oxidized is calculated for 1990 to 2004 by applying the 10 percent oxidation factor to the sum of CH₄ generation minus recovery as presented in Equation A-67. The annual amount of CH₄ oxidized is calculated for 2005 to present by solving for oxidation in Equation A-67 when CH₄ generation, R, and the net CH₄ emission values are known. In other words, when solving Equation A-70 below:

Equation A-70: Back-calculated Methane Oxidation

$$Ox = -(G_{CH_4,MSW} + R - CH_{4,Solid\ Waste})$$

where,

Ox	=	CH ₄ oxidized from MSW landfills before release to the atmosphere
CH _{4,Solid Waste}	=	Net CH ₄ emissions from MSW landfills
G _{CH₄,MSW}	=	CH ₄ generation from MSW landfills
R	=	CH ₄ recovered and combusted from MSW landfills.

The remainder of this step provides supporting documentation on the oxidation factors applied for MSW Landfills.

MSW landfills with landfill gas collection systems are generally designed and managed better to improve gas recovery. More recent research (2006 to 2012) than IPCC (2006) on landfill cover methane oxidation has relied on stable isotope techniques that may provide a more reliable measure of oxidation. Results from this recent research consistently point to higher cover soil methane oxidation rates than the IPCC (2006) default of 10 percent.

A continued effort will be made to review the peer-reviewed literature to better understand how climate, cover type, and gas recovery influence the rate of oxidation at active and closed landfills. At this time, the IPCC recommended oxidation factor of 10 percent will continue to be used for all landfills for the years 1990 to 2004 and for industrial waste landfills for the full time series.

Step 8c: Estimate CH₄ Oxidation from MSW Landfills for 2005 to 2023

For years 2005 to 2023, net CH₄ emissions from MSW landfills as directly reported to EPA's GHGRP, which include the adjustment for oxidation, are used. Subpart HH of the GHGRP includes default values for oxidation which are dependent on the mass flow rate of CH₄ per unit at the bottom of the surface soil prior to any oxidation, also known as methane flux rate. The oxidation factors included in the GHGRP (0, 0.10, 0.25, 0.35) are based on published, peer-reviewed literature and facility data provided through external stakeholder engagement. The EPA concluded, during review of both the literature and facility-reported emissions data, that simply revising the IPCC's Tier 1 oxidation default of 10 percent to a new singular default oxidation value would not take into account the key variable - methane flux rate - entering the surface soil layer. More information regarding analysis of methane oxidation fractions can be found in the memorandums entitled "Review of Oxidation Studies and Associated Cover Depth in the Peer Reviewed Literature", June 17, 2015 (RTI 2015b). More information about the landfill specific conditions required to use higher oxidation factors can be found in Table HH-4 of 40 CFR Part 98, Subpart HH, as shown below.

Table A-219: Table HH-4 to Subpart HH of Part 98—Landfill Methane Oxidation Fractions

Under these conditions:	Use this landfill methane oxidation fraction:
I. For all reporting years prior to the 2013 reporting year	
C1: For all landfills regardless of cover type or methane flux	0.10
II. For the 2013 reporting year and all subsequent years	
C2: For landfills that have a geomembrane (synthetic) cover or other non-soil barrier meeting the definition of final cover with less than 12 inches of cover soil for greater than 50% of the landfill area containing waste	0.10
C3: For landfills that do not meet the conditions in C2 above and for which you elect not to determine methane flux	0.10
C4: For landfills that do not meet the conditions in C2 or C3 above and that do not have final cover, or intermediate or interim cover ^a for greater than 50% of the landfill area containing waste	0.10
C5: For landfills that do not meet the conditions in C2 or C3 above and that have final cover, or intermediate or interim cover ^a for greater than 50% of the landfill area containing waste and for which the methane flux rate ^b is less than 10 grams per square meter per day (g/m ² /d)	0.35
C6: For landfills that do not meet the conditions in C2 or C3 above and that have final cover or intermediate or interim cover ^a for greater than 50% of the landfill area containing waste and for which the methane flux rate ^b is 10 to 70 g/m ² /d	0.25
C7: For landfills that do not meet the conditions in C2 or C3 above and that have final cover or intermediate or interim cover ^a for greater than 50% of the landfill area containing waste and for which the methane flux rate ^b is greater than 70 g/m ² /d	0.10

^a Where a landfill is in a state that does not have an intermediate or interim cover requirement, the landfill must have soil cover of 12 inches or greater in order to use an oxidation fraction of 0.25 or 0.35.

^b Methane flux rate (in grams per square meter per day; g/m²/d) is the mass flow rate of methane per unit area at the bottom of the surface soil prior to any oxidation and is calculated as follows:

For Equation HH-5 of this subpart, or for Equation TT-6 of subpart TT of this part,

$$MF = K \times G_{CH_4} / S_{Area}$$

For Equation HH-6 of this subpart,

$$MF = K \times \left(G_{CH_4} - \sum_{n=1}^N R_n \right) / S_{Area}$$

For Equations HH-7 of this subpart,

$$MF = K \times \left(\frac{1}{CE} \sum_{n=1}^N \left[\frac{R_n}{f_{Rec,n}} \right] \right) / S_{Area}$$

For Equation HH-8 of this subpart,

$$MF = K \times \left(\frac{1}{CE} \left\{ \sum_{n=1}^N \left[\frac{R_n}{f_{Rec,n}} \right] \right\} - \sum_{n=1}^N R_n \right) / S_{Area}$$

The EPA’s GHGRP also requires landfills to report the type of cover material used at their landfill as: organic cover, clay cover, sand cover, and/or other soil mixtures.

The average oxidation factor applied between 2005 and 2023 ranges from 15 percent to 23 percent.

Table A-220: Applied Oxidation Factors for MSW Landfills

	1990	2005	2019	2020	2021	2022	2023
Applied oxidation factor	0.10	0.15	0.21	0.22	0.22	0.23	0.23

Source: weighted average of reported oxidation factors in net emissions from reporting facilities to GHGRP Subpart HH, EPA 2024.

Step 9: Estimate Total Net CH₄ Emissions for the *Inventory*

For 1990 to 2004, total net CH₄ emissions were calculated by adding emissions from MSW and industrial landfills, and subtracting CH₄ recovered and oxidized, as shown in Table 7-4. A different methodology is applied for 2005 to 2023 where directly reported net CH₄ emissions to EPA’s GHGRP plus a scale-up factor to account for landfills that do not report to the GHGRP was applied. For 2005 to 2009, the directly reported GHGRP net emissions from 2010 to 2018 were used to backcast emissions for 2005 to 2009. Note that the emissions values for 2005 to 2009 are recalculated for each *Inventory* and are subject to change if facilities reporting to the GHGRP revise their annual greenhouse gas reports for any year. A 9 percent scale-up factor was applied annually to the net CH₄ reported to the GHGRP for 2005 to 2016, and an 11 percent scale-up factor was applied to the net CH₄ reported to the GHGRP for 2017 to 2023.

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3.16. Methodology for Estimating CH₄ and N₂O Emissions from Wastewater Treatment and Discharge (Source Category 5D)

The following steps outline the source and gas-specific processes used to estimate greenhouse gas (GHG) emissions from wastewater treatment and discharge for the years 1990 through 2023. Detailed summary tables of CH₄ and N₂O emissions from both domestic and industrial wastewater processes are included at the end of this annex, see Table A-255 through Table A-262.

Estimating CH₄ Emissions by Source of Wastewater

Domestic Wastewater CH₄ Emissions

Methodological equations for each of these systems are presented in the subsequent subsections; total domestic CH₄ emissions are summarized as follows:

Equation A-71: Total Domestic CH₄ Emissions from Wastewater Treatment and Discharge

$$\text{Total Domestic CH}_4 \text{ Emissions from Wastewater Treatment and Discharge (kt)} = A + B + C + D + E$$

where,

- A = Septic systems
- B = Centralized treatment, including aerobic systems (B1, other than constructed wetlands) (, constructed wetlands only (B2), and constructed wetlands used as tertiary treatment (B3);
- C = Centralized anaerobic systems
- D = Anaerobic sludge digesters
- E = Centralized wastewater treatment effluent

Table A-255 and Table A-256 presents domestic wastewater CH₄ emissions for both septic and centralized systems, including anaerobic sludge digesters and emissions from centralized wastewater treatment effluent, in 2023.

Methodology for Septic Systems (CH₄) Emissions (A):

Methane emissions for septic systems are estimated as follows:

Equation A-72: CH₄ Emissions from Septic Systems (U.S. Specific) (A)

$$\begin{aligned} \text{Emissions from Septic Systems} \left(\frac{\text{kt CH}_4}{\text{year}} \right) &= A \\ &= \text{US}_{\text{POP}} \times (\text{T}_{\text{SEPTIC}}) \times (\text{EF}_{\text{SEPTIC}}) \times 1/10^9 \times 365.25 \end{aligned}$$

Table A-229: Variables and Data Sources for CH₄ Emissions from Septic Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
US _{POP}	U.S. population ^a	Persons	United States and Puerto Rico: 1990-1999: U.S. Census Bureau (2002); Instituto de Estadísticas de Puerto Rico (2021) 2000-2009: U.S. Census Bureau (2011) 2010-2019: U.S. Census Bureau (2021) 2020-2023: U.S. Census Bureau (2023b) U.S. Territories other than Puerto Rico: 1990-2023: U.S. Census Bureau (2024)
T _{SEPTIC}	Percent treated in septic systems ^a	%	Odd years from 1989 through 2023: U.S. Census Bureau (2023a) Data for intervening years obtained by linear interpolation
EF _{SEPTIC}	Methane emission factor – septic systems (10.7)	g CH ₄ /capita/day	1990-2023: Leverenz et al. (2010)
1/10 ⁹	Conversion factor	g to kt	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion

^a Value of activity data varies over the *Inventory* time series.

Methodology for Centrally Treated Aerobic and Anaerobic Systems (CH₄) Emissions (B, C):

Table A-230 presents the total organically degradable material in wastewater, or TOW, for 1990 through 2023. The equations are as follows:

Equation A-73: Total Wastewater BOD5 Produced per Capita (U.S.-Specific [ERG 2018a])

$$\text{BOD}_{\text{gen rate}} \left(\frac{\text{kg/capita}}{\text{day}} \right) = \text{BOD}_{\text{without scraps}} \times (1 - \% \text{kitchen disposal}) + \text{BOD}_{\text{with scraps}} \times (\% \text{kitchen disposal})$$

Equation A-74: Total Organically Degradable Material in Domestic Wastewater (IPCC 2019 [Eq. 6.3])

$$\text{TOW} \left(\frac{\text{Gg BOD}}{\text{year}} \right) = \text{US}_{\text{POP}} \times \text{BOD}_{\text{gen rate}} \times 365.25 \times \frac{1}{10^6}$$

Table A-230: Variables and Data Sources for Organics in Domestic Wastewater

Variable	Variable Description	Units	Inventory Years: Source of Value
BOD _{gen rate}	Total wastewater BOD produced per capita	kg/capita/day	1990-2023: Calculated per Equation A-73 above
BOD _{without scrap}	Wastewater BOD produced per capita without kitchen scraps ^a	kg/capita/day	1990-2003: Metcalf & Eddy (2003)
BOD _{with scraps}	Wastewater BOD produced per capita with kitchen scraps ^a	kg/capita/day	2004-2013: Linear interpolation 2014-2023: Metcalf & Eddy (2014)
% kitchen disposal	Percent of housing units with kitchen disposal ^a	%	1990-2013: U.S. Census Bureau (2013) 2014-2023: Forecasted from the rest of the time series
TOW	Total wastewater BOD Produced per Capita ^a	Gg BOD/year	1990-2023: Calculated, ERG (2018a)
US _{POP}	U.S. population ^a	Persons	United States and Puerto Rico:

Variable	Variable Description	Units	Inventory Years: Source of Value
			1990-1999: U.S. Census Bureau (2002); Instituto de Estadísticas de Puerto Rico (2021) 2000-2009: U.S. Census Bureau (2011) 2010-2019: U.S. Census Bureau (2021) 2020-2023: U.S. Census Bureau (2023b) U.S. Territories other than Puerto Rico: 1990-2023: U.S. Census Bureau (2024)
365.25	Conversion factor	Days in a year	Standard conversion
1/10 ⁶	Conversion factor	kg to Gg	Standard conversion

^a Value of activity data varies over the *Inventory* time series.

Table A-231: U.S. Population (Millions) and Domestic Wastewater TOW (kt)

Activity	1990	2005	2019	2020	2021	2022	2023
Population	253	300	332	335	336	337	338
TOW	8,131	9,624	10,019	10,133	10,164	10,215	10,281

Sources: U.S. Census Bureau (2002); U.S. Census Bureau (2011); U.S. Census Bureau (2021 and 2023b); Instituto de Estadísticas de Puerto Rico (2021); U.S. Census Bureau (2024); ERG (2018a).

The methodological equations for CH₄ emissions from aerobic and anaerobic systems are:

Equation A-75: Total Domestic CH₄ Emissions from Centrally Treated Aerobic Systems (B)

$$\begin{aligned}
 & [Emissions from Centrally Treated Aerobic Systems (other than Constructed Wetlands)(B1) \\
 & + Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands Only)(B2) \\
 & + Emissions from Centrally Treated Aerobic Systems = B \left(\frac{\text{kt CH}_4}{\text{year}} \right)
 \end{aligned}$$

where,

Equation A-76: Total Organics in Centralized Wastewater Treatment [IPCC 2019 (Eq. 6.3A)]

$$TOW_{CENTRALIZED} \left(\frac{\text{Gg BOD}}{\text{year}} \right) = TOW \times T_{CENTRALIZED} \times I_{COLLECTED}$$

Table A-232: Variables and Data Sources for Organics in Centralized Domestic Wastewater

Variable	Variable Description	Units	Inventory Years: Source of Value
Centrally Treated Organics (Gg BOD/year)			
TOW _{CENTRALIZED}	Total organics in centralized wastewater treatment ^a	Gg BOD/year	1990-2023: Calculated
TOW	Total wastewater BOD Produced per Capita ^a	Gg BOD/capita/year	1990-2023: Calculated, ERG (2018a)
T _{CENTRALIZED}	Percent collected ^a	%	Odd years 1990-2023: U.S. Census Bureau (2023a) Data for intervening years obtained by linear interpolation

I _{COLLECTED}	Correction factor for additional industrial BOD discharged (1.25)	No units	1990-2023: IPCC (2019) Eq. 6.3a

^a Value of this activity data varies over the time series.

Equation A-77: Organic Component Removed from Aerobic Wastewater Treatment (IPCC 2019 [Eq. 6.3B])

$$S_{\text{aerobic}} \left(\frac{\text{Gg}}{\text{year}} \right) = S_{\text{mass}} \times \left[\left(\% \text{ aerobic} \frac{w}{\text{primary}} \times K_{\text{rem,aer,prim}} \right) + \left(\% \text{ aerobic} \frac{w}{\text{out primary}} \times K_{\text{rem,aer,noprime}} \right) + \left(\% \text{ aerobic} + \text{digestion} \times K_{\text{rem,aer,digest}} \right) \right] \times 1000$$

Equation A-78: CH₄ Emissions from Centrally Treated Aerobic Systems (other than Constructed Wetlands) (IPCC 2019 [Eq. 6.1])

$$B1 \left(\frac{\text{kt CH}_4}{\text{year}} \right) = [(TOW_{\text{CENTRALIZED}}) \times (\% \text{ aerobic}_{\text{OTCW}}) - S_{\text{aerobic}}] \times EF_{\text{aerobic}} - R_{\text{aerobic}}$$

Table A-233: Variables and Data Sources for CH₄ Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands) (kt CH₄/year)			
S_{aerobic}	Organic component removed from aerobic wastewater treatment ^a	Gg BOD/year	1990-2023: Calculated
S_{mass}	Raw sludge removed from wastewater treatment as dry mass ^a	Tg dry weight/year	1988: EPA (1993c); EPA (1999) 1990-1995: Calculated based on sewage sludge production change per year EPA (1993c); EPA (1999); Beecher et al. (2007) 1996: EPA (1999) 2004: Beecher et al. (2007) Data for intervening years obtained by linear interpolation 2005-2017: Interpolated 2018: NEBRA (2022), as described in ERG (2023) 2019-2023: Forecasted from the rest of the time series. Methodology for estimating sludge generated from the U.S. territories provided in ERG (2023).
% aerobic_{OTCW}	Percent of flow to aerobic systems, other than wetlands ^a	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: EPA (1992, 1996, 2000, 2004), respectively Data for intervening years obtained by linear interpolation.
% aerobic w/primary	Percent of aerobic systems with primary treatment and no anaerobic sludge digestion (0)	%	2005-2023: Forecasted from the rest of the time series
% aerobic w/out primary	Percent of aerobic systems without primary treatment ^a	%	
%aerobic+ digestion	Percent of aerobic systems with primary and anaerobic sludge digestion ^a	%	
K_{rem,aer_prim}	Sludge removal factor for aerobic treatment plants with primary treatment	kg BOD/kg sludge	1990-2023: IPCC (2019) Table 6.6a

Variable	Variable Description	Units	Inventory Years: Source of Value
	(mixed primary and secondary sludge, untreated or treated aerobically) (0.8)		
$K_{rem,aer\_noprime}$	Sludge removal factor for aerobic wastewater treatment plants without separate primary treatment (1.16)	kg BOD/kg sludge	
K_{rem,aer_digest}	Sludge removal factor for aerobic treatment plants with primary treatment and anaerobic sludge digestion (mixed primary and secondary sludge, treated anaerobically) (1)	kg BOD/kg sludge	
$EF_{aerobic}$	Emission factor – aerobic systems (0.018)	kg CH ₄ /kg BOD	1990-2023: IPCC (2019) Table 6.3
$R_{aerobic}$	Amount CH ₄ recovered or flared from aerobic wastewater treatment (0)	kg CH ₄ /year	1990-2023: IPCC (2019) Eq. 6.1
1000	Conversion factor	metric tons to kilograms	Standard conversion

^a Value of this activity data varies over the time series.

Equation A-79: CH₄ Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands Only) [IPCC 2014 (Eq. 6.1)]

$$B2 \left(\frac{kt \text{ CH}_4}{\text{year}} \right) = [(TOW_{CENTRALIZED}) \times (\% \text{ aerobic}_{CW})] \times (EF_{CW})$$

Equation A-80: CH₄ Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands used as Tertiary Treatment) (U.S. Specific)

$$B3 \left(\frac{kt \text{ CH}_4}{\text{year}} \right) = [(POTW_{flow_{CW}}) \times (BOD_{CW,INF}) \times 3.785 \times (EF_{CW})] \times \frac{1}{10^6} \times 365.25$$

Table A-234: Variables and Data Sources for CH₄ Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Constructed Wetlands Only (kt CH₄/year)			
$TOW_{CENTRALIZED}$	Total organics in centralized wastewater treatment ^a	Gg BOD/year	1990-2023: Calculated
$\% \text{ aerobic}_{CW}$	Flow to aerobic systems, constructed wetlands used as sole treatment / total flow to POTWs. ^a	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004, 2008, and 2012) Data for intervening years obtained by linear interpolation. 2013-2023: Forecasted from the rest of the time series
EF_{CW}	Emission factor for constructed wetlands (0.24)	kg CH ₄ /kg BOD	1990-2023: IPCC (2014)
Emissions from Constructed Wetlands used as Tertiary Treatment (kt CH₄/year)			
$POTW\_flow\_CW$	Wastewater flow to POTWs that use constructed	MGD	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004, 2008, and 2012)

Variable	Variable Description	Units	Inventory Years: Source of Value
	wetlands as tertiary treatment ^a		Data for intervening years obtained by linear interpolation. 2013-2023: Forecasted from the rest of the time series
BOD_{CW,INF}	BOD concentration in wastewater entering the constructed wetland (9.1)	mg/L	1990-2023: EPA (2013)
3.785	Conversion factor	liters to gallons	Standard conversion
EF_{CW}	Emission factor for constructed wetlands (0.24)	kg CH ₄ /kg BOD	1990-2023: IPCC (2014)
1/10⁶	Conversion factor	kg to kt	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion

^a Value of this activity data varies over the time series.

Equation A-81: CH₄ Emissions from Centrally Treated Anaerobic Systems (IPCC 2019 (Eq. 6.1))

$$C \left(\frac{\text{kt CH}_4}{\text{year}} \right) = [(\text{TOW}_{\text{CENTRALIZED}}) \times (\% \text{ anaerobic}) - S_{\text{anaerobic}}] \times \text{EF}_{\text{anaerobic}} - R_{\text{anaerobic}}$$

Table A-235: Variables and Data Sources for CH₄ Emissions from Centrally Treated Anaerobic Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Anaerobic Systems (kt CH₄/year)			
TOW_{CENTRALIZED}	Total organics in centralized wastewater treatment ^a	Gg BOD/year	1990-2023: Calculated
% anaerobic	Percent centralized wastewater that is anaerobically treated ^a	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: EPA (1992, 1996, 2000, 2004), respectively Data for intervening years obtained by linear interpolation. 2005-2023: Forecasted from the rest of the time series
S_{anaerobic}	Organic component removed from anaerobic wastewater treatment (0)	Gg/year	1990-2023: IPCC (2019) Table 6.3
EF_{anaerobic}	Emission factor for anaerobic reactors/deep lagoons (0.48)	kg CH ₄ /kg BOD	
R_{anaerobic}	Amount CH ₄ recovered or flared from anaerobic wastewater treatment (0)	kg CH ₄ /year	

^a Value of this activity data varies over the time series.

Methodology for Anaerobic Sludge Digesters (CH₄) Emissions (D):

Total CH₄ emissions from anaerobic sludge digesters were estimated using Equation A-82.

Equation A-82: CH₄ Emissions from Anaerobic Sludge Digesters (U.S. Specific)

$$D \left(\frac{\text{kt CH}_4}{\text{year}} \right) = \left[(\text{POTW}_{\text{flowAD}}) \times \frac{\text{biogas gen}}{100} \right] \times 0.0283 \times (\text{FRAC}_{\text{CH}_4}) \times 365.25 \times (662) \times (1 - \text{DE}) \times \frac{1}{10^9}$$

Table A-236: Variables and Data Sources for Emissions from Anaerobic Sludge Digesters

Variable	Variable Description	Units	Inventory years: Source of Value
Emissions from Anaerobic Sludge Digesters (kt CH₄/year)			
POTW_flow_AD	POTW Flow to Facilities with Anaerobic Sludge Digesters ^a	MGD	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: EPA (1992, 1996, 2000, and 2004), respectively Data for intervening years obtained by linear interpolation. 2005-2023: Forecasted from the rest of the time series
biogas gen	Gas Generation Rate (1.0)	ft ³ /capita/day	1990-2023: Metcalf & Eddy (2014)
100	Per Capita POTW Flow (100)	gal/capita/day	1990-2023: Ten-State Standards (2004)
0.0283	Conversion factor	ft ³ to m ³	Standard Conversion
FRAC_{CH₄}	Proportion of Methane in Biogas (0.65)	No units	1990-2023: Metcalf & Eddy (2014)
365.25	Conversion factor	Days in a year	Standard conversion
662	Density of Methane (662)	g CH ₄ /m ³ CH ₄	1990-2023: EPA (1993a)
DE	Destruction Efficiency (99% converted to fraction)	No units	1990-2023: EPA (1998); CAR (2011); Sullivan (2007); Sullivan (2010); and UNFCCC (2012)
1/10⁹	Conversion factor	g to kt	Standard conversion

^a Value of this activity data varies over the time series.

Methodology for Discharge of Centralized Treatment Effluent (CH₄) Emissions:

Methane emissions from the discharge of wastewater treatment effluent were estimated using Equation A-83.

Equation A-83: CH₄ Emissions from Centrally Treated Systems Discharge (U.S.-Specific)

$$E \left(\frac{\text{kt CH}_4}{\text{year}} \right) = (\text{TOW}_{\text{RLE}} \times \text{EF}_{\text{RLE}}) + (\text{TOW}_{\text{Other}} \times \text{EF}_{\text{Other}})$$

where,

Equation A-84: Total Organics in Centralized Treatment Effluent (IPCC 2019 [Eq. 6.3D])

$$\begin{aligned} & \text{TOW}_{\text{EFFtreat,CENTRALIZED}} \left(\frac{\text{Gg BOD}}{\text{year}} \right) \\ &= [\text{TOW}_{\text{CENTRALIZED}} \times \% \text{ primary} \times (1 - \text{TOW}_{\text{rem,PRIMARY}})] + [\text{TOW}_{\text{CENTRALIZED}} \times \% \text{ secondary} \times (1 - \text{TOW}_{\text{rem,SECONDARY}})] + [\text{TOW}_{\text{CENTRALIZED}} \times \% \text{ tertiary} \times (1 - \text{TOW}_{\text{rem,TERTIARY}})] \end{aligned}$$

Equation A-85: Total Organics in Effluent Discharged to Reservoirs, Lakes, or Estuaries (U.S.-Specific)

$$\text{TOW}_{\text{RLE}} \left(\frac{\text{Gg BOD}}{\text{year}} \right) = \text{TOW}_{\text{EFFtreat,CENTRALIZED}} \times \text{Percent}_{\text{RLE}}$$

Equation A-86: Total Organics in Effluent Discharged to Other Waterbodies (U.S.-Specific)

$$TOW_{Other} \left(\frac{Gg \text{ BOD}}{year} \right) = TOW_{EFFtreat,CENTRALIZED} \times Percent_{Other}$$

Table A-237: Variables and Data Sources for CH₄ Emissions from Centrally Treated Systems Discharge

Variable	Variable Description	Units	Source of Value
TOW_{EFFtreat,CENTRALIZED}	Total organics in centralized treatment effluent ^a	Gg BOD/year	1990-2023: Calculated
TOW_{CENTRALIZED}	Total organics in centralized wastewater treatment ^a	Gg BOD/year	1990-2023: Calculated
% primary	Percent of primary domestic centralized treatment ^a	%	1990, 1991: Set equal to 1992. 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004, 2008, and 2012), respectively Data for intervening years obtained by linear interpolation. 2013-2023: Forecasted from the rest of the time series
% secondary	Percent of secondary domestic centralized treatment ^a	%	
% tertiary	Percent of tertiary domestic centralized treatment ^a	%	
TOW_{rem,PRIMARY}	Fraction of organics removed from primary domestic centralized treatment (0.4)	No units	1990-2023: IPCC (2019) Table 6.6B
TOW_{rem,SECONDARY}	Fraction of organics removed from secondary domestic centralized treatment (0.85)	No units	
TOW_{rem,TERTIARY}	Fraction of organics removed from tertiary domestic centralized treatment (0.90)	No units	
TOW_{RLE}	Total organics in effluent discharged to reservoirs, lakes, and estuaries ^a	Gg BOD/year	1990-2023: Calculated
TOW_{Other}	Total organics in effluent discharge to other waterbodies ^a	Gg BOD/year	
EF_{RLE}	Emission factor (discharge to reservoirs/lakes/estuaries) (0.114)	kg CH ₄ /kg BOD	
EF_{Other}	Emission factor (discharge to other waterbodies) (0.021)	kg CH ₄ /kg BOD	1990-2023: IPCC (2019) Table 6.8
Percent_{RLE}	% discharged to reservoirs, lakes, and estuaries ^a	%	
Percent_{Other}	% discharged to other waterbodies ^a	%	

^a Value of this activity data varies over the time series.

Industrial Wastewater CH₄ Emissions

Wastewater treatment and discharge 2023 emissions for the top six industries likely to generate CH₄ – pulp and paper manufacturing; meat and poultry processing; vegetables, fruits, and juices processing; starch-based ethanol production; petroleum refining; and breweries – are presented in Table A-238 below.

Methodology for Industrial Wastewater Treatment Systems (CH₄) Emissions (A through F):

Equation A-87 presents the general IPCC equation (Equation 6.4, IPCC 2019) to estimate CH₄ emissions from each type of treatment system used for each industrial category.

Equation A-87: Total CH₄ Emissions from Industrial Wastewater

$$\text{CH}_4 \text{ (industrial sector)} \left(\frac{\text{kg CH}_4}{\text{year}} \right) = [(TOW_i - S_i) \times EF - R_i]$$

where,

CH ₄ (industrial sector)	=	Total CH ₄ emissions from industrial sector wastewater treatment (kg/year)
I	=	Industrial sector
TOW _i	=	Total organics in wastewater for industrial sector <i>i</i> (kg COD/year)
S _i	=	Organic component removed from aerobic wastewater treatment for industrial sector <i>i</i> (kg COD/year)
EF	=	System-specific emission factor (kg CH ₄ /kg COD)
R _i	=	Methane recovered for industrial sector <i>i</i> (kg CH ₄ /year)

Equation A-88 presents the general IPCC equation to estimate the total organics in wastewater (TOW_i) for each industrial category (*i*).

Equation A-88: TOW in Industry Wastewater Treatment Systems

$$TOW_i \left(\frac{\text{kg COD}}{\text{year}} \right) = P_i \times W_i \times COD_i$$

where,

TOW _i	=	Total organically degradable material in wastewater for industry <i>i</i> (kg COD/year)
i	=	Industrial sector
P _i	=	Total industrial product for industrial sector <i>i</i> (t/year)
W _i	=	Wastewater outflow (m ³ /t product)
COD _i	=	Chemical oxygen demand (industrial degradable organic component in wastewater) (kg COD/m ³)

The annual industry production is shown in Table A-238, and the average wastewater outflow and the organics loading in the outflow is shown in Table A-239.

Table A-240 presents the industrial wastewater treatment activity data used in the calculations and described in detail in ERG (2008a), ERG (2013a), ERG (2013b), and ERG (2021a). Table A-241 presents the sludge variables used for industries with aerobic wastewater treatment operations (i.e., pulp and paper, fruit/vegetable processing, and petroleum refining).

Equation A-89: Organic Component Removed from Aerobic Wastewater Treatment – Pulp, Paper, and Paperboard

$$S_{\text{pulp,asb}} \left(\frac{\text{Gg COD}}{\text{year}} \right) = TOW_{\text{pulp}} \times \% \text{ removal w/primary}$$

where,

$S_{\text{pulp,asb}}$	=	Organic component removed from pulp and paper wastewater during primary treatment before treatment in aerated stabilization basins (Gg COD/year)
TOW_{pulp}	=	Total organically degradable material in pulp and paper wastewater (Gg COD/year)
% removal w/primary	=	Percent reduction of organics in pulp and paper wastewater associated with sludge removal from primary treatment (%)

Equation A-90: Organic Component Removed from Aerobic Treatment Plants

$$S_{\text{aerobic}} \left(\frac{\text{Gg COD}}{\text{year}} \right) = S_{\text{mass}} \times K_{\text{rem}} \times 10^{-6}$$

where,

S_{aerobic}	=	Organic component removed from fruit and vegetable or petroleum refining wastewater during primary treatment before treatment in aerated stabilization basins (Gg COD/year)
S_{mass}	=	Raw sludge removed from wastewater treatment as dry mass (kg sludge/year)
K_{rem}	=	Sludge factor (kg BOD/kg sludge)
10^{-6}	=	Conversion factor, kilograms to Gigagrams

Equation A-91: Raw Sludge Removed from Wastewater Treatment as Dry Mass

$$S_{\text{mass}} \left(\frac{\text{Gg COD}}{\text{year}} \right) = (S_{\text{prim}} + S_{\text{aer}}) \times P \times W$$

where,

S_{mass}	=	Raw sludge removed from wastewater treatment as dry mass (kg sludge/year)
S_{prim}	=	Sludge production from primary sedimentation (kg sludge/m ³)
S_{aer}	=	Sludge production from secondary aerobic treatment (kg sludge/m ³)
P	=	Production (t/year)
W	=	Wastewater outflow (m ³ /t)

Default emission factors¹⁵² from IPCC (2019) were used. Information on methane recovery operations varied by industry. See industry descriptions below.

Table A-238: U.S. Pulp and Paper, Meat, Poultry, Vegetables, Fruits and Juices, Ethanol, Breweries, and Petroleum Refining Production (MMT)

Activity	1990	2005	2019	2020	2021	2022	2023
Pulp and Paper^a	83.6	92.4	76.3	74.7	75.6	72.9	71.4
Meat (Live Weight Killed)	27.3	31.4	37.4	37.8	38.1	37.9	37.2
Poultry (Live Weight Killed)	14.6	25.1	30.1	30.5	30.5	31.1	31.3
Vegetables, Fruits and Juices	40.8	45.3	41.7	40.6	39.4	38.4	40.1
Ethanol Production	2.5	11.7	47.1	41.6	44.8	45.9	46.6
Breweries	23.9	23.1	21.1	21.1	21.2	20.5	19.3
Petroleum Refining	702.4	818.6	940	806.5	858.3	892.1	893.7

^aPulp and paper production is the sum of market pulp production plus paper and paperboard production.

