Annexes to the Inventory of U.S. GHG Emissions and Sinks

The following nine annexes provide additional information related to the material presented in the main body of this report as directed in the *UNFCCC Guidelines on Reporting and Review* (UNFCCC 2014). Annex I contains an analysis of the key categories of emissions discussed in this report and a review of the methodology used to identify those key categories. Annex 2 describes the methodologies used to estimate CO_2 emissions from fossil fuel combustion, the carbon content of fossil fuels, and the amount of carbon stored in products from non-energy uses of fossil fuels. Annex 3 discusses the methodologies used for a number of individual source categories in greater detail than was presented in the main body of the report and includes explicit activity data and emission factor tables. Annex 4 presents the IPCC reference approach for estimating CO_2 emissions from fossil fuel combustion. Annex 5 addresses the criteria for the inclusion of an emission source or sink category and discusses some of the sources that are excluded from U.S. estimates. Annex 6 provides a range of additional information that is relevant to the contents of this report. Annex 7 provides data on the uncertainty of the emission estimates included in this report. Annex 8 provides information on the QA/QC methods and procedures used in the development of the Inventory, including responses to UNFCCC reviews. Finally, Annex 9 provides an overview of EPA Greenhouse Gas Reporting Program (GHGRP) data use in the Inventory.

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ANNEX 1 Key Category Analysis

The United States has identified national key categories based on the estimates presented in this report. The *2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) describes a key category as a "[category] that is prioritized within the national inventory system because its estimate has a significant influence on a country's total inventory of greenhouse gases in terms of the absolute level, the trend, or the uncertainty in emissions and removals." By definition, key categories are sources or sinks that have the greatest contribution to the absolute overall level of national emissions in any of the years covered by the time series. In addition, when an entire time series of emission 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.

The methodology for conducting a key category analysis, as defined by Volume 1, Chapter 4 of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006), 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. The UNFCCC common reporting format (CRF) reporting software generates Table 7, which also identifies key categories using an Approach 1 analysis based on the default disaggregation approach provided in Volume 1, Chapter 4, Table 4.1 of the *2006 IPCC Guidelines*, and includes special considerations for further disaggregation by fuel type for fuel combustion categories. The disaggregation of categories presented in CRF Table 7 and this annex vary but the results of the key category analysis are consistent. Consistent with the UNFCCC reporting guidelines, the United States key category analysis uses 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. 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 N_2O 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. 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,* 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.

Table A-1 summarizes key categories for the United States (including and excluding LULUCF categories) ranked according to their sector and CO_2 Eq. emissions and/or removal estimate in 2021. The table also indicates the criteria used in identifying these categories as key (i.e., Approach 1 level/trend, Approach 2 level/trend, and/or qualitative assessments).

Table A-1: Summary of Key Categories for the United States (1990 and 2021) by Sector

CRF Code and Source/Sink Category	Greenhouse Gas	Approach 1				Approach 2				2021 Emissions (MMT CO_2 Eq.)	Overall Key Category Ranking[a]
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF		
Energy											
1.A.3.b CO_2 Emissions from Transportation: Road	CO_2	•	•	•	•	•	•	•	•	1,482.3	2
1.A.1 CO_2 Emissions from Stationary Combustion - Coal - Electricity Generation	CO_2	•	•	•	•	•	•	•	•	909.7	1
1.A.1 CO_2 Emissions from Stationary Combustion - Gas - Electricity Generation	CO_2	•	•	•	•	•	•	•	•	615.1	4
1.A.2 CO_2 Emissions from Stationary Combustion - Gas - Industrial	CO_2	•	•	•	•	•	•	•	•	498.4	8
1.A.4.b CO_2 Emissions from Stationary Combustion - Gas - Residential	CO_2	•	•	•	•	•		•		258.6	20
1.A.2 CO_2 Emissions from Stationary Combustion - Oil - Industrial	CO_2	•	•	•	•	•	•	•	•	220.3	5
1.A.4.a CO_2 Emissions from Stationary Combustion - Gas - Commercial	CO_2	•	•	•	•	•	•	•	•	180.9	16
1.A.3.a CO_2 Emissions from Transportation: Aviation	CO_2	•	•	•	•	•		•		164.5	24
1.A.5 CO_2 Emissions from Non-Energy Use of Fuels	CO_2	•	•	•	•	•	•	•	•	143.2	9
1.A.3.e CO_2 Emissions from Transportation: Other	CO_2	•	•	•	•		•			64.2	27
1.A.4.b CO_2 Emissions from Stationary Combustion - Oil - Residential	CO_2	•	•	•	•		•		•	51.5	26
1.A.2 CO_2 Emissions from Stationary Combustion - Coal - Industrial	CO_2	•	•	•	•	•	•	•	•	43.7	12
1.A.4.a CO_2 Emissions from Stationary Combustion - Oil - Commercial	CO_2	•	•	•	•		•			41.6	29
1.A.3.d CO_2 Emissions from Transportation: Domestic Navigation	CO_2	•		•						41.0	53
1.B.2 CO_2 Emissions from Natural Gas Systems	CO_2	•		•		•				36.8	39
1.A.3.c CO_2 Emissions from Transportation: Railways	CO_2	•		•						32.1	51
1.B.2 CO_2 Emissions from Petroleum Systems	CO_2	•	•	•	•		•		•	24.7	28
1.A.5 CO_2 Emissions from Stationary Combustion - Oil - U.S. Territories	CO_2	•		•						17.5	54

CRF Code and Source/Sink Category	Greenhouse Gas	Approach 1				Approach 2				2021 Emissions (MMT CO_2 Eq.)	Overall Key Category Ranking[a]
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF		
1.A.1 CO_2 Emissions from Stationary Combustion - Oil - Electricity Generation	CO_2	•	•	•	•	•	•		•	17.1	29
1.A.5.b CO_2 Emissions from Transportation: Military	CO_2		•		•					5.2	55
1.A.4.a CO_2 Emissions from Stationary Combustion - Coal - Commercial	CO_2		•		•					1.4	58
1.A.4.b CO_2 Emissions from Stationary Combustion - Coal - Residential	CO_2						•		•	NO	63
1.B.2 CH_4 Emissions from Natural Gas Systems	CH_4	•	•	•	•	•	•	•	•	181.4	11
1.B.2 CH_4 Emissions from Petroleum Systems	CH_4	•		•		•		•		50.2	44
1.B.1 Fugitive Emissions from Coal Mining	CH_4	•	•	•	•	•	•	•	•	44.7	14
1.B.2 CH_4 Emissions from Abandoned Oil and Gas Wells	CH_4					•		•		8.2	49
1.A.4.b CH_4 Emissions from Stationary Combustion - Residential	CH_4					•	•	•	•	4.6	46
1.A.1 N_2O Emissions from Stationary Combustion - Coal - Electricity Generation	N_2O					•				15.1	42
1.A.3.b N_2O Emissions from Transportation: Road	N_2O	•	•	•	•	•	•		•	9.6	36
1.A.1 N_2O Emissions from Stationary Combustion - Gas - Electricity Generation	N_2O						•			3.9	48
2.C.1 CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	•	•	•	•	•	•	•	•	42.0	18
2.A.1 CO_2 Emissions from Cement Production	CO_2	•	•	•	•					41.3	41
2.B.8 CO_2 Emissions from Petrochemical Production	CO_2	•	•	•	•					33.2	43
2.B.3 N_2O Emissions from Adipic Acid Production	N_2O				•					6.6	57
2.F.1 Emissions from Substitutes for Ozone Depleting Substances: Refrigeration and Air Conditioning	HFCs, PFCs	•	•	•	•	•	•	•	•	139.1	7
2.F.4 Emissions from Substitutes for Ozone Depleting Substances: Aerosols	HFCs, PFCs	•	•	•	•	•	•	•	•	17.7	24
2.F.2 Emissions from Substitutes for Ozone Depleting Substances: Foam Blowing Agents	HFCs, PFCs		•		•					10.8	50

CRF Code and Source/Sink Category	Greenhouse Gas	Approach 1				Approach 2				2021 Emissions (MMT CO_2 Eq.)	Overall Key Category Ranking[a]
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF		
2.G SF_6 and CF_4 Emissions from Electrical Transmission and Distribution	SF_6, CF_4			•	•				•	6.0	40
2.E PFC, HFC, SF_6, and NF_3 Emissions from Electronics Industry	PFCs, HFCs, SF_6, NF_3	•	•				•			4.5	62
2.B.9 HFC-23 Emissions from HCFC-22 Production	HFCs	•	•	•	•		•		•	2.2	52
2.C.4 SF_6 Emissions from Magnesium Production and Processing	SF_6	•	•							1.1	61
2.C.3 PFC Emissions from Aluminum Production	PFCs			•	•					0.9	59
Agriculture											
3.A.1 CH_4 Emissions from Enteric Fermentation: Cattle	CH_4	•	•	•	•	•	•	•		188.2	19
3.B.1 CH_4 Emissions from Manure Management: Cattle	CH_4	•	•	•	•	•	•		•	37.9	23
3.B.4 CH_4 Emissions from Manure Management: Other Livestock	CH_4	•		•	•					28.1	38
3.C CH_4 Emissions from Rice Cultivation	CH_4	•				•		•		16.8	47
3.D.1 Direct N_2O Emissions from Agricultural Soil Management	N_2O	•		•		•	•	•	•	257.7	13
3.D.2 Indirect N_2O Emissions from Applied Nitrogen	N_2O	•		•		•	•	•	•	27.5	34
Waste											
5.A CH_4 Emissions from MSW Landfills	CH_4	•	•	•	•	•	•	•	•	103.7	6
5.A CH_4 Emissions from Industrial Landfills	CH_4	•		•			•		•	18.9	35
5.D CH_4 Emissions from Domestic Wastewater Treatment	CH_4					•				13.9	45
5.D N_2O Emissions from Domestic Wastewater Treatment	N_2O	•		•		•	•	•	•	20.4	22
Land Use, Land-Use Change, and Forestry											
4.E.2 Net CO_2 Emissions from Land Converted to Settlements	CO_2			•	•			•	•	81.0	17
4.B.2 Net CO_2 Emissions from Land Converted to Cropland	CO_2			•				•		56.5	32
4.C.1 Net CO_2 Emissions from Grassland Remaining Grassland	CO_2							•	•	10.0	29

CRF Code and Source/Sink Category	Greenhouse Gas	Approach 1				Approach 2				2021 Emissions (MMT CO_2 Eq.)	Overall Key Category Ranking[a]
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF		
4.B.1 Net CO_2 Emissions from Cropland Remaining Cropland	CO_2			•				•	•	(18.9)	21
4.C.2 Net CO_2 Emissions from Land Converted to Grassland	CO_2			•	•			•	•	(24.7)	14
4.A.2 Net CO_2 Emissions from Land Converted to Forest Land	CO_2			•				•		(98.3)	56
4.E.1 Net CO_2 Emissions from Settlements Remaining Settlements	CO_2			•	•			•	•	(134.5)	10
4.A.1 Net CO_2 Emissions from Forest Land Remaining Forest Land	CO_2			•	•			•	•	(695.4)	3
4.D.1 CH_4 Emissions from Flooded Lands Remaining Flooded Lands	CH_4			•						45.4	60
4.A.1 CH_4 Emissions from Forest Fires	CH_4				•				•	15.5	33
4.A.1 N_2O Emissions from Forest Fires	N_2O								•	8.9	37
Subtotal of Key Categories Without LULUCF[c]										**6,172.6**	
Total Gross Emissions Without LULUCF										**6,347.7**	
Percent of Total Without LULUCF										**97%**	
Subtotal of Key Categories With LULUCF[d]										**5,393.2**	
Total Net Emissions With LULUCF										**5,593.5**	
Percent of Total With LULUCF										**96%**	

Note: Parentheses indicate negative values (or sequestration).

[a] Overall Key Category Ranking is the ranking developed by summing the individual rankings of each source/sink category from Level Approach 1 With LULUCF, Level Approach 2 With LULUCF, Trend Approach 1 With LULUCF, and Trend Approach 2 Without LULUCF analyses as suggested in the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Volume 1, Chapter 4, Section 4.4.

[a] Other includes emissions from pipelines.

[c] Subtotal includes key categories from Level Approach 1 Without LULUCF, Level Approach 2 Without LULUCF, Trend Approach 1 Without LULUCF, and Trend Approach 2 Without LULUCF.

[d] Subtotal includes key categories from Level Approach 1 With LULUCF, Level Approach 2 With LULUCF, Trend Approach 1 With LULUCF, and Trend Approach 2 With LULUCF.

Table A-2 provides a complete listing of categories by IPCC sector, along with notations on the criteria used in identifying key categories, excluding the LULUCF sources and sinks. Similarly, Table A-3 provides a complete listing of source and sink categories by IPCC 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 2021) 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-2: U.S. Greenhouse Gas Inventory Source Categories without LULUCF

CRF Code and Source/Sink Category	Greenhouse Gas	1990 Emissions (MMT CO_2 Eq.)	2021 Emissions (MMT CO_2 Eq.)	Key Category	ID Criteria[a]	Level in which year(s)[b]
Energy						
1.A.3.b CO_2 Emissions from Transportation: Road	CO_2	1,157.4	1,482.3	•	L_1 T_1 L_2 T_2	1990, 2021
1.A.1 CO_2 Emissions from Stationary Combustion - Coal - Electricity Generation	CO_2	1,546.5	909.7	•	L_1 T_1 L_2 T_2	1990, 2021
1.A.1 CO_2 Emissions from Stationary Combustion - Gas - Electricity Generation	CO_2	175.4	615.1	•	L_1 T_1 L_2 T_2	1990, 2021
1.A.2 CO_2 Emissions from Stationary Combustion - Gas - Industrial	CO_2	407.4	498.4	•	L_1 T_1 L_2 T_2	1990, 2021
1.A.4.b CO_2 Emissions from Stationary Combustion - Gas - Residential	CO_2	237.8	258.6	•	L_1 T_1 L_2	1990, 2021
1.A.2 CO_2 Emissions from Stationary Combustion - Oil - Industrial	CO_2	287.1	220.3	•	L_1 T_1 L_2 T_2	1990, 2021
1.A.4.a CO_2 Emissions from Stationary Combustion - Gas - Commercial	CO_2	142.0	180.9	•	L_1 T_1 L_2 T_2	1990, 2021
1.A.3.a CO_2 Emissions from Transportation: Aviation	CO_2	187.2	164.5	•	L_1 T_1 L_2	1990, 2021
1.A.5 CO_2 Emissions from Non-Energy Use of Fuels	CO_2	112.4	143.2	•	L_1 T_1 L_2 T_2	1990, 2021
1.A.3.e CO_2 Emissions from Transportation: Other	CO_2	36.0	64.2	•	L_1 T_1 T_2	1990_1, 2021_1
1.A.4.b CO_2 Emissions from Stationary Combustion - Oil - Residential	CO_2	97.8	51.5	•	L_1 T_1 T_2	1990_1, 2021_1
1.A.2 CO_2 Emissions from Stationary Combustion - Coal - Industrial	CO_2	157.8	43.7	•	L_1 T_1 L_2 T_2	1990, 2021
1.A.4.a CO_2 Emissions from Stationary Combustion - Oil - Commercial	CO_2	74.3	41.6	•	L_1 T_1 T_2	1990_1, 2021_1
1.A.3.d CO_2 Emissions from Transportation: Domestic Navigation	CO_2	39.3	41.0	•	L_1	1990_1, 2021_1
1.B.2 CO_2 Emissions from Natural Gas Systems	CO_2	32.4	36.8	•	L_1 L_2	1990_1, 2021

CRF Code and Source/Sink Category	Greenhouse Gas	1990 Emissions (MMT CO_2 Eq.)	2021 Emissions (MMT CO_2 Eq.)	Key Category	ID Criteria[a]	Level in which year(s)[b]
1.A.3.c CO_2 Emissions from Transportation: Railways	CO_2	35.5	32.1	•	L_1	1990_1, 2021_1
1.B.2 CO_2 Emissions from Petroleum Systems	CO_2	9.5	24.7	•	L_1 T_1 T_2	2021_1
1.A.5 CO_2 Emissions from Stationary Combustion - Oil - U.S. Territories	CO_2	19.5	17.5	•	L_1	1990_1, 2021_1
1.A.1 CO_2 Emissions from Stationary Combustion - Oil - Electricity Generation	CO_2	97.5	17.1	•	L_1 T_1 L_2 T_2	1990
5.C.1 CO_2 Emissions from Incineration of Waste	CO_2	12.9	12.5			
1.A.5.b CO_2 Emissions from Transportation: Military	CO_2	13.6	5.2	•	T_1	
1.A.5 CO_2 Emissions from Stationary Combustion - Coal - U.S. Territories	CO_2	0.5	2.9			
1.A.5 CO_2 Emissions from Stationary Combustion - Gas - U.S. Territories	CO_2	0.0	2.6			
1.B.1 CO_2 Emissions from Coal Mining	CO_2	4.6	2.5			
1.A.4.a CO_2 Emissions from Stationary Combustion - Coal - Commercial	CO_2	12.0	1.4	•	T_1	
1.A.1 CO_2 Emissions from Stationary Combustion - Geothermal Energy	CO_2	0.5	0.4			
1.B.2 CO_2 Emissions from Abandoned Oil and Gas Wells	CO_2	+	+			
1.A.4.b CO_2 Emissions from Stationary Combustion - Coal - Residential	CO_2	3.0	0.0	•	T_2	
2.A.4.a CO_2 Emissions from Ceramics Production	CO_2	0.0	0.0			
1.B.2 CH_4 Emissions from Natural Gas Systems	CH_4	215.1	181.4	•	L_1 T_1 L_2 T_2	1990, 2021
1.B.2 CH_4 Emissions from Petroleum Systems	CH_4	51.3	50.2	•	L_1 L_2	1990, 2021
1.B.1 Fugitive Emissions from Coal Mining	CH_4	108.1	44.7	•	L_1 T_1 L_2 T_2	1990, 2021
1.B.2 CH_4 Emissions from Abandoned Oil and Gas Wells	CH_4	7.7	8.2	•	L_2	1990_2, 2021_2
1.B.1 Fugitive Emissions from Abandoned Underground Coal Mines	CH_4	8.1	6.4			
1.A.4.b CH_4 Emissions from Stationary Combustion - Residential	CH_4	5.9	4.6	•	L_2 T_2	1990_2, 2021_2

CRF Code and Source/Sink Category	Greenhouse Gas	1990 Emissions (MMT CO_2 Eq.)	2021 Emissions (MMT CO_2 Eq.)	Key Category	ID Criteria[a]	Level in which year(s)[b]
1.A.2 CH_4 Emissions from Stationary Combustion - Industrial	CH_4	2.0	1.6			
1.A.4.a CH_4 Emissions from Stationary Combustion - Commercial	CH_4	1.2	1.3			
1.A.1 CH_4 Emissions from Stationary Combustion - Gas - Electricity Generation	CH_4	0.1	1.2			
1.A.3.e CO_2 Emissions from Transportation: Other	CH_4	0.8	1.1			
1.A.3.b CO_2 Emissions from Transportation: Road	CH_4	5.8	1.0			
1.A.3.d CO_2 Emissions from Transportation: Domestic Navigation	CH_4	0.4	0.5			
1.A.1 CH_4 Emissions from Stationary Combustion - Coal - Electricity Generation	CH_4	0.4	0.2			
5.B.2 CH_4 Emissions from Anaerobic Digestion at Biogas Facilities	CH_4	+	0.2			
1.A.3.c CO_2 Emissions from Transportation: Railways	CH_4	0.1	0.1			
1.A.5 CH_4 Emissions from Stationary Combustion - U.S. Territories	CH_4	+	+			
1.A.3.a CO_2 Emissions from Transportation: Aviation	CH_4	0.1	+			
1.A.1 CH_4 Emissions from Stationary Combustion - Wood - Electricity Generation	CH_4	+	+			
1.A.1 CH_4 Emissions from Stationary Combustion - Oil - Electricity Generation	CH_4	+	+			
1.A.5.b CO_2 Emissions from Transportation: Military	CH_4	+	+			
5.C.1 CH_4 Emissions from Incineration of Waste	CH_4	+	+			
1.A.1 N_2O Emissions from Stationary Combustion - Coal - Electricity Generation	N_2O	17.9	15.1	•	L_2	1990_2, 2021_2
1.A.3.b N_2O Emissions from Transportation: Road	N_2O	32.2	9.6	•	L_1 T_1 L_2 T_2	1990
1.A.3.e N_2O Emissions from Transportation: Other	N_2O	4.2	5.7			
1.A.1 N_2O Emissions from Stationary Combustion - Gas - Electricity Generation	N_2O	0.3	3.9	•	T_2	

CRF Code and Source/Sink Category	Greenhouse Gas	1990 Emissions (MMT CO_2 Eq.)	2021 Emissions (MMT CO_2 Eq.)	Key Category	ID Criteria[a]	Level in which year(s)[b]
1.A.2 N_2O Emissions from Stationary Combustion - Industrial	N_2O	2.7	2.0			
1.A.3.a N_2O Emissions from Transportation: Aviation	N_2O	1.5	1.3			
1.A.4.b N_2O Emissions from Stationary Combustion - Residential	N_2O	0.9	0.7			
5.C.1 N_2O Emissions from Incineration of Waste	N_2O	0.4	0.4			
1.A.4.a N_2O Emissions from Municipal Solid Waste	N_2O	0.3	0.3			
1.A.3.d N_2O Emissions from Transportation: Domestic Navigation	N_2O	0.2	0.3			
1.A.3.c N_2O Emissions from Transportation: Railways	N_2O	0.2	0.2			
1.A.5 N_2O Emissions from Stationary Combustion - U.S. Territories	N_2O	+	0.1			
1.B.2 N_2O Emissions from Petroleum Systems	N_2O	+	+			
1.A.1 N_2O Emissions from Stationary Combustion - Wood - Electricity Generation	N_2O	+	+			
1.B.2 N_2O Emissions from Natural Gas Systems	N_2O	+	+			
1.A.1 N_2O Emissions from Stationary Combustion - Oil - Electricity Generation	N_2O	0.1	+			
1.A.5.b N_2O Emissions from Transportation: Military	N_2O	+	+			
Industrial Processes and Product Use						
2.C.1 CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	104.7	42.0	•	L_1 T_1 L_2 T_2	1990, 2021
2.A.1 CO_2 Emissions from Cement Production	CO_2	33.5	41.3	•	L_1 T_1	1990_1, 2021_1
2.B.8 CO_2 Emissions from Petrochemical Production	CO_2	21.6	33.2	•	L_1 T_1	1990_1, 2021_1
2.B.1 CO_2 Emissions from Ammonia Production	CO_2	14.4	12.2			
2.A.2 CO_2 Emissions from Lime Production	CO_2	11.7	11.9			
2.A.4 CO_2 Emissions from Other Process Uses of Carbonates	CO_2	6.2	8.0			
2.B.10 CO_2 Emissions from Carbon Dioxide Consumption	CO_2	1.5	5.0			

CRF Code and Source/Sink Category	Greenhouse Gas	1990 Emissions (MMT CO_2 Eq.)	2021 Emissions (MMT CO_2 Eq.)	Key Category	ID Criteria[a]	Level in which year(s)[b]
2.B.10 CO_2 Emissions from Urea Consumption for Non-Ag Purposes	CO_2	3.8	5.0			
2.A.3 CO_2 Emissions from Glass Production	CO_2	2.3	2.0			
2.B.7 CO_2 Emissions from Soda Ash Production	CO_2	1.4	1.7			
2.C.2 CO_2 Emissions from Ferroalloy Production	CO_2	2.2	1.6			
2.C.3 CO_2 Emissions from Aluminum Production	CO_2	6.8	1.5			
2.B.6 CO_2 Emissions from Titanium Dioxide Production	CO_2	1.2	1.5			
2.C.6 CO_2 Emissions from Zinc Production	CO_2	0.6	1.0			
2.B.10 CO_2 Emissions from Phosphoric Acid Production	CO_2	1.5	0.9			
2.C.5 CO_2 Emissions from Lead Production	CO_2	0.5	0.4			
2.B.5 CO_2 Emissions from Silicon Carbide Production and Consumption	CO_2	0.2	0.2			
2.C.4 CO_2 Emissions from Magnesium Production and Processing	CO_2	0.1	+			
2.B.8 CH_4 Emissions from Petrochemical Production	CH_4	0.2	0.4			
2.C.2 CH_4 Emissions from Ferroalloy Production	CH_4	+	+			
2.B.5 CH_4 Emissions from Silicon Carbide Production and Consumption	CH_4	+	+			
2.C.1 CH_4 Emissions from Iron and Steel Production & Metallurgical Coke Production	CH_4	+	+			
2.B.2 N_2O Emissions from Nitric Acid Production	N_2O	10.8	7.9			
2.B.3 N_2O Emissions from Adipic Acid Production	N_2O	13.5	6.6			
2.G N_2O Emissions from Product Uses	N_2O	3.8	3.8			
2.B.4 N_2O Emissions from Caprolactam, Glyoxal, and Glyoxylic Acid Production	N_2O	1.5	1.2			
2.E N_2O Emissions from Electronics Industry	N_2O	+	0.3			
2.F.1 Emissions from Substitutes for Ozone Depleting	HFCs, PFCs	+	139.1	•	L_1 T_1 L_2 T_2	2021

CRF Code and Source/Sink Category	Greenhouse Gas	1990 Emissions (MMT CO_2 Eq.)	2021 Emissions (MMT CO_2 Eq.)	Key Category	ID Criteria[a]	Level in which year(s)[b]
Substances: Refrigeration and Air conditioning						
2.F.4 Emissions from Substitutes for Ozone Depleting Substances: Aerosols	HFCs, PFCs	0.2	17.7	•	L_1 T_1 L_2 T_2	2021
2.F.2 Emissions from Substitutes for Ozone Depleting Substances: Foam Blowing Agents	HFCs, PFCs	+	10.8	•	T_1	
2.F.3 Emissions from Substitutes for Ozone Depleting Substances: Fire Protection	HFCs, PFCs	0.0	2.8			
2.F.5 Emissions from Substitutes for Ozone Depleting Substances: Solvents	HFCs, PFCs	0.0	2.1			
2.G SF6 and CF4 Emissions from Electrical Transmission and Distribution	SF_6, CF_4	24.7	6.0			
2.E PFC, HFC, SF6, and NF3 Emissions from Electronics Industry	PFCs, HFCs, SF_6, NF_3	3.3	4.5	•	L_1 T_1 T_2	1990_1
2.B.9 HFC-23 Emissions from HCFC-22 Production	HFCs	38.6	2.2	•	L_1 T_1 T_2	1990_1
2.C.4 SF6 Emissions from Magnesium Production and Processing	SF_6	5.4	1.1	•	L_1 T_1	1990_1
2.C.3 PFC Emissions from Aluminum Production	PFCs	19.3	0.9			
2.C.4 HFC-134a Emissions from Magnesium Production and Processing	HFCs	0.0	+			
Agriculture						
3.H CO_2 Emissions from Urea Fertilization	CO_2	2.4	5.2			
3.G CO_2 Emissions from Liming	CO_2	4.7	3.0			
3.A.1 CH_4 Emissions from Enteric Fermentation: Cattle	CH_4	176.1	188.2	•	L_1 T_1 L_2 T_2	1990, 2021
3.B.1 CH_4 Emissions from Manure Management: Cattle	CH_4	17.8	37.9	•	L_1 T_1 L_2 T_2	2021
3.B.4 CH_4 Emissions from Manure Management: Other Livestock	CH_4	21.3	28.1	•	L_1	1990_1, 2021_1
3.C CH_4 Emissions from Rice Cultivation	CH_4	17.9	16.8	•	L_1 L_2	1990, 2021_2
3.A.4 CH_4 Emissions from Enteric Fermentation: Other Livestock	CH_4	7.0	6.8			
3.F CH_4 Emissions from Field Burning of Agricultural Residues	CH_4	0.4	0.5			

CRF Code and Source/Sink Category	Greenhouse Gas	1990 Emissions (MMT CO_2 Eq.)	2021 Emissions (MMT CO_2 Eq.)	Key Category	ID Criteria[a]	Level in which year(s)[b]
3.D.1 Direct N_2O Emissions from Agricultural Soil Management	N_2O	252.6	257.7	•	L_1 L_2 T_2	1990, 2021
3.D.2 Indirect N_2O Emissions from Applied Nitrogen	N_2O	25.8	27.5	•	L_1 L_2 T_2	1990, 2021
3.B.1 N_2O Emissions from Manure Management: Cattle	N_2O	9.9	13.8			
3.B.4 N_2O Emissions from Manure Management: Other Livestock	N_2O	2.5	3.6			
3.F N_2O Emissions from Field Burning of Agricultural Residues	N_2O	0.1	0.2			
Waste						
5.A CH_4 Emissions from MSW Landfills	CH_4	185.5	103.7	•	L_1 T_1 L_2 T_2	1990, 2021
5.A CH_4 Emissions from Industrial Landfills	CH_4	12.2	18.9	•	L_1 T_2	2021_1
5.D CH_4 Emissions from Domestic Wastewater Treatment	CH_4	16.5	13.9	•	L_2	1990_2
5.D CH_4 Emissions from Industrial Wastewater Treatment	CH_4	6.2	7.2			
5.B CH_4 Emissions from Composting	CH_4	0.4	2.6			
5.D N_2O Emissions from Domestic Wastewater Treatment	N_2O	14.4	20.4	•	L_1 L_2 T_2	1990_2, 2021
5.B N_2O Emissions from Composting	N_2O	0.3	1.8			
5.D N_2O Emissions from Industrial Wastewater Treatment	N_2O	0.4	0.5			

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

NO (Not Occurring)

[a] If the source is a key category for both L_1 and L_2 (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., 1990_2 designates a category is key for the Approach 2 assessment only in 1990).

[b] Other includes emissions from pipelines.

Note: LULUCF sources and sinks are not included in the analysis presented in this table. See Table A-3 for the results of the analysis with LULUCF.