Sources: Pulp and Paper – FAO (2024a) and FAO (2023); Meat, Poultry, and Fruits and Vegetables – USDA (2024a, 2024b, 2024c, 2024d, 2024e, and 2023), ERG (2023); Ethanol – Cooper (2018) and RFA (2024a and 2024b); Breweries – Beer Institute (2011) and

¹⁵² Emission factors are calculated by multiplying the maximum CH₄-producing capacity of wastewater (B₀, 0.25 kg CH₄/kg COD) and the appropriate methane correction factors (MCF) for aerobic (0), partially anaerobic (0.2), and anaerobic (0.8) systems (IPCC 2019), Table 6.3.

Table A-239: U.S. Industrial Wastewater Characteristics Data (2023)

Industry	Wastewater Outflow (m ³ /ton)	Wastewater BOD (g/L)	Wastewater COD (kg/m ³)	COD:BOD Ratio
Pulp and Paper	See Table A-243	0.3	--	2.5
Meat Processing	5.3	2.8	--	3
Poultry Processing	12.5	1.5	--	3
Fruit/Vegetable Processing	See Table A-244		--	1.5
Ethanol Production – Wet Mill	10 ^a	1.5	--	2
Ethanol Production – Dry Mill	1.25 ^a	3 ^b	--	2
Petroleum Refining	0.8	--	0.45	2.5
Breweries – Craft	3.03	--	17.6	1.67
Breweries – NonCraft	1.72	--	17.6	1.67

^a Units are gallons per gallons ethanol produced.^b Units are COD (g/L).

Sources: Pulp and Paper (BOD, COD:BOD) – Malmberg (2018); Meat and Poultry (Outflow, BOD) – ERG (2006a); Meat and Poultry (COD:BOD) – EPA (1997a); Fruit/Vegetables (Outflow, BOD) – CAST (1995), EPA (1974), EPA (1975); Fruit/Vegetables (COD:BOD) – EPA (1997a); Ethanol Production – Wet Mill (Outflow) – Donovan (1996), NRBP (2001), Ruocco (2006b); Ethanol Production – Wet Mill (BOD) – White and Johnson (2003); Ethanol Production – Dry Mill (Outflow and COD) – Merrick (1998), Ruocco (2006a); Ethanol Production (Dry and Wet, COD:BOD) – EPA (1997a); Petroleum Refining (Outflow) – ERG (2013b); Petroleum Refining (COD) – Benyahia et al. (2006); Petroleum Refining (COD:BOD) – EPA (1982); Breweries – Craft BIER (2024); ERG (2018b); Breweries – NonCraft BIER (2024); ERG (2018b); Breweries (Craft and NonCraft; COD and COD:BOD) – Brewers Association (2016b).

Table A-240: U.S. Industrial Wastewater Treatment Activity Data

Industry	% Wastewater Treated On-Site	% Total Treated On-Site Anaerobically	% Treated Aerobically by System Type		
			Total % Treated On-Site Aerobically	% Treated in Aerobic-ASBs	% Treated in Other Aerobic
Pulp and Paper^b	60	5.2	75.9	38.5	37.4
Meat Processing	33	33 ^a	33	-	33
Poultry Processing	25	25 ^a	25	-	25
Fruit/Vegetable Processing	11	0	11	5.5	5.5
Ethanol Production – Wet Mill	33.3	33.3	66.7	-	-
Ethanol Production – Dry Mill	75	75	25	-	-
Petroleum Refining	62.1	0	62.1	23.6	38.5
Breweries – Craft	0.5	0.5	-	-	-
Breweries – NonCraft	100	99	1	-	1

^c System is not occurring (“NO”) for the industry. Treated as 0 within calculations.^a Wastewater is pretreated in anaerobic lagoons prior to aerobic treatment.^b Remaining onsite treated in other treatment assumed to be non-emissive and not shown here.

Sources: ERG (2008a, 2008b); ERG (2013a); ERG (2013b); ERG (2021a).

Table A-241: Sludge Variables for Aerobic Treatment Systems

Variable	Industry		
	Pulp and Paper	Fruit/ Vegetable Processing	Petroleum Refining
Organic reduction associated with sludge removal (%)	58		
Sludge Production (kg/m³)			
Primary Sedimentation		0.15	
Aerobic Treatment		0.096	0.096
Sludge Factor (kg BOD/kg dry mass sludge)			
Aerobic Treatment w/Primary Sedimentation and No Anaerobic Sludge Digestion		0.8	
Aerobic Treatment w/out Primary Sedimentation			1.16

Sources: Organic reduction (pulp) – ERG (2008a); Sludge production – Metcalf & Eddy (2003); Sludge factors – IPCC (2019), Table 6.6a.

Methodology for Discharge of Industrial Wastewater Treatment Effluent (CH₄) Emissions (G through L):

Equation A-92: CH₄ Emissions from Industrial Wastewater Treatment Discharge

$$\text{CH}_4 \text{ Effluent}_{\text{IND}} \left(\frac{\text{kg CH}_4}{\text{year}} \right) = \text{TOW}_{\text{EFFLUENT,IND}} \times \text{EF}_{\text{EFFLUENT}}$$

where,

- CH₄ Effluent_{IND} = CH₄ emissions from industrial wastewater discharge for inventory year (kg CH₄/year)
- TOW_{EFFLUENT,IND} = Total organically degradable material in wastewater effluent from industry for inventory year (kg COD/year or kg BOD/year)
- EF_{EFFLUENT} = Tier 1 emission factor for wastewater discharged to aquatic environments (0.028 kg CH₄/kg COD or 0.068 kg CH₄/kg BOD) (IPCC 2019)

Table A-240 presents the percent of wastewater treated onsite, while Table A-242 presents the fraction of TOW removed during treatment.

Equation A-93: TOW in Industrial Wastewater Effluent

$$\text{TOW}_{\text{EFFLUENT,IND}} \left(\frac{\text{kg BOD or COD}}{\text{year}} \right) = \text{TOW}_{\text{IND}} \times \% \text{ onsite} \times (1 - \text{TOW}_{\text{REM}})$$

where,

- TOW_{EFFLUENT,IND} = Total organically degradable material in wastewater effluent from industry for inventory year (kg COD/year or kg BOD/year)
- TOW_{IND} = Total organics in untreated wastewater for industry for inventory year (kg COD/year)
- %onsite = Percent of industry wastewater treated on site (%)
- TOW_{REM} = Fraction of organics removed during treatment

Table A-242: Fraction of TOW Removed During Treatment by Industry

Industry	TOW _{REM}	Source
Pulp, Paper, and Paperboard	0.91	Malmberg (2018)
Red Meat and Poultry	0.85	IPCC (2019), Table 6.6b
Fruits and Vegetables	0.85	IPCC (2019), Table 6.6b
Ethanol Production		

Industry	TOW _{REM}	Source
Biomethanator Treatment	0.90	ERG (2008a), ERG (2006b)
Other Treatment	0.85	IPCC (2019), Table 6.6b
Petroleum Refining	0.93	Kenari, Sarrafzadeh, and Tavakoli (2010)
Breweries	0.85	IPCC (2019), Table 6.6b

Industry-Specific Data

Pulp, Paper, and Paperboard Manufacturing Wastewater Treatment. Wastewater treatment for the pulp, paper, and paperboard manufacturing (hereinafter referred to as “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. About 60 percent of pulp and paper mills have on-site treatment with primary treatment and about half of these also have secondary treatment (ERG 2008). 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).

Approximately 42 percent of the BOD passes on to secondary treatment, which consists of activated sludge, aerated stabilization basins, or non-aerated stabilization basins. Pulp and paper mill wastewater treated using anaerobic ponds or lagoons or unaerated ponds were classified as anaerobic (with an MCF of 0.8). Wastewater flow treated in systems with aerated stabilization basins or facultative lagoons was classified as partially anaerobic (with an MCF of 0.2, which is the 2006 IPCC Guidelines-suggested MCF for shallow lagoons). Wastewater flow treated in systems with activated sludge systems or similarly aerated biological systems was classified as aerobic.

A time series of CH₄ emissions for 1990 through 2023 was developed based on paper and paperboard production data and market pulp production data. Market pulp production values were available directly for 1998, 2000 through 2003, and 2010 through 2022. Where market pulp data were unavailable, a percent of woodpulp that is market pulp was applied to woodpulp production values from FAOSTAT to estimate market pulp production (FAO 2024a). The percent of woodpulp that is market pulp for 1990 to 1997 was assumed to be the same as 1998, 1999 was interpolated between values for 1998 and 2000, 2000 through 2009 were interpolated between values for 2003 and 2010, and 2023 was forecasted from the rest of the time series. A time series of the overall wastewater outflow in units of cubic meters of wastewater per ton of total production (i.e., market pulp plus woodpulp) is presented in Table A-243. Data 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 2005 and 2016 were obtained from the 2018 AF&PA Sustainability Report (AF&PA 2018), data for 2018 were obtained from the 2020 AF&PA Sustainability Report (AF&PA 2020), and data for 2020 were obtained from a 2022 AF&PA sustainability update (AF&PA 2022). Data for intervening years were obtained by linear interpolation, while 2021-2023 were set equal to 2020. The average BOD concentration in raw wastewater was estimated to be 0.4 grams BOD/liter for 1990 to 1998, while 0.3 grams BOD/liter was estimated for 2014 through 2023 (EPA 1997b; EPA 1993b; World Bank 1999; Malmberg 2018). Data for intervening years were obtained by linear interpolation.

Table A-243: Wastewater Outflow (m³/ton) for Pulp, Paper, and Paperboard Mills

Wastewater Outflow (m ³ /ton)	1990	2005	2019	2020	2021	2022	2023
Pulp and Paper	68	43	39	39	39	39	39

Sources: ERG (2013a), AF&PA (2014), AF&PA (2016), AF&PA (2018), AF&PA (2020); AF&PA (2022)

Pulp, Paper, and Paperboard Wastewater Treatment Effluent. Methane emissions from pulp, paper, and paperboard wastewater treatment effluent were estimated by multiplying the total BOD of the discharged wastewater effluent by an emission factor associated with the location of the discharge.

Equation A-94: CH₄ Emissions from Pulp and Paper Discharge (U.S. Specific)

$$\begin{aligned} & \text{Emissions from Pulp and Paper Discharge} \left(\frac{\text{kt CH}_4}{\text{year}} \right) \\ &= (\text{TOW}_{\text{RLE,pulp}} \times \text{EF}_{\text{RLE}}) + (\text{TOW}_{\text{Other,pulp}} \times \text{EF}_{\text{Other}}) \end{aligned}$$

Equation A-95: Total Organics in Pulp and Paper Effluent Discharged to Reservoirs, Lakes, Or Estuaries (U.S. Specific)

$$\text{TOW}_{\text{RLE,pulp}} \left(\frac{\text{Gg BOD}}{\text{year}} \right) = \text{TOW}_{\text{EFFLUENT,IND}} \times \text{Percent}_{\text{RLE,pulp}}$$

Equation A-96: Total Organics in Pulp and Paper Effluent Discharged to Other Waterbodies (U.S. Specific)

$$\text{TOW}_{\text{Other,pulp}} \left(\frac{\text{Gg BOD}}{\text{year}} \right) = \text{TOW}_{\text{EFFLUENT,IND}} \times \text{Percent}_{\text{Other,pulp}}$$

where,

$\text{TOW}_{\text{RLE,pulp}}$	=	Total organics in pulp, paper, and paperboard manufacturing wastewater treatment effluent discharged to reservoirs, lakes, or estuaries (Gg BOD/year)
EF_{RLE}	=	Emission factor (discharge to reservoirs/lakes/estuaries) (0.114 kg CH ₄ /kg BOD) (IPCC 2019)
$\text{TOW}_{\text{Other,pulp}}$	=	Total organics in pulp, paper, and paperboard manufacturing wastewater treatment effluent discharged to other waterbodies (Gg BOD/year)
EF_{Other}	=	Emission factor (discharge to other waterbodies) (0.021 kg CH ₄ /kg BOD) (IPCC 2019)
$\text{TOW}_{\text{EFFLUENT,IND}}$	=	Total organically degradable material in pulp, paper, and paperboard manufacturing wastewater effluent for inventory year (Gg BOD/year)
$\text{Percent}_{\text{RLE,pulp}}$	=	Percent of wastewater effluent discharged to reservoirs, lakes, and estuaries (ERG 2021b)
$\text{Percent}_{\text{Other,pulp}}$	=	Percent of wastewater effluent discharged to other waterbodies (ERG 2021b)

The percent of pulp, paper, and paperboard wastewater treatment effluent routed to reservoirs, lakes, or estuaries (3 percent) and other waterbodies (97 percent) were obtained from discussions with NCASI (ERG 2021b). Data for 2019 were assumed the same as the rest of the time series due to lack of available data. Default emission factors for reservoirs, lakes, and estuaries (0.114 kg CH₄/kg BOD) and other waterbodies (0.021 kg CH₄/kg BOD) were obtained from IPCC (2019).

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. Although all meat and poultry processing facilities conduct some sort of treatment 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

emission factor of 0.2 kg CH₄/kg COD for anaerobic lagoons were used to estimate the CH₄ produced from these on-site treatment systems.

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. About half of the operations that treat and discharge wastewater 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). Wastewater treated in partially anaerobic systems were assigned the IPCC default emission factor of 0.12 kg CH₄/kg BOD. Outflow and BOD data, presented in Table A-244, were obtained from CAST (1995) for apples, apricots, asparagus, broccoli, carrots, cauliflower, cucumbers (for pickles), green peas, pineapples, snap beans, and spinach; EPA (1974) for potato and citrus fruit processing; and EPA (1975) for all other commodities.

Table A-244: Wastewater Outflow (m³/ton) and BOD Production (g/L) for U.S. Vegetables, Fruits, and Juices Production

Commodity	Wastewater Outflow (m ³ /ton)	Organic Content in Untreated Wastewater (g BOD/L)
Vegetables		
Potatoes	10.27	1.765
Other Vegetables	9.85	0.751
Fruit		
Apples	9.08	8.16
Citrus Fruits	10.11	0.317
Non-citrus Fruits	12.59	1.226
Grapes (for wine)	2.78	1.831

Sources: CAST (1995); 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 a very small percent of ethanol production 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 sugar or 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 is more efficient in terms of actual ethanol production (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 sludge digesters is commonly collected and either flared or used as fuel in the ethanol production process (ERG 2006b).

About 33 percent of wet milling facilities and 75 percent of dry milling facilities treat their wastewater anaerobically (ERG 2006b). A default emission factor of 0.2 kg CH₄/kg COD for anaerobic treatment was used to estimate the CH₄ produced from these on-site treatment systems. The amount of CH₄ 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 2006b). For facilities using biomethanators, approximately 90 percent of BOD is removed during on-site treatment (ERG 2006b, 2008a). For all other facilities, the removal of organics was assumed to be equivalent to secondary treatment systems, or 85 percent (IPCC 2019).

Petroleum Refining. Petroleum refining wastewater treatment operations have the potential to produce CH₄ emissions from anaerobic wastewater treatment. EPA's Office of Air and Radiation performed an Information Collection Request (ICR) for petroleum refineries in 2011.¹⁵³ Facilities that reported using non-aerated surface impoundments or other biological treatment units (trickling filter, rotating biological contactor), which have the potential to lead to anaerobic conditions, were assigned the IPCC default emission factor of 0.05 kg CH₄/kg COD. In addition, the wastewater generation rate was determined to be 26.4 gallons per barrel of finished product, or 0.8 m³/ton (ERG 2013b).

Breweries. Since 2010, the number of breweries has increased from less than 2,000 to more than 8,000 (Brewers Association 2021). This increase has primarily been driven by craft breweries, which have increased by over 250 percent during that period. Craft breweries were defined as breweries producing less than six million barrels of beer per year, and non-craft breweries produce greater than six million barrels. With their large amount of water use and high strength wastewater, breweries generate considerable CH₄ emissions from anaerobic wastewater treatment. However, because many breweries recover their CH₄, their emissions are much lower.

The Alcohol and Tobacco Tax and Trade Bureau (TTB) provides total beer production in barrels per year for different facility size categories from 2007 to 2023 (TTB 2024). For years prior to 2007, where TTB data were not readily available, the Brewers Almanac (Beer Institute 2011) was used, along with an estimated percent of craft and non-craft breweries based on the breakdown of craft and non-craft for the years 2007 through 2020.

To determine the overall amount of wastewater produced, data on water use per unit of production and a wastewater-to-water ratio were used from the Benchmarking Report (Brewers Association 2016a, BIER 2024) for both craft and non-craft breweries. Since brewing is a batch process, and different operations have varying organic loads, full-strength brewery wastewater can vary widely on a day-to-day basis. However, the organic content of brewery wastewater does not substantially change between craft and non-craft breweries. Some breweries may collect and discharge high strength wastewater from particular brewing processes (known as "side streaming") to a POTW, greatly reducing the organics content of the wastewater that is treated on site. Subsequently, the MCF for discharge to a POTW was assumed to be zero (ERG 2018b).

Breweries may treat some or all of their wastewater on site prior to discharge to a POTW or receiving water. On-site treatment operations can include physical treatment (e.g., screening, settling) which are not expected to contribute to CH₄ emissions, or biological treatment, which may include aerobic treatment or pretreatment in anaerobic reactors (ERG 2018b). The IPCC default emission factor of 0.2 kg

¹⁵³ Available online at <https://www.epa.gov/stationary-sources-air-pollution/comprehensive-data-collected-petroleum-refining-sector>.

CH₄/kg COD for anaerobic treatment and 0 for aerobic treatment were used to estimate the CH₄ produced from these on-site treatment systems (IPCC 2006). The amount of CH₄ recovered through anaerobic wastewater treatment was estimated, and a 99 percent destruction efficiency was used (ERG 2018b; Stier J. 2018). Very limited activity data are available on the number of U.S. breweries that are performing side streaming or pretreatment of wastewater prior to discharge.

Estimating N₂O Emissions by Source of Wastewater

Domestic Wastewater N₂O Emissions

Methodological equations for each of these systems are presented in the subsequent subsections; total domestic N₂O emissions are summarized as follows:

Equation A-97: Total Domestic N₂O Emissions from Wastewater Treatment and Discharge

$$\text{Total Domestic N}_2\text{O Emissions from Wastewater Treatment and Discharge (kt)} = A + B + C + D$$

where,

- A = Septic systems
- B = Centralized treatment, including aerobic systems (B1, other than constructed wetlands), constructed wetlands only (B2), and constructed wetlands used as tertiary treatment (B3);
- C = Centralized anaerobic systems
- D = Centralized wastewater treatment effluent

Table A-259 and Table A-260 present N₂O emissions for both septic and centralized systems, including emissions from centralized wastewater treatment effluent.

Methodology for Septic Systems (N₂O) Emissions (A):

ERG (2024) describes the data sources used to calculate the timeseries for the daily per capita protein supply (Protein_{per capita}) and the fraction of protein consumed (FPC). Protein_{per capita} is sourced from USDA (2014) for 1990 through 2009 while FAO (2024c) provides data for 2010 through 2022. 2023 is forecasted from the rest of the time series. As described in ERG (2008c), the FPC (kg protein consumed/kg protein available) is determined multiplying the percent of protein for each major food group (e.g., grain, fruits, meat, eggs) as determined by USDA (2015) by the percent of protein lost, as determined by USDA (1997).

Fundamental to the N₂O emissions estimated for both septic and centralized wastewater treatment is understanding the total nitrogen in that wastewater (TN_{DOMSEPTIC}, TN_{DOMCENTRALIZED}). These calculations are provided in Equation A-101 and Equation A-103, respectively.

Equation A-98: Fraction of Protein Consumed (U.S. Specific, ERG [2008c])

$$FPC \left(\frac{\text{kg protein consumed}}{\text{kg protein available}} \right) = 1 - \sum_f (\%loss_f \times \%protein_f)$$

Equation A-99: Annual per Capita Protein Supply (U.S. Specific)

$$\text{Protein}_{\text{SUPPLY}} \left(\frac{\text{kg/person}}{\text{day}} \right) = \text{Protein}_{\text{per capita}} / 1000 \times 365.25$$

Equation A-100: Consumed Protein (IPCC 2019 [Eq. 6.10A])

$$\text{Protein} \left(\frac{\text{kg/person}}{\text{day}} \right) = \text{Protein}_{\text{SUPPLY}} \times \text{FPC}$$

Table A-245: Variables and Data Sources for Protein Consumed

Variable	Variable Description	Units	Inventory Years: Source of I Value
Protein			
Protein_{SUPPLY}	Annual per capita protein supply ^a	kg/person/year	1990-2023: Calculated
Protein_{per capita}	Daily per capita protein supply ^a	g/person/day	1990-2009: USDA (2014) 2010-2022: FAO (2024b) 2023: Forecasted from the rest of the time series
1000	Conversion factor	g to kg	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion
FPC	Fraction of Protein Consumed ^a	kg protein consumed / kg protein available	1990-2010: USDA (2015) based on percent lost in USDA (1997), as described in ERG (2008c) 2011-2023: Forecasted from the rest of the time series

^a Value of this activity data varies over the *Inventory* time series.

Equation A-101: Total Nitrogen Entering Septic Systems (IPCC 2019 [Eq. 6.10])

$$\text{TN}_{\text{DOM\_SEPTIC}} \left(\frac{\text{kg N}}{\text{year}} \right) = (\text{US}_{\text{POP}} \times \text{T}_{\text{SEPTIC}}) \times \text{Protein} \times \text{F}_{\text{NPR}} \times \text{N}_{\text{HH}} \times \text{F}_{\text{NON-CON\_septic}} \times \text{F}_{\text{IND-COM\_septic}}$$

Equation A-102: N₂O Emissions from Septic Systems (IPCC 2019 [Eq. 6.9])

$$\text{A} \left(\frac{\text{kt N}_2\text{O}}{\text{year}} \right) = \text{TN}_{\text{DOM\_SEPTIC}} \times (\text{EF}_{\text{SEPTIC}}) \times 44/28 \times 1/10^6$$

Table A-246: Variables and Data Sources for N₂O Emissions from Septic System

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Septic Systems			
TN_{DOM_SEPTIC}	Total nitrogen entering septic systems	kg N/year	1990-2023: Calculated
US_{POP}	U.S. population ^a	Persons	United States and Puerto Rico: 1990-1999: U.S. Census Bureau (2002); Instituto de Estadísticas de Puerto Rico (2021) 2000-2009: U.S. Census Bureau (2011) 2010-2019: U.S. Census Bureau (2021) 2020-2023: U.S. Census Bureau (2023b) U.S. Territories other than Puerto Rico: 1990-2023: U.S. Census Bureau (2024)
T_{SEPTIC}	Percent treated in septic systems ^a	%	Odd years from 1989 through 2023: U.S. Census Bureau (2023a) Data for intervening years obtained by linear interpolation

F_{NPR}	Fraction of nitrogen in protein (0.16)	kg N/kg protein	1990-2023: IPCC (2019) Eq. 6.10
N_{HH}	Additional nitrogen from household products (1.17)	No units	1990-2023: IPCC (2019) Table 6.10a
F_{NON-CON_septic}	Factor for Non-Consumed Protein Added to Wastewater (1.13)	No units	1990-2023: IPCC (2019)
F_{IND-COM_septic}	Factor for Industrial and Commercial Co-Discharged Protein, septic systems (1)	No units	
EF_{SEPTIC}	Emission factor, septic systems (0.0045)	kg N ₂ O-N/kg N	1990-2023: IPCC (2019) Table 6.8a
44/28	Conversion factor	Molecular weight ratio of N ₂ O to N ₂	Standard conversion
1/10⁶	Conversion factor	kg to kt	Standard conversion

^a Value of this activity data varies over the *Inventory* time series.

Methodology for Centrally Treated Aerobic and Anaerobic Systems (N₂O) Emissions (B, C):

Equation A-103: Total Nitrogen Entering Centralized Systems (IPCC 2019 [Eq. 10])

$$\begin{aligned}
 & \text{TN}_{\text{DOMCENTRAL}} \left(\frac{\text{kg N}}{\text{year}} \right) \\
 &= (\text{US}_{\text{POP}} \times \text{T}_{\text{CENTRALIZED}}) \times \text{Protein} \times \text{F}_{\text{NPR}} \times \text{N}_{\text{HH}} \times \text{F}_{\text{NON-CON}} \times \text{F}_{\text{IND-COM}}
 \end{aligned}$$

Table A-247: Variables and Data Sources for Non-Consumed Protein and Nitrogen Entering Centralized Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
US_{POP}	U.S. population ^a	Persons	United States and Puerto Rico: 1990-1999: U.S. Census Bureau (2002); Instituto de Estadísticas de Puerto Rico (2021) 2000-2009: U.S. Census Bureau (2011) 2010-2019: U.S. Census Bureau (2021) 2020-2023: U.S. Census Bureau (2023b) U.S. Territories other than Puerto Rico: 1990-2023: U.S. Census Bureau (2024)
T_{CENTRALIZED}	Percent collected ^a	%	Odd years from 1989 through 2023: U.S. Census Bureau (2023a) Data for intervening years obtained by linear interpolation
Protein	Consumed protein per capita ^a	kg/person/year	1990-2023: Calculated
F_{NPR}	Fraction of nitrogen in protein (0.16)	kg N/kg protein	1990-2023: IPCC (2019), Eq. 6.10
N_{HH}	Factor for additional nitrogen from household products (1.17)	No units	1990-2023: IPCC (2019), Table 6.10a
F_{NON-CON}	Factor for U.S. specific non-consumed protein (1.13)	No units	1990-2023: IPCC (2019) Table 6.11
F_{IND-COM}	Factor for Industrial and Commercial Co-Discharged Protein (1.25)	No units	

^a Value of this activity data varies over the *Inventory* time series.

Table A-251 presents the data for U.S. population, population served by centralized wastewater treatment plants, available protein, and protein consumed. The methodological equations are:

Equation A-104: Total Domestic N₂O Emissions from Centrally Treated Aerobic Systems

Emissions from Centrally Treated Aerobic Systems (other than Constructed Wetlands)(B1)
+ *Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands Only)(B2)*
+ *Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands used as Tertiary Treatment)*

$$(B3) = B \left(\frac{\text{kt N}_2\text{O}}{\text{year}} \right)$$

where,

Equation A-105: N₂O Emissions from Centrally Treated Aerobic Systems (other than Constructed Wetlands) (IPCC 2019 [Eq. 6.9])

$$B1 \left(\frac{\text{kt N}_2\text{O}}{\text{year}} \right) = [(\text{TN}_{\text{DOM\_CENTRAL}}) \times (\% \text{ aerobic}_{\text{OTCW}})] \times \text{EF}_{\text{aerobic}} \times 44/28 \times 1/10^6$$

Table A-248: Variables and Data Sources for N₂O Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands) (kt N₂O/year)			
TN_{DOM_CENTRAL}	Total nitrogen entering centralized systems ^a	kg N/year	1990-2023: Calculated
% aerobic_{OTCW}	Flow to aerobic systems, other than constructed wetlands only / total flow to POTWs ^a	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: EPA (1992, 1996, 2000, 2004), respectively Data for intervening years obtained by linear interpolation. 2005-2023: Forecasted from the rest of the time series
EF_{aerobic}	U.S.-specific emission factor – aerobic systems (0.015)	kg N ₂ O-N/kg N	1990-2023: IPCC (2022)
44/28	Conversion factor	Molecular weight ratio of N ₂ O to N ₂	Standard conversion
1/10⁶	Conversion factor	kg to kt	Standard conversion

^a Value of this activity data varies over the *Inventory* time series.

Equation A-106: N₂O Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands Only) (IPCC 2014 [Eq. 6.9])

$$B2 \left(\frac{\text{kt N}_2\text{O}}{\text{year}} \right) = [(\text{TN}_{\text{DOM\_CENTRAL}}) \times (\% \text{ aerobic}_{\text{CW}})] \times \text{EF}_{\text{CW}} \times 44/28 \times 1/10^6$$

Equation A-107: N₂O Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands used as Tertiary Treatment) (U.S.-Specific)

$$B3 \left(\frac{\text{kt N}_2\text{O}}{\text{year}} \right) = [(\text{POTW\_flow\_CW}) \times (\text{N}_{\text{CW,INF}}) \times 3.785 \times (\text{EF}_{\text{CW}})] \times 1/10^6 \times 365.25$$

Table A-249: Variables and Data Sources for N₂O Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Constructed Wetlands Only (kt N₂O/year)			
TN_{DOM_CENTRAL}	Total nitrogen entering centralized treatment ^a	kg N/year	1990-2023: Calculated
% aerobic_{CW}	Flow to aerobic systems, constructed wetlands used as sole treatment / total flow to POTWs ^a	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004, 2008, and 2012) Data for intervening years obtained by linear interpolation. 2013-2023: Forecasted from the rest of the time series
EF_{CW}	Emission factor for constructed wetlands (0.0013)	kg N ₂ O-N/kg N	1990-2023: IPCC (2014) Table 6.7
44/28	Conversion factor	Molecular weight ratio of N ₂ O to N ₂	Standard conversion
1/10⁶	Conversion factor	kg to kt	Standard conversion
Emissions from Constructed Wetlands used as Tertiary Treatment (kt N₂O/year)			
POTW_flow_CW	Wastewater flow to POTWs that use constructed wetlands as tertiary treatment ^a	MGD	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004, 2008, and 2012) Data for intervening years obtained by linear interpolation. 2013-2023: Forecasted from the rest of the time series
N_{CW,INF}	BOD concentration in wastewater entering the constructed wetland (25)	mg/L	1990-2023: Metcalf & Eddy (2014)
3.785	Conversion factor	liters to gallons	Standard conversion
EF_{CW}	Emission factor for constructed wetlands (0.0013)	kg N ₂ O-N/kg N	1990-2023: IPCC (2014) Table 6.7
1/10⁶	Conversion factor	mg to kg	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion

^a Value of this activity data varies over the *Inventory* time series.

Equation A-108: N₂O Emissions from Centrally Treated Anaerobic Systems (IPCC 2019 [Eq. 6.9])

$$C \left(\frac{\text{kt N}_2\text{O}}{\text{year}} \right) = [(\text{TN}_{\text{DOM\_CENTRAL}}) \times (\% \text{ anaerobic})] \times \text{EF}_{\text{anaerobic}} \times 44/28 \times 1/10^6$$

Table A-250: Variables and Data Sources for N₂O Emissions from Centrally Treated Anaerobic Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Anaerobic Systems			
TN_{DOM_CENTRAL}	Total nitrogen entering centralized treatment ^a	kg N/year	1990-2023: Calculated
% anaerobic	Percent centralized wastewater that is anaerobically treated ^a	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: (EPA 1992, 1996, 2000, 2004), respectively Data for intervening years obtained by linear interpolation. 2005-2023: Forecasted from the rest of the time series
EF_{anaerobic}	Emission factor for anaerobic reactors/deep lagoons (0)	kg N ₂ O-N/kg N	1990-2023: IPCC (2019) Table 6.8A
44/28	Conversion factor	Molecular weight ratio of N ₂ O to N ₂	Standard conversion
1/10⁶	Conversion factor	mg to kg	Standard conversion

^a Value of this activity data varies over the *Inventory* time series.

Table A-251: U.S. Population (Millions) Fraction of Population Served by Centralized Wastewater Treatment (percent), Protein Supply (kg/person-year), and Protein Consumed (kg/person-year)

Year	1990	2005	2019	2020	2021	2022	2023
Population	253	300	332	335	336	337	338
Centralized WWT Population (%)	75.6	78.8	83.6	84.2	84.8	83.1	81.4
Protein Supply	43.1	44.9	45.1	45.9	44.6	44.9	44.9
Protein Consumed	33.2	34.7	34.7	35.4	34.4	34.6	34.6

Sources: Population – U.S. Census Bureau (2002); U.S. Census Bureau (2011); U.S. Census Bureau (2021); Instituto de Estadísticas de Puerto Rico (2021); U.S. Census Bureau (2023b); U.S. Census Bureau (2024); WWTP Population – U.S. Census Bureau (2023a); Available Protein – USDA (2014), FAO (2024b); Protein Consumed – USDA (2015), USDA (1997).