Table A-3: U.S. Greenhouse Gas Inventory Source Categories with LULUCF

CRF Code and Source/Sink Category	Greenhouse Gas	1990 Emissions (MMT CO_2 Eq.)	2021 Emissions (MMT CO_2 Eq.)	Key Category	ID Criteria[a]	Level in which year(s)[b]
Energy						
1.A.3.b CO_2 Emissions from Transportation: Road	CO_2	1,157.4	1,482.3	•	L_1 T_1 L_2 T_2	1990, 2021
1.A.1 CO_2 Emissions from Stationary Combustion - Coal - Electricity Generation	CO_2	1,546.5	909.7	•	L_1 T_1 L_2 T_2	1990, 2021
1.A.1 CO_2 Emissions from Stationary Combustion - Gas - Electricity Generation	CO_2	175.4	615.1	•	L_1 T_1 L_2 T_2	1990_1, 2021
1.A.2 CO_2 Emissions from Stationary Combustion - Gas - Industrial	CO_2	407.4	498.4	•	L_1 T_1 L_2 T_2	1990, 2021
1.A.4.b CO_2 Emissions from Stationary Combustion - Gas - Residential	CO_2	237.8	258.6	•	L_1 T_1 L_2	1990, 2021
1.A.2 CO_2 Emissions from Stationary Combustion - Oil - Industrial	CO_2	287.1	220.3	•	L_1 T_1 L_2 T_2	1990, 2021
1.A.4.a CO_2 Emissions from Stationary Combustion - Gas - Commercial	CO_2	142.0	180.9	•	L_1 T_1 L_2 T_2	1990, 2021
1.A.3.a CO_2 Emissions from Transportation: Aviation	CO_2	187.2	164.5	•	L_1 T_1 L_2	1990, 2021
1.A.5 CO_2 Emissions from Non-Energy Use of Fuels	CO_2	112.4	143.2	•	L_1 T_1 L_2 T_2	1990, 2021
1.A.3.e CO_2 Emissions from Transportation: Other	CO_2	36.0	64.2	•	L_1 T_1	1990_1, 2021_1
1.A.4.b CO_2 Emissions from Stationary Combustion - Oil - Residential	CO_2	97.8	51.5	•	L_1 T_1 T_2	1990_1, 2021_1
1.A.2 CO_2 Emissions from Stationary Combustion - Coal - Industrial	CO_2	157.8	43.7	•	L_1 T_1 L_2 T_2	1990, 2021_1
1.A.4.a CO_2 Emissions from Stationary Combustion - Oil - Commercial	CO_2	74.3	41.6	•	L_1 T_1	1990_1, 2021_1
1.A.3.d CO_2 Emissions from Transportation: Domestic Navigation	CO_2	39.3	41.0	•	L_1	1990_1, 2021_1
1.B.2 CO_2 Emissions from Natural Gas Systems	CO_2	32.4	36.8	•	L_1	1990_1, 2021_1
1.A.3.c CO_2 Emissions from Transportation: Railways	CO_2	35.5	32.1	•	L_1	1990_1, 2021_1
1.B.2 CO_2 Emissions from Petroleum Systems	CO_2	9.5	24.7	•	L_1 T_1 T_2	2021_1
1.A.5 CO_2 Emissions from Stationary Combustion - Oil - U.S. Territories	CO_2	19.5	17.5	•	L_1	1990_1, 2021_1

CRF Code and Source/Sink Category	Greenhouse Gas	1990 Emissions (MMT CO_2 Eq.)	2021 Emissions (MMT CO_2 Eq.)	Key Category	ID Criteria[a]	Level in which year(s)[b]
1.A.1 CO_2 Emissions from Stationary Combustion - Oil - Electricity Generation	CO_2	97.5	17.1	•	L_1 T_1 T_2	1990_1
5.C.1 CO_2 Emissions from Incineration of Waste	CO_2	12.9	12.5			
1.A.5.b CO_2 Emissions from Transportation: Military	CO_2	13.6	5.2	•	T_1	
1.A.5 CO_2 Emissions from Stationary Combustion - Coal - U.S. Territories	CO_2	0.5	2.9			
1.A.5 CO_2 Emissions from Stationary Combustion - Gas - U.S. Territories	CO_2	-	2.6			
1.B.1 CO_2 Emissions from Coal Mining	CO_2	4.6	2.5			
1.A.4.a CO_2 Emissions from Stationary Combustion - Coal - Commercial	CO_2	12.0	1.4	•	T_1	
1.A.1 CO_2 Emissions from Stationary Combustion - Geothermal Energy	CO_2	0.5	0.4			
1.B.2 CO_2 Emissions from Abandoned Oil and Gas Wells	CO_2	0.0	+			
1.A.4.b CO_2 Emissions from Stationary Combustion - Coal - Residential	CO_2	3.0	0.0	•	T_2	
2.A.4.a CO_2 Emissions from Ceramics Production	CO_2	-	0.0			
1.B.2 CH_4 Emissions from Natural Gas Systems	CH_4	215.1	181.4	•	L_1 T_1 L_2 T_2	1990, 2021
1.B.2 CH_4 Emissions from Petroleum Systems	CH_4	51.3	50.2	•	L_1 L_2	1990, 2021
1.B.1 Fugitive Emissions from Coal Mining	CH_4	108.1	44.7	•	L_1 T_1 L_2 T_2	1990, 2021
1.B.2 CH_4 Emissions from Abandoned Oil and Gas Wells	CH_4	7.7	8.2	•	L_2	1990_2, 2021_2
1.B.1 Fugitive Emissions from Abandoned Underground Coal Mines	CH_4	8.1	6.4			
1.A.4.b CH_4 Emissions from Stationary Combustion - Residential	CH_4	5.9	4.6	•	L_2 T_2	1990_2, 2021_2
1.A.2 CH_4 Emissions from Stationary Combustion - Industrial	CH_4	2.0	1.6			
1.A.4.a CH_4 Emissions from Stationary Combustion - Commercial	CH_4	1.2	1.3			

CRF Code and Source/Sink Category	Greenhouse Gas	1990 Emissions (MMT CO_2 Eq.)	2021 Emissions (MMT CO_2 Eq.)	Key Category	ID Criteria[a]	Level in which year(s)[b]
1.A.1 CH_4 Emissions from Stationary Combustion - Gas - Electricity Generation	CH_4	0.1	1.2			
1.A.3.e CO_2 Emissions from Transportation: Other	CH_4	0.8	1.1			
1.A.3.b CO_2 Emissions from Transportation: Road	CH_4	5.8	1.0			
1.A.3.d CO_2 Emissions from Transportation: Domestic Navigation	CH_4	0.4	0.5			
1.A.1 CH_4 Emissions from Stationary Combustion - Coal - Electricity Generation	CH_4	0.4	0.2			
5.B.2 CH_4 Emissions from Anaerobic Digestion at Biogas Facilities	CH_4	0.0	0.2			
1.A.3.c CO_2 Emissions from Transportation: Railways	CH_4	0.1	0.1			
1.A.5 CH_4 Emissions from Stationary Combustion - U.S. Territories	CH_4	0.0	+			
1.A.3.a CO_2 Emissions from Transportation: Aviation	CH_4	0.1	+			
1.A.1 CH_4 Emissions from Stationary Combustion - Wood - Electricity Generation	CH_4	0.0	+			
1.A.1 CH_4 Emissions from Stationary Combustion - Oil - Electricity Generation	CH_4	0.0	+			
1.A.5.b CO_2 Emissions from Transportation: Military	CH_4	0.0	+			
5.C.1 CH_4 Emissions from Incineration of Waste	CH_4	0.0	+			
1.A.1 N_2O Emissions from Stationary Combustion - Coal - Electricity Generation	N_2O	17.9	15.1			
1.A.3.b N_2O Emissions from Transportation: Road	N_2O	32.2	9.6	•	L_1 T_1 T_2	1990_1
1.A.3.e N_2O Emissions from Transportation: Other	N_2O	4.2	5.7			
1.A.1 N_2O Emissions from Stationary Combustion - Gas - Electricity Generation	N_2O	0.3	3.9			
1.A.2 N_2O Emissions from Stationary Combustion - Industrial	N_2O	2.7	2.0			
1.A.3.a N_2O Emissions from Transportation: Aviation	N_2O	1.5	1.3			

CRF Code and Source/Sink Category	Greenhouse Gas	1990 Emissions (MMT CO_2 Eq.)	2021 Emissions (MMT CO_2 Eq.)	Key Category	ID Criteria[a]	Level in which year(s)[b]
1.A.4.b N_2O Emissions from Stationary Combustion - Residential	N_2O	0.9	0.7			
5.C.1 N_2O Emissions from Incineration of Waste	N_2O	0.4	0.4			
1.A.4.a N_2O Emissions from Municipal Solid Waste	N_2O	0.3	0.3			
1.A.3.d N_2O Emissions from Transportation: Domestic Navigation	N_2O	0.2	0.3			
1.A.3.c N_2O Emissions from Transportation: Railways	N_2O	0.2	0.2			
1.A.5 N_2O Emissions from Stationary Combustion - U.S. Territories	N_2O	0.0	0.1			
1.B.2 N_2O Emissions from Petroleum Systems	N_2O	0.0	+			
1.A.1 N_2O Emissions from Stationary Combustion - Wood - Electricity Generation	N_2O	0.0	+			
1.B.2 N_2O Emissions from Natural Gas Systems	N_2O	0.0	+			
1.A.1 N_2O Emissions from Stationary Combustion - Oil - Electricity Generation	N_2O	0.1	+			
1.A.5.b N_2O Emissions from Transportation: Military	N_2O	0.0	+			
Industrial Processes and Product Use						
2.C.1 CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	104.7	42.0	•	L_1 T_1 L_2 T_2	1990, 2021_1
2.A.1 CO_2 Emissions from Cement Production	CO_2	33.5	41.3	•	L_1 T_1	1990_1, 2021_1
2.B.8 CO_2 Emissions from Petrochemical Production	CO_2	21.6	33.2	•	L_1 T_1	1990_1, 2021_1
2.B.1 CO_2 Emissions from Ammonia Production	CO_2	14.4	12.2			
2.A.2 CO_2 Emissions from Lime Production	CO_2	11.7	11.9			
2.A.4 CO_2 Emissions from Other Process Uses of Carbonates	CO_2	6.2	8.0			
2.B.10 CO_2 Emissions from Carbon Dioxide Consumption	CO_2	1.5	5.0			
2.B.10 CO_2 Emissions from Urea Consumption for Non-Ag Purposes	CO_2	3.8	5.0			
2.A.3 CO_2 Emissions from Glass Production	CO_2	2.3	2.0			

CRF Code and Source/Sink Category	Greenhouse Gas	1990 Emissions (MMT CO_2 Eq.)	2021 Emissions (MMT CO_2 Eq.)	Key Category	ID Criteria[a]	Level in which year(s)[b]
2.B.7 CO_2 Emissions from Soda Ash Production	CO_2	1.4	1.7			
2.C.2 CO_2 Emissions from Ferroalloy Production	CO_2	2.2	1.6			
2.C.3 CO_2 Emissions from Aluminum Production	CO_2	6.8	1.5			
2.B.6 CO_2 Emissions from Titanium Dioxide Production	CO_2	1.2	1.5			
2.C.6 CO_2 Emissions from Zinc Production	CO_2	0.6	1.0			
2.B.10 CO_2 Emissions from Phosphoric Acid Production	CO_2	1.5	0.9			
2.C.5 CO_2 Emissions from Lead Production	CO_2	0.5	0.4			
2.B.5 CO_2 Emissions from Silicon Carbide Production and Consumption	CO_2	0.2	0.2			
2.C.4 CO_2 Emissions from Magnesium Production and Processing	CO_2	0.1	+			
2.B.8 CH_4 Emissions from Petrochemical Production	CH_4	0.2	0.4			
2.C.2 CH_4 Emissions from Ferroalloy Production	CH_4	0.0	+			
2.B.5 CH_4 Emissions from Silicon Carbide Production and Consumption	CH_4	0.0	+			
2.C.1 CH_4 Emissions from Iron and Steel Production & Metallurgical Coke Production	CH_4	0.0	+			
2.B.2 N_2O Emissions from Nitric Acid Production	N_2O	10.8	7.9			
2.B.3 N_2O Emissions from Adipic Acid Production	N_2O	13.5	6.6	•	T_1	
2.G N_2O Emissions from Product Uses	N_2O	3.8	3.8			
2.B.4 N_2O Emissions from Caprolactam, Glyoxal, and Glyoxylic Acid Production	N_2O	1.5	1.2			
2.E N_2O Emissions from Electronics Industry	N_2O	0.0	0.3			
2.F.1 Emissions from Substitutes for Ozone Depleting Substances: Refrigeration and Air conditioning	HFCs, PFCs	0.0	139.1	•	L_1 T_1 L_2 T_2	2021
2.F.4 Emissions from Substitutes for Ozone Depleting Substances: Aerosols	HFCs, PFCs	0.2	17.7	•	L_1 T_1 L_2 T_2	2021

CRF Code and Source/Sink Category	Greenhouse Gas	1990 Emissions (MMT CO_2 Eq.)	2021 Emissions (MMT CO_2 Eq.)	Key Category	ID Criteria[a]	Level in which year(s)[b]
2.F.2 Emissions from Substitutes for Ozone Depleting Substances: Foam Blowing Agents	HFCs, PFCs	0.0	10.8	•	T_1	
2.F.3 Emissions from Substitutes for Ozone Depleting Substances: Fire Protection	HFCs, PFCs	-	2.8			
2.F.5 Emissions from Substitutes for Ozone Depleting Substances: Solvents	HFCs, PFCs	-	2.1			
2.G SF6 and CF4 Emissions from Electrical Transmission and Distribution	SF_6, CF_4	24.7	6.0	•	L_1 T_1 T_2	1990_1
2.E PFC, HFC, SF6, and NF3 Emissions from Electronics Industry	PFCs, HFCs, SF_6, NF_3	3.3	4.5			
2.B.9 HFC-23 Emissions from HCFC-22 Production	HFCs	38.6	2.2	•	L_1 T_1 T_2	1990_1
2.C.4 SF6 Emissions from Magnesium Production and Processing	SF_6	5.4	1.1			
2.C.3 PFC Emissions from Aluminum Production	PFCs	19.3	0.9	•	L_1 T_1	1990_1
2.C.4 HFC-134a Emissions from Magnesium Production and Processing	HFCs	-	+			
Agriculture						
3.H CO_2 Emissions from Urea Fertilization	CO_2	2.4	5.2			
3.G CO_2 Emissions from Liming	CO_2	4.7	3.0			
3.A.1 CH_4 Emissions from Enteric Fermentation: Cattle	CH_4	176.1	188.2	•	L_1 T_1 L_2	1990, 2021
3.B.1 CH_4 Emissions from Manure Management: Cattle	CH_4	17.8	37.9	•	L_1 T_1 T_2	2021_1
3.B.4 CH_4 Emissions from Manure Management: Other Livestock	CH_4	21.3	28.1	•	L_1 T_1	1990_1, 2021_1
3.C CH_4 Emissions from Rice Cultivation	CH_4	17.9	16.8	•	L_2	1990_2, 2021_2
3.A.4 CH_4 Emissions from Enteric Fermentation: Other Livestock	CH_4	7.0	6.8			
3.F CH_4 Emissions from Field Burning of Agricultural Residues	CH_4	0.4	0.5			
3.D.1 Direct N_2O Emissions from Agricultural Soil Management	N_2O	252.6	257.7	•	L_1 L_2 T_2	1990, 2021
3.D.2 Indirect N_2O Emissions from Applied Nitrogen	N_2O	25.8	27.5	•	L_1 L_2 T_2	1990, 2021
3.B.1 N_2O Emissions from Manure Management: Cattle	N_2O	9.9	13.8			

CRF Code and Source/Sink Category	Greenhouse Gas	1990 Emissions (MMT CO_2 Eq.)	2021 Emissions (MMT CO_2 Eq.)	Key Category	ID Criteria[a]	Level in which year(s)[b]
3.B.4 N_2O Emissions from Manure Management: Other Livestock	N_2O	2.5	3.6			
3.F N_2O Emissions from Field Burning of Agricultural Residues	N_2O	0.1	0.2			
Waste						
5.A CH_4 Emissions from Commercial Landfills	CH_4	185.5	103.7	•	L_1 T_1 L_2 T_2	1990, 2021
5.A CH_4 Emissions from Industrial Landfills	CH_4	12.2	18.9	•	L_1 T_2	2021_1
5.D CH_4 Emissions from Domestic Wastewater Treatment	CH_4	16.5	13.9			
5.D CH_4 Emissions from Industrial Wastewater Treatment	CH_4	6.2	7.2			
5.B CH_4 Emissions from Composting	CH_4	0.4	2.6			
5.D N_2O Emissions from Domestic Wastewater Treatment	N_2O	14.4	20.4	•	L_1 L_2 T_2	1990_2, 2021
5.B N_2O Emissions from Composting	N_2O	0.3	1.8			
5.D N_2O Emissions from Industrial Wastewater Treatment	N_2O	0.4	0.5			
Land Use, Land Use Change, and Forestry						
4.E.2 Net CO_2 Emissions from Land Converted to Settlements	CO_2	62.5	81.0	•	L_1 T_1 L_2 T_2	1990, 2021
4.B.2 Net CO_2 Emissions from Land Converted to Cropland	CO_2	54.8	56.5	•	L_1 L_2	1990, 2021
4.C.1 Net CO_2 Emissions from Grassland Remaining Grassland	CO_2	8.7	10.0	•	L_2 T_2	1990_2, 2021_2
4.D.2 Net CO_2 Emissions from Lands Converted to Wetlands	CO_2	1.9	0.3			
4.D.1 Net CO_2 Emissions from Coastal Wetlands Remaining Coastal Wetlands	CO_2	(7.4)	(8.1)			
4.B.1 Net CO_2 Emissions from Cropland Remaining Cropland	CO_2	(23.2)	(18.9)	•	L_1 L_2 T_2	1990, 2021
4.C.2 Net CO_2 Emissions from Land Converted to Grassland	CO_2	(6.7)	(24.7)	•	L_1 T_1 L_2 T_2	1990_2, 2021
4.A.2 Net CO_2 Emissions from Land Converted to Forest Land	CO_2	(98.5)	(98.3)	•	L_1 L_2	1990, 2021
4.E.1 Net CO_2 Emissions from Settlements Remaining Settlements	CO_2	(109.6)	(134.5)	•	L_1 T_1 L_2 T_2	1990, 2021
4.A.1 Net CO_2 Emissions from Forest Land Remaining Forest Land	CO_2	(821.4)	(695.4)	•	L_1 T_1 L_2 T_2	1990, 2021
4.D.1 CH_4 Emissions from Flooded Land Remaining Flooded Land	CH_4	44.6	45.4	•	L_1	1990_1, 2021_1
4.A.1 CH_4 Emissions from Forest Fires	CH_4	3.2	15.5	•	T_1 T_2	

CRF Code and Source/Sink Category	Greenhouse Gas	1990 Emissions (MMT CO_2 Eq.)	2021 Emissions (MMT CO_2 Eq.)	Key Category	ID Criteria[a]	Level in which year(s)[b]
4.D.1 CH_4 Emissions from Coastal Wetlands Remaining Coastal Wetlands	CH_4	4.2	4.3			
4.C.1 CH_4 Emissions from Grass Fires	CH_4	0.1	0.3			
4.D.2 CH_4 Emissions from Land Converted to Coastal Wetlands	CH_4	0.3	0.2			
4.D.2 CH_4 Emissions from Land Converted to Flooded Lands	CH_4	1.1	0.2			
4.A.4 CH_4 Emissions from Drained Organic Soils	CH_4	0.0	+			
4.D.1 CH_4 Emissions from Peatlands Remaining Peatlands	CH_4	0.0	+			
4.A.1 N_2O Emissions from Forest Fires	N_2O	2.3	8.9	•	T_2	
4.E.1 N_2O Emissions from Settlement Soils	N_2O	1.8	2.1			
4.A.1 N_2O Emissions from Forest Soils	N_2O	0.1	0.4			
4.C.1 N_2O Emissions from Grass Fires	N_2O	0.1	0.3			
4.D.1 N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	N_2O	0.1	0.1			
4.A.4 N_2O Emissions from Drained Organic Soils	N_2O	0.1	0.1			
4.D.1 N_2O Emissions from Peatlands Remaining Peatlands	N_2O	0.0	+			

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.
NO (Not Occurring)
[a] If the source is a key category for both L_1 and L_2 (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., 1990_2 designates a category is key for the Approach 2 assessment only in 1990).
[b] Other includes emissions from pipelines.
Note: Parentheses indicate negative values (or sequestration).

Approach for Evaluation of Key Categories

Level Assessment

When using an Approach 1 for the level assessment, a predetermined cumulative emissions threshold is used to identify key categories, consistent with the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). When source and sink categories are sorted in order of decreasing absolute emissions, those that fall at the top of the list and cumulatively account for 95 percent of emissions are considered key categories. The 95 percent threshold in the *2006 IPCC Guidelines* was designed to establish a general level where the key category analysis covers approximately 90 percent of inventory uncertainty.

Including the Approach 2 provides additional insight into why certain source and sink categories are considered key, and how to prioritize inventory improvements to reduce overall uncertainties. In the Approach 2, the level assessment for each category from the Approach 1 is multiplied by its percent relative uncertainty. Per the *2006 IPCC Guidelines*, if the uncertainty reported is asymmetrical, the absolute value of the larger uncertainty is used. 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 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 A-1), keeping in mind that the two assessments are not mutually exclusive. The uncertainty associated with CO_2 from mobile combustion is applied to each mode's emission estimate. Note, an uncertainty analysis was conducted for the CO_2 and N_2O emissions from waste incineration but has not yet been conducted for the CH_4 emissions from waste incineration because the estimate is near zero.

It is important to note that a key category analysis can be sensitive to the definitions of the source and sink categories. If a large source or sink category is split into many subcategories, then the subcategories may have contributions to the total inventory that are too small for those source categories to be considered key. Similarly, a collection of small, non-key source categories adding up to less than 5 percent of total emissions could become key source categories if those source categories were aggregated into a single source or sink category. The United States 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 names used in the key category analysis may differ from the names used in the main body of the report. Additionally, the United States accounts for some source categories, including fossil fuel feedstocks, international bunkers, and emissions from U.S. Territories, that are derived from unique data sources using country-specific methodologies. Consistent with UNFCCC reporting guidelines, the level and trend assessments using Approach 1 and Approach 2 are applied including and excluding the LULUCF sector to assess significance of this sector and comprehensively identify key categories that would not have been identified as key given the significance LULUCF sector.

Table KCA-1 through Table KCA-4 contain the 1990 and 2021 level assessments for both with and without LULUCF sources and sinks, and contain further detail on where each source falls within the analysis.[55] In the tables, Approach 1 key categories are shaded dark gray. Additional key categories identified by the Approach 2 assessment are shaded light gray.

Trend Assessment

Approach 1 for trend assessment is defined as the product of the source or sink category level assessment and the absolute difference between the source or sink category trend and the total trend. In turn, the source or sink category trend is defined as the change in emissions or removals from the base year to the current year, as a percentage of current year inventory estimate from that source or sink category. The total trend 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. To determine key categories, the trend assessments are sorted in descending order, so that the source or sink categories with the highest trend assessments appear first. The trend assessments are summed until the threshold of 95 percent is reached; 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 relative uncertainty. If the uncertainty reported is asymmetrical, the larger uncertainty is used. 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 key categories identified by the Approach 2 trend 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, keeping in mind that the two assessments are not mutually exclusive.

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.[56] In the tables, similar to the Approach 1 and 2 level

[55] Tables are available online at: https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021.
[56] Tables are available online at: https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021.

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.

References

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ANNEX 2 Methodology and Data for Estimating CO_2 Emissions from Fossil Fuel Combustion

2.1. Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion

Carbon dioxide (CO_2) 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 CO_2 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 2021 are presented in columns 2 through 8 of Table A-5 through Table A-16 with totals by fuel type in column 8 and totals by end-use sector in the last rows.[57] 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 2021 total adjusted fossil energy consumption across all sectors, including U.S. Territories, and energy types was 69,455.5 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 2022a). 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).

There are also three basic differences between the consumption data presented in Table A-4 and Table A-5 through Table A-16 and those recommended in the IPCC (2006) emission inventory methodology.

[57] 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.

First, consumption data in the U.S. Inventory are presented using higher heating values (HHV)[58] rather than the lower heating values (LHV)[59] 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 reported to the United Nations Framework Convention on Climate Change (UNFCCC) are to include energy use within U.S. Territories. Therefore, estimates for U.S. Territories[60] 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-16. It is reported separately from domestic sectoral consumption, because it is collected separately by EIA with no sectoral disaggregation.

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, (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;[61] 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

[58] Also referred to as gross calorific values (GCV).

[59] Also referred to as net calorific values (NCV).

[60] Fuel 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.

[61] 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.

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 2021, 17,589 thousand tons of coking coal were consumed,[62] resulting in an Energy sector adjustment of 344 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 2021, the iron and steel industry consumed 2,354 tons of coal (bituminous), 47,029 million ft^3 of natural gas, and 2,217 thousand gallons of distillate fuel as fuel. This resulted in Energy chapter adjustments of roughly 50 TBtu for coal, 44 TBtu for natural gas, and 0.3 TBtu for distillate fuel. In addition, an additional 69 TBtu is adjusted to account for coking coal consumed for industrial processes other than iron and steel, lead, and zinc production in 2021.

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 CO_2. Since October 2000, a portion of the CO_2 produced 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.[63] The exported CO_2 is not emitted to the atmosphere in the United States, and therefore the energy associated with the amount of CO_2 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 2021). 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

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

[63] 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 2021b).

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-17, 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, as required by the IPCC (2006) and UNFCCC (2014) inventory reporting 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-18). Emissions from international bunker fuels have been estimated separately and not included in national totals.[64]

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-16) by fuel-specific C content coefficients (see Table A-19) 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-23) by technology-specific C content coefficients (see Table A-19). For industrial energy and non-energy hydrocarbon gas liquids (HGL)[65] consumption, annually variable C contents were estimated by multiplying 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-19).

Step 8: Estimate CO_2 Emissions

Actual CO_2 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 CO_2 Eq.). To convert from C content to CO_2 emissions, the fraction of C that is oxidized was applied. This fraction was 100 percent based on guidance in IPCC (2006).

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-21). 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

[64] 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.

[65] 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 2021b).

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 2021 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 meet the UNFCCC 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.[66]

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 to the UNFCCC, progress was made on certain fuel types for specific industries and has been included in the Common Reporting Format (CRF) tables that are submitted to the UNFCCC along with this report.[67] 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 presented in the CRF tables 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 presented in the CRF tables. 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 2021 time series in the CRF tables. 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.

[66] 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.

[67] See http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html.

Table A-4: 2021 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)
									Unadjusted NEU Consumption			
Fuel Type	**Res.**	**Comm.**	**Ind.**	**Trans.**	**Elec.**	**Terr.**	**Total**	**Bunker Fuel**	**Ind.**	**Trans.**	**Terr.**	
Total Coal	**NO**	**14.9**	**626.3**	**NO**	**9,494.0**	**31.3**	**10,166.6**		**169.8**			**9,996.8**
Residential Coal	NO						NO					NO
Commercial Coal		14.9					14.9					14.9
Industrial Other Coal			466.0				466.0		9.5			456.5
Transportation Coal				NO			NO					NO
Electric Power Coal					9,494.0		9,494.0					9,494.0
U.S. Territory Coal (bit)						31.3	31.3					31.3
Natural Gas	**4,888.4**	**3,418.6**	**10,150.6**	**1,230.2**	**11,625.8**	**50.0**	**31,363.7**		**730.0**			**30,633.7**
Total Petroleum	**770.2**	**599.4**	**8,275.2**	**25,087.0**	**197.0**	**244.4**	**35,173.1**	**957.9**	**5,315.5**	**118.6**	**3.6**	**28,777.6**
Asphalt & Road Oil			898.1				898.1		898.1			
Aviation Gasoline				21.6			21.6					21.6
Distillate Fuel Oil	264.9	179.3	692.7	6,774.1	53.1	71.6	8,035.7	100.1	5.8			7,929.8
Jet Fuel				2,835.0		34.6	2,869.6	565.5				2,304.1
Kerosene	8.6	1.3	2.4			0.5	12.8					12.8
LPG (Propane)	496.7	201.7		4.6			702.9					702.9
HGL			3,091.6			10.2	3,101.8		3,043.9			57.9
Lubricants			113.9	118.6		1.0	233.6		113.9	118.6	1.0	
Motor Gasoline		213.3	154.6	14,726.6		74.1	15,168.7					15,168.7
Residual Fuel		3.6	9.2	606.5	57.8	49.8	727.0	292.3				434.7
Other Petroleum												
AvGas Blend Components			(0.8)				(0.8)					(0.8)
Crude Oil												
MoGas Blend Components												
Misc. Products			170.8			2.6	173.4		170.8		2.6	
Naphtha (<401 deg. F)			354.8				354.8		354.8			
Other Oil (>401 deg. F)			216.9				216.9		216.9			
Pentanes Plus			435.9				435.9		217.1			218.8
Petroleum Coke		0.2	516.8		86.1		603.1		48.3			554.8
Still Gas			1,476.2				1,476.2		152.8			1,323.4
Special Naphtha			81.2				81.2		81.2			
Unfinished Oils			49.0				49.0					49.0
Waxes			11.8				11.8		11.8			
Geothermal					**47.4**		**47.4**					**47.4**
Total (All Fuels)	**5,658.6**	**4,033.0**	**19,052.1**	**26,317.2**	**21,364.2**	**325.7**	**76,750.8**	**957.9**	**6,215.3**	**118.6**	**3.6**	**69,455.5**

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-17), and international bunker fuel consumption (see Table A-18).

[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.

Note: Parentheses indicate negative values.

Table A-5: 2021 Energy Consumption Data and CO_2 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**	**456.5**	**NO**	**9,494.0**	**31.3**	**9,996.8**	**NO**	**1.4**	**43.7**	**NO**	**909.7**	**2.9**	**957.7**
Residential Coal	NO						NO	NO						NO
Commercial Coal		14.9					14.9		1.4					1.4
Industrial Other Coal			456.5				456.5			43.7				43.7
Transportation Coal				NO			NO				NO			NO
Electric Power Coal					9,494.0		9,494.0					909.7		909.7
U.S. Territory Coal (bit)						31.3	31.3						2.9	2.9
Natural Gas	**4,888.4**	**3,418.6**	**9,420.5**	**1,230.2**	**11,625.8**	**50.0**	**30,633.7**	**258.6**	**180.9**	**498.4**	**65.1**	**615.1**	**2.6**	**1,620.7**
Total Petroleum	**770.2**	**599.4**	**2,959.8**	**24,010.6**	**197.0**	**240.7**	**28,777.6**	**51.5**	**41.4**	**220.2**	**1,724.5**	**17.1**	**17.5**	**2,072.2**
Asphalt & Road Oil														
Aviation Gasoline				21.6			21.6				1.5			1.5
Distillate Fuel Oil	264.9	179.3	686.9	6,674.1	53.1	71.6	7,929.8	19.6	13.3	50.9	494.7	3.9	5.3	587.8
Jet Fuel				2,269.6	NA	34.6	2,304.1				163.9	NA	2.5	166.4
Kerosene	8.6	1.3	2.4			0.5	12.8	0.6	0.1	0.2			+	0.9
LPG (Propane)	496.7	201.7		4.6			702.9	31.2	12.7		0.3			44.2
HGL			47.7			10.2	57.9			3.1			0.7	3.8
Lubricants														
Motor Gasoline		213.3	154.6	14,726.6		74.1	15,168.7		15.1	10.9	1,040.5		5.2	1,071.7
Residual Fuel		3.6	9.2	314.2	57.8	49.8	434.7		0.3	0.7	23.6	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			218.8				218.8			14.6				14.6
Petroleum Coke		0.2	468.5		86.1		554.8		+	47.8		8.8		56.6
Still Gas			1,323.4				1,323.4			88.3				88.3
Special Naphtha														
Unfinished Oils			49.0				49.0			3.6				3.6
Waxes														
Geothermal					**47.4**		**47.4**					**0.4**		**0.4**
Total (All Fuels)	**5,658.6**	**4,033.0**	**12,836.8**	**25,240.8**	**21,364.2**	**322.1**	**69,455.5**	**310.1**	**223.7**	**762.3**	**1,789.6**	**1,542.2**	**23.0**	**4,651.0**

+ Does not exceed 0.05 TBtu or 0.05 MMT CO_2 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-17), and international bunker fuel consumption (see Table A-18).

[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.

Note: Parentheses indicate negative values.

Table A-6: 2020 Energy Consumption Data and CO_2 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**	**NO**	**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**	**3,286.1**	**9,187.3**	**1,108.7**	**11,999.7**	**50.0**	**30,477.5**	**256.4**	**173.8**	**486.1**	**58.7**	**634.8**	**2.6**	**1,612.4**
Total Petroleum	**841.7**	**757.9**	**3,204.3**	**21,097.8**	**184.4**	**240.8**	**26,326.9**	**56.8**	**52.8**	**238.6**	**1,514.6**	**16.2**	**17.5**	**1,896.4**
Asphalt & Road Oil														
Aviation Gasoline				20.2			20.2				1.4			1.4
Distillate Fuel Oil	336.0	227.3	872.7	6,032.9	44.3	71.6	7,584.7	24.9	16.9	64.7	447.2	3.3	5.3	562.2
Jet Fuel				1,670.2	NA	34.6	1,704.7				120.6	NA	2.5	123.1
Kerosene	10.8	1.7	3.0			0.5	16.0	0.8	0.1	0.2			+	1.2
LPG (Propane)	494.9	201.0		4.6			700.5	31.1	12.6		0.3			44.0
HGL			16.9			10.2	27.1			1.1			0.7	1.8
Lubricants														
Motor Gasoline		325.3	235.8	13,272.6		74.1	13,907.8		23.0	16.7	937.8		5.2	982.7
Residual Fuel		2.3		97.5	52.7	49.8	202.3		0.2		7.3	4.0	3.7	15.2
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			177.8				177.8			11.9				11.9
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			190.5				190.5			14.2				14.2
Waxes														
Geothermal					**54.2**		**54.2**					**0.4**		**0.4**
Total (All Fuels)	**5,687.4**	**4,058.4**	**12,840.1**	**22,206.5**	**20,467.6**	**324.2**	**65,584.3**	**313.2**	**228.0**	**767.6**	**1,573.3**	**1,439.6**	**23.2**	**4,344.8**

+ Does not exceed 0.05 TBtu or 0.05 MMT CO_2 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-17), and international bunker fuel consumption (see Table A-18).

[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.

Note: Parentheses indicate negative values.

Table A-7: 2019 Energy Consumption Data and CO_2 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**	**517.4**	**NO**	**10,181.3**	**38.6**	**10,754.0**	**NO**	**1.6**	**49.5**	**NO**	**973.5**	**3.6**	**1,028.2**
Residential Coal	NO						NO	NO						NO
Commercial Coal		16.7					16.7		1.6					1.6
Industrial Other Coal			517.4				517.4			49.5				49.5
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**	**9,481.7**	**1,114.1**	**11,658.4**	**71.3**	**31,180.9**	**275.5**	**192.9**	**501.5**	**58.9**	**616.6**	**3.8**	**1,649.3**
Total Petroleum	**975.0**	**801.3**	**3,537.9**	**24,460.1**	**188.6**	**240.8**	**30,203.6**	**65.9**	**56.2**	**264.9**	**1,754.9**	**16.2**	**17.5**	**2,175.6**
Asphalt & Road Oil														
Aviation Gasoline				23.4			23.4				1.6			1.6
Distillate Fuel Oil	400.9	278.8	1,021.1	6,393.0	53.9	71.6	8,219.2	29.7	20.7	75.7	474.0	4.0	5.3	609.4
Jet Fuel				2,461.0	NA	34.6	2,495.5				177.7	NA	2.5	180.2
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		8.7			754.1	35.4	11.4		0.5			47.4
HGL			49.3			10.2	59.5			3.2			0.7	3.9
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			167.9				167.9			11.2				11.2
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			135.9				135.9			10.1				10.1
Waxes														
Geothermal					**52.8**		**52.8**					**0.4**		**0.4**
Total (All Fuels)	**6,183.1**	**4,465.3**	**13,537.0**	**25,574.2**	**22,081.0**	**350.7**	**72,191.3**	**341.4**	**250.7**	**815.9**	**1,813.9**	**1,606.7**	**24.8**	**4,853.4**

+ Does not exceed 0.05 TBtu or 0.05 MMT CO_2 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-17), and international bunker fuel consumption (see Table A-18).

[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.

Note: Parentheses indicate negative values.

Table A-8: 2018 Energy Consumption Data and CO_2 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**	**569.0**	**NO**	**12,053.0**	**27.7**	**12,668.4**	**NO**	**1.8**	**54.4**	**NO**	**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			569.0				569.0			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	**945.7**	**734.6**	**3,548.4**	**24,558.3**	**260.4**	**278.0**	**30,325.4**	**64.4**	**51.5**	**265.6**	**1,762.0**	**22.2**	**20.1**	**2,185.8**
Asphalt & Road Oil														
Aviation Gasoline				22.4			22.4				1.5			1.5
Distillate Fuel Oil	431.0	274.3	1,058.1	6,427.8	80.6	85.4	8,357.2	32.0	20.3	78.5	476.6	6.0	6.3	619.7
Jet Fuel				2,385.1	NA	40.4	2,425.5				172.3	NA	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		8.9			691.4	31.8	11.1		0.6			43.5
HGL			126.1			8.8	134.9			8.2			0.6	8.8
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			112.7				112.7			7.5				7.5
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			30.9				30.9			2.3				2.3
Waxes														
Geothermal					**54.5**		**54.5**					**0.4**		**0.4**
Total (All Fuels)	**6,120.1**	**4,391.6**	**13,442.8**	**25,520.4**	**23,289.3**	**368.2**	**73,132.4**	**338.2**	**245.8**	**813.5**	**1,812.9**	**1,753.4**	**25.9**	**4,989.8**

+ Does not exceed 0.05 TBtu or 0.05 MMT CO_2 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-17), and international bunker fuel consumption (see Table A-18).

[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.

Note: Parentheses indicate negative values.