Methodology for Discharge of Centralized Treatment Effluent (N₂O) Emissions (D):

The methodological equations are:

Equation A-109: N₂O Emissions from Centrally Treated Systems Discharge (U.S.-Specific)

$$D \left(\frac{\text{kt N}_2\text{O}}{\text{year}} \right) = [(\text{N}_{\text{EFFLUENT,IMP}} \times \text{EF}_{\text{IMP}}) + (\text{N}_{\text{EFFLUENT,NONIMP}} \times \text{EF}_{\text{NONIMP}})] \times 44/28 \times 1/10^6$$

where,

Equation A-110: Total Organics in Centralized Treatment Effluent (IPCC 2019 [Eq. 6.8])

$$N_{\text{EFFLUENT,DOM}} \left(\frac{\text{kg N}}{\text{year}} \right) = [\text{TN}_{\text{DOM\_CENTRAL}}^{154} \times \% \text{ primary} \times (1 - N_{\text{rem,PRIMARY}})] + [\text{TN}_{\text{DOM\_CENTRAL}} \times \% \text{ secondary} \times (1 - N_{\text{rem,SECONDARY}})] + [\text{TN}_{\text{DOM\_CENTRAL}} \times \% \text{ tertiary} \times (1 - N_{\text{rem,TERTIARY}})]$$

Equation A-111: Total Nitrogen in Effluent Discharged to Impaired Waterbodies (U.S.-Specific)

$$N_{\text{EFFLUENT,IMP}} \left(\frac{\text{kg N}}{\text{year}} \right) = (N_{\text{EFFLUENT,DOM}} \times \text{Percent}_{\text{IMP}})/1000$$

Equation A-112: Total Nitrogen in Effluent Discharged to Nonimpaired Waterbodies (U.S.-Specific)

$$N_{\text{EFFLUENT,NONIMP}} \left(\frac{\text{kg N}}{\text{year}} \right) = N_{\text{EFFLUENT,DOM}} \times \text{Percent}_{\text{NONIMP}}/1000$$

Table A-252: Variables and Data Sources for N₂O Emissions from Centrally Treated Systems Discharge

Variable	Variable Description	Units	Source of Value
N _{EFFLUENT,DOM}	Total organics in centralized treatment effluent ^a	kg N/year	1990-2023: Calculated
44/28	Conversion factor	Molecular weight ratio of N ₂ O to N ₂	Standard conversion
1/10 ⁶	Conversion factor	kg to kt	Standard conversion
TN _{DOM_CENTRAL}	Total nitrogen entering centralized treatment ^a	kg N/year	1990-2023: Calculated
1000	Conversion factor	kg to kt	Standard Conversion
% primary	Percent of primary domestic centralized treatment ^a	%	1990,1991: Set equal to 1992.
% secondary	Percent of secondary domestic centralized treatment ^a	%	1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004, 2008, and 2012), respectively
% tertiary	Percent of tertiary domestic centralized treatment ^a	%	Data for intervening years obtained by linear interpolation. 2013-2023: Forecasted from the rest of the time series
N _{rem,PRIMARY}	Fraction of nitrogen removed from primary domestic centralized treatment (0.1)	No units	1990-2023: IPCC (2019) Table 6.10c
N _{rem,SECONDARY}	Fraction of nitrogen removed from secondary domestic centralized treatment (0.4)	No units	
N _{rem,TERTIARY}	Fraction of nitrogen removed from tertiary domestic centralized treatment (0.9)	No units	

¹⁵⁴ See emissions from centrally treated aerobic and anaerobic systems for methodological equation calculating TN_{DOM_CENTRAL}.

Variable	Variable Description	Units	Source of Value
$N_{\text{EFFLUENT,IMP}}$	Total nitrogen in effluent discharged to impaired waterbodies	kg N/year	1990-2023: Calculated
$N_{\text{EFFLUENT,NONIMP}}$	Total nitrogen in effluent discharged to nonimpaired waterbodies	kg N/year	
EF_{IMP}	Emission factor (discharge to impaired waterbodies) (0.19)	kg N_2O -N/kg N	
EF_{NONIMP}	Emissions factor (discharge to nonimpaired waterbodies) (0.005)	kg N_2O -N/kg N	
$\text{Percent}_{\text{IMP}}$	Percent of wastewater discharged to impaired waterbodies ^a	%	1990-2010: Set equal to 2010 2010: ERG (2021a) 2011: Obtained by linear interpolation
$\text{Percent}_{\text{NONIMP}}$	Percent of wastewater discharged to nonimpaired waterbodies ^a	%	2012: ERG (2021a) 2013-2023: Set equal to 2012

^a Value for this activity data varies over the *Inventory* time series.

Industrial Wastewater N_2O Emissions

Wastewater treatment and discharge N_2O emissions are displayed in Table A-261 and Table A-262 below.

Methodology for Industrial Wastewater Treatment Systems (N_2O) Emissions (A through D):

Equation A-113: Total Nitrogen in Industrial Wastewater

$$TN_{\text{IND}i} \left(\frac{\text{kg TN}}{\text{year}} \right) = P_i \times W_i \times TN_i$$

where,

$TN_{\text{IND}i}$	=	total nitrogen in wastewater for industry <i>i</i> for inventory year, kg TN/year
<i>i</i>	=	industrial sector
P_i	=	total industrial product for industrial sector <i>i</i> for inventory year, t/year
W_i	=	wastewater generated per unit of production for industrial sector <i>i</i> for inventory year, m ³ /t product
TN_i	=	total nitrogen in untreated wastewater for industrial sector <i>i</i> for inventory year, kg TN/m ³

Table A-238, above, contains production data for these industries, average wastewater outflow is shown in Table A-239 and the nitrogen loading in the outflow shown below in Table A-253.

Table A-253: U.S. Industrial Wastewater Nitrogen Data

Industry	Wastewater Total N (kg N/ m ³)	Source for Total N
Pulp and Paper	0.30 ^a	Cabrera (2017)
Meat Processing	0.19	IPCC (2019), Table 6.12
Poultry Processing	0.19	IPCC (2019), Table 6.12
Petroleum Refining	0.051	Kenari et al. (2010)
Breweries – Craft	0.055	IPCC (2019), Table 6.12
Breweries – NonCraft	0.055	IPCC (2019), Table 6.12

^a Units are kilograms N per air-dried metric ton of production.

Equation A-114: N₂O Emissions from Industrial Wastewater Treatment Plants

$$N_2O \text{ Plants}_{IND} \left(\frac{\text{kg N}_2\text{O}}{\text{year}} \right) = \left[\sum_i (T_{i,j} \times EF_{i,j} \times TN_{INDi}) \right] \times \frac{44}{28}$$

where,

$N_2O \text{ Plants}_{IND}$	=	N ₂ O emissions from industrial wastewater treatment plants for inventory year, kg N ₂ O/year
TN_{INDi}	=	total nitrogen in wastewater from industry <i>i</i> for inventory year, kg N/year
$T_{i,j}$	=	degree of utilization of treatment/discharge pathway or system <i>j</i> , for each industry <i>i</i> for inventory year
<i>i</i>	=	industrial sector
<i>j</i>	=	each treatment/discharge pathway or system
$EF_{i,j}$	=	emission factor for treatment/discharge pathway or system <i>j</i> , kg N ₂ O-N/kg N. 0.015 kg N ₂ O-N/kg N (IPCC 2022)
44/28	=	conversion of kg N ₂ O-N into kg N ₂ O

For each industry, the degree of utilization ($T_{i,j}$)—the percent of wastewater that undergoes each type of treatment—was previously determined for CH₄ emissions and presented in Table A-240.

Methodology for Industrial Wastewater Treatment Effluent (N₂O) Emissions (E through H):

Equation A-115: N₂O Emissions from Industrial Wastewater Treatment Effluent

$$N_2O \text{ Effluent}_{IND} \left(\frac{\text{kg N}_2\text{O}}{\text{year}} \right) = N_{EFFLUENT,IND} \times EF_{EFFLUENT} \times 44/28$$

where,

$N_2O \text{ Effluent}_{IND}$	=	N ₂ O emissions from industrial wastewater discharge for inventory year (kg N ₂ O/year)
$N_{EFFLUENT,IND}$	=	Total nitrogen in industry wastewater effluent discharged to aquatic environments for inventory year (kg N/year)
$EF_{EFFLUENT}$	=	Tier 1 emission factor for wastewater discharged to aquatic environments (0.005 kg N ₂ O-N/kg N) (IPCC 2019)
44/28	=	Conversion of kg N ₂ O-N into kg N ₂ O

Calculated industry-specific percent removals of nitrogen are presented in Table A-254, based on both EPA's Nutrients Tool (as discussed in EPA 2019b) as described in ERG (2021a), as well as IPCC (2019) defaults values for breweries.

Table A-254: Industrial Wastewater Nitrogen Discharged in 2018 by Sector (kg N)

Industry	N Effluent _{IND} (kg N)	Industry-Specific N Removal Factor (unitless)
Meat & Poultry	12,078,919	0.082
Petroleum Refineries	1,698,953	0.045
Pulp & Paper	18,809,623	1.08
Breweries ^a	1,604,878	NA

^a Nitrogen discharged by breweries was estimated as 60 percent of untreated wastewater nitrogen.

NA (Not Available)

Source: ERG (2021a).

Table A-255: Domestic Wastewater CH₄ Emissions from Septic and Centralized Systems (MMT CO₂ Eq. and Percent)

System	1990	2005	2019	2020	2021	2022	2023	2023 % of Domestic Wastewater
Septic Systems (A)	6.6	6.9	6.0	5.8	5.6	6.2	6.9	49.1%
Centrally-Treated Aerobic Systems (B)	0.7	1.1	2.0	2.1	2.2	2.1	2.1	14.8%
Centrally-Treated Anaerobic Systems (C)	7.5	6.4	3.8	3.6	3.4	3.1	2.9	20.4%
Anaerobic Sludge Digesters (D)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	1.6%
Centrally-Treated Wastewater Effluent (E)	1.4	1.4	2.0	2.1	2.1	2.0	2.0	14.0%
Total	16.5	16.0	14.0	13.8	13.5	13.7	14.0	100%

Notes: Totals may not sum due to independent rounding.

Table A-256: Domestic Wastewater CH₄ Emissions from Septic and Centralized Systems (kt and Percent)

System	1990	2005	2019	2020	2021	2022	2023	2023 % of Domestic Wastewater CH ₄
Septic Systems (A)	236	245	213	207	200	222	246	49.1%
Centrally-Treated Aerobic Systems (B)	25	41	71	75	78	76	74	14.8%
Centrally-Treated Anaerobic Systems (C)	269	228	135	129	122	112	102	20.4%
Anaerobic Sludge Digesters (D)	8	8	8	8	8	8	8	1.6%
Centrally-Treated Wastewater Effluent (E)	49	49	73	74	74	72	70	14.0%

Note: Totals may not sum due to independent rounding.

Table A-257: Industrial Wastewater CH₄ Emissions by Sector (MMT CO₂ Eq. and Percent)

Industry	1990	2005	2019	2020	2021	2022	2023	2023 % of Industrial Wastewater
Meat & Poultry (B, H)	3.5	4.7	5.6	5.6	5.7	5.7	5.7	79.3%
Pulp & Paper (A, G)	2.2	1.3	0.9	0.8	0.9	0.8	0.8	11.4%
Fruit & Vegetables (C, I)	0.2	0.3	0.2	0.2	0.2	0.2	0.3	3.5%
Ethanol Refineries (D, J)	0.0	0.1	0.2	0.2	0.2	0.2	0.2	2.3%
Breweries (F, L)	0.2	0.2	0.1	0.1	0.1	0.1	0.1	1.8%
Petroleum Refineries (E, K)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.7%
Total	6.2	6.7	7.2	7.2	7.2	7.2	7.1	100%

Note: Totals may not sum due to independent rounding.

Table A-258: Industrial Wastewater CH₄ Emissions by Sector (kt and Percent)

Industry	1990	2005	2019	2020	2021	2022	2023	2023 % of Industrial Wastewater CH ₄
Meat & Poultry (B, H)	124	167	199	202	202	204	202	79.3%
Pulp & Paper (A, G)	78	48	31	30	31	30	29	11.4%
Fruit & Vegetables (C, I)	9	9	9	9	9	9	9	3.5%
Ethanol Refineries(D, J)	1	4	6	6	6	6	6	2.3%
Breweries (F, L)	8	7	5	5	5	5	5	1.8%
Petroleum Refineries (E,K)	3	4	5	4	4	4	4	1.7%

Note: Totals may not sum due to independent rounding.

Table A-259: Domestic Wastewater N₂O Emissions from Septic and Centralized Systems (MMT CO₂ Eq. and Percent)

System	1990	2005	2019	2020	2021	2022	2023	2023 % of Domestic Wastewater
Septic Systems (A)	0.8	0.9	0.7	0.7	0.7	0.8	0.9	4.2%
Centrally-Treated Aerobic Systems (B)	9.7	12.9	15.5	16.1	15.8	15.6	15.4	75.8%
Centrally-Treated Anaerobic Systems (C)	+	+	+	+	+	+	+	+
Centrally-Treated Wastewater Effluent (D)	3.9	3.9	4.4	4.5	4.3	4.2	4.1	19.9%
Total	14.4	17.6	20.7	21.3	20.8	20.6	20.3	100%

+ Does not exceed 0.05 MMT CO₂ Eq., or 0.5 percent.

Note: Totals may not sum due to independent rounding.

Table A-260: Domestic Wastewater N₂O Emissions from Septic and Centralized Systems (kt and Percent)

System	1990	2005	2019	2020	2021	2022	2023	2023 % of Domestic Wastewater CH ₄
Septic Systems (A)	3	3	3	3	3	3	3	4.2%
Centrally-Treated Aerobic Systems (B)	37	49	58	61	60	59	58	75.8%
Centrally-Treated Anaerobic Systems (C)	+	+	+	+	+	+	+	+
Centrally-Treated Wastewater Effluent (D)	15	15	17	17	16	16	15	19.9%

+ Does not exceed 0.5 kt or 0.5 percent.

Note: Totals may not sum due to independent rounding.

Table A-261: Industrial Wastewater N₂O Emissions by Sector (MMT CO₂ Eq. and Percent)

Industry	1990	2005	2019	2020	2021	2022	2023	2023 % of Industrial Wastewater
Meat & Poultry (B, F)	0.1	0.2	0.2	0.2	0.2	0.2	0.2	47.6%
Petroleum Refineries (C, G)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	30.9%
Pulp & Paper (A, E)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	20.9%
Breweries (D, H)	+	+	+	+	+	+	+	0.6%
Total	0.4	0.4	0.5	0.5	0.5	0.5	0.5	100%

+ Does not exceed 0.05 MMT CO₂ Eq., or 0.5 percent.

Note: Totals may not sum due to independent rounding.

Table A-262: Industrial Wastewater N₂O Emissions by Sector (kt and Percent)

Industry	1990	2005	2019	2020	2021	2022	2023	2023 % of Industrial Wastewater CH ₄
Meat & Poultry (B, F)	0.5	0.7	0.8	0.8	0.8	0.8	0.8	47.6%
Petroleum Refineries (C, G)	+	0.5	0.6	0.5	0.5	0.5	0.5	30.9%
Pulp & Paper (A, E)	+	0.5	+	+	+	+	+	20.9%
Breweries (D, H)	+	+	+	+	+	+	+	0.6%

+ Does not exceed 0.5 kt or 0.5 percent.

Note: Totals may not sum due to independent rounding.

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ANNEX 4 IPCC Reference Approach for Estimating CO₂ Emissions from Fossil Fuel Combustion

It is possible to estimate carbon dioxide (CO₂) emissions from fossil fuel consumption using alternative methodologies and different data sources than those described in Annex 2.1 Methodology for Estimating Emissions of CO₂ from Fossil Fuel Combustion. For example, IPCC national inventory methodological guidelines show that it is good practice for countries, in addition to their “bottom-up” sectoral methodology, to complete a “top-down” Reference Approach for estimating CO₂ emissions from fossil fuel combustion. Volume 2: Energy, Chapter 6: Reference Approach of the *2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) states, “comparability between the sectoral and reference approaches continues to allow a country to produce a second independent estimate of CO₂ emissions from fuel combustion with limited additional effort and data requirements.” This reference method estimates fossil fuel consumption by adjusting national aggregate fuel production data for imports, exports, and stock changes rather than relying on end-user consumption surveys. The basic principle is that once carbon (C)-based fuels are brought into a national economy, they are either saved in some way (e.g., stored in products, kept in fuel stocks, or left unoxidized in ash) or combusted, and therefore the C in them is oxidized and released into the atmosphere. Accounting for actual consumption of fuels at the sectoral or sub-national level is not required. The following discussion provides the detailed calculations for estimating CO₂ emissions from fossil fuel combustion from the United States using the IPCC-recommended Reference Approach.

Step 1: Collect and Assemble Data in Proper Format

To ensure the comparability of national inventories, the IPCC has recommended that countries report energy data using the International Energy Agency (IEA) reporting convention. National energy statistics were collected in physical units from several Energy Information Administration (EIA) documents in order to obtain the necessary data on production, imports, exports, and stock changes.

It was necessary to modify these data to generate more accurate apparent consumption estimates of these fuels. The first modification adjusts for consumption of fossil fuel feedstocks accounted for in the Industrial Processes and Product Use chapter, which include the following: unspecified coal for coal coke used in iron and steel production; natural gas, distillate fuel, and coal used in iron and steel production; natural gas used for ammonia production; petroleum coke used in the production of aluminum, ferroalloys, titanium dioxide, ammonia, and silicon carbide; and other oil and residual fuel oil used in the manufacture of C black. The second modification adjusts for the inclusion of biofuels in motor fuel statistics. Net carbon fluxes from changes in biogenic carbon reservoirs in croplands are accounted for in the estimates for Land Use, Land-Use Change, and Forestry (see Chapter 6). The third modification adjusts for consumption of bunker fuels, which refer to quantities of fuels used for international transportation estimated separately from U.S. totals. The fourth modification consists of the addition of U.S. Territories data that are typically excluded from the national aggregate energy statistics. The territories include Puerto Rico, U.S. Virgin Islands, Guam, American Samoa, Wake Island, and U.S. Pacific Islands. These data, as well as the production, import, export, and stock change statistics, are presented in Table A-255. Furthermore, waste fuels (e.g., MSW combustion) is not captured as part of the reference approach energy statistics. Therefore, waste fuels are not used in the comparison between the sectoral and reference approaches energy use in order to improve consistency between the reference and sectoral approaches in terms of estimation coverage. However, sectoral estimates for MSW combustion emissions are added to the reference approach in order to align CO₂ emissions comparisons across the two different approaches.

The C content of fuel varies with the fuel’s heat content. Therefore, for an accurate estimation of CO₂ emissions, fuel statistics were provided on an energy content basis (e.g., Btu or joules). Because detailed fuel production statistics are typically provided in physical units (as in Table A-255 for 2023), they were converted to units of energy before CO₂ emissions were calculated. Fuel statistics were converted to their energy equivalents by using

conversion factors provided by EIA. These factors and their data sources are displayed in Table A-256. The resulting fuel type-specific energy data for 2023 are provided in Table A-257.

Step 2: Estimate Apparent Fuel Consumption

The next step of the IPCC Reference Approach is to estimate “apparent consumption” of fuels within the country. This requires a balance of primary fuels produced, plus imports, minus exports, and adjusting for stock changes. In this way, C enters an economy through energy production and imports (and decreases in fuel stocks) and is transferred out of the country through exports (and increases in fuel stocks). Thus, apparent consumption of primary fuels (including crude oil, natural gas liquids, anthracite, bituminous, subbituminous and lignite coal, and natural gas) can be calculated as follows:

$$\text{Apparent Consumption} = \text{Production} + \text{Imports} - \text{Exports} - \text{Stock Change}$$

Flows of secondary fuels (e.g., gasoline, residual fuel, coke) should be added to primary apparent consumption. The production of secondary fuels, however, should be ignored in the calculations of apparent consumption since the C contained in these fuels is already accounted for in the supply of primary fuels from which they were derived (e.g., the estimate for apparent consumption of crude oil already contains the C from which gasoline would be refined). Flows of secondary fuels should therefore be calculated as follows:

$$\text{Secondary Consumption} = \text{Imports} - \text{Exports} - \text{Stock Change}$$

Note that this calculation can result in negative numbers for apparent consumption of secondary fuels. This result is perfectly acceptable since it merely indicates a net export or stock increase in the country of that fuel when domestic production is not considered.

Next, the apparent consumption and secondary consumption need to be adjusted for feedstock uses of fuels accounted for in the Industrial Processes and Product Use chapter, international bunker fuels, and U.S. territory fuel consumption. Bunker fuels and feedstocks accounted for in the Industrial Processes and Product Use chapter are subtracted from these estimates, while fuel consumption in U.S. Territories is added.

The IPCC Reference Approach calls for estimating apparent fuel consumption before converting to a common energy unit. However, certain primary fuels in the United States (e.g., natural gas and steam coal) have separate conversion factors for production, imports, exports, and stock changes. In these cases, it is not appropriate to multiply apparent consumption by a single conversion factor since each of its components has different heat contents. Therefore, United States fuel statistics were converted to their heat equivalents before estimating apparent consumption. Results are provided in Table A-256.

Step 3: Estimate Carbon Emissions

Once apparent consumption is estimated, the remaining calculations are similar to those for the “bottom-up” Sectoral Approach (see Annex 2.1 Methodology for Estimating Emissions of CO₂ from Fossil Fuel Combustion). Potential CO₂ emissions were estimated using fuel-specific C coefficients (see Table A-257).¹⁵⁵ The C in products from non-energy uses of fossil fuels (e.g., plastics or asphalt) that is stored was then estimated and subtracted (see Table A-258). This step differs from the Sectoral Approach in that emissions from both fuel combustion and non-energy uses are accounted for directly in the Reference Approach. As a result, the Reference Approach emission estimates are comparable to those of the Sectoral Approach, with the exception that the NEU source category emissions are included in the Reference Approach and reported separately in the Sectoral Approach.¹⁵⁶

¹⁵⁵ Carbon coefficients from EIA were used wherever possible. Because EIA did not provide coefficients for coal, the IPCC-recommended emission factors were used in the top-down calculations for these fuels. See notes in Table A-258 for more specific source information.

¹⁵⁶ The emission scope of the reference and the sectoral approaches is the same since C emissions from NEU (i.e. C not excluded) are included in both approaches, the energy consumption covered by the sectoral approach includes both fuel

Finally, to obtain actual CO₂ emissions, net emissions were adjusted for any C that remained unoxidized as a result of incomplete combustion (e.g., C contained in ash or soot). The fraction oxidized was assumed to be 100 percent for petroleum, coal, and natural gas based on *2006 IPCC Guidelines* (see Annex 2.1 Methodology for Estimating Emissions of CO₂ from Fossil Fuel Combustion).

Step 4: Convert to CO₂ Emissions

Because the *2006 IPCC Guidelines* recommend that countries report greenhouse gas emissions on a full molecular weight basis, the final step in estimating CO₂ emissions from fossil fuel consumption was converting from units of C to units of CO₂. Actual C emissions were multiplied by the molecular-to-atomic weight ratio of CO₂ to C (44/12) to obtain total CO₂ emitted from fossil fuel combustion in million metric tons (MMT). The results are contained in Table A-258.

Comparison Between Sectoral and Reference Approaches

These two alternative approaches can both produce reliable estimates that are comparable within a few percent. Note that the reference approach includes emissions from non-energy uses. Therefore, these totals should be compared to the aggregation of fuel use and emission totals from Annex 2.1 Methodology for Estimating Emissions of CO₂ from Fossil Fuel Combustion and Annex 2.3 Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels. These two sections together are henceforth referred to as the Sectoral Approach. Other than this distinction, the major difference between methodologies employed by each approach lies in the energy data used to derive C emissions (i.e., the actual surveyed consumption for the Sectoral Approach versus apparent consumption derived for the Reference Approach). In theory, both approaches should yield identical results. In practice, however, slight discrepancies occur. Past international peer reviews have highlighted the need to further investigate these discrepancies in data reported in common data tables. The investigation found that the most recent (two to three) inventory years tend to have larger differences in consumption and emissions estimates occurring earlier in the time series. This is a result of annual energy consumption data revisions in the EIA energy statistics, and the revisions have the greatest impact on the most recent few years of inventory estimates. As a result, the differences between the Sectoral and Reference Approach decrease and are resolved over time. For the United States, these differences are discussed below. Note: fossil emissions from the combustion of municipal solid waste (MSW) including from tires are derived following the approach described in Annex 3.7 Incineration of Waste for both the reference and sectoral approaches, as there are no reference data available.

Differences in Total Amount of Energy Consumed

Table A-262 summarizes the differences between the Reference and Sectoral Approaches in estimating total energy consumption in the United States. Although theoretically the two methods should arrive at the same estimate for U.S. energy consumption, the Reference Approach provides an energy consumption total that is 0.5 percent lower than the Sectoral Approach for 2023. The greatest differences lie in higher estimates for natural gas and coal consumption for the Reference Approach (0.9 percent and 0.8 percent, respectively) and lower estimates for petroleum consumption for the Reference Approach (less than 0.05 percent).

There are several potential sources for the discrepancies in consumption estimates:

- *Product Definitions.* The fuel categories in the Reference Approach are different from those used in the Sectoral Approach, particularly for petroleum. For example, the Reference Approach estimates apparent consumption for crude oil. Crude oil is not typically consumed directly but refined into other products. As a result, the United States does not focus on estimating the energy content of the various grades of crude oil, but rather estimating the energy content of the various products resulting from crude oil refining. The United States does not believe that estimating apparent consumption for crude oil, and the resulting energy content of the crude oil,

consumption and NEU, which is reported under category 1.A.5 other, hence the scope of energy consumption under the sectoral approach is comparable with that under the reference approach without excluding NEU. To the extent it is indicated that NEU emissions are subtracted under the sectoral approach, it means that they are reported separately, not that they are not covered by the sectoral approach.

is the most reliable method for the United States to estimate its energy consumption. Other differences in product definitions include using sector-specific coal statistics in the Sectoral Approach (i.e., residential, commercial, industrial coking, industrial other, and transportation coal), while the Reference Approach characterizes coal by rank (e.g., anthracite, bituminous).

- *Heat Equivalents.* It can be difficult to obtain heat equivalents for certain fuel types, particularly for categories such as “crude oil” where the key statistics are derived from thousands of producers in the United States and abroad. Furthermore, Hydrocarbon Gas Liquids (HGL) is a blend of multiple paraffinic hydrocarbons: ethane, propane, isobutane, and normal butane, and their associated olefins: ethylene, propylene, isobutylene, and butylene, each with their own heat content. The heat content for HGL varies annually depending upon the components of the blend.
- *Possible Inconsistencies in U.S. Energy Data.* The United States has not focused its energy data collection efforts on obtaining the type of aggregated information used in the Reference Approach. Rather, the United States believes that its emphasis on collection of detailed energy consumption data is a more accurate methodology for the United States to obtain reliable energy data. Therefore, top-down statistics used in the Reference Approach may not be as accurately collected as bottom-up statistics applied to the Sectoral Approach.
- *Balancing Item.* The Reference Approach uses *apparent* consumption estimates while the Sectoral Approach uses *reported* consumption estimates. While these numbers should be equal, there always seems to be a slight difference that is often accounted for in energy statistics as a “balancing item.”

Differences in Estimated CO₂ Emissions

Given these differences in energy consumption data, the next step for each methodology involved estimating emissions 1a that the “bottom-up” Sectoral Approach provides a more accurate assessment of CO₂ emissions at the fuel level. This improvement in accuracy is largely a result of the data collection techniques used in the United States, where there has been more emphasis on obtaining the detailed products-based information used in the Sectoral Approach than obtaining the aggregated energy flow data used in the Reference Approach. The United States believes that it is valuable to understand both methods.

Table A-255: 2023 U.S. Energy Statistics (Physical Units)

Fuel Category (Units)	Fuel Type	Production	Imports	Exports	Stock Change	Adjustment	Bunkers	U.S. Territories
Solid Fuels (Thousand Short Tons)	Anthracite Coal	2,917	[1]	[1]	[1]			
	Bituminous Coal	263,087	[1]	[1]	[1]			
	Sub-bituminous Coal	271,074	[1]	[1]	[1]	367		
	Lignite	40,876	[1]	[1]	[1]	818		
	Coke		206	1,514	(152)			
	Unspecified Coal		4,010	99,791	42,276	18,034		1,239
Gaseous Fuels	Natural Gas (Million Cubic Feet)	37,865,787	2,928,175	7,609,597	555,020	410,478		81,770
	Still Gas (Thousand Barrels)		0	0	0			
Liquid Fuels (Thousand Barrels)	Crude Oil	4,721,095	2,368,436	1,489,794	(20,957)			
	HGL	2,371,996	61,649	978,453	12,149			2,664
	Other Liquids	0	438,138	180,643	14,677			
	Motor Gasoline	(2,404)	43,048	297,981	989	233,505		12,718
	Aviation Gasoline		220	0	(105)			
	Kerosene		70	1,430	(243)			18
	Jet Fuel		46,424	63,085	4,737		166,286	6,097
	Distillate Fuel		61,797	407,365	11,587	51	16,143	12,395
	Residual Fuel		40,184	45,735	(6,645)	7,000	48,004	10,164
	Naphtha for petrochemical feedstocks		4,079	0	60			
	Petroleum Coke		2,776	206,240	(952)	8,188		

Other Oil for petrochemical feedstocks	1,888	13,995	169	1,240
Special Naphthas	6,541	0	110	
Lubricants	16,303	41,740	(1,284)	172
Waxes	1,463	1,497	55	
Asphalt/Road Oil	19,000	6,809	(2,781)	
Misc. Products	0	861	(86)	1

[1] Included in Unspecified Coal

Note: Parentheses indicate negative values.

Sources: Solid and Gas Fuels: EIA (2025 and 2024b); Liquid Fuels: EIA (2024a).

Table A-256: 2023 Conversion Factors to Energy Units (Heat Equivalents)

Fuel Category (Units)	Fuel Type	Production	Imports	Exports	Stock Change	Adjustment	Bunkers	U.S. Territories
Solid Fuels (Million Btu/Short Ton)	Anthracite Coal	25.50						
	Bituminous Coal	23.90						
	Sub-bituminous Coal	17.49				25.78		
	Lignite	13.13				12.87		
	Coke		21.93	24.06	21.93			
	Unspecified		25.00	25.97	20.86	24.76		25.14
Gaseous Fuels	Natural Gas (BTU/Cubic Foot)	1,036	1,025	1,009	1,036	1,036		1,036
	Still Gas (Million Btu/Barrel)		6.00	6.00	6.00		6.00	6.00
Liquid Fuels (Million Btu/Barrel)	Crude Oil	5.69	6.06	5.73	5.73		5.73	5.73
	HGL	4.22	4.22	4.22	4.22		4.22	4.22
	Other Liquids	5.83	5.83	5.83	5.83		5.83	5.83
	Motor Gasoline	5.05	5.05	5.05	5.05	5.05	5.05	5.05
	Aviation Gasoline		5.05	5.05	5.05		5.05	5.05
	Kerosene		5.67	5.67	5.67		5.67	5.67
	Jet Fuel ^a		5.67	5.67	5.67		5.68	5.67
	Distillate Fuel		5.83	5.83	5.83	5.83	5.83	5.83
	Residual Oil		6.29	6.29	6.29	6.29	6.29	6.29
	Naphtha for petrochemical feedstocks		5.25	5.25	5.25		5.25	5.25
	Petroleum Coke		6.02	6.02	6.02	6.02	6.02	6.02
	Other Oil for petrochemical feedstocks		5.83	5.83	5.83	5.83	5.83	5.83
	Special Naphthas		5.25	5.25	5.25		5.25	5.25

Lubricants	6.07	6.07	6.07	6.07	6.07
Waxes	5.54	5.54	5.54	5.54	5.54
Asphalt/Road Oil	6.64	6.64	6.64	6.64	6.64
Misc. Products	5.80	5.80	5.80	5.80	5.80

^a Jet fuel used in bunkers has a different heating value based on data specific to that source.

Sources: Coal and lignite production: EIA (1992); Coke, Natural Gas Crude Oil, HGL, and Motor Gasoline: EIA (2025); Unspecified Solid Fuels: EIA (2011).