Table A-9: 2017 Energy Consumption Data and CO_2 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**	**614.1**	**NO**	**12,622.2**	**25.0**	**13,281.9**	**NO**	**2.0**	**58.7**	**NO**	**1,207.1**	**2.3**	**1,270.0**
Residential Coal	NO						NO	NO						NO
Commercial Coal		20.7					20.7		2.0					2.0
Industrial Other Coal			614.1				614.1			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	**766.1**	**808.9**	**3,513.7**	**24,217.2**	**217.7**	**292.3**	**29,816.0**	**51.9**	**56.8**	**262.2**	**1,737.8**	**18.9**	**21.1**	**2,148.8**
Asphalt & Road Oil														
Aviation Gasoline				20.9			20.9				1.4			1.4
Distillate Fuel Oil	327.0	244.1	905.2	6,287.9	54.7	68.8	7,887.7	24.2	18.1	67.1	465.9	4.1	5.1	584.4
Jet Fuel				2,377.2	NA	43.9	2,421.0				171.7	NA	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		9.1			595.5	27.1	9.8		0.6			37.4
HGL			173.6			8.8	182.4			11.3			0.6	11.9
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			87.0				87.0			5.8				5.8
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			76.4				76.4			5.7				5.7
Waxes														
Geothermal					**54.3**		**54.3**					**0.4**		**0.4**
Total (All Fuels)	**5,329.6**	**4,102.4**	**12,974.3**	**25,015.8**	**22,449.5**	**365.4**	**70,237.0**	**293.4**	**232.0**	**789.0**	**1,780.1**	**1,732.0**	**25.9**	**4,852.5**

+ Does not exceed 0.05 TBtu or 0.05 MMT CO_2 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-17), and international bunker fuel consumption (see Table A-18).

[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.

Note: Parentheses indicate negative values.

Table A-10: 2016 Energy Consumption Data and CO_2 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**	**661.6**	**NO**	**12,996.4**	**35.5**	**13,717.2**	**NO**	**2.3**	**63.2**	**NO**	**1,242.0**	**3.3**	**1,310.7**
Residential Coal	NO						NO	NO						
Commercial Coal		23.7					23.7		2.3					2.3
Industrial Other Coal			661.6				661.6			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	**799.2**	**834.5**	**3,552.2**	**23,956.5**	**243.9**	**269.6**	**29,655.9**	**54.4**	**58.7**	**265.7**	**1,717.7**	**21.5**	**19.5**	**2,137.5**
Asphalt & Road Oil														
Aviation Gasoline				20.5			20.5				1.4			1.4
Distillate Fuel Oil	355.7	266.9	940.0	6,104.1	54.9	80.2	7,801.8	26.4	19.8	69.7	452.4	4.1	5.9	578.3
Jet Fuel				2,297.8	NA	29.6	2,327.4				166.0	NA	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		8.8			588.7	27.0	9.4		0.6			37.0
HGL			225.7			8.2	233.9			14.7			0.5	15.2
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			56.5				56.5			3.8				3.8
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			8.6				8.6			0.6				0.6
Waxes														
Geothermal					**54.0**		**54.0**					**0.4**		**0.4**
Total (All Fuels)	**5,305.1**	**4,081.8**	**12,983.8**	**24,713.7**	**23,595.6**	**368.7**	**71,048.6**	**292.8**	**231.5**	**792.9**	**1,757.7**	**1,808.9**	**26.2**	**4,909.9**

+ Does not exceed 0.05 TBtu or 0.05 MMT CO_2 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-17), and international bunker fuel consumption (see Table A-18).

[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.

Note: Parentheses indicate negative values.

Table A-11: 2015 Energy Consumption Data and CO_2 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**	**733.9**	**NO**	**14,138.3**	**35.9**	**14,939.2**	**NO**	**3.0**	**70.0**	**NO**	**1,351.4**	**3.3**	**1,427.6**
Residential Coal	NO						NO	NO						NO
Commercial Coal		31.1					31.1		3.0					3.0
Industrial Other Coal			733.9				733.9			70.0				70.0
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	**939.0**	**937.9**	**3,579.7**	**23,419.4**	**276.0**	**305.7**	**29,457.7**	**64.6**	**66.2**	**268.4**	**1,678.8**	**23.7**	**22.2**	**2,123.9**
Asphalt & Road Oil														
Aviation Gasoline				21.1			21.1				1.5			1.5
Distillate Fuel Oil	483.1	315.5	1,018.1	6,154.7	70.4	78.8	8,120.6	35.8	23.4	75.5	456.3	5.2	5.8	602.1
Jet Fuel				2,180.9	NA	36.0	2,217.0				157.5	NA	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		7.7			601.4	28.0	9.3		0.5			37.8
HGL			242.2			8.1	250.2			15.7			0.5	16.3
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			80.9				80.9			5.4				5.4
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			(17.8)				(17.8)			(1.3)				(1.3)
Waxes														
Geothermal					**54.3**		**54.3**					**0.4**		**0.4**
Total (All Fuels)	**5,715.9**	**4,284.7**	**13,001.7**	**24,164.3**	**24,395.0**	**399.0**	**71,960.5**	**317.3**	**244.6**	**798.0**	**1,718.2**	**1,900.6**	**28.5**	**5,007.3**

+ Does not exceed 0.05 TBtu or 0.05 MMT CO_2 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-17), and international bunker fuel consumption (see Table A-18).

[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.

Note: Parentheses indicate negative values.

Table A-12: 2010 Energy Consumption Data and CO_2 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**	**NO**	**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	**1,103.3**	**697.9**	**3,915.5**	**23,028.3**	**370.3**	**407.7**	**29,523.0**	**75.8**	**49.9**	**294.7**	**1,658.4**	**31.4**	**29.8**	**2,140.1**
Asphalt & Road Oil														
Aviation Gasoline				27.0			27.0				1.9			1.9
Distillate Fuel Oil	544.4	379.2	1,108.5	5,729.4	79.7	66.4	7,907.6	40.4	28.1	82.3	425.2	5.9	4.9	586.8
Jet Fuel				2,096.4	NA	36.6	2,133.0				151.4	NA	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		4.5			674.3	33.3	8.8		0.3			42.4
HGL			150.9			15.7	166.6			9.8			1.0	10.9
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			78.4				78.4			5.2				5.2
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			28.0				28.0			2.1				2.1
Waxes														
Geothermal					**51.9**		**51.9**					**0.4**		**0.4**
Total (All Fuels)	**5,981.4**	**3,932.2**	**12,578.4**	**23,747.3**	**27,083.3**	**470.2**	**73,792.9**	**334.8**	**224.5**	**795.9**	**1,696.6**	**2,258.6**	**34.5**	**5,344.9**

+ Does not exceed 0.05 TBtu or 0.05 MMT CO_2 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-17), and international bunker fuel consumption (see Table A-18).

[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.

Note: Parentheses indicate negative values.

Table A-13: 2005 Energy Consumption Data and CO_2 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**	**22,121.4**	**0.8**	**9.3**	**117.8**	**NO**	**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**	**4,599.1**	**25,369.9**	**1,222.1**	**649.5**	**33,967.7**	**95.9**	**54.9**	**345.2**	**1,825.5**	**98.0**	**47.6**	**2,467.0**
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	NA	65.5	2,685.9				189.2	NA	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			281.9			10.6	292.5			18.2			0.7	18.9
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			98.9				98.9			6.6				6.6
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			2.8				2.8			0.2				0.2
Waxes														
Geothermal					**50.1**		**50.1**					**0.5**		**0.5**
Total (All Fuels)	**6,321.2**	**3,930.9**	**13,159.7**	**25,993.8**	**28,024.0**	**706.5**	**78,136.2**	**358.9**	**227.1**	**850.8**	**1,858.6**	**2,400.1**	**51.9**	**5,747.3**

+ Does not exceed 0.05 TBtu or 0.05 MMT CO_2 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-17), and international bunker fuel consumption (see Table A-18).

[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.

Table A-14: 2000 Energy Consumption Data and CO_2 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**	**NO**	**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**	**3,753.8**	**24,295.9**	**1,144.1**	**491.2**	**31,877.4**	**99.8**	**55.3**	**282.2**	**1,756.6**	**88.5**	**35.9**	**2,318.3**
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	NA	68.6	2,767.5				194.9	NA	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			393.8			7.9	401.7			25.4			0.5	25.9
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			172.9				172.9			11.6				11.6
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			(401.2)				(401.2)			(29.7)				(29.7)
Waxes														
Geothermal					**48.1**		**48.1**					**0.5**		**0.5**
Total (All Fuels)	**6,541.4**	**4,110.2**	**13,752.1**	**24,967.9**	**26,705.8**	**509.1**	**76,586.4**	**371.7**	**236.5**	**868.9**	**1,792.2**	**2,296.2**	**37.0**	**5,602.5**

+ Does not exceed 0.05 TBtu or 0.05 MMT CO_2 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-17), and international bunker fuel consumption (see Table A-18).

[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.

Note: Parentheses indicate negative values.

Table A-15: 1995 Energy Consumption Data and CO_2 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**	**NO**	**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**	**3,752.0**	**21,528.1**	**754.5**	**290.4**	**28,308.4**	**88.7**	**52.4**	**279.7**	**1,542.3**	**58.7**	**21.1**	**2,042.9**
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	NA	57.2	2,484.4				172.1	NA	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			277.8			2.3	280.1			17.9			0.1	18.0
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			170.3				170.3			11.4				11.4
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			(320.9)				(320.9)			(23.8)				(23.8)
Waxes														
Geothermal					**45.6**		**45.6**					**0.4**		**0.4**
Total (All Fuels)	**6,231.0**	**3,936.9**	**14,009.5**	**22,252.1**	**22,568.4**	**295.0**	**69,292.9**	**353.1**	**227.8**	**888.4**	**1,580.7**	**1,947.2**	**21.5**	**5,018.7**

+ Does not exceed 0.05 TBtu or 0.05 MMT CO_2 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-17), and international bunker fuel consumption (see Table A-18).

[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.

Note: Parentheses indicate negative values.

Table A-16: 1990 Energy Consumption Data and CO_2 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**	**1,668.2**	**NO**	**16,261.0**	**5.4**	**18,090.1**	**3.0**	**12.0**	**157.8**	**NO**	**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			1,668.2				1,668.2			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	**1,375.8**	**1,022.6**	**3,846.2**	**19,974.7**	**1,289.4**	**268.2**	**27,776.9**	**97.8**	**74.3**	**287.1**	**1,432.9**	**97.5**	**19.5**	**2,009.2**
Asphalt & Road Oil														
Aviation Gasoline				45.0			45.0				3.1			3.1
Distillate Fuel Oil	959.3	525.5	1,098.3	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	NA	48.6	2,636.3				184.1	NA	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			227.1			6.9	234.0			14.5			0.4	15.0
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			126.1				126.1			8.4				8.4
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			(369.0)				(369.0)			(27.3)				(27.3)
Waxes														
Geothermal					**52.7**		**52.7**					**0.5**		**0.5**
Total (All Fuels)	**5,893.5**	**3,826.6**	**13,201.5**	**20,654.0**	**20,911.6**	**273.6**	**64,760.8**	**338.6**	**228.3**	**852.4**	**1,468.9**	**1,820.0**	**20.0**	**4,728.2**

+ Does not exceed 0.05 TBtu or 0.05 MMT CO_2 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-17), and international bunker fuel consumption (see Table A-18).

[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.

Note: Parentheses indicate negative values.

Table A-17: Unadjusted Non-Energy Fuel Consumption (TBtu)

Sector/Fuel Type	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Industry	**4,644.2**	**5,154.8**	**5,575.9**	**5,486.8**	**4,735.1**	**5,022.6**	**5,106.3**	**5,378.9**	**5,789.1**	**5,880.0**	**5,849.4**	**6,215.3**
Industrial Coking Coal	0.0	37.8	53.5	80.4	64.8	122.4	89.6	113.0	124.7	112.8	70.0	160.3
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
Natural Gas to Chemical Plants, Other Uses	305.9	371.0	401.7	270.4	310.0	431.8	532.0	631.1	730.8	732.2	730.0	730.0
Asphalt & Road Oil	1,170.2	1,178.2	1,275.7	1,323.2	877.8	831.7	853.4	849.2	792.8	843.9	832.3	898.1
HGL	1,302.2	1,651.6	1,759.3	1,659.5	1,899.9	2,216.8	2,257.1	2,329.7	2,677.4	2,758.8	2,884.5	3,043.9
Lubricants	186.3	177.8	189.9	160.2	135.9	142.1	135.1	124.9	122.0	118.3	111.1	113.9
Pentanes Plus	125.2	169.0	171.6	98.1	77.7	80.2	56.1	86.4	111.8	166.6	176.5	217.1
Naphtha (<401 deg. F)	347.8	373.0	613.5	698.7	490.6	428.1	420.0	436.2	447.1	396.7	354.6	354.8
Other Oil (>401 deg. F)	753.9	801.0	722.2	708.0	452.5	229.0	222.5	262.9	239.1	234.1	217.0	216.9
Still Gas	36.7	47.9	17.0	67.7	147.8	162.2	166.1	163.8	166.9	158.7	145.4	152.8
Petroleum Coke	123.1	120.6	98.7	186.9	61.0	62.5	61.2	57.0	58.9	56.4	46.2	48.3
Special Naphtha	107.1	70.8	97.4	62.5	26.1	99.3	93.6	100.3	92.0	95.6	86.6	81.2
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
Waxes	33.3	40.6	33.1	31.4	17.1	12.4	12.8	10.2	12.4	10.4	9.2	11.8
Miscellaneous Products	137.8	97.1	119.2	112.8	158.7	188.9	191.3	198.8	198.0	180.2	170.7	170.8
Transportation	**176.0**	**167.9**	**179.4**	**151.3**	**154.8**	**162.8**	**154.4**	**142.0**	**137.0**	**131.3**	**115.6**	**118.6**
Lubricants	176.0	167.9	179.4	151.3	154.8	162.8	154.4	142.0	137.0	131.3	115.6	118.6
U.S. Territories	**50.8**	**55.4**	**140.8**	**114.9**	**27.4**	**10.3**	**10.5**	**3.5**	**3.6**	**3.6**	**3.6**	**3.6**
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
Other Petroleum (Misc. Prod.)	50.1	53.4	137.7	110.3	26.4	9.3	9.5	2.4	2.5	2.6	2.6	2.6
Total	**4,871.1**	**5,378.2**	**5,896.1**	**5,753.1**	**4,917.3**	**5,195.8**	**5,271.1**	**5,524.3**	**5,929.7**	**6,015.0**	**5,968.6**	**6,337.5**

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.

Table A-18: International Bunker Fuel Consumption (TBtu)

Fuel Type	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Aviation Jet Fuel	541.8	705.1	881.5	854.4	866.4	1,023.3	1,052.1	1,104.2	1,147.7	1,147.0	563.7	565.5
Marine Residual Fuel Oil	715.7	523.2	444.1	581.0	619.8	406.8	450.7	445.3	417.6	336.2	294.0	292.3
Marine Distillate Fuel Oil	158.0	125.7	85.9	126.9	128.2	113.5	117.5	121.3	134.4	136.3	105.0	100.1
Total	**1,415.5**	**1,354.0**	**1,411.4**	**1,562.3**	**1,614.4**	**1,543.6**	**1,620.3**	**1,670.8**	**1,699.7**	**1,619.5**	**962.6**	**957.9**

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.

Table A-19: C Content Coefficients by Year (MMT C/QBtu)

Fuel Type	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Coal												
Residential Coal[a]	26.19	26.13	26.00	26.04	25.75	25.98	26.01	26.09	26.09	26.11	26.21	26.16
Commercial Coal	26.19	26.13	26.00	26.04	25.75	25.98	26.01	26.09	26.09	26.11	26.21	26.16
Industrial Coking Coal	25.53	25.57	25.63	25.60	25.58	25.57	25.57	25.56	25.59	25.59	25.60	25.60
Industrial Other Coal	25.81	25.79	25.74	25.79	25.86	26.00	26.03	26.06	26.08	26.07	26.13	26.10
Electric Power Coal [c]	25.94	25.92	25.98	26.08	26.05	26.07	26.06	26.08	26.09	26.08	26.12	26.13
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
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
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
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
Distillate Fuel Oil No. 2[b,d]	20.17	20.17	20.39	20.37	20.24	20.22	20.21	20.21	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
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
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
HGL (Energy Use)[d]	17.46	17.52	17.59	17.60	17.78	17.71	17.73	17.78	17.78	17.83	17.82	17.85
HGL (Non-Energy Use)[d]	17.15	17.17	17.11	17.09	16.96	16.92	16.89	16.87	16.84	16.86	16.80	16.83
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
Motor Gasoline[d]	19.42	19.36	19.47	19.32	19.39	19.25	19.26	19.28	19.27	19.27	19.27	19.27
Residual Fuel Oil No. 6[a,b]	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
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
MoGas Blend Components[c, 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
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
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
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
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
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
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
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
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
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
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
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
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
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
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

[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] Distillate fuel oil No. 2 and residual fuel oil No. 6 are the only fuel oils used in the CO_2 from fossil fuel combustion calculations.

[c] 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 CO_2 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.

[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 2020a). C contents were obtained in pounds CO_2/megawatt hour and were applied to net generation by geotype (in megawatt hours) from EIA (2022a). C contents were converted to MMT Carbon/QBtu in this table.

Source: Non-variable C coefficients from EIA (2009), EPA (2010), and EPA (2020b). Coal C content coefficients calculated from USGS (1998), PSU (2010), Gunderson (2019), IGS (2019), ISGS (2019), EIA (1990 through 2001), EIA (2001 through 2022a), and EIA (2001 through 2022b); pipeline natural gas C content coefficients calculated from EIA (2022) and EPA (2010); petroleum carbon contents from EPA (2010), EIA (1994), EIA (2009), EPA (2020b), and ICF (2020). See Annex 2.2 for information on how these C content coefficients are calculated.

Table A-20: CO_2 Content Coefficients by Year (MMT CO_2/QBtu)

Fuel Type	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Coal												
Residential Coal[a]	96.02	95.79	95.33	95.47	94.42	95.27	95.38	95.65	95.68	95.72	96.10	95.90
Commercial Coal	96.02	95.79	95.33	95.47	94.42	95.27	95.38	95.65	95.68	95.72	96.10	95.90
Industrial Coking Coal	94.62	93.74	93.97	93.87	93.80	93.75	93.75	93.73	93.85	93.84	93.87	93.86
Industrial Other Coal	95.11	94.55	94.37	94.58	94.83	95.35	95.46	95.55	95.63	95.59	95.80	95.69
Electric Power Coal [c]	95.11	95.03	95.27	95.61	95.50	95.58	95.57	95.63	95.65	95.62	95.78	95.82
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
Natural Gas												
Pipeline Natural Gas[d]	53.00	53.04	53.05	53.01	53.08	52.91	52.91	52.92	52.92	52.89	52.91	52.91
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
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
Distillate Fuel Oil No. 2[b,d]	73.96	73.96	74.76	74.69	74.21	74.15	74.12	74.09	74.15	74.15	74.13	74.13
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
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
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
HGL (Energy Use)[d]	64.03	64.25	64.50	64.54	65.19	64.95	65.00	65.18	65.18	65.38	65.35	65.46
HGL (Non-Energy Use)[d]	62.87	62.95	62.74	62.67	62.20	62.03	61.91	61.84	61.74	61.81	61.59	61.69
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
Motor Gasoline[d]	71.22	70.99	71.39	70.84	71.10	70.58	70.62	70.69	70.66	70.66	70.66	70.66
Residual Fuel Oil No. 6[a,b]	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
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
MoGas Blend Components [c, 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
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
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
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
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
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
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
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
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

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
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
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
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

[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] Distillate fuel oil No. 2 and residual fuel oil No. 6 are the only fuel oils used in the CO_2 from fossil fuel combustion calculations.

[c] 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 CO_2 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. CO_2 content coefficients are presented in higher heating value because U.S. energy statistics are reported by higher heating value.

[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 2020a). C contents were obtained in pounds CO_2/megawatt hour and were applied to net generation by geotype (in megawatt hours) from EIA (2022a). CO_2 contents for binary and binary/flash geotypes are zero and have been excluded from this table.

Notes: CO_2 content coefficients calculated based on C content coefficients in Table A-19. Coefficients assume 100% oxidation of C to CO_2. See Annex 2.2 for information on how C content coefficients are calculated.

Table A-21: Electricity Consumption by End-Use Sector (Billion Kilowatt-Hours)

End-Use Sector	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Residential	924	1,043	1,192	1,359	1,446	1,403	1,410	1,377	1,466	1,437	1,461	1,471
Commercial	838	953	1,159	1,275	1,330	1,361	1,367	1,353	1,381	1,360	1,287	1,324
Industrial	1,070	1,163	1,235	1,169	1,103	1,128	1,117	1,125	1,145	1,146	1,098	1,123
Transportation[a]	5	5	5	8	8	9	9	10	11	12	11	13
Total	**2,837**	**3,164**	**3,592**	**3,811**	**3,887**	**3,900**	**3,902**	**3,864**	**4,003**	**3,954**	**3,856**	**3,930**

[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 (2022a). Industrial electricity consumption includes direct use.

Table A-22: Electric Power Generation by Fuel Type (Percent)

Fuel Type	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Coal	54.1%	52.7%	53.3%	51.1%	46.0%	34.2%	31.4%	30.9%	28.4%	24.2%	19.9%	22.5%
Natural Gas	10.7%	13.1%	14.2%	17.5%	22.7%	31.6%	32.7%	30.9%	34.0%	37.3%	39.5%	37.2%
Nuclear	19.9%	21.1%	20.7%	20.0%	20.3%	20.3%	20.6%	20.8%	20.1%	20.4%	20.5%	19.6%
Renewables	11.3%	10.9%	8.8%	8.3%	10.0%	13.0%	14.7%	16.8%	16.8%	17.6%	19.5%	20.1%
Petroleum	4.1%	2.1%	2.9%	3.0%	0.9%	0.7%	0.6%	0.5%	0.6%	0.4%	0.4%	0.4%
Other Gases[a]	+	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Net Electricity Generation (Billion kWh)[b]	*2,905*	*3,197*	*3,643*	*3,902*	*3,971*	*3,918*	*3,918*	*3,878*	*4,020*	*3,966*	*3,851*	*3,961*

+ 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-21 (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 (2022a).

Table A-23: Geothermal Net Generation by Geotype (Billion Kilowatt-Hours)

Geotype	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Binary	0.08	0.28	0.24	0.68	2.41	3.36	3.62	3.56	3.84	4.34	4.22	3.28
Flash Steam	6.15	7.63	7.43	7.93	6.83	7.00	6.65	6.69	6.39	5.92	6.05	5.10
Dry Steam	9.21	5.47	6.43	6.09	5.98	5.56	5.55	5.67	5.73	5.21	5.61	5.52
Total	**15.43**	**13.38**	**14.09**	**14.69**	**15.22**	**15.92**	**15.83**	**15.93**	**15.97**	**15.47**	**15.89**	**13.89**

Source: EIA (2022b).

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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 (CO_2) 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; 2010; 2022c; 1990 through 2001; 2001 through 2022a; 2001 through 2022b)). 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-19.

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-fifth 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-24.[68]

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), 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.

[68] 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.

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 CO_2) 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 statistics[69] through 2021 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.[70] 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

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

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.

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

[70] 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-19 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-24: Carbon Content Coefficients for Coal by Consuming Sector and Coal Rank (MMT C/QBtu) (1990-2021)

Consuming Sector	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Electric Power	25.94	25.92	25.98	26.08	26.05	26.07	26.06	26.08	26.09	26.08	26.12	26.13
Industrial Coking	25.53	25.57	25.63	25.60	25.58	25.57	25.57	25.56	25.59	25.59	25.60	25.60
Other Industrial	25.81	25.79	25.74	25.79	25.86	26.00	26.03	26.06	26.08	26.07	26.13	26.10
Residential/ Commercial[a]	26.19	26.13	26.00	26.04	25.75	25.98	26.01	26.09	26.09	26.11	26.21	26.16
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
Bituminous	25.38	25.42	25.45	25.45	25.42	25.40	25.40	25.40	25.41	25.41	25.43	25.43
Sub-bituminous	26.46	26.47	26.46	26.48	26.47	26.49	26.49	26.20	26.49	26.49	26.49	26.49
Lignite	26.58	26.59	26.61	26.62	26.63	26.66	26.64	26.67	26.76	26.75	26.77	26.80

[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 2022a; 2001 through 2022b).

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

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

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 2022a) is the source for state coal production by rank from 2001 through 2021. 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 2021 was obtained from the EIA's *Annual Coal Distribution Report* (EIA 2001 through 2022b). 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 44.4 percent and 45.9 percent of total U.S. supply in 2021, 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 CO_2 per MMBtu in Texas to a high of 96.36 kg CO_2 per MMBtu in Arkansas. The next lowest average emission factor for bituminous coal is found in Missouri (91.71 kg CO_2 per MMBtu). In 2021, Missouri production accounted for less than 0.1 percent of overall bituminous production. More than 50 percent of bituminous coal was produced in three states in 2021: 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 $\pm$0.7 percent, based on more than 2,000 samples (see Table A-25).

Similarly, the C content coefficients for sub-bituminous coal range from 91.29 kg CO_2 per MMBtu in Utah to 98.09 kg CO_2 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 0.7 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 2021). Thus, the C content coefficient for Wyoming (97.21 kg CO_2 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-25: Variability in Carbon Content Coefficients by Rank Across States (Kilograms CO_2 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 gasoline[71] 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.

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

[71] 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.

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 (1,025 to 1,037 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 well 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-26.

Table A-26: 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 CO_2 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 CO_2 only (n=6,522) and those with less than 1.0 or 1.5 percent CO_2 and less than 1,050 Btu/cf (n=4,888 and 6,166, respectively). These stratifications were chosen to exclude samples with CO_2 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-27.

Table A-27: Carbon Content of Pipeline-Quality Natural Gas by CO_2 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 values[72] for each of the sub-samples ranged from 0.79 for samples with less than 1.5 percent CO_2 and under 1,050 Btu/cf to 0.91 for samples containing less than 1.0 percent CO_2 only. However, the sub-sample with less than 1.5 percent CO_2 and 1,050 Btu/cf was chosen as the representative sample for two reasons. First, it most accurately reflects the range of CO_2 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

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

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

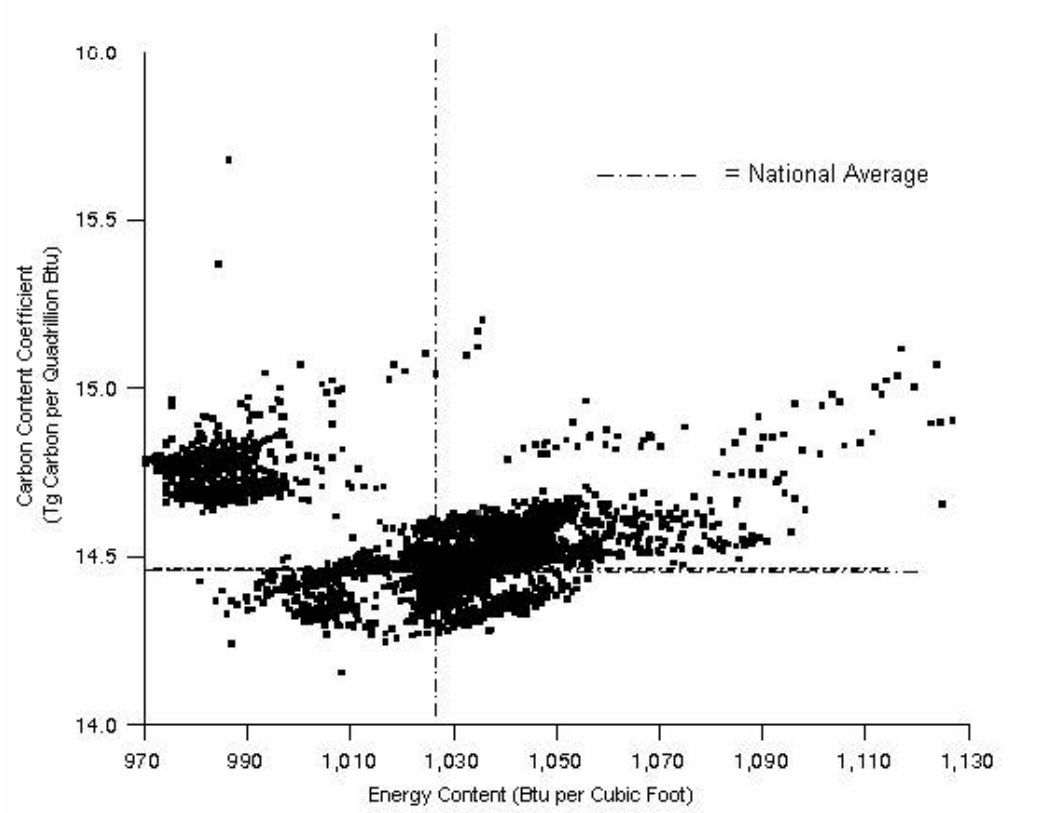
This equation was used to estimate the annual predicted carbon content of natural gas from 1990 to 2021 based on the EIA's national average pipeline-quality gas heat content for each year (EIA 2022a). The table of average C contents for each year is shown below in Table A-28.

Table A-28: Carbon Content Coefficients for Natural Gas (MMT Carbon/QBtu)

Fuel Type	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
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

Source: Calculated from EPA (2010) and EIA (2022a).

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



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 CH_4. 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 CO_2 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-28), based on samples with less than 1.5 percent CO_2 and less than 1,050 Btu per cubic foot, better represents the pipeline-quality fuels typically consumed.

Furthermore, research was done on CO_2 emission factors for fuel gas used by upstream oil and gas producers in order to determine whether a different CO_2 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. It was determined that a different factor was not warranted as natural gas carbon content is based on the heating value of the gas and EIA reports that the heat content of dry natural gas produced (which is used in upstream oil and gas production) is the same value as natural gas consumed in downstream operations (EIA 2022a). Therefore, 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

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

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 gravity[73] (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

[73] 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: API Gravity = (141.5/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.

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.

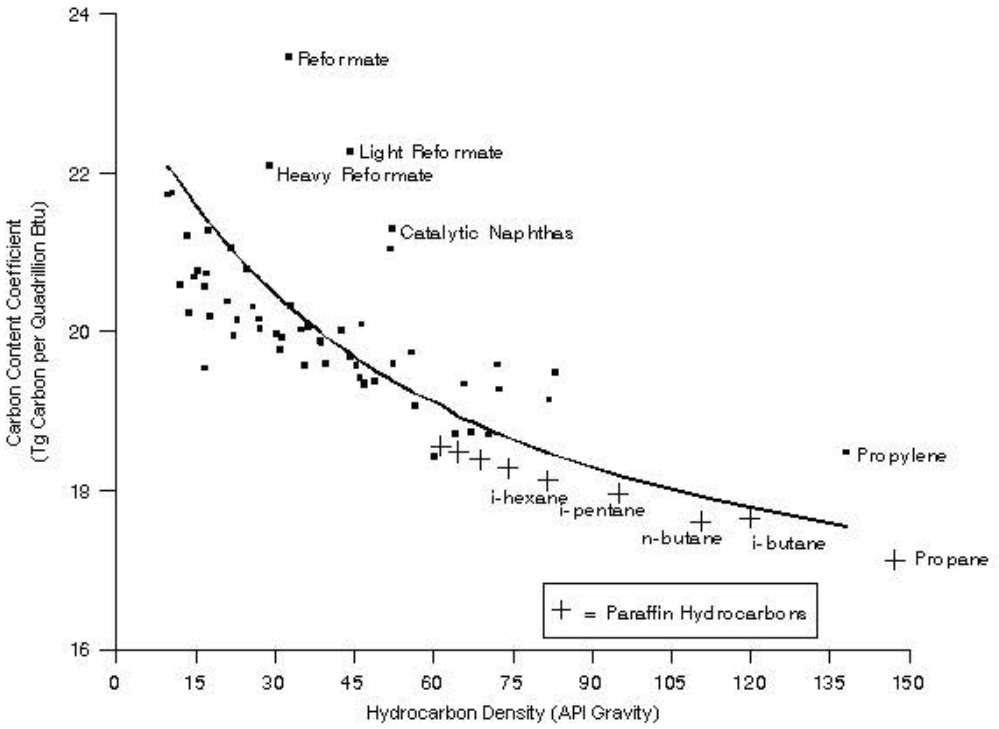
Petroleum Chemistry

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.

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.

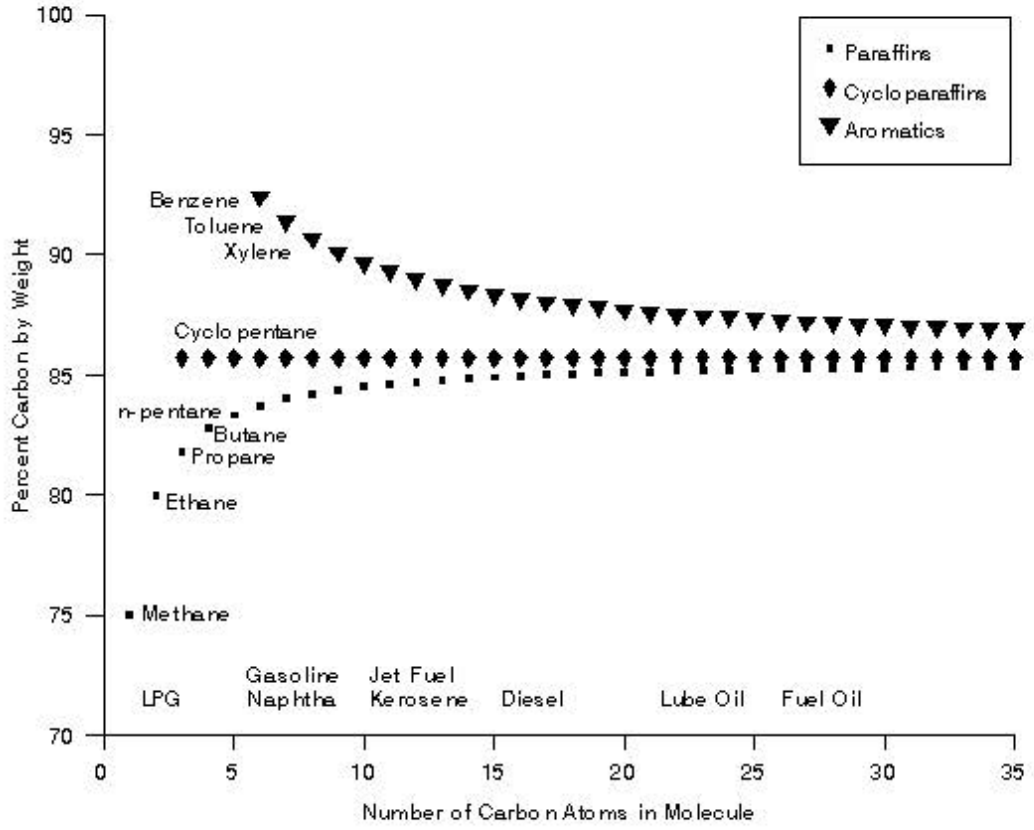
Olefins. Olefins are a very reactive and unstable form of paraffin: a straight chain with two carbon atoms double bonded together (thus are unsaturated) compared to the carbon atoms in a paraffin (which are saturated with hydrogen). They are never found in crude oil but are created in moderate quantities 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 Number



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-29. A description of the methods and data sources for estimating the key parameters for each individual petroleum product appears below.