Table A-257: 2023 Apparent Consumption of Fossil Fuels (TBtu)

Fuel Category	Fuel Type	Production	Imports	Exports	Stock Change	Adjustment	Bunkers	U.S. Territories	Apparent Consumption
Solid Fuels	Anthracite Coal	74.4						-	74.4
	Bituminous Coal	6,287.3						-	6,287.3
	Sub-bituminous Coal	4,741.0				9.5		-	4,731.5
	Lignite	536.8				10.5		-	526.3
	Coke	-	4.5	36.4	(3.3)			-	(28.6)
	Unspecified	-	100.3	2,591.8	881.9	446.6		31.2	(3,788.9)
Gaseous Fuels	Natural Gas	39,229.0	3,001.4	7,678.1	575.0	425.3		84.7	33,636.7
	Still Gas								
Liquid Fuels	Crude Oil	26,858.3	14,362.2	8,535.0	(120.1)		-	-	32,805.5
	HGL	9,999.1	259.9	4,124.6	51.2		-	11.2	6,094.3
	Other Liquids	-	2,552.2	1,052.2	85.5		-	-	1,414.4
	Motor Gasoline	(12.1)	217.3	1,504.5	5.0		-	64.2	(1,240.1)
	Aviation Gasoline	-	1.1	-	(0.5)		-	-	1.6
	Kerosene	-	0.4	8.1	(1.4)		-	0.1	(6.2)
	Jet Fuel	-	263.2	357.7	26.9		943.9	34.6	(1,030.7)
	Distillate Fuel	-	360.0	2,372.9	67.5	0.3	94.0	72.2	(2,102.6)

Residual Oil	-	252.6	287.5	(41.8)	44.0	301.8	63.9	(275.0)
Naphtha for petrochemical feedstocks	-	21.4	-	0.3		-	-	21.1
Petroleum Coke	-	16.7	1,242.4	(5.7)	49.3	-	-	(1,269.3)
Other Oil for petrochemical feedstocks	-	11.0	81.5	1.0	7.2	-	-	(78.7)
Special Naphthas	-	34.3	-	0.6		-	-	33.7
Lubricants	-	98.9	253.2	(7.8)		-	1.0	(145.4)
Waxes	-	8.1	8.3	0.3		-	-	(0.5)
Asphalt/Road Oil	-	126.1	45.2	(18.5)		-	-	99.4
Misc. Products	-	-	5.0	(0.5)		-	0.0	(4.5)
Total	87,713.7	21,691.6	30,184.5	1,495.6	992.7	1,339.7	363.1	75,755.9

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table A-258: 2023 Potential CO₂ Emissions

Fuel Category	Fuel Type	Carbon Coefficients (MMT Carbon/QBtu)		Potential Emissions (MMT CO ₂ Eq.)
Solid Fuels	Anthracite Coal	0.07	28.28	7.7
	Bituminous Coal	6.29	25.42	585.9
	Sub-bituminous Coal	4.73	26.48	459.4
	Lignite	0.53	26.82	51.8
	Coke	(0.03)	24.80	(2.6)
	Unspecified	(3.79)	25.34	(352.0)
Gaseous Fuels	Natural Gas	33.64	14.43	1,780.0
	Still Gas	-	18.20	-
Liquid Fuels	Crude Oil	32.81	20.31	2,442.5
	HGL	6.09	18.52	413.8
	Other Liquids	1.41	20.31	105.3
	Motor Gasoline	(1.24)	19.27	(87.6)
	Aviation Gasoline	0.00	18.86	0.1
	Kerosene	+	19.96	(0.5)
	Jet Fuel	(1.03)	19.70	(74.4)
	Distillate Fuel	(2.10)	20.22	(155.9)
	Residual Oil	(0.28)	20.48	(20.7)
	Naphtha for petrochemical feedstocks	0.02	18.55	1.4
	Petroleum Coke	(1.27)	27.85	(129.6)
	Other Oil for petrochemical feedstocks	(0.08)	20.17	(5.8)
	Special Naphthas	0.03	19.74	2.4
	Lubricants	(0.15)	20.20	(10.8)
	Waxes	(+)	19.80	(+)
	Asphalt/Road Oil	0.10	20.55	7.5
	Misc. Products	(+)	-	-
Total				5,018.0

Sources: Carbon content coefficients by coal rank from USGS (1998), PSU (2010), Gunderson (2019), IGS (2019), ISGS (2019), and eCFR (2024); natural gas carbon content coefficients from EPA (2010) and EIA (2025); unspecified solid fuel and liquid fuel carbon content coefficients from EPA (2010) and ICF (2020).

Table A-259: 2023 Non-Energy Carbon Stored in Products

Fuel Type	Consumption for Non-Energy Use (TBtu)	Carbon Coefficients (MMT Carbon/QBtu)	Carbon Content (MMT Carbon)	Fraction Sequestered	Carbon Stored (MMT CO ₂ Eq.)
Coal	65.4	24.80	1.62	0.10	1.2
Natural Gas	663.7	14.43	9.58	0.66	23.2
Asphalt & Road Oil	891.8	20.55	18.33	1.00	66.9
HGL	2,968.1	16.81	49.88	0.66	120.7
Lubricants	97.5	20.20	1.97	0.09	0.7
Natural Gasoline ^a	0.0	18.24	0.00	0.66	0.0
Petrochemical Feedstocks	[1]	[1]	[1]	[1]	23.1
Petroleum Coke	0.0	27.85	0.00	0.30	0.0
Special Naphtha	83.4	19.74	1.65	0.66	4.0

Waxes/Misc.	[1]	[1]	[1]	[1]	0.6
Misc. U.S. Territories					
Petroleum	[1]	[1]	[1]	[1]	+
Total					240.3

[1] Values for Misc. U.S. Territories Petroleum, Petrochemical Feedstocks, and Waxes/Misc. are not shown because these categories are aggregates of numerous smaller components.

+ Does not exceed 0.05 MMT CO₂ Eq.

Note: Totals may not sum due to independent rounding.

^aFormerly referred to as “pentanes plus.” this source has been adjusted and is reported separately from HGL to align with historic data and revised EIA terminology.

Table A-260: 2023 Reference Approach CO₂ Emissions from Fossil Fuel Consumption (MMT CO₂ Eq.)

Fuel Category	Potential Emissions	Carbon Sequestered	Net Emissions	Fraction Oxidized	Total Emissions
Coal	750.2	1.2	749.0	100.0%	749.0
Petroleum	2,487.9	216.0	2,271.9	100.0%	2,271.9
Natural Gas	1,780.0	23.2	1,756.8	100.0%	1,756.8
Total	5,018.0	240.3	4,777.6	-	4,777.6

Note: Totals may not sum due to independent rounding.

Table A-261: Fuel Consumption in the United States by Estimating Approach (Tbtu)^a

Approach	1990	1995	2000	2005	2010	2016	2017	2018	2019	2020	2021	2022	2023
Sectoral	69,697	74,607	82,491	83,639	78,461	76,170	75,492	78,792	77,804	71,140	75,323	76,615	75,414
Coal	18,098	19,210	21,755	22,213	20,305	13,817	13,405	12,802	10,876	8,815	10,081	9,437	7,742
Natural Gas	19,147	22,148	23,372	22,267	24,297	28,154	27,716	30,815	31,913	31,300	31,392	33,012	33,343
Petroleum	32,452	33,249	37,363	39,159	33,859	34,200	34,371	35,175	35,015	31,025	33,851	34,166	34,329
Reference													
(Apparent)	68,865	74,182	82,005	83,979	78,276	75,562	75,409	78,449	77,563	71,005	75,280	76,258	75,756
Coal	17,723	18,748	21,148	22,211	19,869	13,721	13,296	12,710	10,840	8,754	9,908	9,384	7,802
Natural Gas	19,255	22,252	23,465	22,334	24,394	28,237	27,830	30,945	32,081	31,480	31,608	33,237	33,637
Petroleum	31,887	33,182	37,392	39,434	34,012	33,604	34,283	34,794	34,642	30,771	33,765	33,638	34,317
Difference	-1.2%	-0.6%	-0.6%	0.4%	-0.2%	-0.8%	-0.1%	-0.4%	-0.3%	-0.2%	-0.1%	-0.5%	0.5%
Coal	-2.1%	-2.4%	-2.8%	0.0%	-2.1%	-0.7%	-0.8%	-0.7%	-0.3%	-0.7%	-1.7%	-0.6%	0.8%
Natural Gas	0.6%	0.5%	0.4%	0.3%	0.4%	0.3%	0.4%	0.4%	0.5%	0.6%	0.7%	0.7%	0.9%
Petroleum	-1.7%	-0.2%	0.1%	0.7%	0.5%	-1.7%	-0.3%	-1.1%	-1.1%	-0.8%	-0.3%	-1.5%	0.0%

^a Includes U.S. Territories. Does not include international bunker fuels.

Note: Totals may not sum due to independent rounding.

Table A-262: CO₂ Emissions from Fossil Fuel Combustion by Estimating Approach (MMT CO₂ Eq.)^a

Approach	1990	1995	2000	2005	2010	2016	2017	2018	2019	2020	2021	2022	2023
Sectoral	4,864	5,155	5,757	5,882	5,442	5,019	4,965	5,120	4,972	4,453	4,778	4,817	4,679
Coal	1,720	1,824	2,070	2,121	1,937	1,319	1,280	1,222	1,038	843	964	903	741
Natural Gas	1,005	1,162	1,226	1,172	1,278	1,470	1,444	1,605	1,661	1,628	1,634	1,720	1,738
Petroleum	2,126	2,155	2,447	2,576	2,214	2,216	2,228	2,279	2,260	1,969	2,167	2,181	2,188
MSW	13	14	13	13	13	14	13	13	13	13	12	12	12
Reference													
(Apparent)	4,828	5,171	5,745	5,955	5,469	5,042	5,022	5,171	5,039	4,517	4,852	4,875	4,790
Coal	1,668	1,773	2,005	2,108	1,891	1,304	1,259	1,210	1,034	836	945	897	749
Natural Gas	1,012	1,169	1,232	1,176	1,284	1,476	1,452	1,615	1,673	1,641	1,649	1,735	1,757
Petroleum	2,135	2,215	2,494	2,659	2,282	2,248	2,298	2,333	2,319	2,027	2,245	2,229	2,272
MSW	13	14	13	13	13	14	13	13	13	13	12	12	12
Difference	-0.7%	0.3%	-0.2%	1.2%	0.5%	0.5%	1.2%	1.0%	1.4%	1.4%	1.5%	1.2%	2.4%
Coal	-3.0%	-2.8%	-3.1%	-0.6%	-2.4%	-1.1%	-1.6%	-1.0%	-0.3%	-0.8%	-2.0%	-0.6%	1.1%
Natural Gas	0.7%	0.6%	0.5%	0.3%	0.5%	0.4%	0.6%	0.6%	0.8%	0.8%	0.9%	0.9%	1.1%
Petroleum	0.4%	2.8%	1.9%	3.2%	3.1%	1.4%	3.1%	2.4%	2.6%	2.9%	3.6%	2.2%	3.8%
MSW	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

^a Includes U.S. Territories. Does not include international bunker fuels.

Note: Totals may not sum due to independent rounding.

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ANNEX 5 Assessment of the Sources and Sinks of Greenhouse Gas Emissions Not Included

This report is intended to be a comprehensive assessment of anthropogenic¹⁵⁷ sources and sinks of greenhouse gas emissions for the United States, but certain sources and/or sinks have been identified which are not included in the estimates presented for various reasons. Before discussing these sources and sinks, it is important to note that processes or activities that are not *anthropogenic in origin* or do not result in a *net source or sink* of greenhouse gas emissions are intentionally excluded from a national inventory of anthropogenic greenhouse gas emissions, consistent with the methodological framework from the IPCC for national inventories.

The anthropogenic source and sink categories described in this annex are not included in the U.S. national inventory estimates. The reasons for not including that source or sink category in the national greenhouse gas *Inventory* include one or more of the following:

- Emissions and/or removals do not occur within the United States.
- A methodology for estimating emissions and/or removals from a source and/or sink does not currently exist.
- Though an initial estimating method has been developed, adequate data are unavailable to estimate emissions and/or removals over the time series.
- Emissions and/or removals are determined to be insignificant in terms of overall national emissions, as defined per national inventory reporting guidelines, based on available data or a preliminary assessment of significance. Further, data collection to estimate emissions and/or removals would require disproportionate amount of effort (e.g., dependent on additional resources and impact improvements to key categories, etc.).

In general, data availability remains the primary constraint for estimating and including the emissions and removals from source and sink categories that do occur within the United States but are currently excluded, as discussed further below. Methods to estimate emissions and removals from these categories are available in the *2006 IPCC Guidelines* and or its supplements and refinements. Many of these categories are insignificant in terms of overall national emissions based on available proxy information, qualitative information on activity levels per national circumstances, and/or expert judgment, and not including them introduces a very minor bias.

For transparency, national inventory reports should indicate the sources and sinks not included in their inventories but for which estimation methods are available in the IPCC guidelines and explain the reasons for such exclusion. The notation key “NE,” meaning not estimated, is used reporting tables that accompany this *Inventory* report to indicate when activity data and/or emissions by sources and removals by sinks of GHGs that have not been estimated but for which a corresponding activity may occur within a Party.

Based on the reporting guidance mentioned above, the United States is providing more information on the significance of these excluded categories below and aims to update information on the significance to the extent feasible during each annual compilation cycle. Data availability may impact the feasibility of undertaking a quantitative significance assessment. The United States is continually working to improve its understanding of such sources or sink categories, including seeking data required to estimate related emissions and/or sinks, prioritizing efforts and resources for categories that may be significant. The United States is implementing improvements this cycle, including new emission categories previously not estimated in the *Inventory* to enhance

¹⁵⁷The term “anthropogenic,” in this context, refers to greenhouse gas emissions and removals that are a direct result of human activities or are the result of natural processes that have been affected by human activities (*2006 IPCC Guidelines for National Greenhouse Gas Inventories*).

completeness of the *Inventory*. The full list of sources and sink categories not estimated, along with explanations for their exclusion, is provided in Table 9 of the CRTs.

Source and Sink Categories Not Estimated

This section provides additional information on the reasons each category was not estimated, organized by sector and source or sink category. A summary of these exclusions, including the estimated level of emissions and/or removals where feasible, is included in Table A-263. Per the reporting guidelines considering overall level and trend of gross U.S. emissions, the threshold for significance for estimating emissions and removals from a specific category is 500 kt CO₂ Eq. Collectively, these exclusions should not exceed 0.1 percent of total gross emissions, or 6.2 MMT CO₂ Eq. (6,197.3 kt CO₂ Eq.). While it is not possible to proxy all categories due to the availability of data and the disproportionate efforts to collect data necessary to estimate emissions and/or removals, categories for which proxies have been estimated total 1.9 CO₂ Eq. (1,898 kt CO₂ Eq.).

Table A-263: Summary of Sources and Sinks Not Included in the *Inventory* of U.S. Greenhouse Gas Emissions and Sinks: 1990-2023

Category Code	Source/Sink Category	Gas(es)	Reason for Exclusion	Estimated 2023 Emissions (kt CO ₂ Eq.)
Energy				
1.A Fossil Fuel Combustion				
1.A.3 Transport				
1.A.3.a	Domestic Aviation-Biomass	N ₂ O	Prior to 2011, no biobased jet fuel was assumed to be used for domestic aviation. After 2011 several airlines performed commercial passenger flights with biofuel blends and have offtake agreements with biofuel suppliers. Furthermore, biofuel jet fuel can qualify under the U.S. Renewable Fuel Standard (RFS) program. The RFS is a national policy that requires a certain volume of renewable fuel to replace or reduce the quantity of petroleum-based transportation fuel, heating oil or jet fuel. An analysis was conducted based on the total volume of biofuel jet fuel produced in 2024 under the RFS program. Emissions of N ₂ O were estimated based on the factors for jet fuel combustion. As for jet fuel use in commercial aircraft, contributions of methane (CH ₄) emissions are reported as zero.	8.9
1.A.3.b.iv	Motorcycles-Biomass	CH ₄ and N ₂ O	Emissions from ethanol mixed with gasoline in low blends are included in the on-road gasoline emissions for motorcycles. If there is any use of high blend ethanol fuel in motorcycles, it is considered insignificant. The percent of VMT from high ethanol blends in light duty gas vehicles (flex fuel vehicles) is less than 1 percent. If the same percentage is applied to motorcycle VMT with assumed flex fuel CH ₄ and N ₂ O emission factors, it results in estimated emissions of 0.0015 kt CO ₂ Eq.	0.0015
1.A.3.c	Railways-Biomass	CH ₄ and N ₂ O	There are no readily available data sources to estimate the use of biofuel in railways. Railways represent about 6 percent of all diesel fuel use. An assumption can be made that railways consume that same percentage of biofuels (6 percent of all biodiesel). Based on that assumption for biofuel use and applying fossil fuel CH ₄ and N ₂ O factors results in estimated emissions of 12.9 kt CO ₂ Eq. per year.	12.9
1.A.3.d	Domestic Navigation-Biomass	CH ₄ and N ₂ O	There are no readily available data sources to estimate the use of biofuel in domestic navigation. Domestic navigation represents about 3 percent of all diesel fuel use and about 1 percent of all gasoline fuel use. An assumption can	39.0

			be made that domestic navigation consumes that same percentage of biofuels (3 percent of all biodiesel and 1 percent of all ethanol use). Based on that assumption for biofuel use and applying fossil fuel CH ₄ and N ₂ O factors results in estimated emissions of 39.0 kt CO ₂ Eq. per year.	
1.A.3.d	Domestic Navigation— Gaseous Fuels	CO ₂	Emissions from gaseous fuel use in domestic navigation are not currently estimated. Gaseous fuels are used in liquid natural gas (LNG) tankers and are being demonstrated in a small number of other ships. Data are not available to characterize these uses currently.	NE
1.A.3.e Other Transportation				
1.A.3.e.i	Pipeline Transport—Liquid Fuels	CO ₂ , CH ₄ and N ₂ O	Use of liquid fuels to power pipeline pumps is uncommon but has occurred. Data for fuel used in various activities including pipelines are based on survey data conducted by the U.S. Energy Information Association (EIA). From January 1983 through December 2009, EIA Survey data included information on liquid fuel used to power pipelines reported in terms of crude oil product supplied. Reporting of crude oil used for this purpose was discontinued after December 2009. Beginning with data for January 2010, product supplied for pipeline fuel is assumed to equal zero, or essentially not occurring for latter half of time series). 1997 was the last year of data reported on pipeline fuel. Taking the data reported for 1997 of 797,000 barrels of crude oil and using conversion factors of 5.8 MMBtu/bbl and 20.21 MMT C/Qbtu results in estimated emissions of 342.6 kt CO ₂ .	342.6 (for 1997 and or earlier years, estimated to be 0 in 2022)
1.A.3.e.i	Pipeline Transport— Gaseous Fuels	CH ₄ and N ₂ O	CO ₂ emissions from gaseous fuels used as pipeline transport fuel are estimated in the <i>Inventory</i> , however CH ₄ and N ₂ O emissions from gaseous pipeline fuel use have not been estimated. The CO ₂ / non-CO ₂ emissions split for other stationary source natural gas combustion can be used to estimate emissions. Based on that analysis, non-CO ₂ emissions represent approximately 0.46 percent of CO ₂ emissions from all stationary source natural gas combustion. If that percentage is applied to CO ₂ emissions from natural gas use as pipeline fuel, it results in an emission estimate of 326.6 kt CO ₂ Eq. in 2017.	326.6
1.A.3.e.ii	Non-Transportation Mobile- Biomass	CH ₄ and N ₂ O	There are no readily available data sources to estimate the use of biofuel in non-transportation mobile sources. These sources represent about 21 percent of all diesel fuel use and about 4 percent of all gasoline fuel use. An assumption can be made that these sources consume that same percentage of biofuels (21 percent of all biodiesel and 4 percent of all ethanol use). Based on that assumption for biofuel use and applying fossil fuel CH ₄ and N ₂ O factors results	256.4

in estimated emissions of 256.4 kt CO₂ Eq. per year.

1.A.5.a Other Stationary

1.A.5.a	Incineration of Waste: Medical Waste Incineration	CO ₂	The category 1.A.5.a Other Stationary sources not specified elsewhere includes emissions from waste incineration of the municipal waste stream and waste tires. The category also includes emissions from non-energy uses of fuels which includes an energy recovery component that includes emissions from waste gas, waste oils, tars, and related materials from the industrial sector. While this is not a comprehensive inclusion of hazardous industrial waste, it does capture a subset. A portion of hazardous industrial waste not captured is from medical waste. However, a conservative analysis was conducted based on a study of hospital/medical/infectious waste incinerator (HMIWI) facilities in the United States¹⁵⁸ showing that medical waste incineration emissions could be considered insignificant. The analysis was based on assuming the total amount of annual waste throughput was of fossil origin and an assumption of 68.9 percent carbon composition of the waste. It was determined that annual greenhouse gas emissions for medical waste incineration are approximately 333 kt CO₂ Eq. per year. Related to 5.C.1, based on data on the amount of sewage sludge incinerated and assumed emission factors for N₂O and CH₄ from EPA's GHGRP for biomass solids, emissions were estimated to be approximately 9 kt CO₂ Eq. per year. Approximated emissions associated with sewage sludge incineration are considered insignificant for the purposes of inventory reporting.	342
1.A.5.a	Stationary Fuel Combustion: Biomass in U.S. Territories	CH ₄ and N ₂ O	Data are not available to estimate emissions from biomass in U.S. Territories. However, biomass consumption is likely small in comparison with other fuel types. An estimate of non-CO₂ emissions from biomass fuels used in Territories can be made based on assuming the same ratio of domestic biomass non-CO₂ emissions to fossil fuel CO₂ emissions. Non-Territories data indicate that biomass non-CO₂ emissions represents 0.2 percent of fossil fuel combustion CO₂ emissions. Applying this same percentage to proxy U.S. Territories fossil fuel combustion CO₂ emissions results in estimated emissions of 74.8 kt CO₂ Eq. from biomass in U.S. Territories.	74.8

¹⁵⁸ RTI (2009). Updated Hospital/Medical/Infectious Waste Incinerator (HMIWI) *Inventory Database*.

1.B Fugitive Emissions from Fuels				
1.B.1 – Solid Fuels				
1.B.1.a.1.i i, 1.B.1.a.2.i i	Fugitive Emissions from Coal Mining Related to Post-Mining Activities	CO ₂	A preliminary analysis by EPA determined that fugitive CO₂ emissions for post-mining activities related to underground coal mining and surface coal mining are negligible. EPA calculated the ratio of underground post-mining CH₄ emissions to net underground CH₄ emissions (0.14). This ratio was then applied to the net underground CO₂ emissions to estimate underground post-mining CO₂ emissions. The underground post-mining CO₂ emissions were estimated to be 308 kt for 2023. Similarly, surface post-mining CO₂ emissions were estimated by multiplying the ratio of surface post-mining CH₄ and surface CH₄ emissions (0.22) and then applying this ratio to the surface CO₂ emission estimate. The surface post-mining CO₂ emissions were estimated to be 57 kt for 2023. Total CO₂ emissions from post-mining activities (underground and surface) were estimated to be 366 kt for 2023. Note, fugitive CO₂ emissions from active underground and surface coal mining are reported based on methods in the <i>IPCC 2019 Refinement</i>. Neither the <i>2006 IPCC Guidelines</i> nor the <i>IPCC 2019 Refinement</i> provide any method for estimating fugitive CO₂ emissions from post-mining activities (see section 3.4 of Chapter 3 of the <i>Inventory</i>).	366
1.B.1.a.1.ii	Fugitive Emissions from Abandoned Underground Coal Mines	CO ₂	A preliminary analysis by EPA determined that CO₂ emissions for abandoned underground coal mining activities are negligible. EPA notes that neither the <i>2006 IPCC Guidelines</i> nor the <i>IPCC 2019 Refinement</i> provide any method for estimating fugitive CO₂ emissions from Abandoned Underground Coal Mines. The analysis was based on gas composition data from two abandoned underground mines in two different states.¹⁵⁹ An average ratio of CO₂ to CH₄ composition in mine gas was derived for abandoned mines. This ratio was applied as a percentage (1.5 percent) to CH₄ emission estimates to derive an estimate of CO₂ emissions for abandoned mines. Applying a CO₂ emission rate as a percentage of CH₄ emissions for abandoned coal mines results in a national emission estimate of 92 kt CO₂ for 2023. Future inventories may quantify these emissions, if it is deemed it will not require a disproportionate amount of effort.	92

¹⁵⁹ Ibid.

Industrial Processes and Product Use

2.B. Chemical Industry

2.B.4.b	Glyoxal Production	N ₂ O	Data are currently not available to apply IPCC methods and estimate N₂O emissions from glyoxal production. EPA continues to conduct outreach to relevant trade associations and review EPA and other potential databases that may contain the necessary data. Glyoxal production is believed to have taken place earlier in the time series: two facilities have been identified as having produced some amount of glyoxal but the facility in Geismar, Louisiana closed in 2014 and the other facility in Charlotte, North Carolina ceased production in 2012. Whether production is still occurring in the United States remains unknown.	71
			Data reported to EPA under the Toxic Substances Control Act (TSCA) indicate that several facilities imported glyoxal in 2011 through 2015, but no facility except the Geismar facility self-identified as a domestic manufacturer. In 2015, four facilities claimed that their production status (i.e., as a domestic manufacturer or as an importer) and their quantities of domestically manufactured and/or imported glyoxal were confidential business information (CBI). Thus, it is possible that one or more of these four facilities could be a domestic manufacturer. It is also possible that there are other facilities in the U.S. that do not have to report under TSCA because their total production volume is less than 25,000 pounds per year or they are exempt from reporting because they are a small manufacturer based on their total company sales revenue.	
			To assess the significance of emissions from glyoxal production, EPA used limited data on the range of domestic production and imports (U.S. EPA ChemView for data submitted under TSCA in 2023 and 2016) and assumptions that half of the amount was domestically produced, liquid-phase oxidation of acetaldehyde with nitric acid process accounts for 20 percent of total glyoxal production, and N₂O control equipment have an efficiency of 80 percent, to estimate process emissions of 71,000 mt CO₂ Eq. or 71 kt CO₂ Eq. per year in recent years, which does not exceed the category-level threshold for significance of 500 kt CO₂ Eq. Any further progress on outreach will be included in next (i.e., 1990 through 2022) <i>Inventory</i> report.	
2.B.4.c	Glyoxylic Acid Production	N ₂ O	Data are currently not available to apply IPCC methods and estimate N₂O emissions from glyoxal production. EPA continues to conduct outreach to relevant trade associations reviewing EPA and other potential databases that	NE

may contain the necessary data.

It is unclear how much or whether glyoxylic acid is currently produced in the United States. In 2015, four facilities reported glyoxylic acid data under the Toxic Substances Control Act (TSCA), but each of these facilities reported no domestically manufactured glyoxylic acid. It is possible that there are facilities in the United States that do not have to report under TSCA because their total production volume is less than 25,000 pounds per year or they are exempt from reporting because they are a small manufacturer based on their total company sales revenue.

Research suggests that glyoxylic acid may not be produced in the U.S. at levels that would exceed the category-level threshold for significance of 500 kt CO₂ Eq. Any further progress on outreach will be included in next (i.e., 1990 through 2022) *Inventory* report.

2.B.8.d	Petrochemical and Carbon Black Production	CH ₄ and N ₂ O	A subset of petrochemical facilities reporting under EPA's GHGRP use Continuous Emission Monitoring Systems (CEMS) to monitor CO ₂ emissions from process vents and/or stacks from stationary combustion units or the optional combustion methodology for ethylene production facilities. These facilities are required to also report CO ₂ , CH ₄ and N ₂ O emissions from combustion of process off-gas in flares. The CO ₂ emissions from flares are included in aggregated CO ₂ results. Analysis of aggregated annual reports shows that flared CH ₄ and N ₂ O emissions are less than 300 kt CO ₂ Eq./year. Since data is only available from a subset of facilities and not consistently reported over time and since CH ₄ and N ₂ O emissions are shown to be insignificant, they are excluded from the analysis.	300
2.C. Metal Industry				
2.C.1.c	Iron and Steel Production: Direct Reduced Iron (DRI) Production	CH ₄	Data are currently unavailable to apply IPCC methods and estimate CH ₄ emissions from DRI production. The IPCC default factor for CH ₄ emissions from DRI production is based on the quantity of fuel used. The quantity and type of fuel used in DRI production is not known, only the total amount of DRI produced. An assumed emission factor can be developed based on the default energy consumption of 12.5 GJ natural gas per metric ton of DRI produced. This assumption and annual DRI production in metric tons results in CH ₄ emissions of 0.74 kt CO ₂ Eq.	0.74
2.E Electronics Industry				

2.E.2	Fluorinated Gas Emissions from Electronics Industry: TFT Flat Panel Displays	HFCs, PFCs, SF ₆ , and NF ₃	In addition to requiring reporting of emissions from semiconductor manufacturing, micro-electro-mechanical systems (MEMs), and photovoltaic cells, EPA's GHGRP requires the reporting of emissions from the manufacture of flat panel displays. However, no flat panel displays manufacturing facilities have ever reported to EPA's GHGRP, indicating that there are no facilities in the United States that have exceeded the GHGRP's applicability threshold for display manufacturers since 2010. Per the published literature, the United States has never been a significant display manufacturer aside from a small amount of manufacturing in the 1990s, but never had mass commercial production. ¹⁶⁰ The available information on this sector thus indicates that these emissions were well below the significance threshold in the 1990s and early 2000s, when any emissions would have occurred.	NE for 1990-2002 (estimated to be NO from 2003 to 2023)

Agriculture

3.A Livestock

3.A.4	Enteric Fermentation: Camels	CH ₄	Enteric fermentation emissions from camels are not estimated because there is no significant population of camels in the United States. Due to limited data availability (no population data are available from the USDA Agricultural Census), the estimates are based on use of IPCC defaults and population data from Baum, Doug (2010). ¹⁶¹ Based on this source, a Tier 1 estimate of enteric fermentation CH ₄ emissions from camels results in a value of approximately 2.8 kt CO ₂ Eq. per year from 1990 to 2023. See Chapter 5.1 for more information.	2.8
3.A.4	Enteric Fermentation: Poultry	CH ₄	No IPCC method has been developed for determining enteric fermentation CH ₄ emissions from poultry. See Chapter 5.1.	No method provided in 2006 IPCC Guidelines
3.B.1.4, 3.B.2	Manure Management: Camels	CH ₄ and N ₂ O	Manure management emissions from camels are not estimated because there is no significant population of camels in the United States. Due to limited data availability and disproportionate effort to collect time-series data (i.e., no population data is available from the Agricultural Census), this estimate is based on population data from Baum, Doug (2010). ¹⁶² Based on this source, a Tier 1	0.1

¹⁶⁰ The Display Industry: Fast to Grow, Slow to Change Article in Information Display 28(5):18-21 · May 2012 with 4. DOI: 10.1002/j.2637-496X.2012.tb00504.x The Display Industry: Fast to Grow, Slow to Change. Available online at: <http://archive.informationdisplay.org/id-archive/2012/may-june/display-marketplace-the-display-industry-fast-to>.

¹⁶¹ *The status of the camel in the United States of America*. Available online at: <https://www.soas.ac.uk/camelconference2011/file84331.pdf>.

¹⁶² *The status of the camel in the United States of America*. Available online at: <https://www.soas.ac.uk/camelconference2011/file84331.pdf>.

			estimate of manure management CH ₄ and N ₂ O emissions from camels results in a value of approximately 0.14 kt CO ₂ Eq. per year from 1990 to 2023. See Chapter 5.2 for more information.	
Land Use, Land-Use Change, and Forestry				
4.A Forest Land				
4.A(II)	Emissions and Removals from Rewetting of Organic and Mineral Soils	CO ₂ and CH ₄	Not required based on the <i>2006 IPCC Guidelines</i> . At this time, the necessary activity data is not available. Emissions from this source may be estimated in future Inventories using guidance from the <i>2013 Wetlands Supplement</i> when data necessary for classifying the area of rewetted organic and mineral soils become available.	NE, encouraged not required reporting
4.A.1 Forest Land Remaining Forest Land				
4.A.1	N mineralization/immobilization	N ₂ O	Direct N ₂ O emissions from N mineralization/immobilization associated with loss or gain of soil organic matter resulting from change of land use or management of mineral soils will be estimated in a future <i>Inventory</i> . They are not estimated currently because resources have limited EPA's ability to use the available data on soil carbon stock changes on forest lands to estimate these emissions.	NE
4.B Cropland				
4.B(II)	Emissions and Removals from Rewetting of Organic and Mineral Soils	CO ₂ and CH ₄	Not required based on the <i>2006 IPCC Guidelines</i> . At this time, the necessary activity data is not available. Emissions from this source may be estimated in future Inventories using guidance from the <i>2013 Wetlands Supplement</i> when data necessary for classifying the area of rewetted organic and mineral soils become available, except for CH ₄ emissions from drainage and rewetting for rice cultivation.	NE, encouraged not required reporting
4.B.1 Cropland Remaining Cropland				
4.B.1	Carbon Stock Change in Living Biomass and Dead Organic Matter	CO ₂	The Inventory includes aboveground biomass carbon stock changes for perennial woody crops (e.g., orchards, vineyards) on Cropland Remaining Cropland but does not include biomass changes for agroforestry. because data are currently not available to develop a full, consistent time-series. The impact of agroforestry management on perennial biomass carbon stocks is currently under investigation and will be included in a future <i>Inventory</i> if stock changes are significant and suitable activity data sources can be identified.	NE
4.B.1(V)	Biomass Burning—Controlled Burning	CO ₂	Emissions of CO ₂ from biomass burning on Croplands Remaining Cropland are only relevant for perennial biomass and as noted under 4.B.1 above. EPA does not currently include carbon stock change for perennial biomass on Cropland Remaining Cropland. The CO ₂ emissions from controlled burning of crop	NE

			biomass are not estimated for annual crops as they are part of the annual cycle of C and not considered net emissions. Methane and N ₂ O emissions are included under 3.F Field Burning of Agricultural Residues.	
4.B.1(V)	Biomass Burning—Wildfires	CO ₂ , CH ₄ , and N ₂ O	Emissions from wildfires on Croplands Remaining Croplands are not estimated because the activity data on fire area and fuel load, particularly for perennial vegetation, are not available to apply IPCC methods.	NE
4.B.2 Land Converted to Cropland				
4.B.2	Carbon Stock Change in Perennial Living Biomass and Dead Organic Matter	CO ₂	The Inventory includes aboveground biomass carbon stock changes for perennial woody crops (e.g., orchards, vineyards) on Land converted to Cropland but does not include biomass changes for agroforestry. because data are currently not available to develop a full, consistent time-series. The impact of management on perennial biomass carbon is currently under investigation for agroforestry management and will be included in a future <i>Inventory</i> if stock changes are significant and activity data can be compiled for this source.	NE
4.B.2(V)	Biomass Burning—Wildfires and Controlled Burning	CO ₂	Emissions of CO ₂ from biomass burning on Land Converted to Cropland are only relevant for perennial biomass and as noted under 4.B.2 above EPA does not currently include carbon stock change for perennial biomass on Land Converted to Cropland. Emissions from wildfires are not estimated because the activity data on fire area and fuel load, particularly for perennial vegetation, are not available.	NE
4.C Grassland				
4.C(II)	Emissions and Removals from Rewetting of Organic and Mineral Soils	CO ₂ and CH ₄	Not required based on the 2006 IPCC Guidelines. At this time, the necessary activity data is not available. Emissions from this source may be estimated in future Inventories using guidance from the 2013 Wetlands Supplement when data necessary for classifying the area of rewetted organic and mineral soils become available.	NE, encouraged not required reporting
4.C.2 Land Converted to Grassland				
4.C.2	Carbon Stock Change in Living Biomass and Dead Organic Matter	CO ₂	The Inventory includes aboveground biomass carbon stock changes for perennial woody crops (e.g., orchards, vineyards) on Cropland converted to Grassland but does not include biomass changes for agroforestry. because data are currently not available to develop a full, consistent time-series. The impact of management on perennial biomass C is currently under investigation for agroforestry management and will be included in a future <i>Inventory</i> if stock changes are significant and activity data can be compiled for this source.	NE
4.D Wetlands				

4.D(II)	Flooded Lands and Peat Extraction Lands: Emissions and Removals from Drainage and Rewetting and Other Management of Organic and Mineral Soils	CO ₂ , CH ₄ , and N ₂ O	Data are currently not available to apply IPCC methods and estimate emissions from rewetting of peat extraction lands and flooded lands.	NE
<i>4.D.1 Wetlands Remaining Wetlands</i>				
4.D.1(V)	Biomass Burning: Controlled Burning, Wildfires	CO ₂ , CH ₄ , and N ₂ O	Data are not currently available to apply IPCC methods to estimate emissions from biomass burning in Wetlands.	NE
<i>4.D.2 Land Converted to Wetlands</i>				
4.D.2(V)	Biomass Burning: Controlled Burning, Wildfires	CO ₂ , CH ₄ , and N ₂ O	Data are not currently available to apply IPCC methods to estimate emissions from biomass burning in Wetlands.	NE
4.E Settlements				
4.E(V)	Biomass Burning in Settlements	CO ₂ , CH ₄ , and N ₂ O	Data are currently not available to apply IPCC methods to estimate emissions from biomass burning in Settlements.	NE
<i>4.E.1 Settlements Remaining Settlements</i>				
4.E.1	Settlements Remaining Settlements	CH ₄	Data are not currently available to apply IPCC methods to estimate CH ₄ emissions in Settlements.	NE
4.E.1	Direct N ₂ O Emissions from N Mineralization/Immobilization (Mineral Soils)	N ₂ O	Activity data are not available on N ₂ O emissions from nitrogen mineralization/immobilization in <i>Settlements Remaining Settlements</i> and <i>Land Converted to Settlements</i> as a result of soil organic carbon stock losses from land use conversion and management.	NE
<i>4.E.2 Land Converted to Settlements</i>				
4.E.2	Direct N ₂ O Emissions from N Mineralization/Immobilization	N ₂ O	Activity data are not available on N ₂ O emissions from nitrogen mineralization/immobilization in <i>Settlements Remaining Settlements</i> and <i>Land Converted to Settlements</i> as a result of soil organic carbon stock losses from land use conversion and management.	NE
4.F Other Land				
4.F(V)	Carbon Stock Change, Biomass Burning	CO ₂ , CH ₄ , and N ₂ O	While the United States is conducting research to track carbon pools for other land, it is unable to estimate CO ₂ , CH ₄ and N ₂ O emissions for other land or land converted to other land. See section 6.13 of the NIR.	NE
Waste				
5.A.1 Solid Waste Disposal				

5.A.1.a	Managed Waste Disposal Sites-Anaerobic	CH ₄	The amount of CH ₄ flared and the amount of CH ₄ for energy recovery is not estimated for the years 2005 through 2023 in the time series. A methodological change was made for 2005 to the current <i>Inventory</i> year to use the directly reported net CH ₄ emissions from the EPA's GHGRP versus estimate CH ₄ generation and recovery. See the Methodology explanation in Section 7.1.	NE
5.C Waste Incineration				
5.C.1	Waste Incineration	CH ₄ and N ₂ O from incineration of sewage sludge	See details under 1.A.5.a Incineration of Waste: Medical Waste Incineration.	See above
5.D Wastewater Treatment				
5.D.2	Industrial Wastewater	CH ₄	Emissions associated with sludge generated from the treatment of industrial wastewater is not included because the likely level of emissions is insignificant and because quantitative activity data on who operates anaerobic sludge digesters is unavailable. It would require a disproportionate amount of effort to collect this data, and more recent methodological work also suggests this is the case (i.e., Table 6.3 (Updated) in the <i>IPCC 2019 Refinement</i> only identifies CH₄ emissions from anaerobic digestion of sludge as a source of emissions to be reported in the Wastewater sector [note that N₂O is noted as “not significant” in Table 6.8A]). Methane emissions from the wastewater treatment category are not considered a key source category (see Annex 1, Table A-1). In addition, the United States continues to review the six industries included in the wastewater sector to determine if activity data are sufficient to include methane emissions from anaerobic digestion of sludge. The United States has worked first with the pulp and paper industry to confirm that virtually no pulp and paper mills operate anaerobic sludge digesters and will continue to identify stakeholders in the remaining five industries to confirm sludge management techniques. The United States notes that methane emissions associated with anaerobic digestion of ethanol waste (a combination of process wastewater and solids) is already included in the <i>Inventory</i> and is not considered sludge management. The United States believes the likely level of emissions associated with anaerobic digestion of industrial wastewater sludge is less than 5 kt CO₂ Eq., which is considered insignificant for the purposes of inventory reporting.	5

NE (Not Estimated) noted in the final column also indicates it is not feasible to derive a likely level of emissions and/or removals or quantified estimate due to lack of approximated activity data and/or in some cases also default emission factors but a method is available in the *2006 IPCC Guidelines*. In some cases, the EPA plans to reserve resources for data collection, compilation and review to fully incorporate estimates into the national inventory as a planned improvement given effort to proxy significance would involve the same minimum resources (e.g., 4.B.2).

Geographic Completeness

While summarized below in Table A-264, information on coverage of activities within the United States, the District of Columbia, U.S. Territories and tribal lands is provided in the sectoral chapters with details in the category-specific estimate discussions as relevant. U.S. Territories include American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Commonwealth of Northern Mariana Islands, and other minor outlying Pacific Islands which have no permanent population and are inhabited by military and/or scientific purposes.¹⁶³ As part of continuous improvement efforts, EPA reviews coverage on an ongoing basis to ensure emission and removal categories are included across all geographic areas including U.S. Territories where they are occurring.

Table A-264: Summary of Geographic Completeness

Inventory Sector	Geographic Completeness
Energy	Includes emissions from all 50 states, including Hawaii and Alaska, and the District of Columbia. Emissions are also included from U.S. Territories and tribal lands to the extent they are known to occur (e.g., coal mining does not occur in U.S. Territories). For some sources there is a lack of detailed information on U.S. Territories, including non-CO ₂ emissions from biomass combustion, so emissions estimates may not be available at same levels of disaggregation those covering the states and District of Columbia.
Industrial Processes and Product Use	Includes emissions from all 50 states, including Hawaii and Alaska, as well as from the District of Columbia U.S. Territories and tribal lands to the extent to which industries are occurring. While most IPPU sources do not occur in U.S. Territories (e.g., electronics manufacturing does not occur in U.S. Territories), they are estimated and accounted for where they are known to occur (e.g., substitutes from ozone depleting substance substitutes, cement production, lime production, and electrical transmission and distribution).
Agriculture	Emissions reported in the Agriculture chapter include those from all states and tribal lands; however, for Hawaii and Alaska some agricultural practices that can affect nitrogen availability in the soil, and thus result in N ₂ O emissions, are not included (i.e., for field burning of agricultural residues, agricultural soil management). In addition, U.S. Territories and the District of Columbia are not estimated due to incomplete data, except for Urea Fertilization in Puerto Rico. Emissions currently not estimated for U.S. Territories have not been approximated for significance. Other minor outlying U.S. territories in the Pacific Islands have no permanent populations (e.g., Baker Island) and therefore EPA assumes no agriculture activities are occurring.
Land Use, Land Use Change and Forestry	Emissions and removals reported in the LULUCF chapter include those from all states and tribal lands, however, for Hawaii and Alaska some emissions and removals from land use and land use change are not included in most cases. Specifically for Alaska, carbon stock changes from coastal wetlands, cropland and lands converted to cropland, grasslands and lands converted to grassland, settlements and lands converted to settlements, N ₂ O from settlement soils, non-CO ₂ emission from grassfires, and CO ₂ and non-CO ₂ emissions from flooded lands are not estimated. For Hawaii, all wetlands are not estimated. See chapter sections on Uncertainty and Planned Improvements for more details. In addition,

¹⁶³ More information is available at: <https://www.usgs.gov/tools/usgs-science-american-territories>.

	U.S. Territories are not included (see Box 6) with the exception of forest carbon stocks. Emissions currently not estimated for U.S. Territories have not yet been approximated for significance.
Waste	Emissions reported in the Waste chapter for landfills, wastewater treatment, and anaerobic digestion at biogas facilities include those from all 50 states, including Hawaii and Alaska, the District of Columbia, as well as from U.S. Territories and tribal lands. Emissions from landfills include modern, managed sites in most U.S. Territories except for outlying Pacific Islands. Emissions from domestic wastewater treatment include most U.S. Territories except for outlying Pacific Islands. Those emissions are likely insignificant as those outlying Pacific Islands (e.g., Baker Island) have no permanent population. No industrial wastewater treatment emissions are estimated for U.S. Territories, due to lack of data availability. However, industrial wastewater treatment emissions are not expected for outlying Pacific Islands and assumed to be small for other U.S. Territories. Emissions for composting include all states and Puerto Rico, except Alaska. Some composting operations in Alaska are known, but these consist of aerated composting facilities. Composting emissions are not included from the remaining U.S. Territories, and these are assumed to be small and have not yet been approximated. Similarly, EPA is not aware of any anaerobic digestion at biogas facilities in U.S. Territories but will review this on an ongoing basis to include these emissions if they are occurring.

ANNEX 6 Additional Information

6.1. Global Warming Potential Values

The global warming potential (GWP) metric is intended as a quantified measure of the globally averaged relative radiative forcing impacts of a particular greenhouse gas over time. It is defined as the cumulative radiative forcing—both direct and indirect effects—integrated over a specific period of time from the emission of a unit mass of gas relative to some reference gas (IPCC 2007). Carbon dioxide (CO₂) was chosen as this reference gas. Direct effects occur when the gas itself is a greenhouse gas. Indirect radiative forcing occurs when chemical transformations involving the original gas produce a gas or gases that are greenhouse gases, or when a gas influences other radiatively important processes such as the atmospheric lifetimes of other gases. The relationship between kilotons (kt) of a gas and million metric tons of CO₂ equivalents (MMT CO₂ Eq.) can be expressed as follows:

Equation A-116: Calculating CO₂ Equivalent Emissions

$$\text{MMT CO}_2 \text{ Eq.} = (\text{kt of gas}) \times (\text{GWP}) \times \left(\frac{\text{MMT}}{1,000 \text{ kt}} \right)$$

where,

MMT CO ₂ Eq.	=	Million metric tons of CO ₂ equivalent
kt	=	kilotons (equivalent to a thousand metric tons)
GWP	=	Global warming potential
MMT	=	Million metric tons

GWP values allow policy makers to compare the impacts of emissions and reductions of different gases. According to the IPCC, GWP values typically have an uncertainty of ±40 percent, though some GWP values have larger uncertainty than others, especially those in which lifetimes have not yet been ascertained. For international consistency, national inventories use consistent GWP values from the IPCC *Fifth Assessment Report* (AR5) listed in table 8.A.1 in appendix 8.A, based upon a 100-year time horizon excluding the value for fossil methane (see Table A-265). While this *Inventory* uses agreed-upon GWP values for international consistency, unweighted gas emissions and sinks in kilotons (kt) are provided in the Trends chapter of this report (Table 2-2) and throughout the report so those using *Inventory* data can apply different metrics and different time horizons to compare the impacts of different greenhouse gases.

Greenhouse gases with lifetimes longer than a year or two (e.g., CO₂, CH₄, N₂O, HFCs, PFCs, SF₆, and NF₃) tend to be relatively evenly distributed throughout the atmosphere, and consequently global average concentrations can be determined. Emissions of these gases therefore have very similar climate impacts regardless of the location of those emissions. However, short-lived gases such as water vapor, carbon monoxide, tropospheric ozone, other indirect greenhouse gases (e.g., NO_x and NMVOCs), and tropospheric aerosols (e.g., SO₂ products and black carbon) vary spatially, and consequently it is more difficult to quantify their global radiative forcing impacts. The radiative impact of emissions of these substances can be very location and time specific. Therefore, GWP values are generally not attributed to these gases that are short-lived and spatially inhomogeneous in the atmosphere. See Annex 6.2 for a discussion of GWPs for ozone depleting substances.

Table A-265: IPCC AR5 Global Warming Potentials (GWP) and Atmospheric Lifetimes of Gases Used in this Report

Gas	Atmospheric Lifetime (Years)	100-year GWP ^a	20-year GWP
Carbon dioxide (CO ₂)	See footnote ^b	1	1
Methane (CH ₄) ^c	12.4 ^d	28	84
Nitrous oxide (N ₂ O)	121 ^d	265	264
HFC-23	222.0	12,400	10,800
HFC-32	5.2	677	2,430
HFC-41	2.8	116	427
HFC-125	28.2	3,170	6,090
HFC-134a	13.4	1,300	3,710
HFC-143a	47.1	4,800	6,940
HFC-152a	1.5	138	506
HFC-227ea	38.9	3,350	5,360
HFC-236fa	242.0	8,060	6,940
HFC-43-10mee	16.1	1,650	4,310
HFC-245fa	7.7	858	2,920
HFC-365mfc	8.7	804	2,660
CF ₄	50,000 ^d	6,630	4,880
C ₂ F ₆	10,000	11,100	8,210
C ₃ F ₈	2,600	8,900	6,640
C ₄ F ₆ ^e	<1	<1	<1
C ₄ F ₁₀	2,600	9,200	6,870
c-C ₄ F ₈	3,200	9,540	7,110
C ₅ F ₁₂	4,100	8,550	6,350
C ₆ F ₁₄	3,100	7,910	5,890
SF ₆	3,200	23,500	17,500
NF ₃	500	16,100	12,800

^a GWP values used in this report are calculated over 100-year time horizon.

^b For a given amount of CO₂ emitted, some fraction of the atmospheric increase in concentration is quickly absorbed by the oceans and terrestrial vegetation, some fraction of the atmospheric increase will only slowly decrease over a number of years, and a small portion of the increase will remain for many centuries or more.

^c The methane GWP includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO₂ is not included.

^d Methane and N₂O have chemical feedback systems that can alter how long the atmospheric response persists. Sometimes, the global mean atmospheric lifetime (LT) is given first, followed by perturbation lifetime (PT), but only the perturbation lifetime is listed here and not the atmospheric residence time.

^e See Table A-1 of FR 40 CFR Part 98.

Source: IPCC (2013)

The IPCC published its *Fifth Assessment Report* (AR5) in 2013 and its *Sixth Assessment Report* (AR6) in 2021, providing the most current and comprehensive scientific assessments of climate change (IPCC 2013; IPCC 2021). It is informative to review the changes to the 100-year GWP values from AR5 to AR6 and the impact they have on the total GWP-weighted emissions of the United States. All GWP values use CO₂ as a reference gas; a change in the radiative efficiency of CO₂ thus impacts the GWP of all other greenhouse gases. Since the *Fourth Assessment Report* (AR4), the IPCC has applied an improved calculation of CO₂ radiative forcing and an improved CO₂ response function. The GWP values used in this report are drawn from IPCC (2013), with updates for those cases where new laboratory or radiative transfer results have been published. Additionally, the atmospheric lifetimes of some gases have been recalculated, and updated background concentrations were used. Table A-266 shows how the GWP values of the other gases relative to CO₂ tend to be larger in AR5 and AR6 because the revised temporally integrated radiative forcing of CO₂ is lower than in earlier assessments, taking into account

revisions in lifetimes. Comparisons of GWP values are based on the 100-year time horizon required for national inventory reporting. However, there were some instances in which other variables, such as the radiative efficiency or the chemical lifetime, were altered that resulted in further increases or decreases in particular GWP values in AR5 and AR6, including addressing inconsistencies with incorporating climate carbon feedbacks. In addition, the values for radiative forcing and lifetimes have been calculated for a variety of halocarbons. Updates in some well-mixed HFC compounds (including HFC-23, HFC-32, HFC-134a, and HFC-227ea) for AR5 result from investigation into radiative efficiencies in these compounds, with some GWP values changing by up to 21 percent; with this change, the uncertainties associated with these well-mixed HFCs are thought to be approximately 20-40 percent, depending on lifetimes (IPCC 2013).

It should be noted that the use of IPCC AR5 GWP values for the current *Inventory* applies across the entire time series of the *Inventory* (i.e., from 1990 to 2023). As such, GWP comparisons throughout this chapter are presented relative to AR5 GWP values.

Table A-266: Comparison of GWP values and Lifetimes Used in the AR5, and AR6^c

Gas	Lifetime (years)		GWP (100 year)			Difference in GWP (Relative to AR5)			
	AR5	AR6	AR5 ^a	AR5 with feedbacks ^b	AR6 ^c	AR5 with feedbacks ^b	AR5 with feedbacks ^b (%)	AR6 ^c	AR6 (%)
Carbon dioxide (CO ₂)	^d	^d	1	1	1	NC	NC	NC	NC
Methane (CH ₄) ^e	12.4	11.8	28	34	27	6	21%	(1)	(4%)
Nitrous oxide (N ₂ O)	121	109	265	298	273	33	12%	8	3%
Hydrofluorocarbons									
HFC-23	222	228	12,400	13,856	14,600	1,456	12%	2,200	18%
HFC-32	5.2	5.4	677	817	771	140	21%	94	14%
HFC-41	2.8	2.8	116	141	135	NA	NA	19	16%
HFC-125	28.2	30	3,170	3,691	3,740	521	16%	570	18%
HFC-134a	13.4	14	1,300	1,549	1,530	249	19%	230	18%
HFC-143a	47.1	51	4,800	5,508	5,810	708	15%	1,010	21%
HFC-152a	1.5	1.6	138	167	164	29	21%	26	19%
HFC-227ea	38.9	36	3,350	3,860	3,600	510	15%	250	7%
HFC-236fa	242	213	8,060	8,998	8,690	938	12%	630	8%
HFC-245fa	7.7	7.9	858	1,032	962	174	20%	104	12%
HFC-365mfc	8.7	8.9	804	966	914	162	20%	110	14%
HFC-43-10mee	16.1	17	1,650	1,952	1,600	302	18%	(50)	(3%)
Fully Fluorinated Species									
SF ₆	3,200	1000	23,500	26,087	24,300	2,587	11%	800	3%
CF ₄	50,000	50,000	6,630	7,349	7,380	719	11%	750	11%
C ₂ F ₆	10,000	10,000	11,100	12,340	12,400	1,240	11%	1,300	12%
C ₃ F ₈	2,600	2,600	8,900	9,878	9,290	978	11%	390	4%
C ₄ F ₁₀	2,600	2,600	9,200	10,213	10,000	1,013	11%	800	9%
c-C ₄ F ₈	3,200	3,200	9,540	10,592	10,200	1,052	11%	660	7%
c-C ₅ F ₈	31 days	NA	2.0	NA	NA	NA	NA	NA	NA
C ₅ F ₁₂	4,100	4,100	8,550	9,484	9,220	934	11%	670	8%
C ₆ F ₁₄	3,100	3,100	7,910	8,780	8,620	870	11%	710	9%
C ₄ F ₆	NA	NA	NA	NA	NA	NA	NA	NA	NA
C ₄ F ₈ O	NA	3,000	NA	NA	13,900	NA	NA	NA	NA
NF ₃	500	569	16,100	17,885	17,400	1,785	11%	1,300	8%

NA (Not Applicable)

NC (No Change)

^a The GWP values presented here are from Table 8.A.1 in appendix 8.A of IPCC AR5, excluding climate-carbon feedbacks and fossil methane. See footnote e for more information on GWP for methane of fossil origin.

^b The GWP values presented here from the AR5 report include climate-carbon feedbacks for the non-CO₂ gases in order to be consistent with the approach used in calculating the CO₂ lifetime.

^c The 100-year GWP values from AR6 Table 7.15 include climate-carbon feedbacks.

^d For a given amount of CO₂ emitted, some fraction of the atmospheric increase in concentration is quickly absorbed by the oceans and terrestrial vegetation, some fraction of the atmospheric increase will only slowly decrease over a number of years, and a small portion of the increase will remain for many centuries or more. No single lifetime can be determined for CO₂ (see IPCC 2007). See footnote for more information on GWPs for methane of fossil origin.

^e The methane GWP includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. Additionally, the AR5 reported separate values for fossil versus biogenic methane in order to account for the CO₂ oxidation product. The GWP associated with methane of fossil origin is not shown in this table. Per AR5, the GWP for methane of fossil origin is 30 versus 28 using methodology most consistent with AR4. If using methodology to include climate carbon feedbacks, per the AR5 report, the value is higher by 2 for GWP for methane of fossil origin, so would be 36 versus 34.

^f Methane and N₂O have chemical feedback systems that can alter the length of the atmospheric response. The perturbation lifetime incorporating these feedbacks is reported here, rather than the atmospheric residence time.

Note: Parentheses indicate negative values.

Source: IPCC (2021), IPCC (2013), IPCC (2007).

The choice of 100-year GWP values between the AR5 (with or without climate-carbon feedbacks) and AR6 (includes climate carbon feedbacks) has an impact on both the overall emissions estimated by the *Inventory*, as well as the trend in emissions over time. To summarize, Table A-267 shows the overall trend in U.S. greenhouse gas emissions, by gas, from 1990 through 2023 using the four GWP sets. The table also presents the impact of AR5 GWP values relative to AR5 values with feedbacks, and AR6 on the total emissions for 1990 and for 2023. Note AR6 GWP values also include climate-carbon feedbacks.

Table A-267: Effects on U.S. Greenhouse Gas Emissions Using AR5 and AR6 GWP values (MMT CO₂ Eq.)

Gas	Difference in Emissions Between 1990 and 2023 (Relative to 1990)			Revisions to Annual Emission Estimates (Relative to AR5 ^a)			
	AR5 ^a	AR5 ^b	AR6	AR5 ^b	AR6	AR5 ^b	AR6
				1990		2023	
CO ₂	(213.4)	(213.4)	(213.4)	NC	NC	NC	NC
CH ₄	(186.5)	(226.5)	(179.8)	187.1	(31.2)	147.1	(24.5)
N ₂ O	(20.9)	(23.5)	(21.5)	212.7	12.3	NC	NC
HFCs, PFCs, SF ₆ , and NF ₃	79.7	100.0	100.4	14.2	13.7	34.4	34.4
Total Gross Emissions	(341.0)	(363.3)	(314.3)	252.1	(5.1)	229.8	21.6
Percent Change	-5.2%	-5.4%	-4.8%	3.9%	-0.1%	3.7%	0.3%
LULUCF Emissions	1.5	1.8	1.6	12.2	(1.8)	12.5	(1.8)
CH ₄	0.3	0.4	0.3	11.7	(1.9)	11.7	(2.0)
N ₂ O	1.2	1.4	1.3	0.6	0.1	0.7	0.2
LULUCF Sector Net Total	97.9	98.1	98.0	12.2	(1.8)	12.2	(1.8)
Net Emissions (Sources and Sinks)	(243.1)	(265.2)	(216.3)	264.3	(6.9)	242.2	19.8
Percent Change	-4.4%	-4.6%	-3.9%	4.8%	-0.1%	4.6%	0.4%

NC (No Change)

^a The GWP values in this column reflect values used in this report from AR5 excluding climate-carbon feedbacks and the value for fossil methane.

^b The GWP values presented here from the AR5 report include climate-carbon feedbacks for the non-CO₂ gases to be consistent with the approach used in calculating the CO₂ lifetime.

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table A-270 and Table A-271 show the comparison of emission estimates using AR6 GWP values relative to AR5 GWP values without climate-carbon feedbacks for the non-CO₂ gases, on an emissions and percent change basis. When the GWP values from the AR6 are applied to the emission estimates presented in this report, total emissions for the year 2023 increase 0.3 percent relative to emissions estimated using AR5 GWPs. The percent change in emissions is equal to the percent change in the GWP for each gas or varies by year based on the mix of gases (i.e., HFCs and PFCs).

Table A-268: Change in U.S. Greenhouse Gas Emissions Using AR5 with Climate-Carbon Feedbacks^a Relative to AR5 without Climate-Carbon Feedbacks^b (MMT CO₂ Eq.)

Gas	1990	2005	2019	2020	2021	2022	2023
CO ₂	NC	NC	NC	NC	NC	NC	NC
CH ₄	187.1	170.8	161.3	156.6	153.3	149.3	147.1
N ₂ O	50.9	53.0	52.0	48.8	49.7	48.4	48.3
HFCs	4.6	20.8	29.9	30.4	31.5	32.3	32.8
PFCs	2.4	0.6	0.4	0.4	0.3	0.3	0.3
SF ₆	3.4	1.7	0.8	0.8	0.8	0.7	0.8

NF ₃	+	+	0.1	0.1	0.1	0.1	0.1
Total Gross Emissions (Sources)	248.4	247.0	244.5	237.1	235.8	231.1	229.3
LULUCF Emissions	12.2	14.4	12.9	16.5	16.2	13.9	12.5
CH ₄	11.7	13.0	12.0	14.8	14.5	12.8	11.7
N ₂ O	0.6	1.4	0.9	1.7	1.6	1.1	0.7
LULUCF Sector Net Total	12.2	14.4	12.9	16.5	16.2	13.9	12.5
Net Emissions (Sources and Sinks)	260.52	261.3	257.3	253.5	251.9	244.9	241.7

NC (No Change)

+ Absolute value does not exceed 0.5 MMT CO₂ Eq.

^a The GWP values presented here from the AR5 report include climate-carbon feedbacks for the non-CO₂ gases in order to be consistent with the approach used in calculating the CO₂ lifetime. Additionally, for methane the AR5 reported separate values for fossil versus biogenic methane in order to account for the CO₂ oxidation product and that is not shown on this table.

^b The GWP values in this column reflect values used in this report from AR5 excluding climate-carbon feedbacks and the value for fossil methane.

Note: Totals may not sum due to independent rounding.

Table A-269: Change in U.S. Greenhouse Gas Emissions Using AR5 with Climate-Carbon Feedbacks^a Relative to AR5 without Climate-Carbon Feedbacks^b (Percent)

Gas/Source	1990	2005	2019	2020	2021	2022	2023
CO ₂	NC	NC	NC	NC	NC	NC	NC
CH ₄	21.4%	21.4%	21.4%	21.4%	21.4%	21.4%	21.4%
N ₂ O	12.5%	12.5%	12.5%	12.5%	12.5%	12.5%	12.5%
HFCs	9.6%	16.6%	17.0%	17.1%	17.1%	17.0%	17.2%
PFCs	6.0%	6.1%	5.3%	5.8%	5.2%	5.1%	4.4%
SF ₆	8.9%	8.5%	10.2%	10.2%	10.5%	10.2%	9.9%
NF ₃	2.7%	4.6%	5.4%	5.0%	6.2%	6.1%	6.9%
Total	3.8%	3.3%	3.7%	3.9%	3.7%	3.6%	3.7%
LULUCF Emissions	20.7%	20.1%	20.4%	19.9%	20.0%	20.3%	20.6%
CH ₄	21.4%	21.4%	21.4%	21.4%	21.4%	21.4%	21.4%
N ₂ O	12.5%	12.5%	12.5%	12.5%	12.5%	12.5%	12.5%
LULUCF Sector Net Total	-1.2%	-1.5%	-1.4%	-1.7%	-1.7%	-1.5%	-1.3%
Net Emissions (Sources and Sinks)	4.7%	4.0%	4.5%	5.0%	4.7%	4.5%	4.6%

NC (No Change)

^a The GWP values presented here from the AR5 report include climate-carbon feedbacks for the non-CO₂ gases in order to be consistent with the approach used in calculating the CO₂ lifetime. Additionally, for methane the AR5 reported separate values for fossil versus biogenic methane in order to account for the CO₂ oxidation product and that is not shown on this table. See footnotes to Table A-265.

^b The GWP values in this column reflect values used in this report from AR5 excluding climate-carbon feedbacks and the value for fossil methane.

Note: Totals may not sum due to independent rounding.

Table A-270: Change in U.S. Greenhouse Gas Emissions Using AR6 Relative to AR5 without Climate-Carbon Feedbacks^a (MMT CO₂ Eq.)

Gas	1990	2005	2019	2020	2021	2022	2023
CO ₂	NC	NC	NC	NC	NC	NC	NC
CH ₄	(31.2)	(28.5)	(26.9)	(26.1)	(25.6)	(24.9)	(24.5)
N ₂ O	12.3	12.8	12.6	11.8	12.0	11.7	11.7

HFCs	8.3	21.9	31.1	31.4	32.5	33.3	33.6
PFCs	3.9	1.0	0.7	0.6	0.6	0.6	0.5
SF ₆	1.5	0.8	0.3	0.3	0.3	0.2	0.3
NF ₃	+	0.1	0.1	0.1	0.1	0.1	0.1
Total Gross Emissions (Sources)	(5.1)	8.2	17.8	18.1	19.9	21.1	21.6
LULUCF Emissions	(1.8)	(1.8)	(1.8)	(2.1)	(2.0)	(1.9)	(1.8)
CH ₄	(1.9)	(2.2)	(2.0)	(2.5)	(2.4)	(2.1)	(2.0)
N ₂ O	0.1	0.3	0.2	0.4	0.4	0.3	0.2
LULUCF Sector Net Total	(1.8)	(1.8)	(1.8)	(2.1)	(2.0)	(1.9)	(1.8)
Net Emissions (Sources and Sinks)	(6.9)	6.4	16.0	16.1	17.9	19.2	19.8

NC (No Change)

+ Absolute value does not exceed 0.5 MMT CO₂ Eq.

^a The GWP values in this column reflect values used in this report from AR5 excluding climate-carbon feedbacks and the value for fossil methane.