Table A-29: 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	(See a)	(See a)	(See a)
LPG (Propane)	17.15	3.841	155.3	81.80
HGL (Energy Use)[b]	17.66	(See b)	(See b)	(See b)
HGL (Non-Energy Use)[b]	16.77	(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	4.638	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-31.

[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, 2021 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.[74] "Motor Gasoline" includes conventional gasoline; all types of oxygenated gasoline, including gasohol; and reformulated gasoline; but excludes aviation gasoline.

Gasoline is the most widely used petroleum product in the United States, and its combustion accounts for nearly 21 percent of all U.S. CO_2 emissions. EIA collects consumption data (i.e., "petroleum products supplied" to end-users) for several types of finished gasoline over the 1990 through 2021 time period: regular, mid-grade, and premium

[74] 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.

conventional gasoline (all years) and regular, mid-grade, and premium reformulated gasoline (November 1994 to 2021). Leaded and oxygenated gasoline are not separately included in the data used for this report.[75]

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 2021.

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-30.

Table A-30: 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.[76] Ethanol, also called ethyl alcohol, is an anhydrous alcohol with molecular formula C_2H_5OH. 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.[77] Ethanol blends up to E85 (85 percent ethanol, 15 percent gasoline) are in 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,[78] although production pathways utilizing agricultural waste, woody biomass and other resources are in development.

[75] 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.

[76] 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.

[77] See https://www.epa.gov/renewable-fuel-standard-program.

[78] See https://www.epa.gov/fuels-registration-reporting-and-compliance-help/public-data-renewable-fuel-standard.

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,[79] the density of the constituent, share of the constituent[80] 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-30 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 2022c). 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.

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.

[79] 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.

[80] Saturates are assumed to be octane and aromatics are assumed to be toluene.

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 gasoline[81] 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 2021, 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.

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).

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

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 2021, 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 2021, 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 2021, 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 2021.

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 2021, 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 2021, 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 (2022c).

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 (2022a), 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 2021, 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. HGL also includes pentanes plus, or natural gasoline, but this category is calculated separately from other HGL components in this report. 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, C_3H_8, 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-31 summarizes the physical characteristic of HGL.

Table A-31: 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_2H_6	11.55	80.00	2.783	16.25
Propane	C_3H_8	12.76	81.80	3.841	17.15
Isobutane	C_4H_{10}	11.42	82.80	4.183	17.71
n-butane	C_4H_{10}	10.98	82.30	4.354	17.66
Ethylene	C_2H_4	11.07	85.71	2.436	17.99
Propylene	C_3H_6	12.45	85.71	3.835	18.48
Isobutylene	C_4H_8	10.68	85.71	4.355	18.78
Butylene	C_4H_8	10.70	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 (2022a). 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, excluding pentanes plus, which is calculated separately.

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 (2022a) 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-32.

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 Education. The energy content of each HGL is from EIA (2022a). HGL consumption was based on data obtained from EIA (2022b). Non-fuel use of HGL was obtained from EIA (2022b).

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-32: Industrial Sector Consumption and Carbon Content Coefficients of Hydrocarbon Gas Liquids, 1990-2021

	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Energy Consumption (QBtu)												
Fuel Use	**8.40**	**10.40**	**12.28**	**11.51**	**10.15**	**11.35**	**11.11**	**10.54**	**10.91**	**10.00**	**9.48**	**10.07**
Ethane	0.33	0.26	0.73	0.34	0.03	0.04	0.04	0.05	0.05	0.06	0.06	0.07
Propane	6.60	7.94	7.03	7.09	5.20	6.11	5.82	5.30	5.53	4.63	4.58	4.59
Butane	0.00	0.00	0.74	0.52	0.50	0.63	0.41	0.19	0.17	0.25	(0.05)	0.11
Isobutane	0.00	0.00	0.61	0.14	0.12	0.46	0.61	0.66	0.76	0.89	1.01	1.05
Ethylene	+	0.00	+	+	+	+	+	+	+	+	+	+
Propylene	1.47	2.20	3.15	3.41	4.28	4.13	4.23	4.32	4.36	4.18	3.90	4.27
Butylene	0.00	0.00	0.02	0.02	0.02	(0.03)	(0.01)	0.02	0.04	+	(0.02)	(0.01)
Isobutylene	0.00	0.00	+	+	+	(+)	+	+	(+)	+	(+)	(+)
Non-Fuel Use	**1.21**	**1.56**	**1.68**	**1.59**	**1.80**	**2.10**	**2.13**	**2.19**	**2.51**	**2.59**	**2.69**	**2.84**
Ethane	0.48	0.61	0.71	0.64	0.88	1.09	1.15	1.26	1.50	1.56	1.74	1.83
Propane	0.39	0.49	0.56	0.59	0.57	0.58	0.56	0.54	0.59	0.58	0.55	0.55
Butane	0.17	0.17	0.11	0.12	0.11	0.14	0.09	0.04	0.04	0.06	(0.01)	0.02
Isobutane	0.03	0.10	0.09	0.03	0.03	0.10	0.14	0.15	0.17	0.20	0.23	0.23
Ethylene	+	+	+	+	0.01	+	+	+	+	+	+	+
Propylene	0.14	0.17	0.20	0.21	0.20	0.20	0.20	0.21	0.21	0.20	0.19	0.20
Butylene	0.01	0.01	+	+	+	(0.01)	(+)	+	0.01	+	(+)	(+)
Isobutylene	+	+	+	+	+	(+)	+	+	(+)	+	(+)	(+)
Carbon Content (MMT C/QBtu)												
Fuel Use	17.46	17.52	17.59	17.60	17.78	17.71	17.73	17.78	17.78	17.83	17.82	17.85
Non-Fuel Use	17.15	17.17	17.11	17.09	16.96	16.92	16.89	16.87	16.84	16.86	16.80	16.83

Note: "+" indicates a value less than 0.01 QBtu.
Parentheses indicate negative values.
Sources: Fuel use of HGL based on data from EIA (2022b). Non-fuel use of HGL from (EIA 2022b). Volumes converted using the energy contents provided in Table A-31. 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-33 below shows the composition of those samples.

Table A-33: 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

Sources: 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-33.

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 $\pm$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-34, below.

Table A-34: 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 $\pm$ 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 Cruel 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.[82] 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 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-35. 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-35.

Table A-35: 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

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

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,[83] 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 2021, 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-19 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.

[83] 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.

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 CO_2 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-36 below for comparison.

Table A-36: 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-37 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-29 above. Each of the C coefficients applied in previous Inventories are provided below for comparison (Table A-37).

Table A-37: 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	18.24	4.620	81.7	83.70
Natural Gasoline	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-31.

[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).

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 Momenthy 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-37).

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-38, 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-38: Physical Characteristics of Liquefied Petroleum Gases

		1990-2007	2010 Update	1990-2007	2010 Update	1990-2007	2010 Update
Compound	Chemical Formula	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_2H_6	16.88	11.55	2.916	3.082	16.25	17.16
Propane	C_3H_8	12.44	12.76	3.824	3.836	17.20	16.76
Isobutane	C_4H_{10}	11.20	11.42	4.162	3.974	17.75	17.77
n-butane	C_4H_{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).

2022 Updates

In 2022, 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 2022a; EIA 2022b). 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 (2020a) 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 2022b) 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

2022 Updates

The carbon content of diesel fuel is calculated according to ASTM D3343,[84] *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).[85]

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-29), in the list and proportion of constituents that form the blend and in the blended C share based on those constituents.

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

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

Table A-39: 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

[a] C contents vary annually based on changes in fuel composition.

2022 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-40. 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), pentanes plus, naphthas, other oils, still gas, special naphtha), (2) asphalt and road oil, (3) lubricants, and (4) waxes. The storage factors[86] 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-40: 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]	59%
Natural Gas to Chemical Plants[b]	59%
Asphalt & Road Oil	100%
HGL[b]	59%
Lubricants	9%
Natural Gasoline[b]	59%
Naphtha (<401 deg. F)[b]	59%
Other Oil (>401 deg. F)[b]	59%
Still Gas[b]	59%
Petroleum Coke[c]	30%
Special Naphtha[b]	59%
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 2021. 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.

[86] 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,[87] HGL, natural gasoline, 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 CH_4) to heavier, more complex naphthas and other oils.[88]

After adjustments for (1) use in industrial processes and (2) net exports, these eight fuel categories constituted approximately 276.1 MMT CO_2 Eq., or 73 percent, of the 377.6 MMT CO_2 Eq. of non-energy fuel consumption in 2021. For 2021, the storage factor for the eight fuel categories was 59 percent. In other words, of the net consumption, 59 percent was destined for long-term storage in products—including products subsequently combusted for waste disposal—while the remaining 41 percent was emitted to the atmosphere directly as CO_2 (e.g., through combustion of industrial by-products) or indirectly as CO_2 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 CO_2 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,[89] 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 2021.

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.
- *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

[87] 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.

[88] 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.

[89] 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.

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 available[90] and cover a complete time series from 1990 to 2021. 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-41. As shown in the table, the United States has been a net exporter of chemical intermediates and products throughout the 1990 to 2021 period.

Table A-41: Net Exports of Petrochemical Feedstocks, 1990–2021 (MMT CO_2 Eq.)

	1990	2005	2010	2017	2018	2019	2020	2021
Net Exports	12.0	6.5	7.3	13.9	16.9	20.4	21.5	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).

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-41) 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

[90] See the U.S. International Trade Commission (USITC) Trade Dataweb at http://dataweb.usitc.gov/.

feedstocks (i.e., industrial other coal, natural gas for non-fertilizer uses, HGL, pentanes plus, 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.[91]

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 CO_2 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-42. Summing the C stored and dividing it by total C outputs yields the overall storage factor, as shown in the following equation for 2021:

Equation A-6: NEU Storage Factor Estimate for 2021

Overall Storage Factor = C Stored / (C Stored + C Emitted + C Unaccounted for) =

163.1 MMT CO_2 Eq. / (163.1 + 62.8 + 50.1) MMT CO_2 Eq. = 59%

Table A-42: C Stored and Emitted by Products from Feedstocks in 2021 (MMT CO_2 Eq.)

Product/Waste Type	C Stored (MMT CO_2 Eq.)	C Emitted (MMT CO_2 Eq.)
Industrial Releases	**0.1**	**6.0**
TRI Releases	0.1	1.0
Industrial VOCs	NA	3.6
Non-combustion CO	NA	0.5
Hazardous Waste Incineration	NA	0.9
Energy Recovery	**NA**	**44.4**
Products	**163.0**	**12.4**
Plastics	141.8	NA
Synthetic Rubber	12.7	NA
Antifreeze and Deicers	NA	0.9
Abraded Tire Rubber	NA	0.2
Food Additives	NA	1.1
Silicones	0.5	NA
Synthetic Fiber	7.8	NA
Pesticides	0.2	0.3
Soaps, Shampoos, Detergents	NA	4.9
Solvent VOCs	NA	5.0
Total	**163.1**	**62.8**

NA (Not Applicable)
Note: Totals may not sum due to independent rounding.

[91] 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.

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."[92] The C released in each disposal location is provided in Table A-43.

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 CO_2 (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 2021 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.

Table A-43: 1998 TRI Releases by Disposal Location (kt CO_2 Eq.)

Disposal Location	Carbon Stored (kt CO_2 Eq.)	Carbon Emitted (kt CO_2 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.

[92] 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).

Volatile Organic Compound Emissions from Industrial Processes and Solvent Evaporation Emissions

Data on annual non-methane volatile organic compound (NMVOC) emissions were obtained (EPA 2022) 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 2021 Trends data include information on NMVOC emissions by end-use category; some of these fall into the heading of "industrial releases" in Table A-42 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-44 for 1990 through 2021. Industrial NMVOC emissions in 2021 were 3.6 MMT CO_2 Eq. and solvent evaporation emissions in 2021 were 5.0 MMT CO_2 Eq.

Table A-44: Industrial and Solvent NMVOC Emissions

	1990	1995	2000	2005	2017	2018	2019	2020	2021
Industrial NMVOCs[a]									
NMVOCs ('000 Short Tons)	1,279	1,358	802	825	1,206	1,350	1,287	1,287	1,287
Carbon Content (%)	85%	85%	85%	85%	85%	85%	85%	85%	85%
Carbon Emitted (MMT CO_2 Eq.)	3.6	3.8	2.3	2.3	3.4	3.8	3.6	3.6	3.6
Solvent Evaporation[b]									
Solvents ('000 Short Tons)	5,750	6,183	4,832	4,245	2,972	2,896	2,696	2,696	2,696
Carbon Content (%)	56%	56%	56%	56%	56%	56%	56%	56%	56%
Carbon Emitted (MMT CO_2 Eq.)	10.8	11.6	9.0	7.9	5.6	5.4	5.0	5.0	5.0

[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 NEI data (EPA 2022) 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 CO_2) 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-45 lists the CO emissions that remain after taking into account the exclusions listed above.

Table A-45: Non-Combustion Carbon Monoxide Emissions

	1990	1995	2000	2005	2017	2018	2019	2020	2021
CO Emissions ('000 Short Tons)	489	481	623	461	327	334	323	323	323
Carbon Emitted (MMT CO_2 Eq.)	0.7	0.7	0.9	0.7	0.5	0.5	0.5	0.5	0.5

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).[93] 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. 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). 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 (EPA 2000a, 2009, 2013a, 2015a, 2016a, 2018, 2021b). 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-46). 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 2021 were 0.9 MMT CO_2 Eq. Table A-47 lists the CO_2 emissions from hazardous waste incineration.

[93] [42 U.S.C. §6924, SDWA §3004]

Table A-46: 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-47: CO_2 Emitted from Hazardous Waste Incineration (MMT CO_2 Eq.)

	1990	1995	2000	2005	2017	2018	2019	2020	2021
CO_2 Emissions	1.1	1.7	1.4	1.5	0.9	0.9	0.9	0.9	0.9

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-48). The conversion factors listed in Annex 2.1 were used to convert the Btu values for each fuel feedstock to MMT CO_2. Petrochemical feedstocks combusted for energy recovery corresponded to 42.5 MMT CO_2 Eq. in 1991, 35.1 MMT CO_2 Eq. in 1994, 58.0 MMT CO_2 Eq. in 1998, 70.6 MMT CO_2 Eq. in 2002, 74.7 MMT CO_2 Eq. in 2006, 41.3 MMT CO_2 Eq. in 2010, 45.6 MMT CO_2 Eq. in 2014, and 44.4 MT CO_2 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 2021 are assumed to be the same as the value for 2018 (Table A-49).

Table A-48: 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	0	9	0	0	18
Primary Metals	331	3	0	0	10	3
Fabricated Metal Products	332	0	0	0	0	2
Machinery	333	0	0	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	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-49: Carbon Emitted from Fuels Burned for Energy Recovery (MMT CO_2 Eq.)

	1990	1995	2000	2005	2017	2018	2019	2020	2021
C Emissions	42.5	40.8	64.3	73.7	44.7	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 2021 were taken directly or derived from the American Chemistry Council (ACC 2007 through 2022a supplemented by Vallianos 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022). 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, and 2021 (Vallianos 2011; 2012; 2013; 2014; 2015; 2016; 2017; 2018; 2019; 2020; 2021;

2022). 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-50) 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 2022; Bank of Canada 2022). A C content was then assigned for each resin. These C contents were based on molecular formulae and are listed in Table A-51 and Table A-52. 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-50: 2021 Plastic Resin Production (MMT dry weight) and C Stored (MMT CO_2 Eq.)

Resin Type	2021 Production[a] (MMT dry weight)	Carbon Stored (MMT CO_2 Eq.)
Epoxy	0.2	0.7
Polyester	0.6	1.5
Urea	1.1	1.4
Melamine	0.1	0.1
Phenolic	1.6	4.4
Low-Density Polyethylene (LDPE)	3.5	11.1
Linear Low-Density Polyethylene (LLDPE)	9.0	28.3
High Density Polyethylene (HDPE)	9.2	28.8
Polypropylene (PP)	6.9	21.8
Acrylonitrile-butadiene-styrene (ABS)	0.5	1.6
Other Styrenics[b]	0.5	1.7
Polystyrene (PS)	1.6	5.5
Nylon	0.4	1.0
Polyvinyl chloride (PVC)[c]	6.4	9.0
Thermoplastic Polyester	3.0	6.9
All Other (including Polyester (unsaturated))	6.6	18.2
Total	**51.3**	**141.8**

[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-51: 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[a]
Melamine	29%	Trimethylol melamine[a]
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 A-52)
Polyvinyl Chloride (PVC)	38%	Polyvinyl chloride
Thermoplastic Polyester	63%	Polyethylene terephthalate
All Other	75%	Weighted average of other resin production

[a] Does not include alcoholic hydrogens.

Table A-52: 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 *2021 U.S. Scrap Tire Management Summary* (USTMA 2022), 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 2022). Import and export data were obtained from the published by the U.S. International Trade Commission (U.S. International Trade Commission 1990 through 2022).

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-53). 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-53: 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 2022b), 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, and 2021 consumption was equal to that of 2012. For polyester, nylon, and olefin, the most recent data were for 2020. These data are organized by year and fiber type. For each fiber, a C content was assigned based on molecular formula (see Table A-54). 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-54: 2021 Fiber Production (MMT), C Content (%), and C Stored (MMT CO_2 Eq.)

Fiber Type	Production (MMT)	C Content	C Stored (MMT CO_2 Eq.)
Polyester	1.3	63%	2.9
Nylon	0.5	64%	1.3
Olefin	1.1	86%	3.6
Acrylic	+	68%	0.1
Total	**3.0**	**NA**	**7.7**

+ 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 2021 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-55: Active Ingredient Consumption in Pesticides (Million lbs.) and C Emitted and Stored (MMT CO_2 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 CO_2 Eq.

[a] 2012 estimates (EPA 2017).

Note: Totals may not sum due to independent rounding.

Soaps, Shampoos, and Detergents

Cleansers—soaps, shampoos, and detergents—are 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 2021 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 is 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 liquid[94] 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 CO_2 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 2021, value of shipments was adjusted to 1997 dollars using the producer price index for soap and other detergent manufacturing (Bureau of Labor Statistics 2021). 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-56.

Table A-56: C Emitted from Utilization of Soaps, Shampoos, and Detergents (MMT CO_2 Eq.)

	1990	1995	2000	2005	2017	2018	2019	2020	2021
C Emissions	3.6	4.2	4.5	6.7	5.1	5.1	5.1	5.0	4.9

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 CO_2 or to otherwise biodegrade to CO_2. 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 2022b) 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.[95] 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, and 2021 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 CO_2. Emissions of CO_2 from utilization of antifreeze and deicers are summarized in Table A-57.

Table A-57: C Emitted from Utilization of Antifreeze and Deicers (MMT CO_2 Eq.)

	1990	1995	2000	2005	2017	2018	2019	2020	2021
C Emissions	1.2	1.4	1.5	1.2	1.0	1.1	1.0	0.9	0.9

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 CO_2 or to otherwise biodegrade to CO_2. Certain food additives, e.g., glycerin, are manufactured both from petrochemical feedstocks and from biogenic feedstocks. Food

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

[95] See http://www.icis.com/home/default.aspx.

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 2022b). Historical values for adipic acid, acetic acid, and maleic anhydride were adjusted according to the most recent data in the 2022 *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.[96] 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, and 2021 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 CO_2. Emissions of CO_2 from utilization of synthetic food additives are summarized in Table A-58.

Table A-58: C Emitted from Utilization of Food Additives (MMT CO_2 Eq.)

	1990	1995	2000	2005	2017	2018	2019	2020	2021
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 CO_2 in the manufacturing process. It is also assumed that the C contained in the silicone products is stored, and not emitted as CO_2.

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.[97] ICIS last reported production of methyl chloride in 2007. EPA 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, and 2021 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 CO_2. Storage of silicone manufacturing compounds is summarized in Table A-59.

Table A-59: C Stored in Silicone Products (MMT CO_2 Eq.)

	1990	1995	2000	2005	2017	2018	2019	2020	2021
C Storage	0.3	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5

[96] See http://www.icis.com/home/default.aspx.

[97] See http://www.icis.com/home/default.aspx.

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 2021. 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 48 percent and 72 percent. This compares to the calculated Inventory estimate of 59 percent. The analysis produced a C emission distribution with a standard deviation of 31.4 MMT CO_2 Eq. and 95 percent confidence limits of 59.3 and 178.6 MMT CO_2 Eq. This compares with a calculated Inventory estimate of 112.9 MMT CO_2 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, pentanes plus, 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 CO_2 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 CO_2 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, 2021a). 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.[98] 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 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 2021. 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 percent and 100 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 CO_2 Eq. and 0.7 MMT CO_2 Eq. This compares to an Inventory calculated estimate of 0.3 MMT CO_2 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

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

storage of C in a refractory form or physicochemical degradation and eventual release of CO_2 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 (2021b), the C content from U.S. production of lubricants in 2021 was approximately 4.7 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 2021 were about 4.3 MMT C, or 15.7 MMT CO_2 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.[99] 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-60 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 CO_2 (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 CO_2 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 CO_2, only about 3 percent of the C in oil lubricants goes into long-term storage.

[99] 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-60: 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)

[a] For example, in boilers or space heaters.

Greases

Table A-61 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 90 percent and 50 percent of the C in landfilled and dumped grease, respectively, would be stored. The overall storage factor is 82 percent for grease.

Table A-61: 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 2020. 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 4 percent and 17 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 1.3 and 95 percent confidence limits of 13.0 MMT CO_2 Eq. and 18.2 MMT CO_2 Eq. This compares to an inventory-calculated estimate of 15.7 MMT CO_2 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-62 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-62: 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.

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-63 categorizes wax end uses identified by the NPRA and lists the estimated C storage factor of each end use.

Table A-63: 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 CO_2. 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 CO_2 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 CO_2 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 CO_2; 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 2020. 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 percent and 68 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 0.3 MMT CO_2 Eq. and 0.7 MMT CO_2 Eq. This compares with a calculated Inventory estimate of 0.4 MMT CO_2 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 2020. 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 6 percent and 83 percent. This compares to the Inventory calculation of weighted average (across the various fuels) storage factor of about 11.1 percent. The analysis produced an emission distribution, with the 95 percent confidence limit of 2.5 MMT CO_2 Eq. and 16.2 MMT CO_2 Eq. This compares with the Inventory estimate of 13.9 MMT CO_2 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 CH_4, N_2O, and Indirect Greenhouse Gases from Stationary Combustion

Estimates of CH_4 and N_2O Emissions

Methane (CH_4) and nitrous oxide (N_2O) 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-64 through Table A-69.

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 CH_4 and N_2O 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 2022a). 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 2022b) and Jacobs (2010).[100] Fuel consumption for the industrial sector was adjusted to subtract out construction and agricultural use, which is reported under mobile sources.[101] Construction and agricultural fuel use was obtained from EPA (2022c) and the Federal Highway Administration (FHWA) (1996 through 2021). 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-64 provides annual energy consumption data for the years 1990 through 2021.

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 2022a). Total fuel consumption in the electric power sector from EIA (2022a) was apportioned to each combustion technology type and fuel combination using a ratio of fuel consumption by technology type derived from EPA (2022a) data. The combustion technology and fuel use data by facility obtained from EPA (2022a) were only available from 1996 to 2021, so the consumption estimates from 1990 to 1995 were estimated by applying the 1996 consumption ratio by combustion technology type from EPA (2022a) to the total EIA (2022a) consumption for each year from 1990 to 1995.

Step 2: Determine the Amount of CH_4 and N_2O 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 N_2O emission factors by fuel type (equivalent across sectors) were also assumed for U.S. Territories. The CH_4 emission factors by fuel type for U.S. Territories were

[100] U.S. Territories data also include combustion from mobile activities because data to allocate U.S. Territories' energy use were unavailable. For this reason, CH_4 and N_2O emissions from combustion by U.S. Territories are only included in the stationary combustion totals.

[101] 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.

estimated based on the emission factor for the primary sector in which each fuel was combusted. Table A-65 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-66. 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 2022b) 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 (2022b) 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-64: Fuel Consumption by Stationary Combustion for Calculating CH_4 and N_2O Emissions (TBtu)

Fuel/End-Use Sector	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Coal	**19,637**	**20,912**	**23,088**	**22,966**	**20,731**	**15,446**	**14,268**	**13,770**	**13,161**	**11,132**	**9,121**	**10,429**
Residential	31	17	11	8	0	0	0	0	0	0	0	0
Commercial	124	117	92	97	70	31	24	21	19	17	15	15
Industrial	1,668	1,557	1,362	1,246	993	734	662	614	569	517	449	457
Electric Power	17,807	19,216	21,618	21,582	19,633	14,645	13,547	13,110	12,546	10,559	8,625	9,927
U.S. Territories[a]	5	5	5	33	35	36	35	25	28	39	33	31
Petroleum	**6,063**	**5,591**	**6,408**	**6,676**	**5,030**	**4,615**	**4,267**	**4,041**	**4,148**	**4,119**	**3,664**	**3,129**
Residential	1,376	1,259	1,425	1,366	1,103	939	799	766	946	975	842	770
Commercial	1,023	724	767	761	698	938	834	809	735	801	764	601
Industrial	2,599	2,457	2,456	2,896	2,409	2,260	2,205	2,102	2,097	2,060	1,793	1,495
Electric Power	797	860	1,269	1,003	412	173	159	71	93	42	24	22
U.S. Territories[a]	268	290	491	649	408	306	270	292	278	241	241	241
Natural Gas	**17,229**	**19,315**	**20,900**	**20,921**	**22,897**	**26,545**	**26,566**	**26,111**	**28,952**	**29,967**	**29,263**	**29,277**
Residential	4,487	4,954	5,105	4,946	4,878	4,777	4,506	4,563	5,174	5,208	4,846	4,888
Commercial	2,680	3,096	3,252	3,073	3,165	3,316	3,224	3,273	3,638	3,647	3,286	3,419
Industrial	7,687	8,701	8,637	7,315	7,670	8,688	8,770	8,847	9,325	9,482	9,187	9,421
Electric Power	2,376	2,564	3,894	5,562	7,157	9,707	10,003	9,381	10,752	11,559	11,894	11,499
U.S. Territories[a]	0	0	13	24	28	57	64	48	62	71	50	50
Wood	**2,095**	**2,252**	**2,138**	**1,963**	**2,046**	**2,127**	**2,059**	**2,018**	**2,107**	**2,105**	**1,936**	**1,957**
Residential	580	520	420	430	541	513	445	430	525	546	441	464
Commercial	66	72	71	70	72	79	84	84	84	84	83	83
Industrial	1,442	1,652	1,636	1,452	1,409	1,476	1,474	1,442	1,432	1,407	1,356	1,342
Electric Power	7	8	11	11	25	59	57	62	66	68	56	68
U.S. Territories	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE

NE (Not Estimated)

NO (Not Occurring)

[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-65: CH_4 and N_2O Emission Factors by Fuel Type and Sector (g/GJ)[a]

Fuel/End-Use Sector	CH_4	N_2O
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)

[a] GJ (Gigajoule) = 10^9 joules. One joule = 9.486×10^{-4} Btu.

Table A-66: CH_4 and N_2O Emission Factors by Technology Type and Fuel Type for the Electric Power Sector (g/GJ)[a]

Technology	Configuration	CH_4	N_2O
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)

[a] Ibid.

Table A-67: NOx Emissions from Stationary Combustion (kt)

Sector/Fuel Type	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Electric Power	**6,045**	**5,792**	**4,829**	**3,434**	**2,226**	**1,419**	**1,234**	**1,049**	**1,025**	**886**	**717**	**710**
Coal	5,119	5,061	4,130	2,926	1,896	1,209	1,051	894	873	755	611	605
Fuel Oil	200	87	147	114	74	47	41	35	34	30	24	24
Natural gas	513	510	376	250	162	103	90	76	75	64	52	52
Wood	NA	NA	NA	NA	NA	12	10	9	9	7	6	6
Other Fuels[a]	NA	NA	36	29	19	NA	NA	NA	NA	NA	NA	NA
Internal Combustion	213	134	140	115	75	48	41	35	34	30	24	24
Industrial	**2,559**	**2,650**	**2,278**	**1,515**	**1,087**	**921**	**890**	**859**	**898**	**864**	**864**	**864**
Coal	530	541	484	342	245	208	201	194	203	195	195	195
Fuel Oil	240	224	166	101	73	62	60	57	60	58	58	58
Natural gas	877	999	710	469	336	285	275	266	278	268	268	268
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	119	111	109	76	55	46	45	43	45	44	44	44
Internal Combustion	792	774	809	527	378	320	309	298	312	300	300	300
Commercial	**671**	**607**	**507**	**490**	**456**	**444**	**440**	**537**	**512**	**402**	**402**	**402**
Coal	36	35	21	19	15	14	13	13	13	13	13	13
Fuel Oil	88	94	52	49	38	35	34	33	33	33	33	33
Natural gas	181	210	161	155	120	112	108	105	105	105	105	105
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	366	269	273	267	284	283	284	386	361	250	250	250
Residential	**749**	**813**	**439**	**418**	**324**	**301**	**292**	**283**	**283**	**284**	**284**	**284**
Coal[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Fuel Oil[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Natural Gas[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	42	44	21	20	16	15	14	14	14	14	14	14
Other Fuels[a]	707	769	417	398	308	286	278	269	269	270	270	270
Total	**10,023**	**9,862**	**8,053**	**5,858**	**4,092**	**3,084**	**2,856**	**2,728**	**2,718**	**2,436**	**2,266**	**2,259**

NA (Not Applicable)

[a] Other Fuels include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2022b).

[b] Residential coal, fuel oil, and natural gas emissions are included in the Other Fuels category (EPA 2022b).

Note: Totals may not sum due to independent rounding.

Table A-68: CO Emissions from Stationary Combustion (kt)

Sector/Fuel Type	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Electric Power	**329**	**337**	**439**	**582**	**693**	**618**	**575**	**532**	**505**	**424**	**424**	**424**
Coal	213	227	221	292	347	310	288	267	253	212	212	212
Fuel Oil	18	9	27	37	44	39	36	34	32	27	27	27
Natural gas	46	49	96	122	145	130	121	112	106	89	89	89
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	NA	NA	31	43	51	45	42	39	37	31	31	31
Internal Combustion	52	52	63	89	106	94	88	81	77	65	65	65
Industrial	**797**	**958**	**1,106**	**1,045**	**853**	**806**	**771**	**736**	**758**	**753**	**753**	**753**
Coal	95	88	118	115	94	89	85	81	83	83	83	83
Fuel Oil	67	64	48	42	34	32	31	29	30	30	30	30
Natural gas	205	313	355	336	274	259	248	237	244	242	242	242
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	253	270	300	295	241	228	218	208	214	213	213	213
Internal Combustion	177	222	285	257	209	198	189	181	186	185	185	185
Commercial	**205**	**211**	**151**	**166**	**140**	**124**	**128**	**133**	**133**	**133**	**133**	**133**
Coal	13	14	14	14	12	11	11	12	12	12	12	12
Fuel Oil	16	17	17	19	16	14	14	15	15	15	15	15
Natural gas	40	49	83	91	77	68	71	73	73	73	73	73
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	136	132	36	41	35	31	32	33	33	33	33	33
Residential	**3,668**	**3,877**	**2,644**	**2,856**	**2,416**	**2,140**	**2,215**	**2,291**	**2,286**	**2,286**	**2,286**	**2,286**
Coal[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Fuel Oil[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Natural Gas[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	3,430	3,629	2,416	2,615	2,212	1,959	2,028	2,097	2,093	2,093	2,093	2,093
Other Fuels[a]	238	248	228	241	204	181	187	193	193	193	193	193
Total	**5,000**	**5,383**	**4,340**	**4,648**	**4,103**	**3,688**	**3,690**	**3,691**	**3,682**	**3,596**	**3,596**	**3,596**

NA (Not Applicable)

[a] Other Fuels include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2022b).

[b] Residential coal, fuel oil, and natural gas emissions are included in the Other Fuels category (EPA 2022b).

Note: Totals may not sum due to independent rounding.

Table A-69: NMVOC Emissions from Stationary Combustion (kt)

Sector/Fuel Type	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Electric Power	**43**	**40**	**56**	**44**	**38**	**33**	**31**	**29**	**30**	**28**	**28**	**28**
Coal	24	26	27	21	18	16	15	14	14	13	13	13
Fuel Oil	5	2	4	3	3	3	2	2	2	2	2	2
Natural Gas	2	2	12	10	8	7	7	6	7	6	6	6
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	NA	NA	2	1	1	1	1	1	1	1	1	1
Internal Combustion	11	9	11	8	7	6	6	6	6	5	5	5
Industrial	**165**	**187**	**157**	**120**	**100**	**100**	**101**	**101**	**106**	**107**	**107**	**107**
Coal	7	5	9	8	7	7	7	7	7	7	7	7
Fuel Oil	11	11	9	6	5	5	5	5	6	6	6	6
Natural Gas	52	66	53	41	34	34	34	34	36	36	36	36
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	46	45	27	22	18	18	19	19	20	20	20	20
Internal Combustion	49	60	58	43	36	36	36	36	38	38	38	38
Commercial	**10**	**14**	**304**	**188**	**145**	**118**	**117**	**116**	**116**	**116**	**116**	**116**
Coal	1	1	1	1	+	+	+	+	+	+	+	+
Fuel Oil	3	3	4	2	2	1	1	1	1	1	1	1
Natural Gas	7	10	14	9	7	6	6	6	6	6	6	6
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	NA	NA	285	177	136	111	110	109	109	109	109	109
Residential	**686**	**725**	**837**	**518**	**399**	**324**	**322**	**319**	**319**	**319**	**319**	**319**
Coal[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Fuel Oil[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Natural Gas[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	651	688	809	502	386	314	311	308	309	309	309	309
Other Fuels[a]	35	37	27	17	13	11	10	10	10	10	10	10
Total	**904**	**966**	**1,353**	**871**	**681**	**575**	**570**	**565**	**571**	**571**	**571**	**571**

+ Does not exceed 0.5 kt.

NA (Not Applicable)

[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2022b).

[b] Residential coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 2022b).

Note: Totals may not sum due to independent rounding.

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3.2. Methodology for Estimating Emissions of CH_4, N_2O, and Indirect Greenhouse Gases from Mobile Combustion and Methodology for and Supplemental Information on Transportation-Related Greenhouse Gas Emissions

Estimating CO_2 Emissions by Transportation Mode

Transportation-related CO_2 emissions, as presented in the CO_2 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, CO_2 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), CO_2 emissions were calculated based on transportation sector-wide fuel consumption estimates from the Energy Information Administration (EIA 2022a and EIA 2021d) 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 2022)[102], while CO_2 emissions from other aircraft jet fuel consumption is determined using a top-down approach.

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 2020). Data for 2021 is proxied using FHWA Traffic Volume Travel Trends. 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 the *Fuel Oil and Kerosene Sales* (FOKS) report 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 MOVES3 model (EPA 2021a), 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. With respect to estimating CO_2 emissions from the transportation sector, EPA's MOVES model is used only to estimate fuel use by recreational boats. 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.

Estimates of diesel fuel consumption from rail were taken from: the Association of American Railroads (AAR 2008 through 2021) for Class I railroads, the American Public Transportation Association (APTA 2007 through 2021 and APTA 2006) and Gaffney (2007) for commuter rail, the Upper Great Plains Transportation Institute (Benson 2002 through 2004), Whorton (2006 through 2014), and Railinc (2014 through 2021) 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

[102] Commercial jet fuel for 2021 was not yet available, so this was proxied. The data will be obtained for the Final Inventory.

carloads. Estimates of diesel fuel consumption from ships and boats were taken from EIA's *Fuel Oil and Kerosene Sales* (1991 through 2021).

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 (2022) for domestic and international commercial aircraft,[103] and DLA Energy (2021) for domestic and international military aircraft. 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 CO_2 estimates are obtained directly from the Federal Aviation Administration (FAA 2022), while CO_2 emissions from domestic military and general aviation jet fuel consumption is determined using a top-down approach. Domestic commercial jet fuel CO_2 from FAA is subtracted from total domestic jet fuel CO_2 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 CO_2 from Fossil Combustion, and in Section 3.11 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 2022a).

Table A-70 displays estimated fuel consumption by fuel and vehicle type. Table A-71 displays estimated energy consumption by fuel and vehicle type. The values in both tables correspond to the figures used to calculate CO_2 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 UNFCCC reporting obligations, 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 2021. Biodiesel fuel volumes were removed from diesel fuel consumption volumes for years 2001 through 2021, 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 2021 biodiesel and renewable diesel fuel consumption estimates from EIA (2022a) 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 2022a) were subtracted from the total EIA and FHWA transportation motor gasoline energy consumption estimates. Total ethanol and biodiesel consumption estimates are in Table A-72.[104]

[103] Commercial jet fuel consumption data for 2021 are not yet available and was proxied. The data will be obtained for the Final Inventory published in April 2023.

[104] 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-72. 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-70 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-70: Fuel Consumption by Fuel and Vehicle Type (million gallons unless otherwise specified)

Fuel/Vehicle Type	1990	2000	2010[a]	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Motor Gasoline[b,c]	**107,651**	**125,232**	**119,829**	**117,229**	**116,810**	**116,960**	**121,472**	**120,631**	**123,482**	**123,079**	**124,886**	**123,709**	**106,666**	**118,419**
Passenger Cars	68,795	61,845	51,702	48,158	42,316	43,314	44,773	43,722	44,018	42,691	43,547	43,268	37,342	41,507
Light-Duty Trucks	31,836	57,173	63,422	64,640	69,955	69,067	71,913	72,131	74,458	75,259	76,001	74,987	64,398	71,376
Motorcycles	376	491	708	697	789	764	784	759	803	800	832	840	747	852
Buses	237	157	139	150	175	197	231	241	257	281	302	316	285	328
Medium- and Heavy-Duty Trucks	4,804	3,961	2,544	2,314	2,331	2,397	2,576	2,582	2,741	2,837	2,986	3,078	2,749	3,154
Recreational Boats[d]	1,604	1,606	1,315	1,270	1,243	1,220	1,196	1,197	1,205	1,211	1,218	1,220	1,145	1,202
Distillate Fuel Oil (Diesel Fuel)[b,c]	**25,631**	**39,241**	**41,311**	**41,588**	**41,470**	**41,785**	**43,203**	**44,377**	**44,012**	**45,337**	**46,347**	**46,096**	**43,499**	**48,122**
Passenger Cars	921	301	199	230	235	243	266	321	301	288	273	263	245	272
Light-Duty Trucks	822	1,900	2,753	2,990	3,249	3,012	2,992	3,054	3,007	3,022	3,037	3,039	2,936	3,349
Buses	1,079	1,673	1,408	1,486	1,570	1,589	1,732	1,807	1,806	1,915	1,982	2,013	1,924	2,154
Medium- and Heavy-Duty Trucks	18,423	29,619	32,096	31,643	31,503	31,989	33,208	33,802	34,063	35,233	36,126	36,277	34,379	38,188
Recreational Boats	267	270	263	254	252	246	245	256	262	269	276	279	260	274
Ships and Non-Recreational Boats	658	1,372	809	1,075	830	841	719	1,278	1,060	975	908	725	738	759
Rail[e]	3,461	4,106	3,783	3,910	3,831	3,866	4,041	3,858	3,514	3,635	3,746	3,501	3,016	3,126
Jet Fuel[f]	**19,168**	**19,992**	**15,529**	**15,030**	**14,698**	**15,082**	**15,210**	**16,155**	**17,021**	**17,609**	**17,667**	**18,230**	**12,372**	**16,812**
Commercial Aircraft	11,569	14,672	11,931	12,067	11,932	12,031	12,131	12,534	12,674	13,475	13,650	14,132	9,358	9,358
General Aviation Aircraft	3,940	3,107	2,287	1,865	1,629	2,005	1,751	2,327	3,152	2,952	2,880	2,956	1,914	6,291
Military Aircraft	3,660	2,213	1,311	1,097	1,137	1,046	1,327	1,294	1,194	1,181	1,138	1,141	1,100	1,163
Aviation Gasoline[f]	**374**	**302**	**225**	**225**	**209**	**186**	**181**	**176**	**170**	**174**	**186**	**195**	**168**	**179**
General Aviation Aircraft	374	302	225	225	209	186	181	176	170	174	186	195	168	179
Residual Fuel Oil[f, g]	**2,006**	**2,963**	**1,818**	**1,723**	**1,410**	**1,345**	**517**	**378**	**1,152**	**1,465**	**1,246**	**1,289**	**651**	**2,099**
Ships and Non-Recreational Boats	2,006	2,963	1,818	1,723	1,410	1,345	517	378	1,152	1,465	1,246	1,289	651	2,099
Natural Gas[f] (trillion cubic feet)	**0.7**	**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**
Passenger Cars	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Buses	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Pipelines	0.7	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
LPG[f]	**251**	**130**	**49**	**49**	**48**	**57**	**65**	**84**	**97**	**100**	**98**	**95**	**50**	**50**
Passenger Cars	1	0.6	0	0	0	0	+	0	0	0	0	0	+	+
Light-Duty Trucks	37	18	8	7	3	4	9	8	7	9	10	11	8	9
Medium- and Heavy-Duty Trucks	184	93	30	38	41	46	48	64	69	72	72	71	38	39
Buses	28	19	11	4	4	7	8	12	21	19	16	13	5	2
Electricity[h,i]	**4,751**	**4,771**	**6,839**	**7,317**	**7,716**	**7,811**	**8,930**	**8,756**	**9,333**	**9,821**	**10,886**	**11,556**	**12,077**	**14,279**
Passenger Cars	+	+	23	86	202	441	737	1,076	1,426	1,845	2,721	3,537	3,505	4,541
Light-Duty Trucks	+	+	3	2	4	9	15	21	125	245	405	579	802	1,789

Buses	+	+	4	5	4	4	5	5	15	18	88	120	144	191
Rail	4,751	4,771	6,810	7,224	7,506	7,358	8,173	7,653	7,768	7,712	7,672	7,320	7,625	7,758

+ 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 MOVES3 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 MOVES3 to apportion FHWA fuel consumption data to vehicle type and fuel type. . Data from Table VM-1 is used to estimate the share of consumption between each on-road vehicle class. These fuel consumption estimates are combined with estimates of fuel shares by vehicle type from DOE's TEDB Annex Tables A.1 through A.6 (DOE 1993 through 2021).

[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 2014-2021 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 (2021a). 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).

Table A-71: Energy Consumption by Fuel and Vehicle Type (TBtu)

Fuel/Vehicle Type	1990	2000	2010[a]	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Motor Gasoline[a,b]	**13,464**	**15,663**	**14,899**	**14,576**	**14,523**	**14,542**	**15,103**	**14,999**	**15,353**	**15,303**	**15,528**	**15,381**	**13,262**	**14,723**
Passenger Cars	8,604	7,735	6,428	5,988	5,261	5,385	5,567	5,436	5,473	5,308	5,414	5,380	4,643	5,161
Light-Duty Trucks	3,982	7,151	7,885	8,037	8,698	8,587	8,941	8,968	9,258	9,357	9,450	9,323	8,007	8,874
Motorcycles	47	61	88	87	98	95	97	94	100	99	103	104	93	106
Buses	30	20	17	19	22	25	29	30	32	35	38	39	35	41
Medium- and Heavy-Duty Trucks	601	495	316	288	290	298	320	321	341	353	371	383	342	392
Recreational Boats[c]	201	201	163	158	155	152	149	149	150	151	151	152	142	149
Distillate Fuel Oil (Diesel Fuel)[a,b]	**3,555**	**5,442**	**5,729**	**5,768**	**5,751**	**5,795**	**5,992**	**6,155**	**6,104**	**6,288**	**6,428**	**6,393**	**6,033**	**6,674**
Passenger Cars	128	42	28	32	33	34	37	44	42	40	38	36	34	38
Light-Duty Trucks	114	263	382	415	451	418	415	424	417	419	421	421	407	464
Buses	150	232	195	206	218	220	240	251	250	266	275	279	267	299
Medium- and Heavy-Duty Trucks	2,555	4,108	4,451	4,389	4,369	4,437	4,606	4,688	4,724	4,886	5,010	5,031	4,768	5,296
Recreational Boats	37	37	36	35	35	34	34	36	36	37	38	39	36	38

Ships and Non-Recreational Boats	91	190	112	149	115	117	100	177	147	135	126	101	102	105
Rail[d]	480	569	525	542	531	536	560	535	487	504	520	486	418	434
Jet Fuel[e]	**2,588**	**2,699**	**2,096**	**2,029**	**1,984**	**2,036**	**2,053**	**2,181**	**2,298**	**2,377**	**2,385**	**2,461**	**1,670**	**2,270**
Commercial Aircraft	1,562	1,981	1,611	1,629	1,611	1,624	1,638	1,692	1,711	1,819	1,843	1,908	1,263	1,263
General Aviation Aircraft	532	419	309	252	220	271	236	314	426	399	389	399	258	849
Military Aircraft	494	299	177	148	154	141	179	175	161	159	154	154	149	157
Aviation Gasoline	**45**	**36**	**27**	**27**	**25**	**22**	**22**	**21**	**20**	**21**	**22**	**23**	**20**	**22**
General Aviation Aircraft	45	36	27	27	25	22	22	21	20	21	22	23	20	22
Residual Fuel Oil[e,f,]	**300**	**443**	**272**	**258**	**211**	**201**	**77**	**57**	**172**	**219**	**186**	**193**	**97**	**314**
Ships and Non-Recreational Boats	300	443	272	258	211	201	77	57	172	219	186	193	97	314
Natural Gas[e]	**679**	**672**	**719**	**734**	**780**	**887**	**760**	**745**	**757**	**799**	**962**	**1,114**	**1,109**	**1,230**
Passenger Cars	+	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	+	+
Light-Duty Trucks	+	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Medium- and Heavy-Duty Trucks	+	1.0	1.0	1.0	1.1	1.3	1.5	1.5	1.8	1.8	1.9	1.9	1.9	2.2
Buses	0	4	6	6	7	7	8	8	9	10	10	11	11	14
Pipelines	679	666	712	726	772	879	750	735	746	787	950	1,101	1,095	1,214
LPG[e]	**23**	**12**	**4**	**5**	**4**	**5**	**6**	**8**	**9**	**9**	**9**	**9**	**5**	**5**
Passenger Cars	0.1	0.1	+	+	+	+	+	+	+	+	+	+	+	+
Light-Duty Trucks	3	2	1	1	0	0	1	1	1	1	1	1	1	1
Medium- and Heavy-Duty Trucks	17	8	3	3	4	4	4	6	6	7	7	6	3	4
Buses	3	1.7	1	0	0	1	1	1	2	2	1	1	0	0
Electricity[g]	**16**	**18**	**26**	**26**	**26**	**28**	**29**	**30**	**31**	**33**	**37**	**40**	**38**	**44**
Passenger Cars	+	+	0.1	0.3	0.7	1.5	2.5	3.7	4.9	6.3	9.3	12.1	12.0	15.5
Light-Duty Trucks	+	+	+	+	+	+	0.1	0.1	0.4	0.8	1.4	2.0	2.7	6.1
Buses	+	+	+	+	+	+	+	+	0.1	0.1	0.3	0.4	0.5	0.7
Rail	16	18	26	26	25	26	26	26	26	26	26	26	22	22
Total	**20,670**	**24,986**	**23,774**	**23,422**	**23,305**	**23,517**	**24,042**	**24,194**	**24,745**	**25,049**	**25,558**	**25,615**	**22,234**	**25,282**

1 + Does not exceed 0.5 TBtu

2 [a] 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,
3 Land-Use Change, and Forestry chapter.

4 [b] 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 MOVES3 to
5 apportion FHWA fuel consumption data to vehicle type and fuel type.

6 [c] Fluctuations in recreational boat gasoline estimates reflect the use of this category to reconcile bottom-up values with EIA total gasoline estimates.

7 [d] Class II and Class III diesel consumption data for 2014 through 2021 is estimated by applying the historical average fuel usage per carload factor to the annual number of carloads.

[e] Estimated based on EIA transportation sector energy estimates, with bottom-up data used for apportionment to modes. Transportation sector natural gas and LPG consumption are based on data from EIA (2022a). 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. These changes were first incorporated in the 2016 Inventory and apply to the 1990–2021 time period.

[f] Fluctuations in reported fuel consumption may reflect data collection problems. Residual fuel oil for ships and boats data is based on EIA (2022a).

[g] 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). In Inventory years prior to 2017, CO_2 emissions from electric vehicle charging were allocated to the residential and commercial sectors. They are now allocated to the transportation sector. These changes were first incorporated in the 2017 Inventory and apply to the 2010 through 2021 time period.

Table A-72: Transportation Sector Biofuel Consumption by Fuel Type (million gallons)

Fuel Type	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Ethanol	699	1,556	11,833	11,972	11,997	12,154	12,758	12,793	13,261	13,401	13,573	13,589	11,744	13,164
Biodiesel	NA	NA	260	886	899	1,429	1,417	1,494	2,085	1,985	1,904	1,813	1,873	1,709

NA (Not Applicable)

Estimates of CH_4 and N_2O Emissions

Mobile source emissions of greenhouse gases other than CO_2 are reported by transport mode (e.g., road, rail, aviation, and waterborne), vehicle type, and fuel type. Emissions estimates of CH_4 and N_2O 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 2022). 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 2022) was allocated to fuel types (gasoline, diesel, other) using EPA's MOVES3 model ratios of VMT per vehicle class to total VMT. This corrects historical inconsistencies in vehicle type definitions in FHWA data[105] (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.[106] The resulting national VMT estimates for gasoline and diesel on-road vehicles are presented in Table A-73 and Table A-74, 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 2021 in Table A-75.

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 MOVES3 model for years 1999 forward (EPA 2021a).[107] Age-specific vehicle mileage accumulations were also obtained from EPA's MOVES3 model (EPA 2021a).[108]

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 in Table A-81 through Table A-84. 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 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).[109] EPA Tier 2 regulations affect vehicles produced starting in 2004 and are responsible for a noticeable decrease in N_2O emissions compared to EPA Tier 1 emissions technology (EPA 1999b). EPA Tier 3 regulations affect vehicles

[105] VMT is now allocated to vehicle classes using MOVES3 ratios of VMT in each vehicle class to total VMT

[106] 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.

[107] 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.

[108] The updated vehicle distribution and mileage accumulation rates by vintage obtained from the MOVES3 model resulted in a decrease in emissions due to more miles driven by newer light-duty gasoline vehicles.

[109] For further description, see "Definitions of Emission Control Technologies and Standards" section of this annex below.

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 2021 were determined using confidential engine family sales data submitted to EPA (EPA 2022c). Vehicle classes and emission standard tiers to which each engine family was certified were taken from annual certification test results and data (EPA 2021d). 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 CH_4 and N_2O Emission Factors by Vehicle, Fuel, and Control Technology Type

Methane and N_2O emission factors (in grams of CH_4 and N_2O 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 CH_4 and N_2O Emitted by Vehicle, Fuel, and Control Technology Type

Emissions of CH_4 and N_2O 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 CH_4 and N_2O Emissions from Highway Vehicle Alternative Fuel Vehicles" (Browning 2017) and modified with "Updated Methodology for Estimating CH_4 and N_2O 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 run on either the alternative fuel or gasoline (or diesel), or some combination.[110] 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. 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 2021. 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

[110] 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.

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. For 2018-2021, 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 "More electric buses join transit fleets as costs and technology improve" (SmartCitiesDive 2022). A regression analysis of vehicle counts was used for other fuels for the 2018-2021 period. VMT for those vehicles were assumed to be the same as the baseline conventional fueled vehicle of the same class.

For the current Inventory, 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, 2020, and 2021, EV and PHEV sales were taken from Wards Intelligence U.S. Light Vehicle Sales Report (Wards Intelligence, 2021). EVs were divided into cars and trucks using vehicle type information from fueleconomy.gov publications (EPA 2010-2021). 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 MOVES3. 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 GREET2021 model (ANL 2021). 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). Note that there was an impact of COVID-19 pandemic related declines in travel in 2020. Gasoline VMT was down 11.1 percent and diesel VMT was down 9.8 percent from 2019. For 2021, AFV VMT was adjusted based on the EIA trend in gasoline and diesel consumption for transportation between 2020 and 2021. The EIA data show that gasoline use increased by 9.6 percent between 2020 and 2021 while diesel use increased by 5.1 percent. VMT estimates for AFVs by vehicle category (passenger car, light-duty truck, medium-duty and heavy-duty vehicles) are shown in Table A-75, while more detailed estimates of VMT by control technology are shown in Table A-76.

Step 2: Determine CH_4 and N_2O Emission Factors by Vehicle and Alternative Fuel Type

Methane and N_2O emission factors for alternative fuel vehicles (AFVs) were calculated using Argonne National Laboratory's GREET model (ANL 2022) and are reported in Browning (2018). These emission factors are shown in Table A-86 and Table A-87.

Step 3: Determine the Amount of CH_4 and N_2O Emitted by Vehicle and Fuel Type

Emissions of CH_4 and N_2O 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 N_2O 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-80. Consumption data for ships and boats (i.e., vessel bunkering) were obtained from DHS (2008) and EIA (1991 through 2021) for distillate fuel, and DHS (2008) and EIA (2022a) 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.[111] 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 MOVES3 model (EPA 2021a). Annual diesel consumption for Class I rail

[111] See International Bunker Fuels section of the Energy chapter.

was obtained from the Association of American Railroads (AAR 2008 through 2021), diesel consumption from commuter rail was obtained from APTA (2007 through 2021) and Gaffney (2007), and consumption by Class II and III rail was provided by Benson (2002 through 2004) and Whorton (2006 through 2014).[112] 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 2021) and fuel consumption data provided by Whorton, D. (2006 through 2014). Class II and Class III diesel consumption for 2014-2021 is estimated by multiplying this average historical fuel usage per carload factor by the number of shortline carloads originated each year (RailInc 2014 through 2021). Diesel consumption by commuter and intercity rail was obtained from DOE (1993 through 2021). Data for 2020 and 2021 was estimated by applying a scaling factor to 2019 and 2020 fuel consumption, to account for the COVID-19 pandemic and associated restrictions. The scaling factors were derived from trends in the "fuel, power, and utilities" expenses from 2019 through 2021 for National Railroad Passenger Corporation and Subsidiaries (Amtrak 2022). Data on the consumption of jet fuel and aviation gasoline in aircraft were obtained from EIA (2022a) and FAA (2022), as described in Annex 2.1: Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion and were reduced by the amount allocated to international bunker fuels (DLA 2021 and FAA 2022). Pipeline fuel consumption was obtained from EIA (2007 through 2022) (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 MOVES3 model (EPA 2022a) for gasoline and diesel powered equipment, and from FHWA (1996 through 2022) for gasoline consumption by off-road trucks used in the agriculture, industrial, commercial, and construction sectors.[113] 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 CH_4 and N_2O 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 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 MOVES3 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 2021a). In a similar fashion, trends in all these variables between 2020 and 2021 were used to estimate 2021 values.

Emissions of CH_4 and N_2O from non-road mobile sources were calculated using the updated 2006 IPCC Tier 3 guidance and estimates of activity from EPA's MOVES3 model. CH_4 and N_2O emission factors were calculated from engine certification data by engine and fuel type and weighted by activity estimates calculated by MOVES3 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 2022). 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

[112] Diesel consumption from Class II and Class III railroad were unavailable for 2014-2021. Diesel consumption data for 2014-2021 is estimated by applying the historical average fuel usage per carload factor to the annual number of carloads.

[113] "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.

for each individual category. Table A-90 through Table A-92 provides complete emission estimates for 1990 through 2021.

Table A-73: 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	1,455.0	427.7	44.3	11.4
1991	1,441.0	464.8	43.9	11.5
1992	1,456.9	513.5	44.5	11.8
1993	1,454.2	558.2	44.5	12.0
1994	1,457.3	607.3	44.7	12.3
1995	1,461.0	659.4	44.9	12.5
1996	1,461.5	712.7	45.1	12.8
1997	1,467.4	771.7	45.4	13.1
1998	1,467.7	831.0	45.5	13.4
1999	1,460.2	888.9	45.4	13.6
2000	1,467.2	939.7	42.2	12.2
2001	1,470.3	978.0	41.1	11.1
2002	1,481.3	1,021.7	40.7	11.2
2003	1,473.4	1,053.2	40.7	11.4
2004	1,478.1	1,118.6	38.4	15.0
2005	1,464.9	1,156.1	35.8	13.8
2006	1,436.5	1,185.5	38.2	19.2
2007	1,430.3	1,203.3	35.4	21.4
2008	1,403.8	1,171.4	36.3	20.8
2009	1,397.6	1,181.1	34.0	20.8
2010	1,391.1	1,202.7	30.8	18.5
2011	1,320.1	1,272.9	28.2	18.6
2012	1,191.3	1,408.8	28.2	21.4
2013	1,213.9	1,402.1	28.1	20.4
2014	1,213.4	1,435.0	28.2	20.0
2015	1,219.1	1,494.9	27.8	19.6
2016	1,225.3	1,556.4	28.4	20.5
2017	1,200.1	1,606.5	28.9	20.2
2018	1,210.9	1,613.5	29.0	20.4
2019	1,216.7	1,616.4	29.3	20.5
2020	1,082.9	1,432.5	26.1	18.2
2021	1,202.1	1,585.5	29.1	20.2

[a] Heavy-Duty Vehicles includes Medium-Duty Trucks, Heavy-Duty Trucks, and Buses.

[b] VMT is now allocated to vehicle classes using MOVES3 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 2021 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 2022). VMT estimates were then allocated using EPA's MOVES3 model ratios of VMT per vehicle class to total VMT.

Source: Derived from FHWA (1996 through 2022), DOE (1990 through 2022), Browning (2022a), Browning (2018a), and Browning (2017).

Table A-74: Vehicle Miles Traveled for Diesel On-Road Vehicles (billion miles)

Year	Passenger Cars[b]	Light-Duty Trucks[b]	Heavy-Duty Vehicles[a,b]	Heavy-Duty Buses[b]
1990	40.8	19.8	136.4	8.3
1991	38.1	21.2	142.3	8.7
1992	36.0	23.2	151.4	9.2
1993	33.3	25.0	158.9	9.7
1994	30.6	26.9	167.6	10.2
1995	27.7	29.0	176.7	10.7
1996	24.7	31.1	186.0	11.3
1997	21.6	33.5	196.4	11.9
1998	18.1	35.8	206.7	12.5
1999	14.5	38.1	216.4	13.1
2000	12.5	39.4	219.7	13.0
2001	11.3	41.5	231.5	11.4
2002	9.8	43.1	234.8	11.7
2003	8.7	44.7	245.4	11.6
2004	7.9	48.1	245.6	11.8
2005	7.5	49.6	248.5	11.5
2006	7.1	51.7	260.9	12.3
2007	6.3	51.4	266.8	12.7
2008	5.8	49.5	272.5	12.9
2009	6.1	48.7	252.4	12.5
2010	6.8	47.9	254.5	11.9
2011	7.3	49.2	234.4	11.9
2012	7.8	54.6	236.0	12.7
2013	8.2	50.6	238.6	12.9
2014	8.7	50.0	242.7	13.6
2015	10.6	50.8	243.4	13.8
2016	9.7	51.9	247.0	13.9
2017	9.2	53.8	256.7	14.6
2018	8.7	55.6	262.3	14.9
2019	8.5	58.5	268.5	15.2
2020	7.5	55.1	240.5	13.0
2021	8.5	65.0	269.5	14.6

[a] Heavy-Duty Vehicles includes Medium-Duty Trucks and Heavy-Duty Trucks.

[b] VMT is now allocated to vehicle classes using MOVES3 ratios.

Notes: Gasoline and diesel highway vehicle mileage are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2021). VMT estimates were then allocated using EPA's MOVES3 model ratios of VMT per vehicle class to total VMT. Data for 2021 is proxied using FHWA Traffic Volume Trends Data.

Sources: Derived from FHWA (1996 through 2022), DOE (1993 through 2022), and Browning (2017), Browning (2018a), Browning (2022a).

Table A-75: Vehicle Miles Traveled for Alternative Fuel On-Road Vehicles (billion miles)

Year	Passenger Cars	Light-Duty Trucks	Heavy-Duty Vehicles[a]
1990	0.0	0.1	0.5
1991	0.0	0.1	0.5
1992	0.0	0.1	0.5
1993	0.0	0.1	0.6
1994	0.0	0.1	0.6
1995	0.0	0.1	0.6
1996	0.0	0.1	0.6
1997	0.0	0.1	0.6
1998	0.0	0.1	0.7
1999	0.0	0.1	0.7
2000	0.1	0.1	0.7
2001	0.1	0.2	0.7
2002	0.2	0.2	0.9
2003	0.1	0.3	0.9
2004	0.2	0.2	0.9
2005	0.2	0.3	1.2
2006	0.2	0.5	2.3
2007	0.2	0.6	2.8
2008	0.2	0.5	2.7
2009	0.2	0.6	2.8
2010	0.2	0.5	2.2
2011	0.6	1.3	6.0
2012	0.9	1.5	6.1
2013	1.8	2.1	9.4
2014	2.7	2.0	9.2
2015	3.8	2.1	9.5
2016	5.0	3.2	13.2
2017	6.2	3.5	12.7
2018	9.1	3.9	12.2
2019	12.0	4.3	11.8
2020	12.0	5.0	10.8
2021	15.5	8.1	10.8

[a] Heavy Duty-Trucks includes medium-duty trucks and heavy-duty trucks.

Sources: Derived from Browning (2017), Browning (2018a), Browning (2022b), and EIA (2022).

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 2021 time period.

Table A-76: Detailed Vehicle Miles Traveled for Alternative Fuel On-Road Vehicles (10^6 Miles)

Vehicle Type/Year	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Light-Duty Cars	**3.7**	**86.7**	**237.4**	**552.1**	**937.7**	**1,825.3**	**2,722.6**	**3,811.3**	**4,991.4**	**6,234.3**	**9,086.7**	**12,049.6**	**12,013.8**	**15,512.6**
Methanol-Flex Fuel ICE	-	+	+	+	+	+	+	+	+	+	+	+	+	+
Ethanol-Flex Fuel ICE	-	18.2	109.1	107.3	137.5	157.9	117.9	106.4	117.4	81.0	79.2	76.0	72.4	67.9
CNG ICE	+	4.8	9.6	10.2	10.6	11.1	10.1	10.4	11.8	10.9	9.3	8.0	6.6	5.4
CNG Bi-fuel	+	15.7	7.1	6.4	4.1	3.1	2.2	1.6	1.3	1.4	1.3	1.3	1.3	1.2
LPG ICE	1.1	1.0	+	+	+	+	0.1	0.1	0.2	0.2	0.3	0.1	0.1	+
LPG Bi-fuel	2.6	2.6	1.1	0.3	0.2	0.2	0.1	0.1	0.1	+	+	+	+	+
Biodiesel (BD100)	-	1.6	45.5	168.1	181.4	297.7	302.6	379.3	481.4	423.0	372.1	345.8	313.9	309.6
NEVs	-	41.5	61.7	102.9	98.9	103.8	113.2	124.3	83.8	89.9	86.5	83.5	76.9	68.7
Electric Vehicle	-	1.2	1.3	108.1	265.7	772.5	1,441.6	2,238.3	2,984.5	3,878.5	6,208.5	8,846.0	9,056.3	12,134.2
SI PHEV - Electricity	-	-	2.0	48.5	238.9	478.4	734.2	949.8	1,304.0	1,722.0	2,290.2	2,633.1	2,434.9	2,847.6
Fuel Cell Hydrogen	-	-	+	0.3	0.5	0.6	0.8	0.8	7.0	27.4	39.3	55.8	51.5	77.9
Light-Duty Trucks	**71.3**	**148.9**	**495.5**	**1,308.5**	**1,474.3**	**2,091.7**	**2,008.2**	**2,106.7**	**3,194.3**	**3,524.6**	**3,896.2**	**4,339.7**	**4,985.1**	**8,060.0**
Ethanol-Flex Fuel ICE	-	18.9	114.0	129.9	173.6	203.0	190.8	206.7	258.7	384.3	411.4	438.2	462.1	480.7
CNG ICE	+	4.5	7.5	8.1	8.3	7.8	6.5	4.3	3.6	5.0	4.4	3.7	3.1	2.7
CNG Bi-fuel	+	38.2	17.8	17.5	14.2	15.3	17.6	19.3	24.4	22.3	26.8	25.1	23.2	21.1
LPG ICE	20.6	22.3	8.7	9.0	4.4	5.1	5.5	5.2	5.1	5.2	5.1	5.2	5.1	4.9
LPG Bi-fuel	50.7	54.8	22.3	12.0	4.8	5.7	20.4	8.5	6.3	7.6	8.5	9.6	10.6	11.3
LNG	+	0.1	+	+	+	+	+	+	+	0.1	0.1	0.1	0.1	0.1
Biodiesel (BD100)	-	6.0	321.7	1,128.6	1,263.6	1,837.7	1,736.4	1,820.9	2,581.6	2,464.2	2,377.0	2,368.0	2,282.7	2,359.8
Electric Vehicle	-	4.1	3.5	3.2	5.2	16.9	30.5	33.3	268.6	527.4	845.4	1,171.5	1,791.2	4,083.3
SI PHEV - Electricity	-	-	+	+	+	+	0.4	8.1	45.4	103.5	212.0	311.3	399.6	1,070.0
Fuel Cell Hydrogen	-	-	+	0.2	0.2	0.2	0.2	0.4	0.6	5.0	5.6	7.0	7.3	26.1
Medium-Duty Trucks	**220.9**	**257.1**	**613.9**	**1,751.2**	**1,816.0**	**2,809.1**	**2,800.6**	**2,895.6**	**4,072.3**	**3,869.1**	**3,695.4**	**3,579.8**	**3,287.7**	**3,265.2**
CNG ICE	+	3.3	8.1	9.0	9.8	11.2	12.8	12.7	15.2	15.4	16.2	17.1	15.4	17.7
CNG Bi-fuel	+	38.1	28.4	26.5	28.4	30.2	39.3	42.3	40.7	41.6	44.4	47.2	43.1	49.7
LPG ICE	178.9	167.8	37.2	34.2	29.9	27.8	29.4	21.5	18.6	16.4	14.8	13.3	9.9	9.0
LPG Bi-fuel	42.0	39.4	18.0	15.5	25.2	26.7	29.6	23.3	28.7	26.4	25.1	23.6	18.8	18.6
LNG	-	-	+	+	+	0.1	+	0.2	0.2	0.5	0.6	0.7	0.7	0.9
Biodiesel (BD100)	-	8.4	522.2	1,666.1	1,722.8	2,713.1	2,689.6	2,795.5	3,968.9	3,768.8	3,594.3	3,478.0	3,199.7	3,169.4
Heavy-Duty Trucks	**217.4**	**274.6**	**1,277.3**	**3,782.8**	**3,779.4**	**5,989.1**	**5,768.6**	**5,947.4**	**8,322.0**	**8,001.7**	**7,633.3**	**7,388.2**	**6,725.1**	**6,563.8**
Neat Methanol ICE	-	-	+	+	+	+	+	+	+	+	+	+	+	+
Neat Ethanol ICE	-	-	+	+	+	+	1.0	1.2	4.3	10.4	8.8	7.4	3.7	1.9
CNG ICE	0.5	9.4	16.3	16.3	17.7	23.9	24.9	21.9	31.8	32.0	33.1	34.0	29.7	32.5
LPG ICE	201.9	224.7	73.1	74.6	48.1	48.7	37.9	33.3	31.0	26.8	22.6	17.9	10.9	6.3

LPG Bi-fuel	15.0	16.7	12.6	18.0	13.9	15.7	6.6	5.8	5.9	5.7	5.6	5.4	4.4	4.3
LNG	-	0.6	4.5	4.7	4.7	4.4	4.1	4.0	3.4	3.2	3.0	2.5	1.7	1.1
Biodiesel (BD100)	-	23.2	1,170.8	3,669.2	3,695.0	5,896.4	5,694.0	5,881.2	8,245.6	7,923.5	7,560.2	7,320.9	6,674.7	6,517.8
Buses	**36.9**	**206.9**	**356.2**	**464.8**	**497.2**	**619.1**	**658.2**	**663.7**	**819.7**	**835.7**	**872.3**	**900.3**	**831.8**	**907.1**
Neat Methanol ICE	6.4	-	+	+	+	+	+	+	+	+	+	+	+	+
Neat Ethanol ICE	-	0.1	+	2.1	4.9	5.0	5.5	5.7	5.1	3.7	1.9	0.9	0.4	+
CNG ICE	7.4	153.1	271.9	262.3	277.0	289.6	327.8	319.6	339.3	367.2	392.5	421.1	385.6	443.2
LPG ICE	23.1	27.8	13.9	3.9	3.8	5.9	6.5	5.6	9.3	7.1	5.6	4.1	2.1	0.8
LNG	-	22.9	13.8	13.1	14.3	10.4	10.2	8.1	7.4	5.5	3.5	1.8	0.8	0.3
Biodiesel (BD100)	-	1.1	54.0	180.4	194.6	305.5	304.9	321.1	450.0	441.5	420.5	406.7	371.6	364.6
Electric	-	2.0	2.7	2.8	2.2	2.3	2.7	3.0	8.1	9.9	47.3	64.4	69.7	95.8
Fuel Cell Hydrogen	-	-	+	0.4	0.4	0.4	0.5	0.5	0.6	0.7	1.1	1.4	1.6	2.4
Total VMT	**550.1**	**974.3**	**2,980.3**	**7,859.4**	**8,504.6**	**13,334.3**	**13,958.3**	**15,424.7**	**21,399.7**	**22,465.5**	**25,184.0**	**28,257.7**	**27,843.5**	**34,308.8**

+ Does not exceed 0.05 million vehicle miles traveled.