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table A-271: Change in U.S. Greenhouse Gas Emissions Using AR6 Relative to AR5 without Climate-Carbon Feedbacks (Percent)

Gas/Source	1990	2005	2019	2020	2021	2022	2023
CO ₂	NC	NC	NC	NC	NC	NC	NC
CH ₄	(3.6%)	(3.6%)	(3.6%)	(3.6%)	(3.6%)	(3.6%)	(3.6%)
N ₂ O	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%
HFCs	17.4%	17.5%	17.7%	17.7%	17.6%	17.6%	17.6%
PFCs	9.8%	9.9%	8.9%	9.4%	9.1%	9.3%	8.9%
SF ₆	4.0%	4.0%	3.4%	3.4%	3.4%	3.4%	3.4%
NF ₃	8.1%	8.1%	8.1%	8.1%	8.1%	8.1%	8.1%
Total	(0.1%)	0.1%	0.3%	0.3%	0.3%	0.3%	0.3%
LULUCF Emissions	(3.0%)	(2.6%)	(2.8%)	(2.5%)	(2.5%)	(2.7%)	(2.9%)
CH ₄	(3.6%)	(3.6%)	(3.6%)	(3.6%)	(3.6%)	(3.6%)	(3.6%)
N ₂ O	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%
LULUCF Sector Net Total	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
Net Emissions (Sources and Sinks)	(0.1%)	0.1%	0.3%	0.3%	0.3%	0.4%	0.4%

NC (No Change)

^a The GWP values in this column reflect values used in this report from AR5 excluding climate-carbon feedbacks and the value for fossil methane.

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

6.2 Ozone Depleting Substance Emissions

Ozone is present in both the stratosphere,¹⁶⁴ where it shields the earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere,¹⁶⁵ where it is the main component of anthropogenic photochemical “smog.” Chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl chloroform, and hydrochlorofluorocarbons (HCFCs), along with certain other chlorine and bromine containing compounds, have been found to deplete the ozone levels in the stratosphere. These compounds are commonly referred to as ozone depleting substances (ODSs). If left unchecked, stratospheric ozone depletion could result in a dangerous increase of ultraviolet radiation reaching the earth’s surface. In the United States and globally, countries are limiting, and ultimately eliminating, the production of most ozone depleting substances. ODSs have historically been used in a variety of industrial applications, including refrigeration and air conditioning, foam blowing, fire extinguishing, sterilization, solvent cleaning, and as an aerosol propellant.

The Clean Air Act classifies ozone depleting substances as either Class I or Class II, depending upon the ozone depletion potential (ODP) of the compound.¹⁶⁶ The production of CFCs, halons, carbon tetrachloride, and methyl chloroform—all Class I substances—has already ended in all countries, including the United States. However, large amounts of these chemicals remain in existing equipment,¹⁶⁷ and stockpiles of the ODSs, as well as material recovered from equipment being decommissioned, are used for maintaining the existing equipment. As a result, emissions of Class I compounds will continue, albeit generally in decreasing amounts, for many more years. Class II designated substances, all of which are HCFCs, have been, or are being, phased out at later dates than Class I compounds because they have lower ODPs. These compounds served as interim replacements for Class I compounds in many industrial applications. The use and emissions of HCFCs in the United States is anticipated to continue for several decades as equipment that use Class II substances and closed-cell foam made with such substances are retired from use. The production for domestic use of all HCFCs as an ODS substitute in the United States will end by the year 2030.

In addition to contributing to ozone depletion, CFCs, halons, carbon tetrachloride, methyl chloroform, and HCFCs are also potent greenhouse gases. However, the depletion of the ozone layer has a cooling effect on the climate that counteracts the direct warming from tropospheric emissions of ODSs. Stratospheric ozone influences the earth’s radiative balance by absorption and emission of longwave radiation from the troposphere as well as absorption of shortwave radiation from the sun; overall, stratospheric ozone has a warming effect.

The IPCC has prepared both direct GWP values and net (combined direct warming and indirect cooling) GWP ranges for some of the most common ozone depleting substances (IPCC 2013). Table A-272 presents direct GWP values for ozone depleting substances. Ozone depleting substances directly absorb infrared radiation and contribute to positive radiative forcing; however, their effect as ozone-depleters also leads to a negative radiative forcing because ozone itself is a potent greenhouse gas. There is considerable uncertainty regarding this indirect effect; direct GWP values are shown, but AR5

¹⁶⁴ The stratosphere is the layer from the top of the troposphere up to about 50 kilometers. Approximately 90 percent of atmospheric ozone is within the stratosphere. The greatest concentration of ozone occurs in the middle of the stratosphere, in a region commonly called the ozone layer.

¹⁶⁵ The troposphere is the layer from the ground up to about 11 kilometers near the poles and 16 kilometers in equatorial regions (i.e., the lowest layer of the atmosphere, where humans live). It contains roughly 80 percent of the mass of all gases in the atmosphere and is the site for weather processes including most of the water vapor and clouds.

¹⁶⁶ Substances with an ozone depletion potential of 0.2 or greater are designated as Class I. All other designated substances that deplete stratospheric ozone but which have an ODP of less than 0.2 are Class II.

¹⁶⁷ Older refrigeration and air-conditioning equipment, fire extinguishing systems, and foam products blown with CFCs/HCFCs may still contain Class I ODS.

does provide a range of net GWP values for ozone depleting substances. The relevant methodological guidance (i.e., methods from the *2006 IPCC Guidelines*) do not include reporting instructions for estimating emissions of ODSs because their use is being globally phased out (see note below Table A-272). The effects of these compounds on radiative forcing are not addressed in this report.

Table A-272: 100-Year Direct Global Warming Potentials for Select Ozone Depleting Substances

Gas	Direct GWP
CFC-11	4,600
CFC-12	10,200
CFC-113	5,820
HCFC-22	1,760
HCFC-123	79
HCFC-124	527
HCFC-141b	782
HCFC-142b	1,980
CH ₃ CCl ₃	160
CCl ₄	1,730
CH ₃ Br	2
Halon-1211	1,750
Halon-1301	6,290

Notes: Because these compounds have been shown to deplete stratospheric ozone, they are typically referred to as ODSs. However, they are also potent greenhouse gases. Recognizing the harmful effects of these compounds on the ozone layer, ODS are being phased out globally. The United States ended the production and importation of halons in 1994, and CFCs in 1996, and will end production and importation of HCFCs by 2030.

Source: IPCC (2013).

Emission estimates for several ozone depleting substances are provided in Table A-273.

Table A-273: Emissions of Ozone Depleting Substances (kt)

Compound	1990	2005	2019	2020	2021	2022	2023
Class I							
CFC-11	28	12	5	5	5	4	4
CFC-12	137	24	1	+	+	+	+
CFC-113	59	17	0	0	0	0	0
CFC-114	4	1	0	0	0	0	0
CFC-115	9	3	+	+	0	0	0
Carbon Tetrachloride	4	0	0	0	0	0	0
Methyl Chloroform	223	0	0	0	0	0	0
Halon-1211	2	1	+	+	+	+	+
Halon-1301	2	+	+	+	+	+	+
Class II							
HCFC-22	34	80	46	43	36	30	26
HCFC-123	0	1	1	1	1	1	1
HCFC-124	0	2	+	+	+	+	+
HCFC-141b	1	4	7	7	7	6	6
HCFC-142b	1	4	5	5	5	5	5
HCFC-225ca/cb	0	+	+	+	+	+	+

+ Absolute value does not exceed 0.5 kt.

Methodology and Data Sources

Emissions of ozone depleting substances were estimated using the EPA's Vintaging Model. The model, named for its method of tracking the emissions of annual "vintages" of new equipment that enter into service, is a "bottom-up" model. It models the consumption of chemicals based on estimates of the quantity of equipment or products sold, serviced, and retired each year, and the amount of the chemical required to manufacture and/or maintain the equipment. The Vintaging Model makes use of this market information to build an inventory of the in-use stocks of the equipment in each of the end-uses. Emissions are estimated by applying annual leak rates, service emission rates, and disposal emission rates to each population of equipment. By aggregating the emission and consumption output from the different end-uses, the model produces estimates of total annual use and emissions of each chemical. Please see Annex 3.10, Methodology and QA/QC and Verification Details for Estimating HFC, PFC, and CO₂ Emissions from Substitution of Ozone Depleting Substances, of this *Inventory* for a more detailed discussion of the Vintaging Model.

Uncertainty Assessment

Uncertainties exist with regard to the levels of chemical production, equipment sales, equipment characteristics, and end-use emissions profiles that are used by these models. Please see the Substitution of Ozone Depleting Substances section of this report for a more detailed description of the input uncertainties that exist in the Vintaging Model.

6.3 Greenhouse Gas Precursors: Mapping of National Emission Inventory (NEI) Categories to the National Inventory Report (NIR) Categories

Emissions of precursor gases (CO, NO_x, NMVOC, and SO₂) occur in all sectors and are summarized in Section 2.3, presented in sectoral chapters of this *Inventory*. Emissions of these gases are provided by EPA's National Emissions *Inventory* (NEI). The categories used in the NEI vary from those presented in this *Inventory* and included in IPCC methodological guidelines. Table A-274 below indicates how NEI source categories are assigned to those more closely aligned with the categories in this report, based on EPA (2024) and detailed mapping of categories between this *Inventory* and the NEI. Precursor emissions from Agriculture and LULUCF categories are estimated separately and therefore are not taken from EPA (2024); see Sections 5.7, 6.2, and 6.6.

Table A-274: Crosswalk of NEI and NIR Categories by NIR Chapter for Greenhouse Gas Precursors

EIS Category ^a	Subcategory	NIR Subcategory/Category	Category
Energy			
Fuel Combustion - Electric Generation	Coal	Fossil Fuel Combustion – Electric Power Sector	1.A.1.a Public Electricity and Heat Production
	Biomass		
	Natural Gas		
	Oil		
	Other		
Fuel Combustion - Industrial Boilers, ICES	Coal	Fossil Fuel Combustion - Industrial	1.A.2.g Other
	Biomass		
	Natural Gas		
	Oil		
	Other		
Dust – Construction Dust		Fossil Fuel Combustion - Industrial	1.A.2.g Other
Mobile – Aircraft		Fossil Fuel Combustion - Transportation	1.A.3.a Domestic Aviation
Mobile – On-Road Diesel	Heavy Duty Vehicles	Fossil Fuel Combustion - Transportation	1.A.3.b Road Transportation
	Light Duty Vehicles		
Mobile – On-Road non-Diesel	Heavy Duty Vehicles	Fossil Fuel Combustion - Transportation	1.A.3.b Road Transportation
	Light Duty Vehicles		
Mobile - Locomotives		Fossil Fuel Combustion - Transportation	1.A.3.c Railways
Mobile – Commercial Marine Vessels		Fossil Fuel Combustion - Transportation	1.A.3.d Domestic Navigation
Mobile – Non-Road Equipment	Diesel	Fossil Fuel Combustion - Transportation	1.A.3.e Other Transportation
	Gasoline		
	Other		
Fuel Combustion – Commercial/Institutional	Coal	Fossil Fuel Combustion - Commercial	1.A.4.a Commercial/Institutional
	Biomass		
	Natural Gas		
	Oil		
	Other		
Fuel Combustion – Residential	Natural Gas	Fossil Fuel Combustion - Residential	1.A.4.b Residential
	Oil		
	Other		
	Wood		
Bulk Gasoline Terminals		Petroleum and Natural Gas Systems	1.B.2.d Other
Commercial Cooking		Petroleum and Natural Gas Systems	1.B.2.d Other
Gas Stations		Petroleum and Natural Gas Systems	1.B.2.d Other
Industrial Processes – Oil & Gas Production		Petroleum and Natural Gas Systems	1.B.2.d Other

Industrial Processes – Petroleum Refineries	Petroleum and Natural Gas Systems	1.B.2.d Other
Industrial Processes and Product Use		
Industrial Processes – Cement Manufacturing	Mineral Industry	2.H.3 Other - Other Industrial Processes
Industrial Processes – Chemical Manufacturing	Chemical Industry	2.B.10 Other - Other non-specified
Industrial Processes – Ferrous Metals	Metal Industry	2.C.7 Other - Other non-specified
Industrial Processes – Non-ferrous Metals	Metal Industry	2.C.7 Other - Other non-specified
Solvent – Degreasing	Other Industrial Processes	2.G.4 Other - Degreasing and Dry Cleaning
Solvent – Dry Cleaning	Other Industrial Processes	2.G.4 Other - Degreasing and Dry Cleaning
Solvent – Consumer & Commercial Solvent Use	Other Industrial Processes	2.G.4 Other – Domestic Solvent Use
Solvent - Graphic Arts	Other Industrial Processes	2.G.4 Other - Graphic Arts
Miscellaneous Non-Industrial NEC	Other Industrial Processes	2.G.4 Other - Nonindustrial
Solvent– Industrial Surface Coating & Solvent Use	Other Industrial Processes	2.G.4 Other - Surface Coating
Solvent - Non-Industrial Surface Coating	Other Industrial Processes	2.G.4 Other - Surface Coating
Industrial Processes – Storage and Transfer	Other Industrial Processes	2.H.3 Other – Storage and Transport
Industrial Processes – Mining	Other Industrial Processes	2.H.3 Other - Other Industrial Processes
Industrial Processes – NEC	Other Industrial Processes	2.H.3 Other - Other Industrial Processes
Industrial Processes – Pulp & Paper	Other Industrial Processes	2.H.3 Other - Other Industrial Processes
Agriculture		
Agriculture – Livestock Waste	Manure Management	3.J Other
Waste		
Waste Disposal	Waste	5.E Other

^a Emissions from the EIS Fires category (including agricultural field burning, prescribed fires, and wildfires) are not from the NEI and are calculated separately in the NIR.

6.4 Constants, Units, and Conversions

Metric Prefixes

Although most activity data for the United States is gathered in customary U.S. units, these units are converted into metric units per international reporting guidelines. Table A-275 provides a guide for determining the magnitude of metric units.

Table A-275: Guide to Metric Unit Prefixes

Prefix/Symbol	Factor
atto (a)	10^{-18}
femto (f)	10^{-15}
pico (p)	10^{-12}
nano (n)	10^{-9}
micro (μ)	10^{-6}
milli (m)	10^{-3}
centi (c)	10^{-2}
deci (d)	10^{-1}
deca (da)	10
hecto (h)	10^2
kilo (k)	10^3
mega (M)	10^6
giga (G)	10^9
tera (T)	10^{12}
peta (P)	10^{15}
exa (E)	10^{18}

Unit Conversions

1 kilogram = 2.205 pounds
1 pound = 0.454 kilograms
1 short ton = 2,000 pounds = 0.9072 metric tons
1 metric ton = 1,000 kilograms = 1.1023 short tons

1 cubic meter = 35.315 cubic feet
1 cubic foot = 0.02832 cubic meters
1 U.S. gallon = 3.785412 liters
1 barrel (bbl) = 0.159 cubic meters
1 barrel (bbl) = 42 U.S. gallons
1 liter = 0.001 cubic meters

1 foot = 0.3048 meters
1 meter = 3.28 feet
1 mile = 1.609 kilometers
1 kilometer = 0.621 miles

1 acre = 43,560 square feet = 0.4047 hectares = 4,047 square meters

1 square mile = 2.589988 square kilometers

Degrees = (Degrees Fahrenheit – 32)*5/9
Celsius

Degrees Kelvin = Degrees Celsius + 273.15

Density Conversions¹⁶⁸

Methane 1 cubic meter = 0.67606 kilograms
Carbon dioxide 1 cubic meter = 1.85387 kilograms

Natural gas liquids	1 metric ton	=	11.6 barrels	=	1,844.2 liters
Unfinished oils	1 metric ton	=	7.46 barrels	=	1,186.04 liters
Alcohol	1 metric ton	=	7.94 barrels	=	1,262.36 liters
Liquefied petroleum gas	1 metric ton	=	11.6 barrels	=	1,844.2 liters
Aviation gasoline	1 metric ton	=	8.9 barrels	=	1,415.0 liters
Naphtha jet fuel	1 metric ton	=	8.27 barrels	=	1,314.82 liters
Kerosene jet fuel	1 metric ton	=	7.93 barrels	=	1,260.72 liters
Motor gasoline	1 metric ton	=	8.53 barrels	=	1,356.16 liters
Kerosene	1 metric ton	=	7.73 barrels	=	1,228.97 liters
Naphtha	1 metric ton	=	8.22 barrels	=	1,306.87 liters
Distillate	1 metric ton	=	7.46 barrels	=	1,186.04 liters
Residual oil	1 metric ton	=	6.66 barrels	=	1,058.85 liters
Lubricants	1 metric ton	=	7.06 barrels	=	1,122.45 liters
Bitumen	1 metric ton	=	6.06 barrels	=	963.46 liters
Waxes	1 metric ton	=	7.87 barrels	=	1,251.23 liters
Petroleum coke	1 metric ton	=	5.51 barrels	=	876.02 liters
Petrochemical feedstocks	1 metric ton	=	7.46 barrels	=	1,186.04 liters
Special naphtha	1 metric ton	=	8.53 barrels	=	1,356.16 liters
Miscellaneous products	1 metric ton	=	8.00 barrels	=	1,271.90 liters

Energy Conversions

Converting Various Energy Units to Joules

The common energy unit used in international reports of greenhouse gas emissions is the joule. A joule is the energy required to push with a force of one Newton for one meter. A terajoule (TJ) is one trillion (10^{12}) joules. A British thermal unit (Btu, the customary U.S. energy unit) is the quantity of heat required to raise the temperature of one pound of water one degree Fahrenheit at or near 39.2 degrees Fahrenheit.

2.388 × 10¹¹ calories
23.88 metric tons of crude oil
1 TJ = equivalent
947.8 million Btus
277,800 kilowatt-hours

Converting Various Physical Units to Energy Units

¹⁶⁸ Reference: EIA (2007).

Data on the production and consumption of fuels are first gathered in physical units. These units must be converted to their energy equivalents. The conversion factors in Table A-276 can be used as default factors if local data are not available. See Appendix A of EIA's *Monthly Energy Review, November 2024* (EIA 2024 for more detailed information on the energy content of various fuels.

Table A-276: Conversion Factors to Energy Units (Heat Equivalents)

Fuel Type (Units)	Factor
Solid Fuels (Million Btu/Short ton)	
Anthracite coal	22.57
Bituminous coal	23.89
Sub-bituminous coal	17.14
Lignite	12.87
Coal Coke	24.80
Natural Gas (Btu/Cubic foot)	1,036
Liquid Fuels (Million Btu/Barrel)	
Motor gasoline	5.222
Aviation gasoline	5.048
Kerosene	5.670
Jet fuel, kerosene-type	5.670
Distillate fuel	5.825
Residual oil	6.287
Naphtha for petrochemicals	5.248
Petroleum coke	6.024
Other oil for petrochemicals	5.825
Special naphthas	5.248
Lubricants	6.065
Waxes	5.537
Asphalt	6.636
Still gas	6.287
Misc. products	5.796

Notes: For petroleum and natural gas, *Monthly Energy Review, November 2023* (EIA 2023). For coal ranks, *State Energy Data Report 1992* (EIA 1993). All values are given in higher heating values (gross calorific values).

6.5 Chemical Formulas

Table A-277: Guide to Chemical Formulas

Symbol	Name
Al	Aluminum
Al ₂ O ₃	Aluminum oxide
Br	Bromine
C	Carbon
CH ₄	Methane
C ₂ H ₆	Ethane
C ₃ H ₈	Propane
CF ₄	Perfluoromethane
C ₂ F ₆	Perfluoroethane, hexafluoroethane
c-C ₃ F ₆	Perfluorocyclopropane
C ₃ F ₈	Perfluoropropane
C ₄ F ₆	Hexafluoro-1,3-butadiene
c-C ₄ F ₈	Perfluorocyclobutane
C ₄ F ₈ O	Octafluorotetrahydrofuran
C ₄ F ₁₀	Perfluorobutane
c-C ₅ F ₈	Perfluorocyclopentene
C ₅ F ₁₂	Perfluoropentane
C ₆ F ₁₄	Perfluorohexane
CF ₃ I	Trifluoroiodomethane
CFCl ₃	Trichlorofluoromethane (CFC-11)
CF ₂ Cl ₂	Dichlorodifluoromethane (CFC-12)
CF ₃ Cl	Chlorotrifluoromethane (CFC-13)
C ₂ F ₃ Cl ₃	Trichlorotrifluoroethane (CFC-113)*
CCl ₃ CF ₃	CFC-113a*
C ₂ F ₄ Cl ₂	Dichlorotetrafluoroethane (CFC-114)
C ₂ F ₅ Cl	Chloropentafluoroethane (CFC-115)
CHCl ₂ F	HCFC-21
CHF ₂ Cl	Chlorodifluoromethane (HCFC-22)
C ₂ F ₃ HCl ₂	HCFC-123
C ₂ F ₄ HCl	HCFC-124
C ₂ FH ₃ Cl ₂	HCFC-141b
C ₂ H ₃ F ₂ Cl	HCFC-142b
CF ₃ CF ₂ CHCl ₂	HCFC-225ca
CClF ₂ CF ₂ CHClF	HCFC-225cb
CCl ₄	Carbon tetrachloride
CHClCCl ₂	Trichloroethylene
CCl ₂ CCl ₂	Perchloroethylene, tetrachloroethene
CH ₃ Cl	Methylchloride
CH ₃ CCl ₃	Methylchloroform
CH ₂ Cl ₂	Methylenechloride
CHCl ₃	Chloroform, trichloromethane
CHF ₃	HFC-23
CH ₂ F ₂	HFC-32
CH ₃ F	HFC-41
C ₂ HF ₅	HFC-125
C ₂ H ₂ F ₄	HFC-134
CH ₂ FCF ₃	HFC-134a
C ₂ H ₃ F ₃	HFC-143*
C ₂ H ₃ F ₃	HFC-143a*
CH ₂ FCH ₂ F	HFC-152*
C ₂ H ₄ F ₂	HFC-152a*
CH ₃ CH ₂ F	HFC-161

C ₃ HF ₇	HFC-227ea
CF ₃ CF ₂ CH ₂ F	HFC-236cb
CF ₃ CHFCHF ₂	HFC-236ea
C ₃ H ₂ F ₆	HFC-236fa
C ₃ H ₃ F ₅	HFC-245ca
CHF ₂ CH ₂ CF ₃	HFC-245fa
CF ₃ CH ₂ CF ₂ CH ₃	HFC-365mfc
C ₅ H ₂ F ₁₀	HFC-43-10mee
CF ₃ OCHF ₂	HFE-125
CF ₂ HOCF ₂ H	HFE-134
CH ₃ OCF ₃	HFE-143a
CF ₃ CHFOCF ₃	HFE-227ea
CF ₃ CHCLOCHF ₂	HCFE-235da2
CF ₃ CHFOCHF ₂	HFE-236ea2
CF ₃ CH ₂ OCF ₃	HFE-236fa
CF ₃ CF ₂ OCH ₃	HFE-245cb2
CHF ₂ CH ₂ OCF ₃	HFE-245fa1
CF ₃ CH ₂ OCHF ₂	HFE-245fa2
CHF ₂ CF ₂ OCH ₃	HFE-254cb2
CF ₃ CH ₂ OCH ₃	HFE-263fb2
CF ₃ CF ₂ OCF ₂ CHF ₂	HFE-329mcc2
CF ₃ CF ₂ OCH ₂ CF ₃	HFE-338mcf2
CF ₃ CF ₂ CF ₂ OCH ₃	HFE-347mcc3
CF ₃ CF ₂ OCH ₂ CHF ₂	HFE-347mcf2
CF ₃ CHF ₂ CF ₂ OCH ₃	HFE-356mec3
CHF ₂ CF ₂ CF ₂ OCH ₃	HFE-356pcc3
CHF ₂ CF ₂ OCH ₂ CHF ₂	HFE-356pcf2
CHF ₂ CF ₂ CH ₂ OCHF ₂	HFE-356pcf3
CF ₃ CF ₂ CH ₂ OCH ₃	HFE-365mcf3
CHF ₂ CF ₂ OCH ₂ CH ₃	HFE-374pcf2
C ₄ F ₉ OCH ₃	HFE-7100
C ₄ F ₉ OC ₂ H ₅	HFE-7200
CH ₂ CF ₂ CF ₃	HFO-1234yf
CHFCHCF ₃	HFO-1234ze(E)
CF ₃ CHCHCF ₃	HFO-1336mzz(Z)
C ₃ H ₂ ClF ₃	HCFO-1233zd(E)
CHF ₂ OCF ₂ OC ₂ F ₄ OCHF ₂	H-Galden 1040x
CHF ₂ OCF ₂ OCHF ₂	HG-10
CHF ₂ OCF ₂ CF ₂ OCHF ₂	HG-01
CH ₃ OCH ₃	Dimethyl ether
CH ₂ Br ₂	Dibromomethane
CH ₂ BrCl	Dibromochloromethane
CHBr ₃	Tribromomethane
CHBrF ₂	Bromodifluoromethane
CH ₃ Br	Methylbromide
CF ₂ BrCl	Bromodichloromethane (Halon 1211)
CF ₃ Br(CBrF ₃)	Bromotrifluoromethane (Halon 1301)
CF ₃ I	FIC-13I1
CO	Carbon monoxide
CO ₂	Carbon dioxide
CaCO ₃	Calcium carbonate, Limestone
CaMg(CO ₃) ₂	Dolomite
CaO	Calcium oxide, Lime
Cl	atomic Chlorine
F	Fluorine
Fe	Iron
Fe ₂ O ₃	Ferric oxide

FeSi	Ferrosilicon
GaAs	Gallium arsenide
H, H ₂	atomic Hydrogen, molecular Hydrogen
H ₂ O	Water
H ₂ O ₂	Hydrogen peroxide
OH	Hydroxyl
N, N ₂	atomic Nitrogen, molecular Nitrogen
NH ₃	Ammonia
NH ₄ ⁺	Ammonium ion
HNO ₃	Nitric acid
MgO	Magnesium oxide
NF ₃	Nitrogen trifluoride
N ₂ O	Nitrous oxide
NO	Nitric oxide
NO ₂	Nitrogen dioxide
NO ₃	Nitrate radical
NO _x	Nitrogen oxides
Na	Sodium
Na ₂ CO ₃	Sodium carbonate, soda ash
Na ₃ AlF ₆	Synthetic cryolite
O, O ₂	atomic Oxygen, molecular Oxygen
O ₃	Ozone
S	atomic Sulfur
H ₂ SO ₄	Sulfuric acid
SF ₆	Sulfur hexafluoride
SF ₅ CF ₃	Trifluoromethylsulphur pentafluoride
SO ₂	Sulfur dioxide
Si	Silicon
SiC	Silicon carbide
SiO ₂	Quartz

* Distinct isomers.

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ANNEX 7 Uncertainty

The annual *Inventory* presents the best effort to produce emission estimates for greenhouse gas source and sink categories in the United States. These estimates were following the recommendations set forth in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) and *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019). This Annex provides an overview of the overall uncertainty analysis conducted to support the *Inventory*, including informing and prioritizing inventory improvements.

7.1. Overview

The uncertainty analysis conducted in support of the *Inventory* (1) evaluates the relative contribution of the input parameters to the uncertainty associated with each source or sink category estimate, (2) determines the quantitative uncertainty associated with the emission source and sink estimates presented in the main body of this report and (3) estimates the uncertainty in the overall emissions and removals for the latest year, the base year and in the emissions trend. Note, overall uncertainty estimates in the *Inventory* capture quantifiable uncertainties in the input activity and emission factors data, but do not account for the potential of additional sources of uncertainty such as modeling uncertainties, measurement errors, and misreporting or misclassification. Thus, the *Inventory* uncertainty analysis helps inform and prioritize improvements for source and sink categories estimation process which are discussed in the “Planned Improvements” sections of each source or sink category’s discussion within the main body of the report. For each source or sink category, the uncertainty analysis highlights opportunities for changes to data measurement, data collection, and calculation methodologies to reduce uncertainties.

For some category estimates, the uncertainty ranges or bounds are smaller, such as CO₂ emissions from energy-related combustion activities. This is primarily because the methodologies and data utilized for these estimates have remained stable over time, which tends to minimize fluctuations in uncertainty bounds. However, it is important to note that this does not necessarily imply smaller absolute uncertainties, but rather a smaller relative variation in uncertainty over time. Importantly, if a large source were updated for the base year of 1990 with higher uncertainty bounds, it may contribute to an increase in the uncertainty of the overall emission estimates for the base year. For some other limited categories of emissions, uncertainties could have a larger impact on the uncertainties of estimates presented (i.e., storage factors of non-energy uses of fossil fuels). In all source and sink category chapters, the inventory emission (or removal) estimates include “Uncertainty” sections that consider both quantitative and qualitative assessments of uncertainty, considering factors consistent with good practices noted in Volume 1, Chapter 3 of the *2006 IPCC Guidelines* (e.g., completeness of data, representativeness of data and models, sampling errors, measurement errors). The two major types of uncertainty associated with these emission estimates are (1) model uncertainty, which arises when the emission and/or removal estimation models used in developing the *Inventory* estimates do not fully and accurately characterize the respective emission and/or removal processes (due to a lack of technical details or other resources), and (2) parameter uncertainty, which arises due to potential bias or a lack of accurate, complete, representative, or precise input data such as emission factors and activity data and inherent variability.

The uncertainty associated with emission (or removal) estimation models can be partially analyzed by comparing the model emission (or removal) results with those of other models developed to characterize the same emission (or removal) process, after taking into account differences in their conceptual framework, capabilities, data, and underlying assumptions. However, in many cases it would be very difficult—if not impossible—to use this approach to quantify the model uncertainty associated with the emission estimates in this report, primarily because most categories only have a single model that has been developed to estimate emissions. Therefore, model uncertainty was not quantified in this report. Nonetheless, it has been discussed qualitatively, where appropriate, along with the individual source or sink category description and inventory estimation methodology.

Parameter uncertainty encompasses several causes such as lack of completeness, lack of data or representative data, sampling error, random or systematic measurement error, or misreporting or misclassification. Uncertainties associated with input emission parameters have been quantified for all of the emission sources and sinks included in the U.S. *Inventory* totals.

7.2. Methodology and Results

The EPA has developed a *Quality Assurance/Quality Control and Uncertainty Management Plan for the U.S. Greenhouse Gas Inventory* (QA/QC plan) (EPA 2018). Like the QA/QC plan, the uncertainty management plan is part of a continually evolving process. The uncertainty management plan provides for a quantitative assessment of the *Inventory* analysis itself, thereby contributing to continuing efforts to understand both what causes uncertainty and how to improve *Inventory* and accuracy. Although the plan provides both general and specific guidelines for implementing a quantitative uncertainty analysis, its components are intended to evolve over time, consistent with the inventory estimation process. The plan includes procedures and guidelines, and forms and templates, for developing quantitative assessments of uncertainty in the national *Inventory* estimates (EPA 2018). For the current *Inventory*, EPA has used the uncertainty management plan as well as the methodology presented in the *2006 IPCC Guidelines* and *2019 Refinement*.

The *2006 IPCC Guidelines* and *2019 Refinement* recommend two methods—Approach 1 and Approach 2—for developing quantitative estimates of uncertainty associated with individual categories and the overall *Inventory* estimates. The EPA is continuing efforts to develop quantitative estimates of uncertainty for all source categories using Approach 2. Consistent with national inventory reporting standards, emissions from International Bunker Fuels, Wood Biomass and Biofuel Consumption, and Indirect Greenhouse Gas Emissions are not included in the total emissions estimated for the *Inventory* but are estimated and reported separately; therefore, no quantitative uncertainty estimates have been developed for these categories but are identified as an improvement area.¹⁶⁹ CO₂ Emissions from Biomass and Biofuel Consumption are accounted for implicitly in the Land Use, Land-Use Change and Forestry (LULUCF) chapter through the calculation of changes in carbon stocks. The Energy sector provides an estimate of CO₂ emissions from Biomass and Biofuel Consumption as a memo item for informational purposes, consistent with the national inventory reporting standards.

Approach 1 and Approach 2 Methods

The Approach 1 method for estimating uncertainty is based on the propagation of errors, as shown in Eq. 3.1 and Eq. 3.2 of the *2006 IPCC Guidelines* and *2019 Refinement*. These equations combine the random component of uncertainty associated with the activity data and the emission (or the other) factors. Inherent in employing the Approach 1 method are the assumptions that, for each source and sink category, (i) both the uncertainties in the activity data and the emission factor values are approximately normally distributed, (ii) the coefficient of variation (i.e., the ratio of the standard deviation to the mean) associated with each input variable is less than 30 percent, and (iii) the input variables within and across sub- source categories are not correlated (i.e., value of each variable is independent of the values of other variables).