Sources: Derived from Browning (2017), Browning (2018a), Browning (2022b), and EIA (2021).

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 2021 time period.

Table A-77: Age Distribution by Vehicle/Fuel Type for On-Road Vehicles,[a] 2021

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC	HDDB
0	5.9%	5.8%	5.1%	5.6%	9.6%	5.7%	5.9%	5.5%
1	5.9%	5.7%	5.1%	4.9%	9.4%	5.8%	6.0%	5.6%
2	5.9%	5.8%	5.2%	2.8%	8.2%	6.0%	5.9%	5.9%
3	6.0%	5.8%	4.9%	0.9%	6.8%	5.7%	5.6%	5.5%
4	5.2%	7.2%	5.3%	0.2%	7.1%	6.1%	4.1%	8.1%
5	5.7%	6.8%	4.9%	1.0%	6.0%	5.8%	3.9%	7.4%
6	6.1%	6.2%	4.7%	21.5%	4.7%	6.0%	3.6%	6.8%
7	6.2%	5.4%	4.3%	13.4%	3.2%	5.4%	3.4%	6.4%
8	5.7%	4.2%	2.7%	11.1%	2.4%	3.4%	2.9%	3.5%
9	5.0%	3.6%	3.4%	9.2%	2.8%	4.0%	3.0%	3.4%
10	3.8%	3.5%	2.5%	6.4%	2.5%	2.7%	2.1%	3.1%
11	3.8%	2.7%	1.3%	5.8%	1.1%	1.5%	1.6%	3.3%
12	3.4%	2.0%	1.9%	3.8%	1.0%	1.9%	3.5%	3.8%
13	4.1%	3.3%	3.5%	0.4%	3.0%	3.1%	4.4%	3.6%
14	4.1%	3.4%	2.6%	0.3%	2.7%	4.7%	5.4%	3.3%
15	3.5%	3.3%	3.8%	3.5%	4.1%	4.4%	5.2%	3.3%
16	3.1%	3.3%	3.0%	2.2%	3.3%	3.8%	4.7%	2.4%
17	2.5%	3.2%	2.6%	1.2%	3.6%	2.5%	3.8%	2.5%
18	2.2%	2.8%	2.2%	1.3%	2.9%	2.2%	4.1%	2.2%
19	1.8%	2.5%	2.2%	1.2%	2.4%	1.9%	3.3%	2.2%
20	1.5%	2.1%	2.4%	0.7%	2.4%	2.4%	2.7%	2.5%
21	1.4%	2.0%	2.5%	0.6%	1.6%	2.7%	2.2%	2.4%
22	1.0%	1.7%	3.9%	0.3%	1.8%	2.0%	1.6%	1.4%
23	0.8%	1.3%	1.9%	0.3%	0.5%	1.2%	1.2%	1.1%
24	0.7%	1.1%	2.1%	0.1%	1.4%	1.2%	1.0%	0.9%
25	0.5%	0.8%	1.5%	0.1%	0.9%	1.0%	0.9%	0.8%
26	0.5%	0.8%	2.0%	0.1%	0.8%	1.2%	0.7%	0.7%
27	0.3%	0.6%	1.2%	0.0%	0.6%	0.9%	0.6%	0.4%
28	0.3%	0.4%	1.0%	0.0%	0.5%	0.6%	0.5%	0.4%
29	0.2%	0.3%	0.9%	0.0%	0.3%	0.4%	0.4%	0.3%
30	3.0%	2.3%	9.5%	1.2%	2.3%	4.0%	5.9%	1.3%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

[a] The 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 MOVES3 Model.

Source: EPA (2022a)

Table A-78: Annual Average Vehicle Mileage Accumulation per Vehicles[a] (miles)

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC[b]	HDDB
0	14,398	16,274	20,089	14,398	16,274	44,230	9,377	24,870
1	14,125	15,968	20,033	14,125	15,968	44,991	5,007	24,061
2	13,829	15,623	19,961	13,829	15,623	45,969	3,788	23,289
3	13,514	15,245	19,857	13,514	15,245	45,850	3,132	22,540
4	13,181	14,838	21,308	13,181	14,838	45,028	2,710	21,668
5	12,832	14,405	19,952	12,832	14,405	43,386	2,410	21,301
6	12,470	13,951	18,578	12,470	13,951	44,814	2,185	20,061
7	12,096	13,479	17,311	12,096	13,479	41,017	2,007	19,479
8	11,714	12,995	15,198	11,714	12,995	41,753	1,857	19,341
9	11,324	12,501	14,819	11,324	12,501	34,633	1,735	18,436
10	10,931	12,002	12,839	10,931	12,002	27,505	1,632	16,870

11	10,535	11,502	13,396	10,535	11,502	30,391	1,538	17,978
12	10,140	11,006	11,189	10,140	11,006	27,159	1,463	16,604
13	9,746	10,518	9,569	9,746	10,518	14,875	1,388	15,568
14	9,357	10,041	7,941	9,357	10,041	19,673	1,322	15,703
15	8,975	9,579	6,767	8,975	9,579	14,356	1,266	15,805
16	8,602	9,138	5,622	8,602	9,138	12,029	1,219	13,943
17	8,240	8,719	5,219	8,240	8,719	10,030	1,172	13,265
18	7,890	8,330	5,062	7,890	8,331	9,473	1,125	14,662
19	7,557	7,974	4,710	7,557	7,974	7,792	1,088	13,308
20	7,241	7,654	4,354	7,241	7,654	8,177	1,050	12,968
21	6,947	7,374	4,055	6,947	7,374	8,696	1,022	13,465
22	6,673	7,138	3,698	6,673	7,138	8,404	994	13,538
23	6,424	6,952	3,393	6,424	6,952	8,312	938	12,507
24	6,203	6,819	3,332	6,203	6,819	6,298	881	12,126
25	6,010	6,741	2,971	6,010	6,741	6,274	825	11,698
26	5,848	6,726	2,714	5,848	6,726	4,951	760	11,015
27	5,720	6,726	2,693	5,720	6,726	4,487	703	12,131
28	5,627	6,726	2,216	5,627	6,726	3,781	666	10,818
29	5,573	6,726	1,999	5,573	6,726	2,973	619	9,383
30	5,573	6,726	888	5,573	6,726	1,199	572	10,804

[a] The 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).

[b] Because 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 (2022a).

Table A-79: VMT Distribution by Vehicle Age and Vehicle/Fuel Type,[a] 2021

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC	HDDB
0	7.67%	7.69%	8.90%	6.96%	12.50%	8.62%	23.73%	20.59%
1	7.53%	7.52%	8.93%	5.94%	11.90%	8.93%	12.74%	11.29%
2	7.37%	7.42%	9.02%	3.39%	10.22%	9.42%	9.47%	8.89%
3	7.23%	7.19%	8.50%	1.07%	8.28%	8.88%	7.44%	6.95%
4	6.10%	8.77%	9.81%	0.22%	8.39%	9.35%	4.74%	8.74%
5	6.62%	8.05%	8.56%	1.10%	6.84%	8.55%	3.97%	7.17%
6	6.78%	7.12%	7.70%	23.12%	5.26%	9.22%	3.39%	5.92%
7	6.69%	5.95%	6.50%	14.00%	3.46%	7.54%	2.92%	5.10%
8	5.96%	4.50%	3.54%	11.26%	2.46%	4.83%	2.28%	2.61%
9	5.10%	3.66%	4.38%	8.96%	2.83%	4.77%	2.23%	2.34%
10	3.69%	3.46%	2.81%	6.06%	2.40%	2.52%	1.44%	2.05%
11	3.60%	2.58%	1.55%	5.31%	0.97%	1.56%	1.05%	2.04%
12	3.07%	1.81%	1.85%	3.32%	0.89%	1.75%	2.20%	2.22%
13	3.60%	2.88%	2.94%	0.34%	2.52%	1.56%	2.58%	2.00%
14	3.47%	2.81%	1.83%	0.22%	2.18%	3.18%	3.03%	1.73%
15	2.81%	2.57%	2.22%	2.70%	3.16%	2.16%	2.81%	1.66%
16	2.37%	2.46%	1.47%	1.61%	2.42%	1.55%	2.44%	1.17%
17	1.84%	2.26%	1.18%	0.86%	2.47%	0.87%	1.91%	1.18%
18	1.56%	1.88%	0.98%	0.90%	1.94%	0.73%	1.97%	1.00%
19	1.24%	1.66%	0.89%	0.79%	1.55%	0.51%	1.53%	0.97%
20	0.97%	1.34%	0.92%	0.45%	1.46%	0.67%	1.23%	1.04%
21	0.85%	1.19%	0.90%	0.36%	0.96%	0.82%	0.95%	0.97%
22	0.62%	0.98%	1.26%	0.16%	1.03%	0.57%	0.69%	0.54%
23	0.47%	0.75%	0.56%	0.14%	0.26%	0.35%	0.48%	0.42%
24	0.38%	0.63%	0.61%	0.05%	0.75%	0.25%	0.37%	0.33%
25	0.27%	0.44%	0.38%	0.05%	0.49%	0.22%	0.31%	0.25%

26	0.24%	0.42%	0.47%	0.03%	0.44%	0.20%	0.23%	0.21%
27	0.17%	0.35%	0.27%	0.00%	0.31%	0.13%	0.18%	0.12%
28	0.13%	0.24%	0.19%	0.01%	0.27%	0.08%	0.15%	0.11%
29	0.10%	0.18%	0.15%	0.02%	0.18%	0.05%	0.10%	0.08%
30	1.50%	1.25%	0.74%	0.58%	1.21%	0.16%	1.44%	0.29%
Total	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**	**100.00%**

[a] The 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: Estimated by weighting data in Table A-78. This year's Inventory includes updated vehicle population data based on the MOVES3 model that affects this distribution.

Table A-80: Fuel Consumption for Non-Road Sources by Fuel Type (million gallons unless otherwise noted)

Vehicle Type/Year	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Aircraft[a]	**19,542**	**20,294**	**15,754**	**15,255**	**14,907**	**15,268**	**15,390**	**16,331**	**17,191**	**17,783**	**17,854**	**18,424**	**12,540**	**16,991**
Aviation Gasoline	374	302	225	225	209	186	181	176	170	174	186	195	168	179
Jet Fuel	19,168	19,992	15,529	15,030	14,698	15,082	15,210	16,155	17,021	17,609	17,667	18,230	12,372	16,812
Commercial Aviation[b]	*11,569*	*14,672*	*11,931*	*12,067*	*11,932*	*12,031*	*12,131*	*12,534*	*12,674*	*13,475*	*13,650*	*14,132*	*9,358*	*9,358*
Ships and Boats	**4,826**	**6,544**	**4,693**	**4,833**	**4,239**	**4,175**	**3,191**	**3,652**	**4,235**	**4,469**	**4,190**	**4,053**	**3,420**	**4,907**
Diesel	1,156	1,882	1,361	1,641	1,389	1,414	1,284	1,881	1,680	1,593	1,525	1,342	1,342	1,377
Gasoline	1,611	1,636	1,446	1,401	1,372	1,349	1,323	1,325	1,335	1,344	1,352	1,355	1,359	1,363
Residual	2,060	3,027	1,886	1,791	1,477	1,413	584	445	1,219	1,532	1,313	1,356	719	2,167
Construction/Mining Equipment[c]														
Diesel	4,317	5,181	5,727	5,650	5,533	5,447	5,313	5,200	5,483	5,978	6,262	6,464	6,692	6,761
Gasoline	472	357	678	634	651	1,100	710	367	375	375	385	387	389	389
CNG (million cubic feet)	5,082	6,032	6,219	6,121	5,957	5,802	5,598	5,430	5,629	6,018	6,204	6,321	6,458	6,488
LPG	22	27	26	25	24	24	23	22	23	25	26	27	28	28
Agricultural Equipment[d]														
Diesel	3,514	3,278	3,942	3,876	3,932	3,900	3,925	3,862	3,760	3,728	3,732	3,742	3,724	3,700
Gasoline	813	652	692	799	875	655	644	159	168	168	160	129	135	135
CNG (million cubic feet)	1,758	1,678	1,647	1,600	1,611	1,588	1,590	1,561	1,517	1,503	1,502	1,507	1,499	1,491
LPG	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rail	**3,461**	**4,106**	**3,807**	**3,999**	**3,921**	**4,025**	**4,201**	**4,020**	**3,715**	**3,832**	**3,936**	**3,696**	**3,203**	**3,315**
Diesel	3,461	4,106	3,807	3,999	3,921	4,025	4,201	4,020	3,715	3,832	3,936	3,696	3,203	3,315
Other[e]														
Diesel	2,095	2,047	2,450	2,523	2,639	2,725	2,811	2,832	2,851	2,919	3,027	3,110	3,180	3,257
Gasoline	4,371	4,673	5,525	5,344	5,189	5,201	5,281	5,083	5,137	5,178	5,238	5,287	5,339	5,360
CNG (million cubic feet)	20,894	25,035	29,891	32,035	35,085	37,436	39,705	38,069	37,709	38,674	40,390	41,474	42,458	43,349
LPG	1,412	2,191	2,165	2,168	2,181	2,213	2,248	2,279	2,316	2,408	2,526	2,616	2,691	2,781
Total (gallons)	**44,845**	**49,351**	**45,459**	**45,106**	**44,092**	**44,734**	**43,737**	**43,808**	**45,254**	**46,864**	**47,335**	**47,936**	**41,342**	**47,624**
Total (million cubic feet)	**27,735**	**32,745**	**37,757**	**39,755**	**42,653**	**44,826**	**46,893**	**45,060**	**44,854**	**46,194**	**48,097**	**49,301**	**50,415**	**51,328**

[a] For aircraft, this is aviation gasoline. For all other categories, this is motor gasoline.

[b] Commercial aviation, as modeled in FAA's AEDT, consists of passenger aircraft, cargo, and other chartered flights. Data for 2021 is proxied, but will be available in the Final Inventory.

[c] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

[d] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

[e] "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.

Table A-81: 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
1973-1974	100%	-	-	-	-	-	-	-	-
1975	20%	80%	-	-	-	-	-	-	-
1976-1977	15%	85%	-	-	-	-	-	-	-
1978-1979	10%	90%	-	-	-	-	-	-	-
1980	5%	88%	7%	-	-	-	-	-	-
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%

- (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 (2022d), and EPA (2022c).

Table A-82: 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
1973-1974	100%	-	-	-	-	-	-	-	-
1975	30%	70%	-	-	-	-	-	-	-
1976	20%	80%	-	-	-	-	-	-	-
1977-1978	25%	75%	-	-	-	-	-	-	-
1979-1980	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%	0%	44%	53%
2020	-	-	-	-	-	-	-	50%	50%
2021	-	-	-	-	-	-	-	50%	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 (2022d), and EPA (2022c).

Table A-83: 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%

" - " (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 (2022d), and EPA (2022c).

Table A-84: 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	2007-2021
Diesel Medium- and Heavy-Duty Trucks and Buses	
Uncontrolled	1960–1989
Moderate control	1990–2003
Advanced control	2004–2006
Aftertreatment	2007–2021
Motorcycles	
Uncontrolled	1960–1995
Non-catalyst controls	1996–2005
Advanced	2006-2021

Note: Detailed descriptions of emissions control technologies are provided in the following section of this Annex.

Source: EPA (1998) and Browning (2005).

Table A-85: Emission Factors for CH_4 and N_2O for On-Road Vehicles

Vehicle Type/Control Technology	N_2O (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	0.0083	0.0070
Non-Catalyst Control	0.0000	0.0000
Uncontrolled	0.0083	0.0070

[a] The 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 (2006b and 2017a), Browning (2022a).

Table A-86: Emission Factors for N_2O for Alternative Fuel Vehicles (g/mi)

	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Light-Duty Cars														
Methanol-Flex Fuel ICE	0.040	0.027	0.006	0.006	0.006	0.006	0.006	0.006	0.005	0.005	0.005	0.004	0.004	0.004
Ethanol-Flex Fuel ICE	0.040	0.027	0.006	0.006	0.006	0.006	0.006	0.006	0.005	0.005	0.005	0.004	0.004	0.004
CNG ICE	0.024	0.022	0.006	0.006	0.006	0.006	0.006	0.006	0.005	0.005	0.005	0.004	0.004	0.004
CNG Bi-fuel	0.024	0.022	0.006	0.006	0.006	0.006	0.006	0.006	0.005	0.005	0.005	0.004	0.004	0.004
LPG ICE	0.024	0.022	0.006	0.006	0.006	0.006	0.006	0.006	0.005	0.005	0.005	0.004	0.004	0.004
LPG Bi-fuel	0.024	0.022	0.006	0.006	0.006	0.006	0.006	0.006	0.005	0.005	0.005	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	0.007	0.007	0.006	0.006	0.005	0.005	0.005
CNG ICE	0.046	0.045	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.006	0.006	0.005	0.005	0.005
CNG Bi-fuel	0.046	0.045	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.006	0.006	0.005	0.005	0.005
LPG ICE	0.046	0.045	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.006	0.006	0.005	0.005	0.005
LPG Bi-fuel	0.046	0.045	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.006	0.006	0.005	0.005	0.005
LNG	0.046	0.045	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.006	0.006	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	0.104	0.105	0.106	0.108	0.109	0.110	0.095	0.080	0.065	0.049	0.034	0.034
CNG Bi-fuel	0.127	0.127	0.104	0.105	0.106	0.108	0.109	0.110	0.095	0.080	0.065	0.049	0.034	0.034
LPG ICE	0.127	0.127	0.104	0.105	0.106	0.108	0.109	0.110	0.095	0.080	0.065	0.049	0.034	0.034
LPG Bi-fuel	0.127	0.127	0.104	0.105	0.106	0.108	0.109	0.110	0.095	0.080	0.065	0.049	0.034	0.034
LNG	0.127	0.127	0.104	0.105	0.106	0.108	0.109	0.110	0.095	0.080	0.065	0.049	0.034	0.034
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	0.114	0.117	0.121	0.124	0.127	0.130	0.110	0.089	0.069	0.048	0.028	0.027
Neat Ethanol ICE	0.128	0.128	0.114	0.117	0.121	0.124	0.127	0.130	0.110	0.089	0.069	0.048	0.028	0.027
CNG ICE	0.077	0.077	0.110	0.109	0.109	0.108	0.108	0.108	0.090	0.071	0.053	0.035	0.017	0.017
LPG ICE	0.077	0.077	0.110	0.109	0.109	0.108	0.108	0.108	0.090	0.071	0.053	0.035	0.017	0.017
LPG Bi-fuel	0.077	0.077	0.110	0.109	0.109	0.108	0.108	0.108	0.090	0.071	0.053	0.035	0.017	0.017
LNG	0.077	0.077	0.110	0.109	0.109	0.108	0.108	0.108	0.090	0.071	0.053	0.035	0.017	0.017
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	0.144	0.142	0.141	0.139	0.137	0.136	0.114	0.093	0.072	0.051	0.029	0.029
Neat Ethanol ICE	0.198	0.198	0.144	0.142	0.141	0.139	0.137	0.136	0.114	0.093	0.072	0.051	0.029	0.029
CNG ICE	0.119	0.119	0.086	0.085	0.084	0.083	0.082	0.081	0.069	0.056	0.043	0.030	0.018	0.017
LPG ICE	0.119	0.119	0.086	0.085	0.084	0.083	0.082	0.081	0.069	0.056	0.043	0.030	0.018	0.017
LNG	0.119	0.119	0.086	0.085	0.084	0.083	0.082	0.081	0.069	0.056	0.043	0.030	0.018	0.017

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-87: Emission Factors for CH_4 for Alternative Fuel Vehicles (g/mi)

	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Light-Duty Cars														
Methanol-Flex Fuel ICE	0.126	0.083	0.022	0.021	0.020	0.018	0.017	0.016	0.016	0.015	0.015	0.015	0.015	0.013
Ethanol-Flex Fuel ICE	0.126	0.083	0.022	0.021	0.020	0.018	0.017	0.016	0.016	0.015	0.015	0.015	0.015	0.013
CNG ICE	1.793	1.103	0.225	0.211	0.198	0.185	0.171	0.158	0.156	0.153	0.151	0.149	0.146	0.133
CNG Bi-fuel	1.793	1.103	0.225	0.211	0.198	0.185	0.171	0.158	0.156	0.153	0.151	0.149	0.146	0.133
LPG ICE	0.179	0.110	0.022	0.021	0.020	0.018	0.017	0.016	0.016	0.015	0.015	0.015	0.015	0.013
LPG Bi-fuel	0.179	0.110	0.022	0.021	0.020	0.018	0.017	0.016	0.016	0.015	0.015	0.015	0.015	0.013
Biodiesel (BD100)	-	0.002	-	0.006	0.012	0.018	0.024	0.030	0.019	0.030	0.030	0.030	0.030	0.036
Light-Duty Trucks														
Ethanol-Flex Fuel ICE	0.184	0.118	0.024	0.023	0.021	0.019	0.018	0.016	0.016	0.016	0.016	0.016	0.016	0.014
CNG ICE	2.632	1.580	0.242	0.226	0.211	0.195	0.179	0.164	0.162	0.161	0.160	0.159	0.158	0.144
CNG Bi-fuel	2.632	1.580	0.242	0.226	0.211	0.195	0.179	0.164	0.162	0.161	0.160	0.159	0.158	0.144
LPG ICE	0.263	0.158	0.024	0.023	0.021	0.019	0.018	0.016	0.016	0.016	0.016	0.016	0.016	0.014
LPG Bi-fuel	0.263	0.158	0.024	0.023	0.021	0.019	0.018	0.016	0.016	0.016	0.016	0.016	0.016	0.014
LNG	2.632	1.580	0.242	0.226	0.211	0.195	0.179	0.164	0.162	0.161	0.160	0.159	0.158	0.144
Biodiesel (BD100)	-	-	-	0.026	0.052	0.078	0.104	0.130	0.131	0.132	0.133	0.134	0.135	0.127
Medium Duty Trucks														
CNG ICE	6.800	6.800	5.566	5.632	5.697	5.762	5.827	5.893	5.080	4.267	3.454	2.641	1.829	1.807
CNG Bi-fuel	6.800	6.800	5.566	5.632	5.697	5.762	5.827	5.893	5.080	4.267	3.454	2.641	1.829	1.807
LPG ICE	0.680	0.680	0.557	0.563	0.570	0.576	0.583	0.589	0.508	0.427	0.345	0.264	0.183	0.181
LPG Bi-fuel	0.680	0.680	0.557	0.563	0.570	0.576	0.583	0.589	0.508	0.427	0.345	0.264	0.183	0.181
LNG	6.800	6.800	5.566	5.632	5.697	5.762	5.827	5.893	5.080	4.267	3.454	2.641	1.829	1.807
Biodiesel (BD100)	0.000	0.000	0.052	0.050	0.047	0.044	0.042	0.039	0.039	0.039	0.040	0.040	0.040	0.040
Heavy-Duty Trucks														
Neat Methanol ICE	0.287	0.287	0.256	0.263	0.271	0.278	0.285	0.292	0.249	0.205	0.162	0.118	0.075	0.073
Neat Ethanol ICE	0.287	0.287	0.256	0.263	0.271	0.278	0.285	0.292	0.249	0.205	0.162	0.118	0.075	0.073
CNG ICE	4.100	4.100	5.871	5.849	5.827	5.805	5.783	5.761	4.793	3.825	2.857	1.889	0.921	0.921
LPG ICE	0.410	0.410	0.587	0.585	0.583	0.581	0.578	0.576	0.479	0.383	0.286	0.189	0.092	0.092
LPG Bi-fuel	0.410	0.410	0.587	0.585	0.583	0.581	0.578	0.576	0.479	0.383	0.286	0.189	0.092	0.076
LNG	4.100	4.100	5.871	5.849	5.827	5.805	5.783	5.761	4.793	3.825	2.857	1.889	0.921	0.921
Biodiesel (BD100)	0.000	0.000	0.061	0.052	0.043	0.034	0.025	0.016	0.016	0.015	0.015	0.015	0.014	0.014

Buses														
Neat Methanol ICE	1.316	1.316	0.960	0.948	0.937	0.926	0.915	0.904	0.762	0.620	0.478	0.337	0.195	0.193
Neat Ethanol ICE	1.316	1.316	0.960	0.948	0.937	0.926	0.915	0.904	0.762	0.620	0.478	0.337	0.195	0.193
CNG ICE	18.800	18.800	13.710	13.550	13.389	13.229	13.068	12.908	10.884	8.860	6.836	4.811	2.787	2.753
LPG ICE	1.880	1.880	1.371	1.355	1.339	1.323	1.307	1.291	1.088	0.886	0.684	0.481	0.279	0.275
LNG	18.800	18.800	13.710	13.550	13.389	13.229	13.068	12.908	10.884	8.860	6.836	4.811	2.787	2.753
Biodiesel (BD100)	0.000	0.000	0.070	0.060	0.050	0.040	0.030	0.020	0.020	0.020	0.020	0.020	0.019	0.016

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-88: Emission Factors for N_2O Emissions from Non-Road Mobile Combustion (g/kg fuel)

	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
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	0.024	0.025	0.025	0.026	0.026	0.026	0.027	0.027	0.027	0.027	0.027	0.028
4 Stroke	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	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
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	0.170
4 Stroke	0.355	0.365	0.409	0.411	0.415	0.417	0.420	0.422	0.423	0.425	0.427	0.429	0.431	0.433
Gasoline-Off-road Trucks	0.355	0.365	0.409	0.411	0.415	0.417	0.420	0.422	0.423	0.425	0.427	0.429	0.431	0.433
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	0.336
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	0.174
CNG	0.061	0.061	0.074	0.074	0.075	0.075	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076
LPG	0.389	0.389	0.437	0.440	0.444	0.446	0.449	0.451	0.452	0.454	0.456	0.458	0.460	0.462
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	0.516	0.519	0.521	0.523	0.524	0.525	0.526	0.527	0.527	0.528	0.528	0.528
Gasoline-Off-road Trucks	0.408	0.450	0.516	0.519	0.521	0.523	0.524	0.525	0.526	0.527	0.527	0.528	0.528	0.528
Diesel-Equipment	0.295	0.295	0.294	0.295	0.295	0.295	0.295	0.295	0.295	0.295	0.295	0.295	0.295	0.295

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	0.174
CNG	0.367	0.367	0.391	0.395	0.398	0.402	0.405	0.409	0.416	0.424	0.431	0.437	0.442	0.445
LPG	0.197	0.197	0.223	0.226	0.229	0.231	0.233	0.235	0.237	0.239	0.240	0.242	0.243	0.243
Lawn and Garden Equipment														
Gasoline-Residential														
2 Stroke	0.107	0.120	0.171	0.171	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172
4 Stroke	0.519	0.578	0.684	0.688	0.690	0.692	0.693	0.694	0.695	0.695	0.695	0.696	0.696	0.696
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	0.110
4 Stroke	0.409	0.476	0.530	0.531	0.532	0.533	0.534	0.534	0.534	0.535	0.535	0.535	0.535	0.535
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	0.153
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	0.153
LPG	0.245	0.245	0.291	0.297	0.300	0.302	0.303	0.304	0.305	0.306	0.306	0.306	0.306	0.306
Airport Equipment														
Gasoline														
4 Stroke	0.299	0.316	0.372	0.376	0.378	0.380	0.381	0.382	0.382	0.383	0.383	0.383	0.383	0.383
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	0.364
LPG	0.346	0.346	0.414	0.421	0.424	0.427	0.429	0.430	0.431	0.431	0.432	0.432	0.432	0.432
Industrial/Commercial Equipment														
Gasoline														
2 Stroke	0.107	0.123	0.177	0.177	0.177	0.178	0.178	0.178	0.178	0.178	0.178	0.178	0.178	0.178
4 Stroke	0.425	0.473	0.542	0.545	0.548	0.550	0.551	0.552	0.553	0.553	0.552	0.551	0.551	0.550
Diesel	0.183	0.180	0.187	0.188	0.190	0.191	0.192	0.190	0.190	0.189	0.189	0.189	0.189	0.189
CNG	0.034	0.031	0.040	0.041	0.043	0.044	0.044	0.044	0.043	0.043	0.043	0.043	0.043	0.042
LPG	0.250	0.250	0.291	0.297	0.303	0.305	0.307	0.308	0.309	0.310	0.311	0.311	0.311	0.312
Logging Equipment														
Gasoline														
2 Stroke	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4 Stroke	0.579	0.604	0.672	0.678	0.688	0.699	0.709	0.719	0.725	0.730	0.733	0.735	0.736	0.737
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	0.398
Railroad Equipment														
Gasoline														
4 Stroke	0.498	0.555	0.643	0.645	0.646	0.647	0.648	0.649	0.649	0.650	0.650	0.650	0.650	0.650
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	0.297
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	0.035	0.035	0.036	0.036	0.037	0.037	0.037	0.038	0.038	0.039	0.039	0.039
4 Stroke	0.487	0.503	0.534	0.535	0.535	0.536	0.536	0.536	0.536	0.536	0.536	0.537	0.537	0.531
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	0.207
LPG	0.255	0.255	0.270	0.272	0.275	0.277	0.279	0.281	0.284	0.286	0.288	0.290	0.293	0.295

- 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 (2022a).

Table A-89: Emission Factors for CH_4 Emissions from Non-Road Mobile Combustion (g/kg fuel)

	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
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	0.309
Gasoline														
2 Stroke	1.255	1.270	1.465	1.489	1.514	1.536	1.557	1.578	1.597	1.615	1.629	1.642	1.652	1.661
4 Stroke	0.717	0.725	0.760	0.763	0.768	0.773	0.777	0.783	0.788	0.793	0.797	0.801	0.805	0.808
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	2.008	2.008	2.008
Rail														
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	0.250
Aircraft														
Jet Fuel[c]	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	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	2.640
Agricultural Equipment[a]														
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	2.480	2.480	2.480
4 Stroke	0.570	0.586	0.656	0.660	0.666	0.670	0.674	0.677	0.679	0.682	0.686	0.689	0.692	0.695
Gasoline-Off-road Trucks	0.570	0.586	0.656	0.660	0.666	0.670	0.674	0.677	0.679	0.682	0.686	0.689	0.692	0.695
Diesel-Equipment	0.397	0.397	0.397	0.397	0.397	0.397	0.397	0.397	0.397	0.397	0.397	0.397	0.397	0.397
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	0.286	0.286	0.286
CNG	1.391	1.391	1.676	1.698	1.710	1.719	1.726	1.731	1.734	1.736	1.736	1.736	1.736	1.736
LPG	0.135	0.135	0.152	0.153	0.154	0.155	0.156	0.157	0.157	0.158	0.158	0.159	0.160	0.160
Construction/Mining Equipment[b]														
Gasoline-Equipment														
2 Stroke	1.868	1.997	2.857	2.858	2.858	2.858	2.858	2.858	2.858	2.858	2.858	2.858	2.858	2.858
4 Stroke	0.789	0.871	0.999	1.005	1.009	1.011	1.013	1.015	1.017	1.019	1.020	1.021	1.022	1.022
Gasoline-Off-road Trucks	0.789	0.871	0.999	1.005	1.009	1.011	1.013	1.015	1.017	1.019	1.020	1.021	1.022	1.022
Diesel-Equipment	0.317	0.317	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.317	0.317	0.317	0.317	0.317
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	0.286	0.286	0.286
CNG	1.322	1.322	1.409	1.422	1.434	1.447	1.459	1.473	1.499	1.529	1.554	1.574	1.595	1.605

LPG	0.233	0.233	0.264	0.267	0.271	0.273	0.276	0.278	0.280	0.283	0.285	0.286	0.287	0.288
Lawn and Garden Equipment														
Gasoline-Residential														
2 Stroke	1.489	1.666	2.361	2.373	2.379	2.381	2.381	2.382	2.382	2.382	2.382	2.383	2.383	2.384
4 Stroke	0.803	0.894	1.058	1.063	1.067	1.070	1.072	1.073	1.074	1.075	1.075	1.075	1.076	1.076
Gasoline-Commercial														
2 Stroke	1.685	1.859	2.609	2.609	2.609	2.609	2.609	2.609	2.609	2.610	2.610	2.610	2.611	2.611
4 Stroke	0.821	0.956	1.064	1.067	1.069	1.071	1.072	1.072	1.073	1.073	1.073	1.073	1.073	1.074
Diesel-Residential	0.236	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208
Diesel-Commercial	0.236	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208
LPG	0.162	0.162	0.192	0.196	0.198	0.199	0.200	0.201	0.202	0.202	0.202	0.202	0.202	0.202
Airport Equipment														
Gasoline														
4 Stroke	0.287	0.303	0.356	0.360	0.362	0.364	0.365	0.366	0.366	0.366	0.367	0.367	0.367	0.367
Diesel	0.593	0.593	0.593	0.593	0.593	0.593	0.593	0.593	0.593	0.593	0.593	0.593	0.593	0.593
LPG	0.137	0.137	0.164	0.167	0.168	0.169	0.170	0.171	0.171	0.171	0.171	0.171	0.171	0.171
Industrial/Commercial Equipment														
Gasoline														
2 Stroke	1.541	1.774	2.545	2.547	2.549	2.550	2.551	2.552	2.553	2.553	2.554	2.554	2.554	2.555
4 Stroke	0.758	0.837	0.965	0.972	0.979	0.984	0.987	0.987	0.987	0.987	0.986	0.985	0.984	0.983
Diesel	0.120	0.106	0.127	0.131	0.137	0.140	0.143	0.141	0.139	0.135	0.134	0.133	0.133	0.132
CNG	2.334	2.420	2.824	2.836	2.840	2.837	2.832	2.854	2.867	2.877	2.885	2.892	2.897	2.904
LPG	0.174	0.174	0.203	0.206	0.210	0.212	0.213	0.214	0.215	0.215	0.216	0.216	0.216	0.216
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	3.468	3.468	3.468
4 Stroke	0.914	0.950	1.072	1.084	1.099	1.114	1.127	1.137	1.143	1.149	1.153	1.157	1.159	1.161
Diesel	0.153	0.153	0.154	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.153
Railroad Equipment														
Gasoline														
4 Stroke	0.897	0.990	1.147	1.151	1.153	1.155	1.157	1.158	1.158	1.159	1.160	1.160	1.160	1.160
Diesel	0.125	0.125	0.126	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
LPG	0.784	0.787	0.870	0.893	0.905	0.919	0.927	0.936	0.943	0.956	0.962	0.966	0.970	0.973
Recreational Equipment														
Gasoline														
2 Stroke	5.170	5.252	5.553	5.616	5.700	5.781	5.862	5.944	6.024	6.100	6.176	6.244	6.310	3.510
4 Stroke	0.935	0.965	1.026	1.028	1.028	1.029	1.030	1.030	1.030	1.031	1.031	1.031	1.032	0.975
Diesel	0.228	0.228	0.228	0.228	0.228	0.228	0.228	0.228	0.228	0.228	0.228	0.228	0.228	0.228

LPG	0.182	0.182	0.193	0.195	0.196	0.198	0.200	0.201	0.203	0.204	0.206	0.208	0.209	0.211

Table A-90: NO_x Emissions from Mobile Combustion (kt)

Fuel Type/Vehicle Type	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Gasoline On-Road	**5,746**	**3,812**	**2,724**	**2,805**	**2,647**	**2,489**	**2,332**	**2,122**	**1,751**	**1,670**	**1,363**	**1,340**	**1,205**	**1,070**
Passenger Cars	3,847	2,084	1,486	1,530	1,444	1,358	1,272	1,158	955	911	744	731	657	584
Light-Duty Trucks	1,364	1,303	942	970	915	861	806	734	605	578	471	464	417	370
Medium- and Heavy-Duty Trucks and Buses	515	411	286	294	278	261	245	223	184	175	143	141	126	112
Motorcycles	20	13	10	10	10	9	9	8	6	6	5	5	4	4
Diesel On-Road	**2,956**	**3,803**	**2,448**	**2,520**	**2,379**	**2,237**	**2,095**	**1,907**	**1,573**	**1,501**	**1,225**	**1,204**	**1,083**	**961**
Passenger Cars	39	7	4	4	4	4	4	3	3	3	2	2	2	2
Light-Duty Trucks	20	6	4	4	4	4	3	3	3	2	2	2	2	2
Medium- and Heavy-Duty Trucks	2,731	3,579	2,331	2,393	2,253	2,119	1,981	1,802	1,488	1,418	1,158	1,139	1,024	909
Medium – and Heavy-Duty Buses	166	212	109	119	118	110	107	98	79	77	63	62	55	49
Alternative Fuel On-Road[a]	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**
Non-Road	**2,160**	**2,584**	**2,118**	**1,968**	**1,883**	**1,797**	**1,712**	**1,605**	**1,416**	**1,348**	**1,316**	**1,245**	**1,214**	**1,183**
Ships and Boats	402	506	438	407	389	372	354	332	293	279	272	257	251	245
Rail	338	451	391	363	348	332	316	296	261	249	243	230	224	218
Aircraft[b]	25	40	32	29	28	27	26	24	21	20	20	19	18	18
Agricultural Equipment[c]	437	484	383	356	340	325	309	290	256	244	238	225	219	214
Construction/Mining Equipment[d]	641	697	550	511	489	467	445	417	368	350	342	323	315	307
Other[e]	318	407	324	301	288	275	262	246	217	206	201	191	186	181
Total	**10,862**	**10,199**	**7,290**	**7,294**	**6,909**	**6,523**	**6,138**	**5,634**	**4,739**	**4,519**	**3,903**	**3,790**	**3,502**	**3,214**

IE (Included Elsewhere)

[a] NO_x emissions from alternative fuel on-road vehicles are included under gasoline and diesel on-road.

[b] Aircraft estimates include only emissions related to LTO cycles, and therefore do not include cruise altitude emissions.

[c] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

[d] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

[e] "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: The source of this data is the National Emissions Inventory. Updates to estimates from MOVES3 is a change that affects the emissions time series. Totals may not sum due to independent rounding.

Table A-91: CO Emissions from Mobile Combustion (kt)

Fuel Type/Vehicle Type	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Gasoline On-Road	**98,328**	**60,657**	**25,235**	**24,442**	**23,573**	**22,704**	**21,834**	**20,864**	**17,995**	**17,435**	**15,463**	**15,100**	**14,302**	**13,504**
Passenger Cars	60,757	32,867	14,060	13,618	13,134	12,649	12,165	11,625	10,026	9,714	8,615	8,413	7,968	7,524
Light-Duty Trucks	29,237	24,532	10,044	9,729	9,383	9,037	8,690	8,304	7,162	6,940	6,155	6,010	5,693	5,375
Medium- and Heavy-Duty Trucks and Buses	8,093	3,104	1,073	1,039	1,002	965	928	887	765	741	657	642	608	574
Motorcycles	240	154	58	57	55	53	51	48	42	40	36	35	33	31
Diesel On-Road	**1,696**	**1,088**	**387**	**375**	**361**	**348**	**335**	**320**	**276**	**267**	**237**	**231**	**219**	**207**
Passenger Cars	35	7	3	3	2	2	2	2	2	2	2	2	1	1
Light-Duty Trucks	22	6	2	2	2	2	2	2	2	2	1	1	1	1
Medium- and Heavy-Duty Trucks	1,567	1,034	363	350	337	324	311	297	257	249	222	217	205	194
Medium- and Heavy-Duty Buses	71	41	19	19	20	19	19	18	15	15	12	12	11	10
Alternative Fuel On-Road[a]	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**
Non-Road	**19,337**	**21,814**	**13,853**	**13,488**	**12,981**	**12,474**	**11,966**	**11,451**	**10,518**	**10,240**	**10,257**	**10,249**	**10,276**	**10,304**
Ships and Boats	1,559	1,825	1,140	1,109	1,068	1,026	984	942	865	842	844	843	845	848
Rail	85	90	56	54	52	50	48	46	42	41	41	41	41	42
Aircraft[b]	217	245	145	141	136	131	125	120	110	107	108	107	108	108
Agricultural Equipment[c]	581	626	386	376	362	348	334	319	293	286	286	286	287	287
Construction/Mining Equipment[d]	1,090	1,047	648	631	607	583	560	535	492	479	480	479	480	482
Other[e]	15,805	17,981	11,479	11,176	10,756	10,335	9,915	9,488	8,715	8,485	8,499	8,492	8,515	8,537
Total	**119,360**	**83,559**	**39,475**	**38,305**	**36,915**	**35,525**	**34,135**	**32,635**	**28,789**	**27,942**	**25,957**	**25,580**	**24,798**	**24,015**

IE (Included Elsewhere)

[a] CO emissions from alternative fuel on-road vehicles are included under gasoline and diesel on-road.

[b] Aircraft estimates include only emissions related to LTO cycles, and therefore do not include cruise altitude emissions.

[c] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

[d] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

[e] "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: The source of this data is the National Emissions Inventory. Updates to estimates from MOVES3 is a change that affects the emissions time series. Totals may not sum due to independent rounding.

Table A-92: NMVOCs Emissions from Mobile Combustion (kt)

Fuel Type/Vehicle Type	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Gasoline On-Road	**8,110**	**4,615**	**2,393**	**2,485**	**2,342**	**2,200**	**2,058**	**1,929**	**1,626**	**1,570**	**1,030**	**1,021**	**949**	**877**
Passenger Cars	5,120	2,610	1,336	1,388	1,308	1,229	1,149	1,077	908	877	575	570	530	490
Light-Duty Trucks	2,374	1,750	929	965	910	854	799	749	631	610	400	396	369	341
Medium- and Heavy-Duty Trucks and Buses	575	232	115	120	113	106	99	93	78	76	50	49	46	42
Motorcycles	42	23	12	13	12	11	11	10	8	8	5	5	5	4
Diesel On-Road	**406**	**216**	**116**	**120**	**113**	**106**	**100**	**93**	**79**	**76**	**50**	**49**	**46**	**42**
Passenger Cars	16	3	2	2	2	2	1	1	1	1	1	1	1	1
Light-Duty Trucks	14	4	2	2	2	2	2	2	1	1	1	1	1	1
Medium- and Heavy-Duty Trucks	360	201	107	110	104	97	91	85	72	69	46	45	42	39
Medium-and Heavy-Duty Buses	16	8	5	6	6	6	6	5	4	4	2	2	2	2
Alternative Fuel On-Road[a]	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**
Non-Road	**2,415**	**2,398**	**2,082**	**1,957**	**1,837**	**1,717**	**1,597**	**1,435**	**1,168**	**1,082**	**1,034**	**994**	**968**	**943**
Ships and Boats	608	744	639	600	564	527	490	440	358	332	317	305	297	289
Rail	33	35	31	29	27	26	24	21	17	16	15	15	14	14
Aircraft[b]	28	24	17	16	15	14	13	12	9	9	8	8	8	8
Agricultural Equipment[c]	85	76	63	60	56	52	49	44	36	33	31	30	29	29
Construction/Mining Equipment[d]	149	130	109	103	96	90	84	75	61	57	54	52	51	50
Other[e]	1,512	1,390	1,223	1,149	1,079	1,008	938	843	686	636	608	584	569	554
Total	**10,932**	**7,230**	**4,591**	**4,562**	**4,293**	**4,023**	**3,754**	**3,458**	**2,873**	**2,728**	**2,114**	**2,064**	**1,963**	**1,862**

IE (Included Elsewhere)

[a] NMVOC emissions from alternative fuel on-road vehicles are included under gasoline and diesel on-road.

[b] Aircraft estimates include only emissions related to LTO cycles, and therefore do not include cruise altitude emissions.

[c] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

[d] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

[e] "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: The source of this data is the National Emissions Inventory. Updates to estimates from MOVES3 is a change that affects the emissions time series. Totals may not sum due to independent rounding.

Definitions of Emission Control Technologies and Standards

The N_2O and CH_4 emission factors used depend on the emission standards in place and the corresponding level of control technology for each vehicle type. Table A-81 through Table A-84 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 (1993, 1994a, 1994b, 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 CO_2 and H_2O, 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 CH_4 or N_2O 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 CH_4 or N_2O 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 GHG 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 CO_2, N_2O, CH_4, and HFC emissions. Although the Inventory is not required to provide details beyond what is contained in the body of this report, the IPCC allows presentation of additional data and detail on emission sources. The purpose of this sub-annex, within the Annex that details the calculation methods and data used for non-CO_2 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 CO_2 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 CO_2 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 CO_2 from Non-Transportation Mobile Sources

The estimates of N_2O and CH_4 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 CO_2 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-93 provides estimates of CO_2 from these other mobile sources, developed from the Nonroad component of EPA's MOVES3 model, and FHWA's Highway Statistics. These other mobile source estimates were developed using the same fuel consumption data utilized in developing the N_2O and CH_4 estimates (see Table A-80). Note that the method used to estimate fuel consumption volumes for CO_2 emissions from non-transportation mobile sources for the supplemental information presented in Table A-93, Table A-95, and Table A-96 differs from the method used to estimate fuel consumption volumes for CO_2 in the industrial and commercial sectors in this Inventory, which include CO_2 emissions from all non-transportation mobile sources (see Section 3.1 for a discussion of that methodology).

Table A-93: CO_2 Emissions from Non-Transportation Mobile Sources (MMT CO_2 Eq.)[a]

Fuel Type/ Vehicle Type	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Agricultural Equipment[a]	43.4	39.9	46.6	46.8	48.0	45.8	45.9	41.1	40.2	39.8	39.8	39.7	39.1	39.7
Construction/Mining Equipment[b]	48.9	57.4	65.3	64.0	62.9	65.9	61.1	57.0	60.0	65.1	68.2	70.3	66.2	69.3
Other Sources[c]	69.6	76.3	86.6	85.8	85.9	87.0	88.8	87.4	88.3	89.9	92.3	94.1	89.3	93.1
Total	**161.9**	**173.6**	**198.4**	**196.6**	**196.8**	**198.7**	**195.9**	**185.6**	**188.4**	**194.8**	**200.3**	**204.1**	**194.5**	**202.1**

[a] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture. The non-transportation mobile 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.

[b] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

[c] "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: The method used to estimate CO_2 emissions in this supplementary information table differs from the method used to estimate CO_2 in the industrial and commercial sectors in the Inventory, which include CO_2 emissions from all non-transportation mobile sources (see Section 3.1 for the methodology for estimating CO_2 emissions from fossil fuel combustion in this Inventory). The current Inventory uses the Nonroad component of MOVES3 for years 1999 through 2021.

Estimation of HFC Emissions from Transportation Sources

In addition to CO_2, N_2O and CH_4 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-94 below presents these HFC emissions. Table A-95 presents all transportation and mobile source greenhouse gas emissions, including HFC emissions.

Table A-94: HFC Emissions from Transportation Sources (MMT CO_2 Eq.)

Vehicle Type	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Mobile AC	**+**	**55.2**	**64.7**	**58.6**	**52.7**	**46.7**	**43.4**	**40.5**	**36.9**	**33.3**	**31.0**	**28.8**	**26.6**	**24.7**
Passenger Cars	+	28.0	27.5	23.9	20.6	17.2	15.8	14.7	13.2	11.4	10.4	9.3	8.3	7.7
Light-Duty Trucks	+	25.6	34.1	31.6	29.2	26.5	24.7	23.0	21.1	19.2	18.1	16.9	15.6	14.3
Heavy-Duty Vehicles	+	1.6	3.1	3.0	2.9	2.9	2.9	2.8	2.7	2.6	2.6	2.6	2.7	2.7
Comfort Cooling for Trains and Buses	**+**	**0.1**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
School and Tour 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	0.4
Transit Buses	+	+	+	+	+	+	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Rail	+	+	+	+	+	+	+	+	+	+	+	0.1	0.1	0.1
Refrigerated Transport	**+**	**0.8**	**2.9**	**3.4**	**3.9**	**4.4**	**4.9**	**5.4**	**5.9**	**6.4**	**6.9**	**7.4**	**7.9**	**8.4**
Medium- and Heavy-Duty Trucks	+	0.4	1.6	1.8	2.1	2.3	2.5	2.7	2.9	3.1	3.3	3.5	3.7	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	1.2	1.5	1.7	2.0	2.3	2.6	2.9	3.3	3.6	3.9	4.2	4.5
Total	**+**	**56.2**	**68.1**	**62.4**	**57.1**	**51.6**	**48.8**	**46.3**	**43.3**	**40.1**	**38.5**	**36.7**	**35.0**	**33.6**

+ Does not exceed 0.05 MMT CO_2 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-95 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 CO_2 equivalents. In total, transportation and non-transportation mobile sources emitted 2,102.4 MMT CO_2 Eq. in 2021, an increase of 21 percent from 1990.[114] Transportation sources account for 1,893.5 MMT CO_2 Eq. while non-transportation mobile sources account for 208.9 MMT CO_2 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 CO_2 emissions from transportation sources reported in Section 3.1 CO_2 Emissions from Fossil Fuel Combustion, and CH_4 emissions and N_2O 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 CO_2 emitted from non-transportation mobile sources reported in Table A-93 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 N_2O and CH_4, 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 CO_2 emissions. N_2O estimates for both jet fuel and aviation gasoline, and CH_4 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 2022 and DLA 2021). Emissions of CH_4 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.[115] 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, CH_4 emission factors for jet aircraft were reported as zero to reflect the latest emissions testing data.

Similarly, N_2O and CH_4 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 2021). Carbon dioxide emissions from non-transportation mobile sources are calculated using data from the Nonroad component of EPA's MOVES3 model (EPA 2021a). 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 CO_2), Chapter 4, and Annex 3.9 (for HFCs), and earlier in this Annex (for CH_4 and N_2O).

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 CO_2 from lubricants (such as motor oil) used in transportation. Together, transportation sources were responsible for 1,893.5 MMT CO_2 Eq. in 2021.

On-road vehicles were responsible for about 73 percent of all transportation and non-transportation mobile greenhouse gas emissions in 2021. 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 42 percent between 1990 and 2021. Greenhouse gas emissions from light duty trucks increased by 125 percent between 1990 and 2021. Overall, between 1990 and 2021, greenhouse gas emissions from passenger cars and light-duty trucks increased by 11.5 percent. Meanwhile, greenhouse

[114] 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).

[115] VMT is allocated to vehicle classes using MOVES3 ratios of VMT in each vehicle class to total VMT.

gas emissions from medium- and heavy-duty trucks increased 84 percent between 1990 and 2021, reflecting the increased volume of total freight movement and an increasing share transported by trucks.

Greenhouse gas emissions from aircraft decreased 12 percent between 1990 and 2021. Emissions from military aircraft decreased 68 percent between 1990 and 2021. Commercial aircraft emissions rose 27 percent between 1990 and 2007, dropped 4 percent from 2007 to 2019, and then dropped 32 percent from 2019 to 2020, a reduction by approximately 17 percent between 1990 and 2021[116].

Non-transportation mobile sources, such as construction/mining equipment, agricultural equipment, and industrial/commercial equipment, emitted approximately 208.9MMT CO_2 Eq. in 2021. Together, these sources emitted more greenhouse gases than ships and boats, and rail combined. Emissions from non-transportation mobile sources increased, growing approximately 25 percent between 1990 and 2021. Methane and N_2O emissions from these sources are included in the "Mobile Combustion" section and CO_2 emissions are included in the relevant economic sectors.

Contribution of Transportation and Mobile Sources to Greenhouse Gas Emissions, by Gas

Table A-96 presents estimates of greenhouse gas emissions from transportation and other mobile sources broken down by greenhouse gas. As this table shows, CO_2 accounts for most transportation greenhouse gas emissions (approximately 97 percent in 2021). Emissions of CO_2 from transportation and mobile sources increased by 359 MMT CO_2 Eq. between 1990 and 2021. In contrast, the combined emissions of CH_4 and N_2O decreased by 25.9 MMT CO_2 Eq. over the same period, due largely to the introduction of control technologies designed to reduce criteria pollutant emissions.[117] Meanwhile, HFC emissions from mobile air-conditioners and refrigerated transport increased from virtually no emissions in 1990 to 33.6 MMT CO_2 Eq. in 2021 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 UNFCCC reporting requirements.

Greenhouse Gas Emissions from Freight and Passenger Transportation

Table A-97 and Table A-98 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-97. 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-98. 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 to allocate to the passenger and freight categories was calculated using BTS data on freight shipped by commercial aircraft, and the total number of passengers enplaned. 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-95. In addition, estimates of fuel consumption from DOE (1993 through 2022) were used to allocate rail emissions between passenger and freight categories.

In 2021, passenger transportation modes emitted 1,253.8 MMT CO_2 Eq., while freight transportation modes emitted 573.3 MMT CO_2 Eq. Between 1990 and 2021, the percentage growth of greenhouse gas emissions from freight sources was 62 percent. Emissions from passenger sources decreased by 2 percent from 1990 to 2021. This difference in growth is due largely to the rapid increase in emissions associated with medium- and heavy-duty trucks.

[116] Commercial aircraft emissions were unavailable and were proxied for 2021 but will be included in the Final Inventory published in April 2023.

[117] The decline in CFC emissions is not captured in the official transportation estimates.

Table A-95: Total U.S. Greenhouse Gas Emissions from Transportation and Mobile Sources (MMT CO_2 Eq.)

Mode / Vehicle Type / Fuel Type	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Percent Change 1990-2021
Transportation Total[a]	**1,524.6**	**1,912.4**	**1,805.7**	**1,772.1**	**1,752.4**	**1,755.3**	**1,789.3**	**1,797.3**	**1,831.9**	**1,849.1**	**1,879.1**	**1,879.4**	**1,631.7**	**1,849.2**	**21%**
On-Road Vehicles	**1,202.0**	**1,553.4**	**1,514.0**	**1,482.4**	**1,471.9**	**1,465.1**	**1,513.2**	**1,509.3**	**1,532.3**	**1,538.2**	**1,560.8**	**1,551.8**	**1,376.6**	**1,525.0**	**27%**
Passenger Cars	**648.4**	**604.8**	**496.2**	**460.4**	**403.1**	**406.7**	**417.3**	**406.8**	**407.4**	**393.7**	**399.7**	**396.3**	**342.5**	**379.2**	**-42%**
Gasoline[b]	639.0	573.7	466.6	434.0	380.0	386.7	398.3	388.2	390.4	378.5	385.3	382.8	330.3	366.8	**-43%**
Diesel[b]	9.5	3.1	2.1	2.4	2.4	2.5	2.8	3.3	3.1	3.0	2.8	2.7	2.6	2.8	**-70%**
AFVs[c]	+	+	+	0.1	0.1	0.2	0.4	0.5	0.7	0.8	1.2	1.4	1.3	1.8	**NA**
HFCs from Mobile AC	-	28.0	27.5	23.9	20.6	17.2	15.8	14.7	13.2	11.4	10.4	9.3	8.3	7.7	**NA**
Light-Duty Trucks	**302.5**	**577.6**	**635.1**	**645.4**	**691.2**	**674.6**	**695.7**	**695.3**	**712.8**	**718.0**	**722.3**	**713.3**	**616.8**	**681.4**	**125%**
Gasoline[b]	293.8	532.2	572.5	582.8	628.4	616.8	640.0	640.6	660.5	667.3	672.4	664.6	570.4	631.6	**115%**
Diesel[b]	8.4	19.7	28.4	30.9	33.6	31.2	31.0	31.6	31.1	31.3	31.5	31.5	30.5	34.8	**312%**
AFVs[c]	0.2	0.1	0.1	0.1	+	+	0.1	0.1	0.1	0.2	0.3	0.3	0.4	0.8	**264%**
HFCs from Mobile AC	-	25.6	34.1	31.6	29.2	26.5	24.7	23.0	21.1	19.2	18.1	16.9	15.6	14.3	**NA**
Medium- and Heavy-Duty Trucks	**234.3**	**347.1**	**359.7**	**352.8**	**351.8**	**357.8**	**372.2**	**378.6**	**382.8**	**395.8**	**407.0**	**409.8**	**387.0**	**430.3**	**84%**
Gasoline[b]	44.0	37.1	23.2	21.1	21.1	21.5	23.0	23.0	24.3	25.2	26.4	27.2	24.3	27.8	**-37%**
Diesel[b]	189.2	307.4	331.5	326.6	325.3	330.7	343.5	349.6	352.4	364.5	374.1	375.9	356.0	395.6	**109%**
AFVs[c]	1.1	0.6	0.2	0.3	0.3	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.3	0.4	**-66%**
HFCs from Refrigerated Transport and Mobile AC[e]	-	2.0	4.7	4.8	5.0	5.2	5.3	5.5	5.5	5.7	5.9	6.1	6.3	6.5	**NA**
Buses	**13.4**	**19.4**	**16.7**	**17.6**	**18.7**	**19.2**	**21.0**	**21.9**	**22.1**	**23.5**	**24.4**	**24.9**	**23.6**	**26.5**	**97%**
Gasoline[b]	2.2	1.5	1.3	1.4	1.6	1.8	2.1	2.1	2.3	2.5	2.7	2.8	2.5	2.9	**34%**
Diesel[b]	11.1	17.4	14.5	15.3	16.2	16.4	17.9	18.7	18.7	19.8	20.5	20.9	19.9	22.3	**101%**
AFVs[c]	0.2	0.4	0.5	0.5	0.5	0.5	0.6	0.6	0.7	0.7	0.8	0.8	0.7	0.9	**376%**
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	**NA**
Motorcycles	**3.4**	**4.4**	**6.4**	**6.3**	**7.1**	**6.8**	**7.0**	**6.8**	**7.2**	**7.2**	**7.4**	**7.5**	**6.7**	**7.6**	**123%**
Gasoline[b]	3.4	4.4	6.4	6.3	7.1	6.8	7.0	6.8	7.2	7.2	7.4	7.5	6.7	7.6	**123%**
Aircraft	**188.8**	**199.1**	**154.6**	**149.7**	**146.3**	**149.8**	**151.0**	**160.3**	**168.8**	**174.6**	**175.3**	**180.9**	**123.0**	**166.8**	**-12%**
General Aviation Aircraft	**42.0**	**35.3**	**26.3**	**22.2**	**19.6**	**23.3**	**20.5**	**26.5**	**34.8**	**32.9**	**32.4**	**33.3**	**20.2**	**63.3**	**51%**
Jet Fuel[f]	38.8	32.7	24.4	20.3	17.8	21.7	19.0	25.0	33.3	31.5	30.8	31.7	18.8	61.8	**59%**
Aviation Gasoline	3.2	2.6	1.9	1.9	1.8	1.6	1.5	1.5	1.5	1.5	1.6	1.7	1.4	1.5	**-52%**
Commercial Aircraft	**110.8**	**140.5**	**114.2**	**115.5**	**114.2**	**115.2**	**116.1**	**120.0**	**121.4**	**129.0**	**130.7**	**135.3**	**92.0**	**92.0**	**-17%**
Jet Fuel[f]	110.8	140.5	114.2	115.5	114.2	115.2	116.1	120.0	121.4	129.0	130.7	135.3	92.0	92.0	**-17%**
Military Aircraft	**36.0**	**23.3**	**14.0**	**11.9**	**12.4**	**11.3**	**14.4**	**13.9**	**12.6**	**12.6**	**12.2**	**12.2**	**10.8**	**11.4**	**-68%**

Jet Fuel[f]	36.0	23.3	14.0	11.9	12.4	11.3	14.4	13.9	12.6	12.6	12.2	12.2	10.8	11.4	**-68%**
Ships and Boats[d]	**47.0**	**65.9**	**45.0**	**46.5**	**40.3**	**39.7**	**29.1**	**33.8**	**40.7**	**43.8**	**41.1**	**40.0**	**32.4**	**50.0**	**6%**
Gasoline	14.4	14.5	11.8	11.4	11.1	10.9	10.7	10.7	10.7	10.8	10.9	10.9	10.2	10.7	**-26%**
Distillate Fuel	9.8	17.4	11.3	14.0	11.4	11.5	10.2	16.2	14.0	13.1	12.5	10.6	10.6	10.9	**12%**
Residual Fuel[e]	22.8	33.6	20.7	19.6	16.0	15.3	5.9	4.3	13.1	16.6	14.2	14.6	7.4	23.8	**5%**
HFCs from Refrigerated Transport[e]	+	0.3	1.2	1.5	1.7	2.0	2.3	2.6	2.9	3.3	3.6	3.9	4.2	4.5	**NA**
Rail	**39.0**	**46.6**	**44.0**	**45.1**	**43.9**	**44.4**	**46.3**	**44.0**	**40.2**	**41.3**	**42.5**	**39.7**	**34.0**	**35.2**	**-10%**
Distillate Fuel[f]	35.8	42.9	39.3	40.6	39.7	40.1	41.9	40.0	36.5	37.7	38.9	36.3	31.3	32.4	**-9%**
Electricity	3.1	3.5	4.5	4.3	3.9	4.1	4.1	3.8	3.5	3.4	3.4	3.2	2.5	2.6	**-16%**
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	**9%**
HFCs from Comfort Cooling	-	+	+	+	+	+	+	+	+	+	+	0.1	0.1	0.1	**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	0.1	**NA**
Pipelines[h]	**36.0**	**35.4**	**37.8**	**38.5**	**41.0**	**46.6**	**39.7**	**38.9**	**39.5**	**41.6**	**50.2**	**58.2**	**57.9**	**64.2**	**78%**
Natural Gas	36.0	35.4	37.8	38.5	41.0	46.6	39.7	38.9	39.5	41.6	50.2	58.2	57.9	64.2	**78%**
Other Transportation	**11.8**	**12.1**	**10.4**	**10.0**	**9.1**	**9.6**	**10.0**	**11.0**	**10.4**	**9.6**	**9.2**	**8.8**	**7.8**	**8.0**	**-33%**
Lubricants	**11.8**	**12.1**	**10.4**	**10.0**	**9.1**	**9.6**	**10.0**	**11.0**	**10.4**	**9.6**	**9.2**	**8.8**	**7.8**	**8.0**	**-33%**
Non-Transportation Mobile[i] Total	**166.9**	**179.1**	**205.3**	**203.4**	**203.6**	**205.6**	**202.8**	**192.0**	**194.9**	**201.4**	**207.0**	**210.9**	**201.1**	**208.9**	**25%**
Agricultural Equipment[i,j]	**44.7**	**41.1**	**48.1**	**48.3**	**49.6**	**47.3**	**47.4**	**42.4**	**41.4**	**41.1**	**41.1**	**40.9**	**40.3**	**40.9**	**-9%**
Gasoline	7.5	6.0	6.2	7.1	7.8	5.8	5.7	1.4	1.5	1.5	1.4	1.1	1.2	1.2	**-84%**
Diesel	37.2	35.0	41.8	41.1	41.7	41.4	41.6	40.9	39.8	39.5	39.6	39.7	39.0	39.7	**7%**
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	**-13%**
LPG	+	+	+	+	+	+	+	+	+	+	+	+	+	+	**-9%**
Construction/Mining Equipment[i,k]	**50.2**	**58.9**	**67.1**	**65.8**	**64.7**	**67.8**	**62.9**	**58.6**	**61.6**	**66.9**	**70.0**	**72.2**	**68.0**	**71.2**	**42%**
Gasoline	4.4	3.3	6.1	5.7	5.9	9.9	6.4	3.3	3.4	3.4	3.5	3.5	3.5	3.5	**-20%**
Diesel	45.4	55.1	60.5	59.6	58.4	57.5	56.1	54.8	57.8	63.0	66.0	68.2	64.0	67.2	**48%**
CNG	0.3	0.3	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.3	0.4	**25%**
LPG	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.2	**19%**
Other Equipment[i,l]	**71.9**	**79.1**	**90.1**	**89.3**	**89.3**	**90.5**	**92.4**	**90.9**	**91.8**	**93.5**	**96.0**	**97.9**	**92.8**	**96.7**	**34%**
Gasoline	40.5	43.2	50.0	48.3	46.8	46.8	47.5	45.6	46.1	46.5	47.1	47.5	45.8	47.2	**16%**
Diesel	21.9	21.6	25.7	26.4	27.6	28.5	29.4	29.6	29.8	30.5	31.7	32.5	30.3	31.9	**46%**
CNG	1.2	1.4	1.7	1.8	2.0	2.1	2.2	2.2	2.1	2.2	2.3	2.4	2.2	2.3	**98%**
LPG	8.3	12.9	12.8	12.8	12.9	13.1	13.3	13.5	13.7	14.3	15.0	15.5	14.5	15.3	**84%**

Transportation and Non-Transportation Mobile Total[l]	**1,691.4**	**2,091.4**	**2,011.0**	**1,975.6**	**1,956.0**	**1,960.9**	**1,992.1**	**1,989.2**	**2,026.7**	**2,050.5**	**2,086.1**	**2,090.3**	**1,832.8**	**2,058.1**	**22%**

+ Does not exceed 0.05 MMT CO_2 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 CO_2 estimates in this Inventory are based on data from FHWA Highway Statistics Table MF-21, MF-27 and ratios developed from MOVES3 to apportion FHWA fuel consumption data to vehicle type and fuel type. MOVES3 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 CH_4 and N_2O emissions estimates, gasoline and diesel highway vehicle mileage estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2021). Total VMT estimates were then allocated using EPA's MOVES3 model ratios of VMT per vehicle class to total VMT. Data for 2021 is proxied using FHWA Traffic Volume Trends Data.

[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 CH_4 and N_2O from U.S. Territories are included in this value, but not CO_2 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 2021 is not available. Diesel consumption data for 2014-2021 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 CO_2 from natural gas used to power natural gas pipelines; does not include emissions from electricity use or non-CO_2 gases.

[i] Note that the method used to estimate CO_2 emissions from non-transportation mobile sources in this supplementary information table differs from the method used to estimate CO_2 in the industrial and commercial sectors in the Inventory, which include CO_2 emissions from all non-transportation mobile sources (see Section 3.1 for the methodology for estimating CO_2 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 CH_4 and N_2O emissions from mobile combustion relative to previous Inventories are largely due to updates made to the Motor Vehicle Emissions Simulator (MOVES3) 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 "CH_4 and N_2O from Mobile Combustion" for more detail. This year's Inventory uses the Nonroad component of MOVES3 for years 1999 through 2021. 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.