The Approach 2 method is preferred if (i) the uncertainty associated with the input variables is large (i.e., >30 percent), (ii) the distributions of uncertainties in the underlying the input variables are not normal (e.g., triangular or uniformly distributed), (iii) the estimates of uncertainty associated with the input variables are correlated, and/or if (iv) a complex estimation methodology and/or several input variables are used to characterize the emission (or removal) process. Due to the input parameters and estimation methodologies used in the *Inventory*, the uncertainties are assessed using the Approach 2 method for all categories where sufficient and reliable data are available to characterize the uncertainty of the input variables.

The Approach 2 method employs the Monte Carlo Stochastic Simulation technique (also referred to as the Monte Carlo method). Under this method, emission (or removal) estimates for a particular source (or sink) category are estimated by randomly selecting values of emission factors, activity data, and other estimation parameters according to their individual Probability Density Functions (PDFs). This process is repeated many times using

¹⁶⁹ However, because the input variables that determine the emissions from the Fossil Fuel Combustion and the International Bunker Fuels source categories are correlated, uncertainty associated with the activity variables in the International Bunker Fuels was taken into account in estimating the uncertainty associated with the Fossil Fuel Combustion.

computer software, in order to build up the probability density function, which is then used to estimate the final uncertainty values of the overall emission (or removal) estimates for that source (or sink). For most categories, the Monte Carlo approach is implemented using commercially available simulation software such as Palisade's @RISK Microsoft Excel add-in.

Characterization of Uncertainty in Input Variables

Both Approach 1 and Approach 2 uncertainty analyses require that all the input variables have defined PDFs. In the absence of sufficient data measurements, data samples, or expert judgments that determined otherwise, the PDFs incorporated in the current source or sink category uncertainty analyses were limited to normal, lognormal, uniform, triangular, pert, and beta distributions. The choice among these six PDFs depended largely on the observed or measured data and expert judgment. If no additional uncertainty information is available, then the previous year's *Inventory* uncertainty data is used. Input variables with asymmetrical PDFs shift the overall output which can lead to asymmetrical bounds for a source (or sink) category and in turn, for the overall *Inventory* uncertainty analysis.

Individual Source and Sink Category Inventory Uncertainty Estimates

The main report provides an overview of the input parameters and sources of uncertainty for each source and sink category within the Uncertainty section of each category. Table A-278 summarizes results based on assessments of source and sink category-level uncertainty, as presented in the main chapter text. The table presents base year (1990) and current year (2023) emissions for each source and sink category. The combined uncertainty (at the 95 percent confidence interval) for each source and category is expressed as the percentage above and below the total 2023 emissions estimated for each source and sink category. Uncertainty in the trend of each source and sink category is described subsequently in this Appendix.

Table A-278: Summary Results of Source and Sink Category Uncertainty Analyses

Source or Sink Category	Base Year Emissions ^a	2023 Emissions ^b	2023 Uncertainty ^b	
	(MMT CO ₂ Eq.)	(MMT CO ₂ Eq.)	Lower Bound	Upper Bound
CO₂	5,131.8	4,918.4	-2%	4%
Fossil Fuel Combustion	4,752.2	4,559.4	-2%	4%
Non-Energy Use of Fuels	99.1	107.1	-36%	62%
Cement Production	33.5	40.6	-4%	5%
Iron and Steel Production & Metallurgical Coke Production	104.7	46.2	-16%	16%
Natural Gas Systems	32.5	37.7	-14%	17%
Petrochemical Production	20.1	30.5	-4%	4%
Petroleum Systems	9.6	23.3	-18%	22%
Ammonia Production	14.4	12.2	-4%	4%
Incineration of Waste	12.9	12.4	-17%	20%
Lime Production	11.7	11.5	-2%	2%
Other Process Uses of Carbonates	7.1	7.2	-11%	15%
Urea Consumption for Non-Agricultural Purposes	3.8	5.4	-5%	4%
Urea Fertilization	2.4	5.3	-43%	3%
Carbon Dioxide Consumption	1.5	2.1	-5%	5%
Liming	4.7	5.3	-85%	89%
Coal Mining	4.6	2.4	-68%	76%
Glass Production	2.3	1.8	-3%	3%

Soda Ash Production	1.4	1.7	-9%	8%
Titanium Dioxide Production	1.2	1.2	-13%	13%
Aluminum Production	6.8	1.2	-3%	3%
Ferroalloy Production	2.2	1.2	-13%	13%
Zinc Production	0.6	0.9	-19%	21%
Phosphoric Acid Production	1.5	0.9	-18%	20%
Lead Production	0.5	0.5	-15%	15%
Carbide Production and Consumption	0.2	0.2	-10%	10%
Magnesium Production and Processing	0.1	+	-6%	6%
Abandoned Oil and Gas Wells	+	+	-83%	235%
Substitution of Ozone Depleting Substances	+	+	-3%	20%
CO ₂ Transport, Injection, and Geological Storage	+	0.1	-51%	51%
<i>Wood Biomass, Ethanol, and Biodiesel Consumption^c</i>	237.9	300.5	-9%	12%
<i>International Bunker Fuels^d</i>	103.6	96.2	-5%	5%
CH₄	873.1	686.7	-7%	11%
Enteric Fermentation	183.1	187.1	-11%	18%
Natural Gas Systems	219.6	162.4	-10%	11%
Landfills	197.8	119.5	-9%	14%
Manure Management	39.1	65.1	-18%	20%
Coal Mining	108.1	45.4	-10%	21%
Petroleum Systems	50.0	38.0	-13%	24%
Wastewater Treatment	22.7	21.1	-28%	32%
Rice Cultivation	18.9	18.7	-75%	75%
Stationary Combustion	9.7	8.8	-34%	125%
Abandoned Oil and Gas Wells	7.8	8.5	-83%	230%
Abandoned Underground Coal Mines	8.1	6.1	-20%	24%
Mobile Combustion	7.2	2.5	-4%	30%
Composting	0.4	2.6	-58%	58%
Field Burning of Agricultural Residues	0.5	0.6	-14%	14%
Carbide Production and Consumption	+	+	-10%	11%
Iron and Steel Production & Metallurgical Coke Production	+	+	-20%	21%
Ferroalloy Production	+	+	-12%	13%
Petrochemical Production	+	+	-14%	14%
Anaerobic Digestion at Biogas Facilities	+	+	-54%	54%
Incineration of Waste	+	+	-102%	103%

<i>International Bunker Fuels^d</i>	<i>0.2</i>	<i>0.1</i>	<i>-57%</i>	<i>100%</i>
N₂O	407.8	387.0	-15%	28%
Agricultural Soil Management	289.1	296.3	-31%	37%
Stationary Combustion	22.3	19.6	-23%	51%
Wastewater Treatment	14.8	20.8	-37%	193%
Manure Management	13.4	16.8	-16%	24%
Mobile Combustion	37.8	16.2	-7%	22%
Nitric Acid Production	10.8	8.3	-6%	6%
N ₂ O from Product Uses	3.8	3.8	-24%	24%
Adipic Acid Production	13.5	1.2	-4%	4%
Composting	0.3	1.8	-58%	58%
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.5	1.3	-31%	31%
Incineration of Waste	0.4	0.3	-53%	161%
Electronics Industry	+	0.3	-10%	11%
Field Burning of Agricultural Residues	0.2	0.2	-18%	18%
Natural Gas Systems	+	0.01	-14%	17%
Petroleum Systems	+	+	-18%	22%
<i>International Bunker Fuels^d</i>	<i>0.8</i>	<i>0.8</i>	<i>-70%</i>	<i>150%</i>
HFCs, PFCs, SF₆ and NF₃	125.6	205.3	-11%	6%
Substitution of Ozone Depleting Substances	0.3	189.0	-3%	20%
Fluorochemical Production	71.0	4.7	-20%	20%
Electrical Equipment	24.6	5.1	-20%	21%
Electronics Industry	3.3	3.9	-6%	6%
Magnesium Production and Processing	5.6	1.1	-8%	8%
Aluminum Production	19.3	0.5	-8%	10%
SF ₆ and PFCs from Other Product Use	1.5	1.0	-49%	51%
HCFC-22 Production	+	+	-7%	10%
Total Gross Emissions^e	6,538.3	6,197.3	-2%	4%
LULUCF Emissions ^f	59.1	60.6	-5%	7%
LULUCF Carbon Stock Change Flux ^g	(1,096.9)	(1,000.5)	26%	-14%
LULUCF Sector Net Total^h	(1,037.9)	(939.94)	28%	-15%
Net Emissions (Sources and Sinks)^e	5,500.4	5,257.4	-5%	6%

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration. Total emissions (excluding emissions for which uncertainty was not quantified) are presented without LULUCF. Net emissions are presented with LULUCF. Uncertainty for the base year is available upon request.

+ Does not exceed 0.05 MMT CO₂ Eq. or 0.5 percent.

NE (Not Estimated)

^a Base Year is 1990 for all sources.

^b The uncertainty estimates correspond to a 95 percent confidence interval, with the lower bound corresponding to 2.5th percentile and the upper bound corresponding to 97.5th percentile.

^c Emissions from Wood Biomass and Biofuel Consumption are not included in the energy sector totals.

^dEmissions from International Bunker Fuels are not included in the totals.

^eTotals exclude emissions for which uncertainty was not quantified.

^fLULUCF emissions include the CH₄ and N₂O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH₄ emissions from land converted to coastal wetlands, land converted to flooded land, and flooded land remaining flooded land; and N₂O emissions from forest soils and settlement soils.

^gLULUCF carbon stock change is the net C stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements. Since the resulting flux is negative the signs of the resulting lower and upper bounds are reversed.

^hThe LULUCF sector net total is the net sum of all CH₄ and N₂O emissions to the atmosphere plus net carbon stock changes.

Overall (Aggregate) *Inventory* Level Uncertainty Estimates

The overall level uncertainty estimate for the *Inventory* was developed using the IPCC Approach 2 uncertainty estimation methodology for 1990 and 2023. The overall *Inventory* uncertainty estimates were estimated by combining the Monte Carlo simulation output data for each emission source or sink category (as described above) into a comprehensive overall uncertainty model. This overall uncertainty model combines uncertainties and produces uncertainty results at the gas level. If such detailed output data were not available for a particular source or sink category, individual PDFs were assigned based on the most detailed data available from the category-specific quantitative uncertainty analysis. The overall *Inventory* uncertainty was then derived through the resulting PDF of the combined emissions data.

For select categories such as composting, several LULUCF source categories, and parts of Agricultural Soil Management source categories, Approach 1 uncertainty results were used in the overall uncertainty analysis. However, for all other emission sources, Approach 2 uncertainty results were used in the overall uncertainty estimation.

The overall uncertainty model results indicate that the 1990 U.S. greenhouse gas emissions are estimated to be within the range of approximately 6,379.7 to 6,784.4 MMT CO₂ Eq., reflecting a relative 95 percent confidence interval uncertainty range of -2 percent to 4 percent with respect to the total U.S. greenhouse gas emission estimate of approximately 6,538.3 MMT CO₂ Eq. The uncertainty interval associated with total CO₂ emissions ranges from -2 percent to 5 percent of total CO₂ emissions estimated. The results indicate that the uncertainty associated with the inventory estimate of the total CH₄ emissions ranges from -12 percent to 5 percent, uncertainty associated with the total inventory N₂O emission estimate ranges from -15 percent to 25 percent, and uncertainty associated with fluorinated greenhouse gas (F-GHG) emissions ranges from -18 percent to 19 percent. When the LULUCF sector is included in the analysis, the uncertainty is estimated to be -6 to 5 percent of Net Emissions (sources and sinks) in 1990. The uncertainties presented are quantifiable uncertainties in the input activity and emission factors data, not uncertainties in the models, data representativeness, measurement errors, or misreporting or misclassification of data.

Table A-279: Quantitative Uncertainty Assessment of Overall National Inventory Emissions for 1990 (MMT CO₂ Eq. and Percent)

Gas	1990 Emission Estimate (MMT CO ₂ Eq.)	Uncertainty Range Relative to Greenhouse Gas Estimate ^a				Standard Mean ^b Deviation ^b (MMT CO ₂ Eq.)	
		(MMT CO ₂ Eq.)		(%)			
		Lower Bound ^c	Upper Bound ^c	Lower Bound	Upper Bound		
CO ₂	5,131.8	5,024.0	5,365.2	-2%	5%	4,972.0	88.0
CH ₄ ^d	873.1	767.4	914.6	-12%	5%	680.0	37.5

N ₂ O ^d	407.8	348.7	509.8	-15%	25%	428.6	40.7
PFCs, HFCs, SF ₆ , and NF ₃ ^d	125.6	103.3	149.7	-18%	19%	220.7	12.2
Total Gross Emissions	6,538.3	6,384.5	6,787.1	-2%	4%	6,301.2	104.8
LULUCF Emissions ^e	59.1	55.9	63.3	-6%	7%	61.1	2.0
LULUCF Carbon Stock Change Flux ^f	(1,096.9)	(1,386.3)	(949.2)	26%	-13%	(1,061.5)	111.7
LULUCF Sector Net Total^g	(1,037.9)	(1,326.8)	(889.2)	28%	-14%	(1,000.4)	111.7
Net Emissions (Sources and Sinks)	5,500.4	5,177.2	5,779.7	-6%	5%	5,300.8	154.6

^a The lower and upper bounds for emission estimates correspond to a 95 percent confidence interval, with the lower bound corresponding to 2.5th percentile and the upper bound corresponding to 97.5th percentile.

^b Mean value indicates the arithmetic average of the simulated emission estimates; standard deviation indicates the extent of deviation of the simulated values from the mean.

^c The lower and upper bound emission estimates for the sub-source categories do not sum to total emissions because the low and high estimates for total emissions were calculated separately through simulations.

^d The overall uncertainty estimates did not take into account the uncertainty in the GWP values for CH₄, N₂O, and high GWP gases used in the inventory emission calculations for 1990.

^e LULUCF emissions include the CH₄ and N₂O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH₄ emissions from land converted to coastal wetlands, land converted to flooded land, and flooded land remaining flooded land; and N₂O emissions from forest soils and settlement soils.

^f LULUCF carbon stock change is the net C stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements. Since the resulting flux is negative the signs of the resulting lower and upper bounds are reversed.

^g The LULUCF sector net total is the net sum of all CH₄ and N₂O emissions to the atmosphere plus net carbon stock changes.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration. Total emissions (excluding emissions for which uncertainty was not quantified) are presented without LULUCF. Net emissions are presented with LULUCF.

The overall uncertainty model results indicate that the 2023 U.S. greenhouse gas emissions are estimated to be within the range of approximately 6,088.8 to 6,466.6 MMT CO₂ Eq., reflecting a relative 95 percent confidence interval uncertainty range of -2 percent to 4 percent with respect to the total gross U.S. greenhouse gas emission estimate of approximately 6,197.3 MMT CO₂ Eq. The uncertainty interval associated with total CO₂ emissions, which constitute about 79.4 percent of the total U.S. greenhouse gas emissions in 2023, ranges from -2 percent to 4 percent of total CO₂ emissions estimated. The results indicate that the uncertainty associated with the inventory estimate of the total CH₄ emissions ranges from -7 percent to 11 percent, uncertainty associated with the total inventory N₂O emission estimate ranges from -15 percent to 28 percent, and uncertainty associated with fluorinated greenhouse gas (F-GHG) emissions ranges from -11 percent to 6 percent. When the LULUCF sector is included in the analysis, the uncertainty is estimated to be -5 to 6 percent of Net Emissions (sources and sinks) in 2023.

The uncertainty of total gross and net emissions for 1990 was slightly reduced this year due to updates in methods and data compared to the previous *Inventory*; the 95 percent uncertainty bounds for total gross emissions are -2 percent to 4 percent for 1990 in the current *Inventory* compared to -3 percent to 4 percent for the previous (1990 through 2022) *Inventory*. Similarly, the bounds for net emissions are -5 percent to 6 percent for 1990 in the current *Inventory* compared to -6 percent to 6 percent for in the previous *Inventory*. This reflects consistency among the different categories. For example, the 95 percent uncertainty bounds for carbon dioxide emissions from Fossil Fuel Combustion remained the same as the previous *Inventory*, from -2 percent to 4 percent. The 95 percent uncertainty bounds for carbon dioxide emissions from Cement Production also remained the same as the previous *Inventory*, from -4 percent to 5 percent. Furthermore, uncertainty estimates were included for Wood Biomass, Ethanol, and Biodiesel Consumption and International Bunker Fuels this *Inventory*, though these sources are memo items and are not included in totals or overall uncertainty estimates.

Compared to 1990, the uncertainty of total gross and net emissions for the latest year did not change significantly this year; the 95 percent uncertainty bounds for total gross emissions in 2023 are -2 percent to 4 percent for the current *Inventory* compared to -2 percent to 4 percent for 2022 in the previous *Inventory*. Similarly, the bounds for net emissions in 2023 are -5 percent to 6 percent for the current *Inventory*, the same as the bounds for net emissions in 2022 in the previous *Inventory*. However, this does not mean that the methodology and data quality was not improved for *Inventory* emissions estimates, rather it reflects offsetting impacts from improvements where uncertainty both decreased and increased (i.e., the latter represents situations where a more realistic acknowledgement of the limitations of emissions estimates is reflected in the input data), as noted in the 2006 IPCC Guidelines. More detail on changes in uncertainty can be found under “Recent and Ongoing Improvements.”

A summary of the overall quantitative uncertainty estimates is shown below.

Table A-280: Quantitative Uncertainty Assessment of Overall National Inventory Emissions for 2023 (MMT CO₂ Eq. and Percent)

Gas	2023 Emission Estimate (MMT CO ₂ Eq.)	Uncertainty Range Relative to Greenhouse Gas Estimate ^a				Mean ^b	Standard Deviation ^b
		(MMT CO ₂ Eq.)		(%)			
		Lower Bound ^c	Upper Bound ^c	Lower Bound	Upper Bound		
						(MMT CO ₂ Eq.)	
CO ₂	4,918.4	4,818.4	5,128.7	-2%	4%	4,969.4	80.5
CH ₄ ^d	686.7	638.6	762.4	-7%	11%	700.4	31.8
N ₂ O ^d	387.0	328.8	493.6	-15%	28%	404.2	42.3
PFC, HFC, SF ₆ , and NF ₃ ^d	205.3	183.0	217.6	-11%	6%	199.7	8.9
Total Gross Emissions	6,197.3	6,088.8	6,466.6	-2%	4%	6,273.6	96.7
LULUCF Emissions ^e	60.6	57.5	65.0	-5%	7%	61.1	2.0
LULUCF Carbon Stock Change Flux ^f	(1,000.5)	(1,257.8)	(862.8)	26%	-14%	(1,061.9)	101.6
LULUCF Sector Net Total^g	(939.9)	(1,196.5)	(801.5)	27%	-15%	(1,000.8)	101.6
Net Emissions (Sources and Sinks)	5,257.4	5,002.9	5,549.1	-5%	6%	5,272.9	140.5

^a The lower and upper bounds for emission estimates correspond to a 95 percent confidence interval, with the lower bound corresponding to 2.5th percentile and the upper bound corresponding to 97.5th percentile.

^b Mean value indicates the arithmetic average of the simulated emission estimates; standard deviation indicates the extent of deviation of the simulated values from the mean.

^c The lower and upper bound emission estimates for the sub-source categories do not sum to total emissions because the low and high estimates for total emissions were calculated separately through simulations.

^d The overall uncertainty estimates did not take into account the uncertainty in the GWP values for CH₄, N₂O, and high GWP gases used in the inventory emission calculations for 2023.

^e LULUCF emissions include the CH₄ and N₂O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH₄ emissions from land converted to coastal wetlands, land converted to flooded land, and flooded land remaining flooded land; and N₂O emissions from forest soils and settlement soils.

^f LULUCF carbon stock change is the net C stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements. Since the resulting flux is negative the signs of the resulting lower and upper bounds are reversed.

^g The LULUCF sector net total is the net sum of all CH₄ and N₂O emissions to the atmosphere plus net carbon stock changes.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration. Total emissions (excluding emissions for which uncertainty was not quantified) are presented without LULUCF. Net emissions are presented with LULUCF.

As summarized, uncertainty in 2023 is similar to overall uncertainty in 1990, and this is due to offsetting impacts from changes in uncertainty from methodological improvements over the time series. As indicated in section 3.1.7 (Implications of Methodological Choice) in Volume 3, *2006 IPCC Guidelines*, while in some cases methodological refinements have reduced uncertainty (as noted below), in some cases, in particular for key categories, they can also increase uncertainty with improved representation of the “complexity of the system” (IPCC 2006). For example, this is true of uncertainty associated with inputs to estimating N₂O emissions from Agricultural Soil Management.

Trend Uncertainty

In addition to the estimates of uncertainty associated with the current and base year emission estimates, this Annex also presents the estimates of trend uncertainty. The *2006 IPCC Guidelines* define trend as the difference in emissions between the base year (i.e., 1990) and the current year (i.e., 2023) *Inventory* estimates. However, for purposes of understanding the concept of trend uncertainty, the emission trend is defined in this *Inventory* as the percentage change in the emissions (or removal) estimated for the current year, relative to the emission (or removal) estimated for the base year. The uncertainty of the trend is “a function of the uncertainties of the activity data and the emission factors at both these points in time”, as defined in the *2019 IPCC Refinement*. The uncertainty associated with this emission trend is referred to as trend uncertainty.

Under the Approach 1 method, there are two types of uncertainty to consider when estimating the trend uncertainty in an individual source or sink category. As described in the *2006 IPCC Guidelines*, correlated (Type A) uncertainties are estimated by comparing the change in emissions trend given a 1 percent change in both base (i.e., 1990) and current emissions (i.e., 2023), while uncorrelated or random errors in the emissions trend (Type B) are estimated by comparing the change in emissions trend given a 1 percent change in only the current year emissions. When combined, both types of uncertainty capture the sensitivity in trend emission estimates to sources of uncertainty that are correlated between the base and current year (Type A), as well as the random component of uncertainty in the emission estimates (Type B).

Under the Approach 2 method, the trend uncertainty is estimated using the Monte Carlo Stochastic Simulation technique. As described in the *2006 IPCC Guidelines*, this Approach follows four steps. First, the PDFs for emission factors, activity data, and other input estimation parameters are determined for both the current and base year. For purposes of this *Inventory*, due to data limitations, for some categories where uncertainty assessments for 1990 are undergoing updates for future reports but were not ready to incorporate for this report, a simple approach has been adopted, under which the base year source or sink category emissions are assumed to exhibit the same uncertainty characteristics as the current year emissions (or removals). Source and sink category-specific PDFs for base year estimates were developed using current year (i.e., 2023) uncertainty output data. These were adjusted to account for differences in magnitude between the two years’ inventory estimates. The second and third steps follow the Monte Carlo approach described previously to calculate repeated emission estimates for each source and sink category in the base and current years according to the input data PDFs. The overall *Inventory* trend uncertainty estimate was developed by combining all source and sink category-specific trend uncertainty estimates. These trend uncertainty estimates represent the 95 percent confidence interval of the estimated percent change in emissions between 1990 and 2023 and are shown in Table A-281. Of note, the Fossil Fuel Combustion emissions estimate decreased by 4 percent this *Inventory* (1990-2023), compared to a 1 percent decrease in the previous *Inventory* (1990-2022). This decrease caused the overall CO₂ trend bounds to shift (-9 percent to 0 percent compared to -6 percent to 4 percent in the previous year).

Table A-281: Quantitative Assessment of Trend Uncertainty (MMT CO₂ Eq. and Percent)

Gas/Source	Base Year	2023	Emissions	Trend Range ^b	
	Emissions ^a	Emissions	Trend		
	(MMT CO ₂ Eq.)		(%)	(%)	
				Lower Bound	Upper Bound
CO₂	5,131.8	4,918.4	-4%	-8%	0%
Fossil Fuel Combustion	4,752.2	4,599.4	-4%	-9%	0%
Non-Energy Use of Fuels	99.10	107.1	8%	-41%	87%
Cement Production	33.5	40.6	21%	8%	38%

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Iron and Steel Production & Metallurgical Coke Production	104.7	46.2	-56%	-65%	-45%
Natural Gas Systems	32.5	37.7	16%	15%	60%
Petrochemical Production	20.1	30.5	52%	31%	52%
Petroleum Systems	9.6	23.3	142%	82%	225%
Ammonia Production	14.4	12.2	-15%	-19%	10%
Incineration of Waste	12.9	12.4	-4%	-26%	25%
Lime Production	11.7	11.5	-1%	-4%	2%
Other Process Uses of Carbonates	7.1	7.2	1%	-4%	39%
Urea Consumption for Non-Agricultural Purposes	3.8	5.4	43%	23%	71%
Urea Fertilization	2.4	5.3	118%	24%	284%
Carbon Dioxide Consumption	1.5	2.1	46%	81%	137%
Liming	4.7	5.3	13%	-1,198%	1,252%
Coal Mining	4.6	2.4	-48%	-85%	92%
Glass Production	2.3	1.8	-22%	-26%	-19%
Soda Ash Production	1.4	1.7	20%	6%	36%
Titanium Dioxide Production	1.2	1.2	3%	-14%	24%
Aluminum Production	6.8	1.2	-82%	-83%	-81%
Ferroalloy Production	2.2	1.2	-42%	-51%	-31%
Zinc Production	0.6	0.9	46%	10%	91%
Phosphoric Acid Production	1.5	0.9	-44%	-58%	-24%
Lead Production	0.5	0.5	-13%	-30%	7%
Carbide Production and Consumption	0.2	0.2	-25%	-38%	7%
Abandoned Oil and Gas Wells	+	+	13%	-1,453%	1,344%
Magnesium Production and Processing	0.1	+	-98%	-98%	-98%
CO ₂ Transport, Injection, and Geological Transport	+	0.1	NA	NE	NE
Ceramics Production	+	+	NA	NE	NE
Substitution of Ozone Depleting Substances	+	+	NA	NE	NE
<i>Wood Biomass and Biofuel Consumption^c</i>	237.9	300.5	26%	3%	54%
<i>International Bunker Fuels^d</i>	103.6	96.2	-7%	-14%	0%
CH₄	873.1	686.7	-21%	-28%	-9%
Enteric Fermentation	183.1	187.1	2%	-25%	38%
Natural Gas Systems	219.6	162.4	-26%	-36%	-14%
Landfills	197.8	119.5	-40%	-47%	-4%
Manure Management	39.1	65.1	66%	7%	160%
Coal Mining	108.1	45.4	-58%	-66%	-48%
Petroleum Systems	50.0	38.0	-24%	-43%	2%
Wastewater Treatment	22.7	21.1	-7%	-40%	42%
Rice Cultivation	18.9	18.7	-1%	-570%	787%
Stationary Combustion	9.7	8.8	-11%	-63%	178%
Abandoned Oil and Gas Wells	7.8	8.5	9%	-87%	778%
Abandoned Underground Coal Mines	8.1	6.1	-24%	-44%	9%
Mobile Combustion	7.2	2.5	-65%	-72%	-56%
Composting	0.4	2.6	508%	164%	1322%
Field Burning of Agricultural Residues	0.5	0.6	15%	-16%	56%
Carbide Production and Consumption	+	+	-38%	-45%	-10%
Iron and Steel Production & Metallurgical Coke Production	+	+	-67%	-72%	-51%
Ferroalloy Production	+	+	-49%	-52%	-32%
Petrochemical Production	+	+	-12%	-98%	-94%
Anaerobic Digestion at Biogas Facilities	+	+	1,428%	543%	3552%
Incineration of Waste	+	+	-19%	NE	NE
<i>International Bunker Fuels^d</i>	0.2	0.1	-55%	-290%	344%

N₂O	407.8	387.0	-5%	-31%	49%
Agricultural Soil Management	289.1	296.3	2%	-33%	87%
Stationary Combustion	22.3	19.6	-12%	-52%	52%
Wastewater Treatment	14.8	20.8	41%	-54%	269%
Manure Management	13.4	16.8	25%	-16%	90%
Mobile Combustion	37.8	16.2	-57%	-64%	-48%
Nitric Acid Production	10.8	8.3	-23%	-31%	-13%
N ₂ O from Product Uses	3.8	3.8	0%	-34%	13%
Adipic Acid Production	13.5	1.1	-91%	-93%	-90%
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.5	1.3	-11%	-50%	26%
Incineration of Waste	0.4	0.3	-19%	-75%	102%
Electronics Industry	+	0.3	666%	557%	789%
Natural Gas Systems	+	+	73%	23%	139%
Field Burning of Agricultural Residues	0.2	0.2	16%	-15%	58%
Petroleum Systems	+	+	57%	2%	142%
<i>International Bunker Fuels^d</i>	0.8	0.8	0%	-1,103%	1,202%
HFCs, PFCs, SF₆, and NF₃	125.6	205.3	64%	43%	119%
Substitution of Ozone Depleting Substances	0.3	189.0	74,863%	15,322%	691,313%
Electrical Equipment	24.6	5.1	-79%	-87%	-67%
Electronics Industry	3.3	4.3	20%	10%	32%
Aluminum Production	19.3	0.5	-98%	-98%	-97%
SF ₆ and PFCs from Other Product Use	1.5	1.0	-33%	-66%	2%
HCFC-22 Production	+	+	NA	NE	NE
Total Gross Emissions^e	6,538.3	6,197.3	-5%	-9%	0%
LULUCF Emissions ^f	59.1	60.6	3%	-6%	13%
LULUCF Carbon Stock Change Flux ^g	(1,096.9)	(1,000.5)	-9%	-30%	19%
LULUCF Sector Net Total^h	(1,037.9)	(939.9)	-9%	-32%	20%
Net Emissions (Sources and Sinks)^e	5,500.4	5,257.4	-4%	-11%	5%

+ Does not exceed 0.05 MMT CO₂ Eq. or 0.5 percent.

NE (Not Estimated)

^aBase Year is 1990 for all sources.

^bThe trend range represents a 95 percent confidence interval for the emission trend, with the lower bound corresponding to 2.5th percentile value and the upper bound corresponding to 97.5th percentile value.

^cEmissions from Wood Biomass and Biofuel Consumption are not included specifically in the energy sector totals.

^dEmissions from International Bunker Fuels are not included in the totals.

^eTotals exclude emissions for which uncertainty was not quantified.

^fLULUCF emissions include the CH₄ and N₂O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH₄ emissions from land converted to coastal wetlands, land converted to flooded land, and flooded land remaining flooded land; and N₂O emissions from forest soils and settlement soils.

^gLULUCF carbon stock change is the net C stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements.

^hThe LULUCF sector net total is the net sum of all CH₄ and N₂O emissions to the atmosphere plus net carbon stock changes.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration. Total emissions (excluding emissions for which uncertainty was not quantified) are presented without LULUCF. Net emissions are presented with LULUCF.

7.3. Information on Uncertainty Analyses by Source and Sink Category

The quantitative uncertainty estimates associated with each emission and removal category are reported within sectoral chapters of this *Inventory* following the discussions of inventory estimates and their estimation methodology. To better understand the uncertainty analysis details, refer to the respective chapters and

Uncertainty sections in the body of this report. EPA provides additional documentation on uncertainty information consistent with the guidance presented in Table 3.3 in Vol. 1, Chapter 3 of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) in an Uncertainty Addendum. Due to the number of detailed tables, it is not published with the *Inventory* but is available upon request. EPA plans to publish this in a more easily accessible format with future reports. All uncertainty estimates are reported relative to the current *Inventory* estimates for the 95 percent confidence interval, unless otherwise specified.

7.4. Reducing Uncertainty and Planned Improvements

The EPA has implemented many improvements over the last several years that have reduced uncertainties across the source and sink categories. These improvements largely result from new data sources that provide more accurate data and/or increased data coverage, as well as other methodological and completeness improvements, as described below.

Box A-4: Reducing Uncertainty

The *2006 IPCC Guidelines* provides the following guidance for ways to reduce *Inventory* uncertainty and improve the quality of an *Inventory* and its uncertainty estimates.

- *Improving conceptualization.* Improving the inclusiveness of the structural assumptions chosen can reduce uncertainties. An example is better treatment of seasonality effects that leads to more accurate annual estimates of emissions or removals for the Agriculture, Land Use, Land Use Change and Forestry sector.
- *Improving models.* Improving the model structure and parameterization can lead to better understanding and characterization of the systematic and random errors, as well as reductions in these causes of uncertainty.
- *Improving representativeness.* This may involve stratification or other sampling strategies. For example, continuous emissions monitoring systems (CEMS) can be used to reduce uncertainty for some sources and gases as long as the representativeness is guaranteed. CEMS produces representative data at the facilities where it is used, but in order to be representative of an entire source category, CEMS data must be available for a random sample or an entire set of individual facilities that comprise the category. When using CEMS both concentration and flow will vary, requiring simultaneous sampling of both attributes.
- *Incorporating excluded emission sources.* Quantitative estimates for some of the sources and sinks of greenhouse gas emissions, such as from some land-use activities, industrial processes, and parts of mobile sources, could not be developed at this time either because data are incomplete or because methodologies do not exist for estimating emissions from these source categories. See Annex 5 of this report for a discussion of the sources of greenhouse gas emissions and sinks excluded from this report. Consistent with IPCC good practice principles, EPA continues efforts to estimate emissions and sinks from excluded emission and removal sources occurring in U.S. and developing uncertainty estimates for all source and sink categories for which emissions and removals are estimated.
- *Collecting more measured data.* Uncertainty associated with bias and random sampling error can be reduced by increasing the sample size and filling in data gaps. This applies to both measurements and surveys.
- *Using more precise measurement methods.* Measurement error can be reduced by using more precise measurement methods, avoiding simplifying assumption, and ensuring that measurement technologies are appropriately used and calibrated.
- *Eliminating known risk of bias.* This is achieved by ensuring instrumentation is properly positioned and

calibrated, models or other estimation procedures are appropriate and representative, and by applying expert judgements in a systematic way.

- *Improving state of knowledge.* Improve the understanding of categories and processes leading to emissions and removals, which can help to discover and correct for problems in incompleteness. It is *Good Practice* to continuously improve emissions and removal estimates based on new knowledge.

The following sections describe the ongoing and planned *Inventory* and uncertainty analysis improvements in the context of these specific areas.

Recent and Ongoing Improvements

To collect more measured data, improve representativeness, and use more precise measurement methods, several source categories in the *Inventory* now use the U.S. EPA's Greenhouse Gas Reporting Program (GHGRP) data, which improves *Inventory* emission (or sink) estimation methods by allowing the incorporation of country-specific data rather than using default IPCC estimates. EPA's GHGRP relies on facility-level data reported from large facilities emitting over 25,000 metric tons of CO₂ equivalent each year. See Annex 9 for more information on use of GHGRP data in the *Inventory*. EPA has initiated efforts to review and update uncertainty assessments for sources based on GHGRP for some key categories where not already updated due to prioritization of resources, e.g., cement production.

In addition to improving *Inventory* input data and methodologies, the uncertainty analysis now includes estimates for CO₂ Transport, Injection, and Geological Storage, and the memo items of Wood Biomass, Ethanol, and Biodiesel Consumption, and International Bunker Fuels. With the addition of the CO₂ Transport, Injection, and Geological Storage source this year, an Approach 2 uncertainty model was developed for this estimate using the 2006 IPCC Guidelines and expert opinion and is included in both the Energy Chapter and Annex 7. An uncertainty model for the memo item, Wood Biomass, Ethanol, and Biodiesel Consumption, was also developed this year and included in both the Energy Chapter and Annex 7, though it is not included in totals. Furthermore, uncertainty estimates for International Bunker Fuels were added to the overall level and trend uncertainty assessments this year, using bounds consistent with 2006 IPCC Guidelines for civil aviation. A future improvement would be developing an uncertainty model for this source and incorporating it into the Energy chapter. Methodological and data quality improvements were also made for HFCs, PFCs, SF₆ and NF₃, including breaking out the parent chemical uncertainty inputs to estimate uncertainties for the child chemicals of Substitution of Ozone Depleting Substances for HFCs and PFCs.

As noted, above, Tables A-287, A-288, and A-289 show uncertainties associated with emissions estimates in 1990 and 2023 in the current *Inventory* are similar. This is due to offsetting impacts from changes in uncertainty from methodological improvements over the time series because some improvements to significant *Inventory* emission categories do not necessarily reduce uncertainties. Improving completeness and moving to higher tiers may reflect better representation of the activity and emissions but also better knowledge of uncertainties. For example, the 95 percent uncertainty bounds for HFCs, PFCs, SF₆ and NF₃ were -4 percent to 14 percent in the 1990 through 2022 *Inventory*, and they are -11 percent to 6 percent in this current (1990 through 2023) *Inventory*. Other improvements to significant categories or the use of extrapolation techniques to ensure time series consistency, such as for direct N₂O emissions from agricultural soil management, may also result in higher uncertainties in the current year relative to the base year of the time series. The 95 percent confidence intervals for direct nitrous oxide emissions from agricultural soil management increased from -24 percent to 24 percent in 1990 to -28 percent to 28 percent in 2023. Use of a splicing technique to extrapolate activity data from the last available year to the current year of the time series introduces additional uncertainty into the estimate of direct N₂O agricultural soil management emissions, resulting in higher uncertainty in 2023 emissions estimates as compared to the 1990 uncertainty bounds. In general, higher uncertainty associated with source category emission estimates in more recent years of the time series can stem from an underestimation of uncertainties associated with lower-tier methods and the use of splicing techniques to ensure time series consistency when data are limited for portions of the time series. These uncertainty estimates "reveal a more realistic acknowledgment of the limitations of existing knowledge," as stated in the 2006 IPCC Guidelines, Volume 1, Chapter 3.1.7. Furthermore, some methods and data for emission

categories have not changed significantly over time, such as for sources of CO₂ from fossil fuel combustion, and therefore uncertainties have not changed significantly either.

Additional ongoing improvements to the *Inventory* uncertainty analyses for select categories will help to *eliminate or reduce known risk of bias, improve models*, and advance *the state of knowledge*, which may lead to further *Inventory* and uncertainty analysis improvements in other areas including *improved conceptualization* and *data representativeness*. Finally, ongoing improvements include review of documentation of source-specific input data and references, PDF distributions, and Monte Carlo analysis results through the implementation of standardized source-specific uncertainty reporting and documentation templates. Ongoing improvements to the overall *Inventory* Uncertainty Analysis documentation will additionally ensure consistency with IPCC *Good Practice* and increase the transparency of the overall analysis.

Planned Improvements

EPA continuously seeks new knowledge to improve the *Inventory* emissions and removal estimates. With available resources, planned future improvements to the *Inventory* and Uncertainty Analysis are prioritized by focusing improvements on categories identified in the Key Category Analysis (Chapter 1.5), or by quantitatively comparing the relative contributions of uncertainties from various input parameters (e.g., activity data and emission factors) to the total uncertainty levels within a source or sink category. To enhance the accuracy of *Inventory* emission (or sink) estimate uncertainty, EPA plans to review uncertainty inputs and assumptions, with a particular focus on accounting for the covariance between different parameters to ensure a more comprehensive and reliable uncertainty analysis. Quantifying the sensitivity of the overall *Inventory* uncertainty bounds to the uncertainty within each source or sink category can also prioritize future *Inventory* updates,

As described in Chapter 1.5, Key Categories in the current *Inventory* include (but are not limited to) categories that fall under fossil fuel combustion (Chapter 3.1), petroleum and natural gas systems (Chapter 3.6 and 3.7), Industrial Processes and Product Use (Chapter 3), and Agriculture (Chapter 4). Planned improvements for these key categories largely include the incorporation of more accurate and/or representative input parameters and making corresponding updates to the uncertainty assessments, including accounting for any relevant covariance. For example, as described in Chapter 3.1, planned inventory improvements for emissions from fossil fuel combustion categories include efforts to assess the incorporation of more measured input activity data (e.g., GHGRP data, domestic marine activity) and other input parameters (e.g., updated carbon factors for petroleum fuels, emission factors for non-road equipment, etc.). Similarly, Chapters 3.6 and 3.7 discuss plans to continue stakeholder engagement to assess the potential for incorporating new input data (e.g., from peer-reviewed publications, industry studies, additional information reported to GHGRP not yet incorporated, etc.). Categories within the IPPU sector (Chapter 4) also discuss plans to assess the future incorporation of additional facility-level GHGRP data, improve emission models (e.g., for ozone depleting substance substitutes) and the methodological descriptions in the *Inventory* report. Similar to other categories, planned improvements to Agricultural emissions from manure management and enteric fermentation. For example, further research is needed in some cases to improve the accuracy of emission factors, including those currently applied to CH₄ and N₂O emissions from manure management. Lastly, for many individual source categories, further research is also needed to characterize the PDFs of their input parameters more accurately (e.g., emission factors and activity data). This might involve using measured or published statistics or implementing a rigorous protocol to elicit expert judgment, if published or measured data are not available. Continued efforts in these areas will reduce *Inventory* uncertainty and increase the completeness, accuracy, and transparency of the category-specific and overall *Inventory* estimates. Details describing the planned improvements for these and nearly all other individual source and sink categories are included in the category-specific chapters of this report. Implementation of these planned improvements will occur on an ongoing basis as new information becomes available. Improvements are prioritized to make best use of available resources.

Additional planned improvements for the overall *Inventory* uncertainty analysis include improving the presentation of uncertainties in a format consistent with suggested tables in Volume 1, Chapter 3 of the *2006 IPCC Guidelines*. As resources permit, in particular for key categories, improvements include reviewing and updating the existing uncertainty models for the base year. This process would improve the base year and trend uncertainty analyses

but may not eliminate every simplifying assumption described above due to limited data availability in the base year.

References

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ANNEX 8 QA/QC Procedures

8.1. Background

The purpose of this annex is to describe in more detail the Quality Assurance/Quality Control (QA/QC) procedures and information quality considerations that are used throughout the process of creating and compiling the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. This includes the evaluation of the quality and relevance of data and models used as inputs into the *Inventory*; the proper management, incorporation, and aggregation of data; and the review of emission and removal estimates to ensure that they are as accurate and transparent as possible. Quality control measures are applied at every stage of inventory development and document preparation, and quality assurance occurs through an expert review and a public review during the process of developing the report. While these QA reviews contribute to improving the quality of the *Inventory*, the public review phase is also essential for promoting the openness of the inventory development process and the transparency of inventory data and methods. As described in respective source and sink category text, comments received from these reviews may also result in updates or changes to continue to improve inventory quality.

8.2. Purpose

The *Quality Assurance/Quality Control and Uncertainty Management Plan for the U.S. Greenhouse Gas Inventory* (QA/QC plan) guides the process of ensuring the quality of the *Inventory*. The QA/QC Plan describes data and methodology checks, develops processes governing peer review and public comments, and provides guidance on conducting an analysis of the uncertainty surrounding the emission estimates. The QA/QC Plan procedures also stress continual improvement, providing for corrective actions that are designed to improve the inventory estimates over time.

Key elements of the QA/QC Plan are summarized in Figure A-21. These elements include:

- *Procedures, Templates, and Forms*: which standardize the implementation, documentation and archival of QA/QC activities and related information throughout the whole *Inventory* development process. They also guide the implementation of additional QC for more significant sources. Uncertainty analysis templates facilitate compilation and review of uncertainty inputs.
- *Quality Assurance (QA)*: processes for implementing annual expert and public reviews of the *Inventory*. See Section 1.4 for more details on these QA processes.
- *Quality Control (QC)*: procedures that apply General (Tier 1) and Category-specific (Tier 2) methodology or checks as recommended by *2006 IPCC Guidelines* (IPCC 2006) to be completed by staff compiling estimates. General check are implemented on an annual basis for each greenhouse gas emissions source or sink category included in this *Inventory*. Where QC activities for a particular category go beyond the minimum general checks and include category-specific checks (Tier 2) or include verification, further explanation is provided within the respective source or sink category text.
- *Communication and Improvement*: QA/QC and findings within the EPA, across federal agencies and departments, research institutions and organizations involved in supplying data or compiling estimates for the *Inventory*. These communications include periodic trainings reviewing procedures and lessons from recent cycles.
- *Recordkeeping*: practices that ensure transparent documentation to track which procedures have been followed, the results of the QA/QC, uncertainty analysis, and feedback mechanisms

for corrective action to improve the inventory estimates over time. Records also includes tracking the application of more involved QA/QC procedures which may take more than one cycle to fully implement as part of improvement planning, especially for category-specific QC, prioritizing key categories (see Section 1.4).

For each greenhouse gas emissions source or sink included in this Inventory, minimum general QA/QC analysis consistent with Vol. 1, Chapter 6 of the *2006 IPCC Guidelines* has been undertaken. Where QA/QC activities for a particular source or sink category go beyond the general level, and include category-specific checks, further explanation is provided within the respective category text. Similarly, responses or updates based on comments from the expert and public reviews are also addressed within the respective source or sink category text. For transparency, responses to public and expert review comments are also posted on the EPA website with the final report. See section 8.4 of this Annex to learn more about responses to reviews.

Figure A-21: Summary of Key QC Processes from U.S. QA/QC Plan

	Data Gathering	Data Documentation	Calculating Emissions	Cross-Cutting Coordination
Inventory Analyst QC	- Review data input files - Check input data for transcription errors - Confirm data units - Check integrity of raw data - Inspect input data automatic checkers for: - Input ranges (e.g. negative values), or missing data - Variable types match values - Time series inconsistency (e.g. outliers) - Check data completeness (geographic scope, thresholds, etc.) - Update data tracking tab for status of gathering efforts - Record implementation of data QC checks, date, findings, and any corrective actions	- Confirm documentation of references for primary data elements - Confirm copies of all data sources - Confirm access and location of any working data input or data processing/calculation files - Check assumptions are documented and cited appropriately - Confirm records for contact reports for non-electronic communications use standard form, are complete, and are archived per procedures - Record implementation of documentation QC checks, date, findings, and any corrective actions	- Check that parameter labels, units, and conversion factors are correct - Review estimates and methods for completeness - Review calculation workbooks integrity - Reproduce a sample of calculations - Inspect automated checkers for issues: - Recalculations - Trend and implied emission factor inconsistencies - Confirm consistency of key data and estimates between report and electronic estimation files - Record implementation of calculation QC checks, date, findings, and any corrective actions	- Confirm upload of all source and sink category data files and references - Confirm use of standardized data summary templates - Inspect flags from automated data aggregation checkers for issues with: - Sectoral sums - Gas sums - Significant recalculations - Missing values - Record implementation of cross-cutting QC checks, date, and findings - Identify improvements to data management, compilation and documentation based on QC findings
Supporting Inventory Analyst QC	- Check input data for transcription errors - Identify input data outliers for further investigation - Inspect automatic checkers - Identify modifications that could provide additional QA/QC checks - Document data checks implemented	- Check citations in data input/calculation workbooks and text for accuracy and style - Check reference docket for new citations - Check that documentation for any data / methodology changes is included	- Reproduce a sample of calculations - Review time series consistency - Review changes in data/consistency with IPCC methodology	

8.3. Assessment Factors

The Inventory of U.S. Greenhouse Gas Emissions and Sinks development process follows guidance outlined in EPA’s Guidelines for Ensuring and Maximizing the Quality, Objectivity, Utility, and Integrity of

Information Disseminated by the Environmental Protection Agency¹⁷⁰ and A Summary of General Assessment Factors for Evaluating the Quality of Scientific and Technical Information.¹⁷¹ This includes evaluating the data and models used as inputs into the Inventory against the five general assessment factors: soundness, applicability and utility, clarity and completeness, uncertainty and variability, evaluation and review. Table A-282 defines each factor and explains how it was considered during the process of creating the current Inventory.

Table A-282: Assessment Factors and Definitions

General Assessment Factor	Definition	How the Factor was Considered
Soundness (AF1)	The extent to which the scientific and technical procedures, measures, methods or models employed to generate the information are reasonable for, and consistent with their intended application.	The underlying data, methodologies, and models used to generate the <i>Inventory of U.S. Greenhouse Gas Emissions and Sinks</i> are reasonable for and consistent with their intended application, to provide information regarding all sources and sinks of greenhouse gases in the United States for the Inventory year. The U.S. emissions calculations follow the <i>2006 IPCC Guidelines</i> . They are based on the best available, peer-reviewed scientific information, and have been used by the international community for over 25 years. When possible, Tier 2 and Tier 3 methodologies from the <i>2006 IPCC Guidelines</i> are applied to calculate U.S. emissions more accurately.
Applicability and Utility (AF2)	The extent to which the information is relevant for the Agency's intended use.	The Inventory's underlying data, methodology, and models are relevant for their intended application because they generate the sector-specific greenhouse gas emissions trends necessary for assessing and understanding all sources and sinks of greenhouse gases in the United States for the Inventory year. They are relevant for communicating U.S. emissions information to domestic audiences, and they are consistent with the <i>2006 IPCC Guidelines</i> .
Clarity and Completeness (AF3)	The degree of clarity and completeness with which the data, assumptions, methods, quality assurance, sponsoring organizations and analyzes employed to generate the information are documented.	The methodological and calculation approaches applied to generate the <i>Inventory of U.S. Greenhouse Gas Emissions and Sinks</i> are extensively documented in the <i>2006 IPCC Guidelines</i> . The Inventory report describes its adherence to the <i>2006 IPCC Guidelines</i> , and the U.S. Government agencies provide data to implement the <i>2006 IPCC Guidelines</i> approaches. Any changes made to calculations,

¹⁷⁰ EPA report #260R-02-008, October 2002, Available online at <http://www.epa.gov/quality/guidelines-ensuring-and-maximizing-quality-objectivity-utility-and-integrity-information>.

¹⁷¹ EPA report #100/B-03/001, June 2003, Available online at <http://www.epa.gov/risk/guidance-evaluating-and-documenting-quality-existing-scientific-and-technical-information>, and Addendum to: A Summary of General Assessment Factors for Evaluating the Quality of Scientific and Technical Information, December 2012, Available online at <http://www.epa.gov/risk/summary-general-assessment-factors-evaluating-quality-scientific-and-technical-information>.

		due to updated data and methods, are explained and documented in the report.
Uncertainty and Variability (AF4)	The extent to which the variability and uncertainty (quantitative and qualitative) in the information or in the procedures, measures, methods or models are evaluated and characterized.	The evaluation of uncertainties for underlying data is documented in the Annex 7 Uncertainty to the <i>Inventory of U.S. Greenhouse Gas Emissions and Sinks</i> . In accordance with the <i>2006 IPCC Guidelines</i> , the uncertainty associated with the Inventory's underlying input data was evaluated by running a Monte Carlo uncertainty analysis on most source and/or category emissions data to produce a 95 percent confidence interval for the annual greenhouse gas emissions for that source and/or sink. The error propagation approach is used to quantify uncertainties for some categories that are not significant contributors to emissions across the time series. To develop overall uncertainty estimates, the Monte Carlo simulation output data for each emission source and/or sink category uncertainty analysis were combined by type of gas, and the probability distributions were fitted to the combined simulation output data where such simulated output data were available.
Evaluation and Review (AF5)	The extent of independent verification, validation and peer review of the information or of the procedures, measures, methods or models.	The majority of the underlying methodology, calculations, and models used to generate the <i>Inventory of U.S. Greenhouse Gas Emissions and Sinks</i> have been independently verified and peer reviewed as part of their publication in the <i>2006 IPCC Guidelines</i> and the <i>2019 Refinement</i>. In cases where the methodology differs slightly from the <i>2006 IPCC Guidelines</i>, these were independently verified and validated by technical experts during the annual expert review phase of the Inventory development process. For the data used in calculating greenhouse gas emissions for each source, multiple levels of evaluation and review occur. Data are compared to results from previous years, and calculations and equations are continually evaluated and updated as appropriate. Throughout the process, inventory data and methodological improvements are planned and incorporated. The Inventory undergoes annual cycles of expert and public review before publication. This process ensures that both experts and the general public can review each category of emissions and sinks and have an extended opportunity to provide feedback on the methodologies used, calculations, data sources, and presentation of information.

8.4. Responses to Review Processes

EPA is continually working to improve transparency, accuracy, completeness, comparability, and consistency of emission and sink estimates in the *Inventory* in response to the feedback received during reviews, as well as supplemental stakeholder outreach efforts. For instance, as mentioned in the

Planned Improvements section of the petroleum and natural gas systems source categories (Section 3.6 and 3.7), EPA has engaged in stakeholder outreach to increase the transparency in the Inventory methodology and to identify supplemental data sources that can lead to methodological improvements. During the annual preparation of the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, in considering and prioritizing improvements, EPA reviews the significance of the source and sink category (i.e., key categories), along with QC, QA, and uncertainty assessments. Identified planned improvements to methods (including data, emissions factors, and other key parameters), along with QA/QC and uncertainty assessments are documented within the chapter text of each source and sink category to complement the Recalculations and Improvements chapter. Additionally, the Executive Summary also highlights key changes in methodologies from previous *Inventory* reports.

As noted in the previous section, for transparency, responses to comments received while developing the annual estimates from Public Review and Expert Review are posted on the EPA website with the final *Inventory*. Find responses to previous expert and public review responses to comments at the following URLs: <https://www.epa.gov/system/files/documents/2024-08/us-ghg-inventory-1990-2022-expert-review-comment-log.pdf> and https://www.epa.gov/system/files/documents/2024-07/us-ghg-inventory-1990-2022-public-review-comment-log_0.pdf.

ANNEX 9 Use of EPA Greenhouse Gas Reporting Program in Inventory

This Annex provides background information on the Greenhouse Gas Reporting Program (GHGRP) and its relationship to this *Inventory*. The U.S. Environmental Protection Agency (EPA) tracks U.S. greenhouse gas emissions through two complementary programs: the *Inventory* (estimates in this report), and the GHGRP. The *Inventory* provides a comprehensive accounting of all emissions from source categories that are identified in the 2006 IPCC Guidelines and that are needed to understand the United States' total net greenhouse gas emissions, while the GHGRP provides bottom-up detailed information that helps improve understanding of the sources and types of greenhouse gas emissions at individual facilities and suppliers. The GHGRP provides facility-level greenhouse gas data from major industrial sources across the United States; it does not provide full coverage of total annual U.S. greenhouse gas emissions (e.g., the GHGRP excludes emissions from the agricultural, land use, and forestry sectors).

On October 30, 2009, the EPA published a regulation requiring annual reporting of greenhouse gas data from large facilities¹⁷² in the United States. The program implementing the regulation, codified at 40 CFR Part 98, is referred to as EPA's Greenhouse Gas Reporting Program (GHGRP). The GHGRP covers sources or suppliers in 46 industrial categories ("Subparts"¹⁷³), including direct greenhouse gas emitters,¹⁷⁴ fossil fuel suppliers, industrial gas suppliers, and facilities that inject carbon dioxide (CO₂) underground for sequestration or other reasons.¹⁷⁵ In general, the threshold for reporting is 25,000 metric tons or more of CO₂ Eq. per year.¹⁷⁶

Facilities in most source categories subject to the GHGRP began collecting data in 2010 while additional types of industrial operations began collecting data in 2011. Currently, more than 8,000 facilities and suppliers are required to report their data annually. Facilities calculate their emissions using methodologies that are specified at 40 CFR Part 98, and they report their data to EPA using the electronic Greenhouse Gas Reporting Tool (e-GGRT). Annual reports covering emissions from the prior calendar year are due by March 31st of each year. EPA verifies reported data through a multi-step process to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. All reports submitted to EPA are evaluated by electronic validation and verification checks, including industry-specific checks. If potential errors are identified, EPA will notify the reporter, who can resolve the issue either by providing an acceptable response describing why the flagged issue is not an error or by correcting the flagged issue and resubmitting their annual greenhouse gas report.¹⁷⁷

The reported data are made available to the public each fall. EPA presents the data collected by its GHGRP in a number of ways, such as through a data publication tool known as the Facility Level Information on GHGs Tool (FLIGHT). FLIGHT allows data to be viewed in several formats including maps, tables, charts and graphs for

¹⁷² Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases (i.e., reporting at the corporate level).

¹⁷³ See <https://www.epa.gov/ghgreporting/resources-subpart-ghg-reporting>.

¹⁷⁴ Data reporting by affected facilities includes the reporting of emissions from fuel combustion at that affected facility.

¹⁷⁵ See <https://www.epa.gov/ghgreporting/resources-subpart-ghg-reporting> and <http://ghgdata.epa.gov/ghgp/main.do>.

¹⁷⁶ For some industrial categories ("Subparts") under the GHGRP, facilities must report if their combined emissions from stationary fuel combustion and all applicable source categories are above a given threshold (e.g., 25,000 metric tons CO₂ Eq. or more per year or another industry-specific threshold). For other source categories, new facilities must report regardless of their quantity of annual emissions. These categories include, for example, cement production (Subpart H) and aluminum production (Subpart F). However, any facility regardless of threshold can cease reporting if its emissions fall below 25,000 metric tons CO₂ Eq. for five years or below 15,000 metric tons CO₂ Eq. for three years, and it informs EPA of its intention to cease reporting and the reason(s) for any reduction in emissions. See 40 CFR 98.2(a), 98.2(i), and Tables A-3, A-4, and A-4 for more information.

¹⁷⁷ See GHGRP Verification Fact Sheet https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

individual facilities or groups of facilities.¹⁷⁸ More information on EPA’s GHGRP can be found at <https://www.epa.gov/ghgreporting>.

The GHGRP dataset is an important resource for the *Inventory*. EPA uses GHGRP data in a number of categories to improve the national estimates, consistent with IPCC guidance, as summarized in Table A-283 below. Methodologies used in the GHGRP are consistent with methods in *2006 IPCC Guidelines*, in particular “higher tier” methods which include collecting facility or plant-specific measurements. The GHGRP provides not only annual emissions information for reporting facilities and suppliers, but also other annual information, such as activity data and emission factors that can be used to 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. Consistent with considerations outlined in the *2019 Refinement to the 2006 IPCC Guidelines* and the related *Technical Bulletin 1 on Use of Facility-Specific Data in National Greenhouse Gas Inventories* from the IPCC Task Force on National Greenhouse Gas Inventories (IPCC 2011),¹⁷⁹ EPA has paid particular attention both to ensuring completeness in national coverage of emission estimates over time and to ensuring time-series consistency by recalculating emissions for 1990 to 2010/2011 when incorporating GHGRP data into source category estimates.¹⁸⁰ These issues are discussed further in the chapters where source category emissions estimates use GHGRP data. Source category definitions are also considered in order to ensure completeness when using GHGRP data. For certain source categories in the Industrial Processes and Product Use chapter, EPA has relied on data values that have been calculated by aggregating GHGRP data that are considered confidential business information (CBI) at the facility level. EPA, with industry engagement, has put forth criteria to confirm that a given data aggregation shields underlying CBI from public disclosure. EPA is only publishing data values that meet these aggregation criteria.¹⁸¹ Specific uses of aggregated facility-level data that are CBI are described in the respective methodological sections in Chapter 4 of the *Inventory*. Beyond the current uses, EPA continues to analyze the GHGRP data on an annual basis to identify other source categories where it could be further integrated in future editions of this report (see the Planned Improvement sections of those specific source categories for details).

¹⁷⁸ See <http://ghgdata.epa.gov>.

¹⁷⁹ IPCC Task Force on National Greenhouse Gas Inventories (TFI) (2011). Technical Bulletin 1: Use of Facility-Specific Data National Greenhouse Gas Inventories. Available at https://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

¹⁸⁰ See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

¹⁸¹ U.S. EPA Greenhouse Gas Reporting Program. Confidential Business Information GHG Reporting. See <http://www.epa.gov/ghgreporting/confidential-business-information-ghg-reporting>.

Table A-283: Summary of EPA GHGRP Data Use in U.S. Inventory

Inventory Sector/Category	GHGRP Industry Subpart	First Calendar Year whose Emissions/ Supplies were Reported under GHGRP	Reporting Threshold ¹⁸²	Type of GHGRP Data Use				National Inventory Report (NIR) Section with Details on Data Use
				Emissions or Quantity Supplied	Emission Factor (EF)	Activity Data (AD)	QA/QC ¹⁸³	
Energy Sector								
Fossil Fuel Combustion: Industrial Sector	C – General Stationary Fuel Combustion Sources	2010	Y	•				Section 3.1 and Box 3-4
Coal Mining: Underground Mines	FF – Underground Coal Mines	2011	Y	•			•	3.4
Petroleum Systems	W – Petroleum and Natural Gas Systems; Y – Petroleum Refineries	2010, 2011	Y, N ^a	•	•	•	•	3.6
Natural Gas Systems	W – Petroleum and Natural Gas Systems	2011	Y		•	•	•	3.7
Waste Incineration	C – General Stationary Fuel Combustion Sources	2010	Y			•		3.3
CO ₂ Transport, Injection, and Geological Storage	PP – Suppliers of Carbon Dioxide;	2010	Y	•		•		3.9

¹⁸² Y=25,000 MTCO₂ Eq., or industry-specific threshold other than 25,000 MTCO₂ Eq.; N = all facilities in industry category must report regardless of annual emissions. Information on industry-specific threshold and implications of the reporting threshold or lack of threshold in estimating national greenhouse gas emissions is discussed in the respective source category methodology sections. However, any facility regardless of threshold can cease reporting if its emissions fall below 25,000 metric tons CO₂ Eq. for five years or below 15,000 metric tons CO₂ Eq for three years, and it informs EPA of its intention to cease reporting and the reason(s) for any reduction in emissions. See 40 CFR 98.2(a), 98.2(i), and Tables A-3, A-4, and A-4 for more information.

¹⁸³ Consistent with IPCC good practices, QA/QC using GHGRP may not be appropriate if this is the primary data source for estimating emissions. Depending on use, other data sets may be more appropriate for QA/QC of *Inventory* estimates.

Inventory Sector/Category	GHGRP Industry Subpart	First Calendar Year whose Emissions/Supplies were Reported under GHGRP	Reporting Threshold ¹⁸²	Type of GHGRP Data Use				National Inventory Report (NIR) Section with Details on Data Use
				Emissions or Quantity Supplied	Emission Factor (EF)	Activity Data (AD)	QA/QC ¹⁸³	
	RR – Geological Sequestration of Carbon Dioxide							
Industrial Processes and Product Use Sector								
Cement Production	H – Cement Production	2010	N			•	•	4.1
Lime Production	S – Lime Production	2010	N	•				4.2
Glass Production	N – Glass Production	2010	Y			•		4.3
Ammonia Production	G – Ammonia Manufacturing	2010	N	•		•		4.5
Urea Consumption from Non-Agricultural Use	G – Ammonia Manufacturing	2010	N			•		4.6
Nitric Acid Production	V – Nitric Acid Production	2010	N	•	•	•		4.7
Adipic Acid Production	E – Adipic Acid Production	2010	N	•				4.8
Petrochemical Production	X – Petrochemical Production	2010	N	•	•	•		4.13
HCFC-22 Production	O – HCFC-22 Production and HFC-23 Destruction	2010	Y	•				4.14
Production of Fluorochemicals Other Than HCFC-22	L-Fluorinated Gas Production; OO – Suppliers of Industrial Gases	2010, 2011	Y	•	•	•	•	4.15
Carbon Dioxide Consumption	PP – Suppliers of Carbon Dioxide	2010	Y	•				4.16

Inventory Sector/Category	GHGRP Industry Subpart	First Calendar Year whose Emissions/Supplies were Reported under GHGRP	Reporting Threshold ¹⁸²	Type of GHGRP Data Use				National Inventory Report (NIR) Section with Details on Data Use
				Emissions or Quantity Supplied	Emission Factor (EF)	Activity Data (AD)	QA/QC ¹⁸³	
Iron and Steel Production and Metallurgical Coke Production	Q – Iron and Steel Production	2010	Y	•				4.18
Aluminum Production	F – Aluminum Production	2010	N	•				4.20
Magnesium Production and Processing	T – Magnesium Production	2011	Y	•				4.21
Lead Production	R – Lead Production	2010	Y				•	4.22
Electronics Industry	I – Electronics Manufacturing	2011	Y	•	•		•	4.24
Substitution of ODS	OO – Suppliers of Industrial Gases; QQ – Imports and Exports of Equipment Pre-charged with Fluorinated GHGs or Containing Fluorinated GHGs in Closed-cell Foams	2010, 2011	N (producers) Y (all others)				•	4.25

Inventory Sector/Category	GHGRP Industry Subpart	First Calendar Year whose Emissions/Supplies were Reported under GHGRP	Reporting Threshold ¹⁸²	Type of GHGRP Data Use				National Inventory Report (NIR) Section with Details on Data Use
				Emissions or Quantity Supplied	Emission Factor (EF)	Activity Data (AD)	QA/QC ¹⁸³	
Electrical Equipment	DD – Use of Electric Transmission and Distribution Equipment; SS – Manufacture of Electric Transmission and Distribution Equipment	2011	Y	•	•	•		4.26
Waste Sector								
MSW Landfills	HH – Municipal Solid Waste Landfills	2010	Y	•	•		•	7.1
Industrial Landfills	TT – Industrial Waste Landfills	2011	Y				•	7.1
Industrial Wastewater	II – Industrial Wastewater Treatment	2011	Y				•	7.2