Table A-96: Transportation and Mobile Source Emissions by Gas (MMT CO_2 Eq.)

	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Percent Change 1990-2021
CO_2 [a]	1,645.7	1,981.3	1,909.9	1,881.3	1,869.3	1,881.5	1,917.7	1,919.1	1,960.7	1,988.8	2,027.2	2,031.6	1,778.9	2,004.6	22%
N_2O	38.4	48.3	29.2	28.1	26.1	24.3	22.4	20.6	19.5	18.5	17.5	19.0	16.1	17.1	-55%
CH_4	7.2	5.6	3.7	3.6	3.5	3.4	3.2	3.1	3.0	2.9	2.9	2.9	2.6	2.6	-64%
HFC	+	56.2	68.1	62.4	57.1	51.6	48.8	46.3	43.3	40.1	38.5	36.7	35.0	33.6	NA
Total[b]	**1,691.3**	**2,091.4**	**2,010.9**	**1,975.5**	**1,955.9**	**1,960.8**	**1,992.0**	**1,989.1**	**2,026.6**	**2,050.4**	**2,086.0**	**2,090.2**	**1,832.7**	**2,057.9**	**22%**

+ Does not exceed 0.05 MMT CO_2 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] The method used to estimate CO_2 emissions from non-transportation mobile sources in this supplementary information table differs from the method used to estimate CO_2 in the industrial and commercial sectors in the Inventory, which include CO_2 emissions from all non-transportation mobile sources (see Section 3.1 for the methodology for estimating CO_2 emissions from fossil fuel combustion in this Inventory).

[b] Total excludes other emissions from electricity generation and CH_4 and N_2O emissions from electric rail.

Notes: Gasoline and diesel highway vehicle fuel consumption estimates used to develop CO_2 estimates in this Inventory are based on data from FHWA Highway Statistics Table MF-21, MF-27 and ratios developed from MOVES3 to apportion FHWA fuel consumption data to vehicle type and fuel type. For mobile CH_4 and N_2O emissions estimates, gasoline and diesel highway vehicle miles travelled estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2022). VMT estimates were then allocated to vehicle type using ratios of VMT per vehicle type to total VMT, derived from EPA's MOVES3 model. Data for 2021 is proxied using FHWA Traffic Volume Trends Data.

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.

Figure A-4: Domestic Greenhouse Gas Emissions by Mode and Vehicle Type, 1990 to 2021

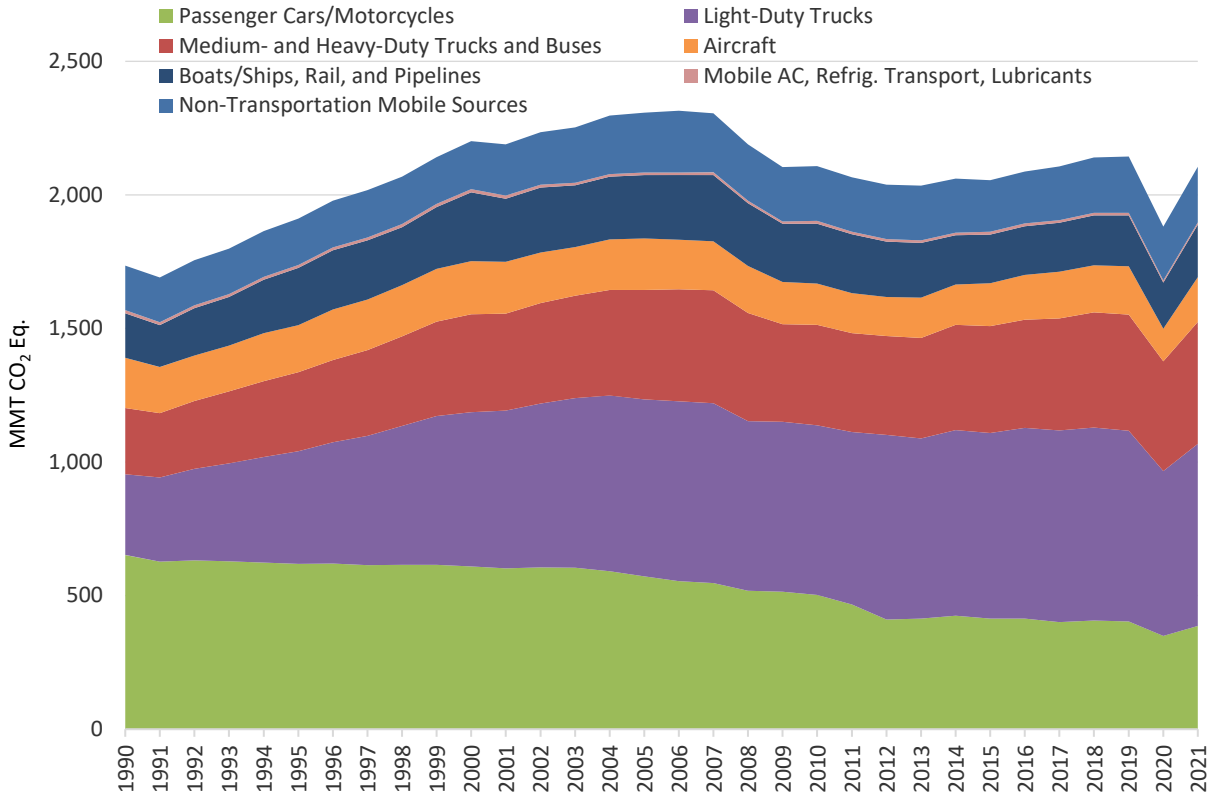

Table A-97: Greenhouse Gas Emissions from Passenger Transportation (MMT CO_2 Eq.)

Vehicle Type	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Percent Change 1990-2021
On-Road Vehicles[a,b]	**967.7**	**1,206.3**	**1,154.4**	**1,129.7**	**1,120.1**	**1,107.3**	**1141.0**	**1,130.8**	**1,149.5**	**1142.3**	**1,153.8**	**1,142.0**	**989.5**	**1,094.7**	**13%**
Passenger Cars	648.4	604.8	496.2	460.4	403.1	406.7	417.3	406.8	407.4	393.7	399.7	396.3	342.5	379.2	**-42%**
Light-Duty Trucks	302.5	577.6	635.1	645.4	691.2	674.6	695.7	695.3	712.8	718.0	722.3	713.3	616.8	681.4	**125%**
Buses	13.4	19.4	16.7	17.6	18.7	19.2	21.0	21.9	22.1	23.5	24.4	24.9	23.6	26.5	**97%**
Motorcycles	3.4	4.4	6.4	6.3	7.1	6.8	7.0	6.8	7.2	7.2	7.4	7.5	6.7	7.6	**123%**
Aircraft	**133.6**	**151.5**	**124.3**	**121.7**	**118.1**	**122.6**	**120.4**	**130.0**	**139.3**	**143.6**	**144.4**	**149.3**	**99.1**	**142.2**	**6%**
General Aviation	42.0	35.3	26.3	22.2	19.6	23.3	20.5	26.5	34.8	32.9	32.4	33.3	20.2	63.3	**51%**
Commercial Aircraft	91.6	116.1	97.9	99.5	98.5	99.4	99.9	103.5	104.6	110.6	112.0	116.0	78.9	78.9	**-14%**
Recreational Boats	**17.2**	**17.3**	**14.5**	**14.0**	**13.7**	**13.4**	**13.2**	**13.3**	**13.4**	**13.6**	**13.7**	**13.8**	**12.9**	**13.5**	**-21%**
Passenger Rail	**4.4**	**5.2**	**6.2**	**5.9**	**5.5**	**5.8**	**5.7**	**5.4**	**5.2**	**5.1**	**4.5**	**4.2**	**3.4**	**3.4**	**-23%**
Total	**1,122.9**	**1,380.3**	**1,299.3**	**1,271.3**	**1,257.5**	**1,249.1**	**1,280.4**	**1,279.5**	**1,307.5**	**1,304.6**	**1,316.4**	**1,309.3**	**1,104.9**	**1,253.8**	**-2%**

[a] The current Inventory includes updated vehicle population data based on the MOVES3 Model.

[b] Gasoline and diesel highway vehicle fuel consumption estimates used to develop CO_2 estimates in this Inventory are based on data from FHWA Highway Statistics Table MF-21, MF-27 and ratios developed from MOVES3 to apportion FHWA fuel consumption data to vehicle type and fuel type.. For mobile CH_4 and N_2O emissions estimates, gasoline and diesel highway vehicle mileage estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2021). These total mileage estimates are combined with MOVES3 model ratios to apportion VMT.

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. The Inventory uses the Nonroad component of MOVES3 for years 1999 through 2020. 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).

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.

Table A-98: Greenhouse Gas Emissions from Domestic Freight Transportation (MMT CO_2 Eq.)

By Mode	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Percent Change 1990-2021
Trucking[a,b]	234.3	345.5	356.6	349.8	348.8	354.9	369.3	375.8	380.1	393.2	404.3	407.1	384.3	427.7	83%
Freight Rail	34.5	41.3	37.8	39.1	38.3	38.6	40.5	38.5	35.0	36.2	38.0	35.4	30.5	31.8	-8%
Ships and Non-Recreational Boats	29.8	48.6	30.5	32.5	26.6	26.3	15.9	20.5	27.3	30.3	27.4	26.3	19.5	36.4	22%

Pipelines[c]	36.0		35.4		37.8	38.5	41.0	46.6	39.7	38.9	39.5	41.6	50.2	58.2	57.9	64.2	78%
Commercial Aircraft	19.2		24.3		16.3	16.0	15.7	15.9	16.2	16.5	16.8	18.4	18.7	19.3	13.1	13.1	-31%
Total	**353.8**		**495.1**		**478.9**	**475.9**	**470.4**	**482.3**	**481.6**	**490.1**	**498.6**	**519.7**	**538.6**	**546.3**	**505.4**	**573.3**	**62%**

[a] The current Inventory includes updated vehicle population data based on the MOVES3 Model.

[b] Gasoline and diesel highway vehicle fuel consumption estimates used to develop CO_2 estimates in this Inventory are based on data from FHWA Highway Statistics Table MF-21, MF-27 and ratios developed from MOVES3 to apportion FHWA fuel consumption data to vehicle type and fuel type. For mobile CH_4 and N_2O emissions estimates, gasoline and diesel highway vehicle mileage estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2021) and MOVES3 model ratios of VMT per vehicle class to total VMT.

[c] Pipelines reflect CO_2 emissions from natural gas-powered pipelines transporting natural gas.

Notes: Data from DOE (1993 through 2021) 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 MOVES3 for years 1999 through 2020. 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).

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.

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 GHGs in this Inventory. The model is not used to directly estimate GHG emissions. With respect to estimating CO_2 emissions from the transportation sector, MOVES is used to estimate fuel use by recreational boats. For non-CO_2 GHG 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 CH_4 and N_2O 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 GHG Emissions from Transportation and Other Mobile Sources section of this Annex provides estimates of CO_2 from non-transportation mobile sources, developed from the Nonroad component of MOVES.

The MOtor Vehicle Emission Simulator (EPA 2021a) 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. MOVES3 is the latest official version of MOVES; previous versions of the model include MOVES2010 and MOVES2014.

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 onroad 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% and 10%, respectively, of FHWA estimates. For earlier years, MOVES3 gasoline consumption estimates are within 9% of FHWA data while MOVES3 diesel fuel consumption is within 20% 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 (2021e)) 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 – TO BE UPDATED FOR FINAL INVENTORY REPORT

IPCC Tier 3B Method: Commercial aircraft jet fuel burn and carbon dioxide (CO_2) emissions estimates were developed by the U.S. Federal Aviation Administration (FAA) using radar-informed data from the FAA Enhanced Traffic Management System (ETMS) for 2000 through 2019 as modeled with the Aviation Environmental Design Tool (AEDT). This bottom-up approach is built from modeling dynamic aircraft performance for each flight occurring within an individual calendar year. The analysis incorporates data on the aircraft type, date, flight identifier, departure time, arrival time, departure airport, arrival airport, ground delay at each airport, and real-world flight trajectories. To generate results for a given flight within AEDT, the radar-informed aircraft data is correlated with engine and aircraft performance data to calculate fuel burn and exhaust emissions. Information on exhaust emissions for in-production aircraft engines comes from the International Civil Aviation Organization (ICAO) Aircraft Engine Emissions Databank (EDB). This bottom-up approach is in accordance with the Tier 3B method from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*.

International Bunkers: The IPCC guidelines define international aviation (International Bunkers) as emissions from flights that depart from one country and arrive in a different country. Bunker fuel emissions estimates for commercial aircraft were developed for this report for 2000 through 2020 using the same radar-informed data modeled with AEDT. Since this process builds estimates from flight-specific information, the emissions estimates for commercial aircraft can include emissions associated with the U.S. Territories (i.e., American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other U.S. Pacific Islands). However, to allow for the alignment of emissions estimates for commercial aircraft with other data that is provided without the U.S. Territories, this annex includes emissions estimates for commercial aircraft both with and without the U.S. Territories included.

Time Series and Analysis Update: The FAA incrementally improves the consistency, robustness, and fidelity of the CO_2 emissions modeling for commercial aircraft, which is the basis of the Tier3B inventories presented in this report. While the FAA does not anticipate significant changes to the AEDT model in the future, recommended improvements are limited by budget and time constraints, as well as data availability. For instance, previous reports included reported annual CO_2 emission estimates for 2000 through 2005 that were modeled using the FAA's System for assessing Aviation's Global Emissions (SAGE). That tool and its capabilities were significantly improved after it was incorporated and evolved into AEDT. For this report, the AEDT model was used to generate annual CO_2 emission estimates for 2000, 2005, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019 and 2020 only. The reported annual CO_2 emissions values for 2001 through 2004 were estimated from the previously reported SAGE data. Likewise, CO_2 emissions values for 2006 through 2009 were estimated by interpolation to preserve trends from past reports.

Commercial aircraft radar data sets are not available for years prior to 2000. Instead, the FAA applied a Tier3B methodology by developing Official Airline Guide (OAG) schedule-informed estimates modeled with AEDT and great circle trajectories for 1990, 2000 and 2010. The ratios between the OAG schedule-informed and the radar-informed inventories for the years 2000 and 2010 were applied to the 1990 OAG scheduled-informed inventory to generate the best possible CO_2 inventory estimate for commercial aircraft in 1990. The resultant 1990 CO_2 inventory served as the reference for generating additional 1995-1999 emissions estimates, which were established using previously available trends. International consumption estimates for 1991-1999 and domestic consumption estimates for 1991-1994 are calculated using fuel consumption estimates from the Bureau of Transportation Statistics (DOT 1991 through 2013), adjusted based on the ratio of DOT to AEDT data.

Notes on the 1990 CO_2 Emissions Inventory for Commercial Aircraft: There are uncertainties associated with the modeled 1990 data that do not exist for the modeled 2000 to 2020 data. Radar-based data is not available for 1990. The OAG schedule information generally includes fewer carriers than radar information, and this will result in a different fleet mix, and in turn, different CO_2 emissions than would be quantified using a radar-based data set. For this reason, the FAA adjusted the OAG-informed schedule for 1990 with a ratio based on radar-informed information. In addition, radar trajectories are also generally longer than great circle trajectories. While the 1990 fuel burn data was adjusted to address these differences, it inherently adds greater uncertainty to the revised 1990 commercial aircraft CO_2 emissions as compared to data from 2000 forward. Also, the revised 1990 CO_2 emissions inventory now reflects only commercial aircraft jet fuel consumption, while previous reports may have aggregated jet fuel sales data from non-commercial

aircraft into this category. Thus, it would be inappropriate to compare 1990 to future years for other than qualitative purposes.

The 1990 commercial aircraft CO_2 emissions inventory is approximately 18 percent lower than the 2020 CO_2 emissions inventory. It is important to note that the distance flown increased by more than 63 percent over this 31- year period and that fuel burn and aviation activity trends over the past two decades indicate significant improvements in commercial aviation's ability to provide increased service levels while using less fuel.[118]

Methane Emissions: Contributions of methane (CH_4) emissions from commercial aircraft are reported as zero. Years of scientific measurement campaigns conducted at the exhaust exit plane of commercial aircraft gas turbine engines have repeatedly indicated that CH_4 emissions are consumed over the full mission flight envelope (*Aircraft Emissions of Methane and Nitrous Oxide during the Alternative Aviation Fuel Experiment*, Santoni et al., Environ. Sci. Technol., 2011, 45, 7075-7082). As a result, the U.S. Environmental Protection Agency published that "*…methane is no longer considered to be an emission from aircraft gas turbine engines burning Jet A at higher power settings and is, in fact, consumed in net at these higher powers.*"[119] In accordance with the following statements in the *2006 IPCC Guidelines* (IPCC 2006), the FAA does not calculate CH_4 emissions for either the domestic or international bunker commercial aircraft jet fuel emissions inventories. *"Methane (CH_4) may be emitted by gas turbines during idle and by older technology engines, but recent data suggest that little or no CH_4 is emitted by modern engines." "Current scientific understanding does not allow other gases (e.g., N_2O and CH_4) to be included in calculation of cruise emissions."* (IPCC 1999)

Results: For each inventory calendar year the graph and table below include four jet fuel burn values. These values are comprised of domestic and international fuel burn totals for the U.S. 50 States and the U.S. 50 States + Territories. Data are presented for domestic defined as jet fuel burn from any commercial aircraft flight departing and landing in the U.S. 50 States and for the U.S. 50 States + Territories. The data presented as international is respective of the two different domestic definitions, and represents flights departing from the specified domestic area and landing anywhere in the world outside of that area.

Note that the graph and table present more fuel burn for the international U.S. 50 States + Territories than for the international U.S. 50 States. This is because the flights between the 50 states and U.S. Territories are "international" when only the 50 states are defined as domestic, but they are "domestic" for the U.S. 50 States + Territories definition.

[118] Additional information on the AEDT modeling process is available at: http://www.faa.gov/about/office_org/headquarters_offices/apl/research/models/.

[119] 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, http://www.epa.gov/otaq/aviation.htm.

Figure A-5: Commercial Aviation Fuel Burn for the United States and Territories

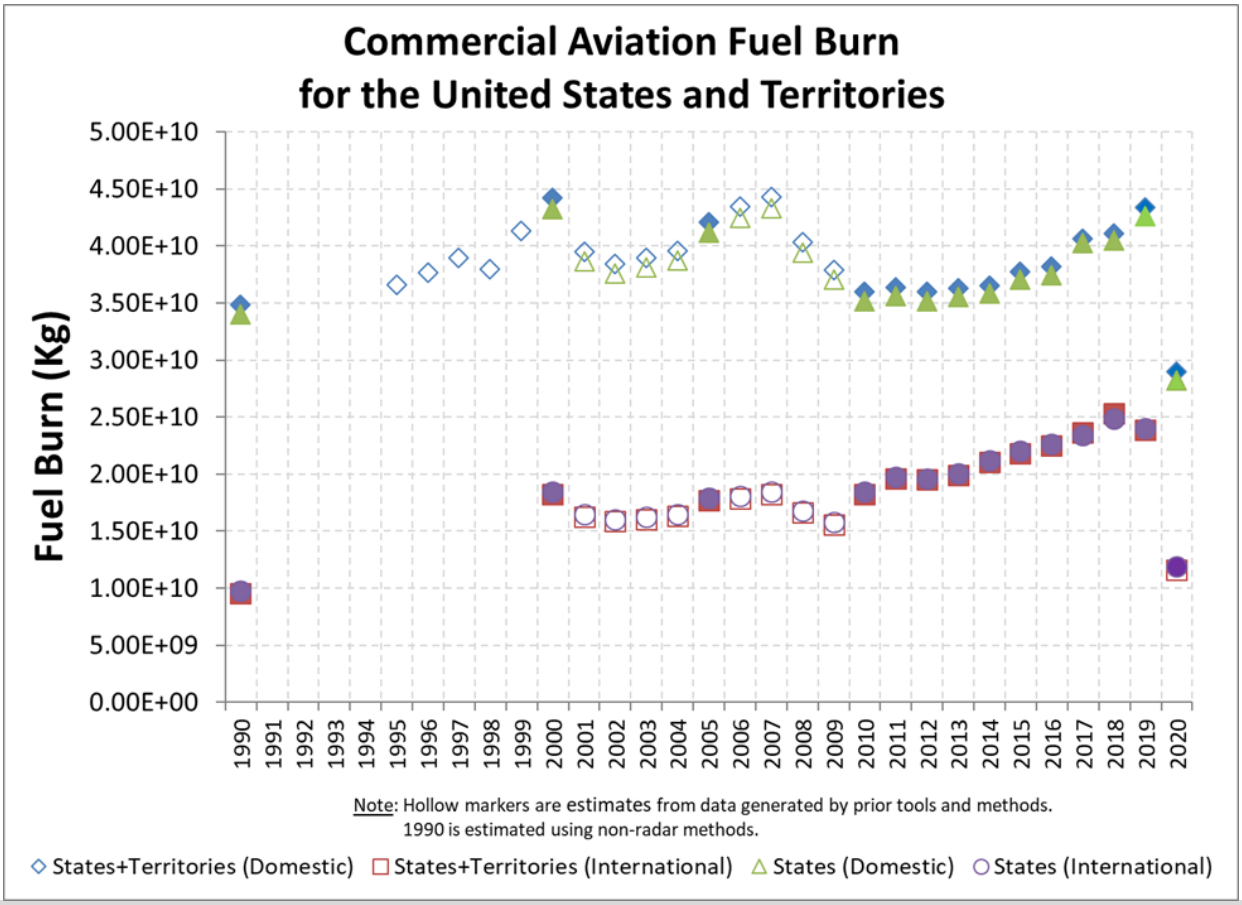

Table A-99: Commercial Aviation Fuel Burn for the United States and Territories

Year	Region	Distance Flown (nmi)	Fuel Burn (M Gallon)	Fuel Burn (TBtu)	Fuel Burn (Kg)	CO_2 (MMT)
1990	Domestic U.S. 50 States and U.S. Territories	4,057,195,988	11,568	1,562	34,820,800,463	109.9
	International U.S. 50 States and U.S. Territories	599,486,893	3,155	426	9,497,397,919	30.0
	Domestic U.S. 50 States	3,984,482,217	11,287	1,524	33,972,832,399	107.2
	International U.S. 50 States	617,671,849	3,228	436	9,714,974,766	30.7
1995[a]	Domestic U.S. 50 States and U.S. Territories	N/A	12,136	1,638	36,528,990,675	115.2
1996[a]	Domestic U.S. 50 States and U.S. Territories	N/A	12,492	1,686	37,600,624,534	118.6
1997[a]	Domestic U.S. 50 States and U.S. Territories	N/A	12,937	1,747	38,940,896,854	122.9
1998[a]	Domestic U.S. 50 States and U.S. Territories	N/A	12,601	1,701	37,930,582,643	119.7
1999[a]	Domestic U.S. 50 States and U.S. Territories	N/A	13,726	1,853	41,314,843,250	130.3
2000	Domestic U.S. 50 States and U.S. Territories	5,994,679,944	14,672	1,981	44,161,841,348	139.3
	International U.S. 50 States and U.S. Territories	1,309,565,963	6,040	815	18,181,535,058	57.4
	Domestic U.S. 50 States	5,891,481,028	14,349	1,937	43,191,000,202	136.3
	International U.S. 50 States	1,331,784,289	6,117	826	18,412,169,613	58.1
2001[a]	Domestic U.S. 50 States and U.S. Territories	5,360,977,447	13,121	1,771	39,493,457,147	124.6
	International U.S. 50 States and U.S. Territories	1,171,130,679	5,402	729	16,259,550,186	51.3
	Domestic U.S. 50 States	5,268,687,772	12,832	1,732	38,625,244,409	121.9
	International U.S. 50 States	1,191,000,288	5,470	739	16,465,804,174	51.9
2002[a]	Domestic U.S. 50 States and U.S. Territories	5,219,345,344	12,774	1,725	38,450,076,259	121.3
	International U.S. 50 States and U.S. Territories	1,140,190,481	5,259	710	15,829,987,794	49.9

	Domestic U.S. 50 States	5,129,493,877	12,493	1,687	37,604,800,905	118.6
	International U.S. 50 States	1,159,535,153	5,326	719	16,030,792,741	50.6
2003[a]	Domestic U.S. 50 States and U.S. Territories	5,288,138,079	12,942	1,747	38,956,861,262	122.9
	International U.S. 50 States and U.S. Territories	1,155,218,577	5,328	719	16,038,632,384	50.6
	Domestic U.S. 50 States	5,197,102,340	12,658	1,709	38,100,444,893	120.2
	International U.S. 50 States	1,174,818,219	5,396	728	16,242,084,008	51.2
2004[a]	Domestic U.S. 50 States and U.S. Territories	5,371,498,689	13,146	1,775	39,570,965,441	124.8
	International U.S. 50 States and U.S. Territories	1,173,429,093	5,412	731	16,291,460,535	51.4
	Domestic U.S. 50 States	5,279,027,890	12,857	1,736	38,701,048,784	122.1
	International U.S. 50 States	1,193,337,698	5,481	740	16,498,119,309	52.1
2005	Domestic U.S. 50 States and U.S. Territories	6,476,007,697	13,976	1,887	42,067,562,737	132.7
	International U.S. 50 States and U.S. Territories	1,373,543,928	5,858	791	17,633,508,081	55.6
	Domestic U.S. 50 States	6,370,544,998	13,654	1,843	41,098,359,387	129.7
	International U.S. 50 States	1,397,051,323	5,936	801	17,868,972,965	56.4
2006[a]	Domestic U.S. 50 States and U.S. Territories	5,894,323,482	14,426	1,948	43,422,531,461	137.0
	International U.S. 50 States and U.S. Territories	1,287,642,623	5,939	802	17,877,159,421	56.4
	Domestic U.S. 50 States	5,792,852,211	14,109	1,905	42,467,943,091	134.0
	International U.S. 50 States	1,309,488,994	6,015	812	18,103,932,940	57.1
2007[a]	Domestic U.S. 50 States and U.S. Territories	6,009,247,818	14,707	1,986	44,269,160,525	139.7
	International U.S. 50 States and U.S. Territories	1,312,748,383	6,055	817	18,225,718,619	57.5
	Domestic U.S. 50 States	5,905,798,114	14,384	1,942	43,295,960,105	136.6
	International U.S. 50 States	1,335,020,703	6,132	828	18,456,913,646	58.2
2008[a]	Domestic U.S. 50 States and U.S. Territories	5,475,092,456	13,400	1,809	40,334,124,033	127.3
	International U.S. 50 States and U.S. Territories	1,196,059,638	5,517	745	16,605,654,741	52.4
	Domestic U.S. 50 States	5,380,838,282	13,105	1,769	39,447,430,318	124.5
	International U.S. 50 States	1,216,352,196	5,587	754	16,816,299,099	53.1
2009[a]	Domestic U.S. 50 States and U.S. Territories	5,143,268,671	12,588	1,699	37,889,631,668	119.5
	International U.S. 50 States and U.S. Territories	1,123,571,175	5,182	700	15,599,251,424	49.2
	Domestic U.S. 50 States	5,054,726,871	12,311	1,662	37,056,676,966	116.9
	International U.S. 50 States	1,142,633,881	5,248	709	15,797,129,457	49.8
2010	Domestic U.S. 50 States and U.S. Territories	5,652,264,576	11,931	1,611	35,912,723,830	113.3
	International U.S. 50 States and U.S. Territories	1,474,839,733	6,044	816	18,192,953,916	57.4
	Domestic U.S. 50 States	5,554,043,585	11,667	1,575	35,116,863,245	110.8
	International U.S. 50 States	1,497,606,695	6,113	825	18,398,996,825	58.0
2011	Domestic U.S. 50 States and U.S. Territories	5,767,378,664	12,067	1,629	36,321,170,730	114.6
	International U.S. 50 States and U.S. Territories	1,576,982,962	6,496	877	19,551,631,939	61.7
	Domestic U.S. 50 States	5,673,689,481	11,823	1,596	35,588,754,827	112.3
	International U.S. 50 States	1,596,797,398	6,554	885	19,727,043,614	62.2
2012	Domestic U.S. 50 States and U.S. Territories	5,735,605,432	11,932	1,611	35,915,745,616	113.3
	International U.S. 50 States and U.S. Territories	1,619,012,587	6,464	873	19,457,378,739	61.4
	Domestic U.S. 50 States	5,636,910,529	11,672	1,576	35,132,961,140	110.8
	International U.S. 50 States	1,637,917,110	6,507	879	19,587,140,347	61.8
2013	Domestic U.S. 50 States and U.S. Territories	5,808,034,123	12,031	1,624	36,212,974,471	114.3
	International U.S. 50 States and U.S. Territories	1,641,151,400	6,611	892	19,898,871,458	62.8
	Domestic U.S. 50 States	5,708,807,315	11,780	1,590	35,458,690,595	111.9
	International U.S. 50 States	1,661,167,498	6,657	899	20,036,865,038	63.2
2014	Domestic U.S. 50 States and U.S. Territories	5,825,999,388	12,131	1,638	36,514,970,659	115.2
	International U.S. 50 States and U.S. Territories	1,724,559,209	6,980	942	21,008,818,741	66.3
	Domestic U.S. 50 States	5,725,819,482	11,882	1,604	35,764,791,774	112.8
	International U.S. 50 States	1,745,315,059	7,027	949	21,152,418,387	66.7
2015	Domestic U.S. 50 States and U.S. Territories	5,900,440,363	12,534	1,692	37,727,860,796	119.0
	International U.S. 50 States and U.S. Territories	1,757,724,661	7,227	976	21,752,301,359	68.6
	Domestic U.S. 50 States	5,801,594,806	12,291	1,659	36,997,658,406	116.7
	International U.S. 50 States	1,793,787,700	7,310	987	22,002,733,062	69.4
2016	Domestic U.S. 50 States and U.S. Territories	5,929,429,373	12,674	1,711	38,148,578,811	120.4

	International U.S. 50 States and U.S. Territories	1,817,739,570	7,453	1,006	22,434,619,940	70.8
	Domestic U.S. 50 States	5,827,141,640	12,422	1,677	37,391,339,601	118.0
	International U.S. 50 States	1,839,651,091	7,504	1,013	22,588,366,704	71.3
2017	Domestic U.S. 50 States and U.S. Territories	6,264,650,997	13,475	1,819	40,560,206,261	128.0
	International U.S. 50 States and U.S. Territories	1,944,104,275	7,841	1,059	23,602,935,694	74.5
	Domestic U.S. 50 States	6,214,083,068	13,358	1,803	40,207,759,885	126.9
	International U.S. 50 States	1,912,096,739	7,755	1,047	23,343,627,689	73.6
2018	Domestic U.S. 50 States and U.S. Territories	6,408,870,104	13,650	1,843	41,085,494,597	129.6
	International U.S. 50 States and U.S. Territories	2,037,055,865	8,402	1,134	25,291,329,878	79.8
	Domestic U.S. 50 States	6,318,774,158	13,425	1,812	40,410,478,534	127.5
	International U.S. 50 States	2,066,756,708	8,254	1,114	24,843,232,462	78.4
2019	Domestic U.S. 50 States and U.S. Territories	6,721,417,987	14,397	1,944	43,334,968,184	136.7
	International U.S. 50 States and U.S. Territories	1,980,425,952	7,908	1,068	23,803,403,228	75.1
	Domestic U.S. 50 States	6,617,074,577	14,131	1,908	42,535,165,758	134.2
	International U.S. 50 States	2,008,158,986	7,973	1,076	23,997,773,004	75.7
2020	Domestic U.S. 50 States and U.S. Territories	4,391,123,811	9,613	1,298	28,934,254,672	91.3
	International U.S. 50 States and U.S. Territories	910,801,671	3,863	521	11,626,780,467	36.7
	Domestic U.S. 50 States	4,297,034,877	9,358	1,263	28,167,145,166	88.9
	International U.S. 50 States	944,600,496	3,954	534	11,900,792,661	37.5

NA (Not Applicable)

[a] Estimates for these years were derived from previously reported tools and methods.

1

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3.4. Methodology for Estimating CH_4 Emissions from Coal Mining

EPA uses an IPCC Tier 3 method for estimating CH_4 emissions from underground mining and an IPCC Tier 2 method for estimating CH_4 emissions from surface mining and post-mining activities (for both coal production from underground mines and surface mines). The methodology for estimating CH_4 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 CH_4 liberated. The CH_4 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 CH_4 Liberated and CH_4 Emitted from Underground Mines

Underground mines generate CH_4 from ventilation systems and degasification systems. Some mines recover and use the generated CH_4, thereby reducing emissions to the atmosphere. Total CH_4 emitted from underground mines equals the CH_4 liberated from ventilation systems, plus the CH_4 liberated from degasification systems, minus CH_4 recovered and used.

Step 1.1: Estimate CH_4 Liberated from Ventilation Systems

All coal mines with detectable CH_4 emissions use ventilation systems to ensure that CH_4 levels remain within safe concentrations. Many coal mines do not have detectable levels of CH_4; 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 CH_4 concentration levels at underground mines. MSHA maintains a database of measurement data from all underground mines with detectable levels of CH_4 in their ventilation air (MSHA 2022).[120] Based on quarterly measurements, MSHA estimates average daily CH_4 liberated at each of these underground mines.

For 1990 through 1999, average daily CH_4 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 2021, the average daily CH_4 emission rate for each mine is determined using the CH_4 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 CH_4 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 CH_4 per year (about 17,525 MT CO_2 Eq.)—have been required to report to EPA's GHGRP (EPA 2022).[121] Mines that report to EPA's GHGRP must report quarterly measurements of CH_4 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 CH_4 concentrations.

Since 2013, ventilation emission estimates have been calculated based on both EPA's GHGRP[122] data submitted by underground mines, and on mine-specific CH_4 measurement data obtained directly from MSHA for the remaining mines.

[120] 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.

[121] Underground coal mines report to EPA under subpart FF of EPA's GHGRP (40 CFR part 98). In 2021, 60 underground coal mines reported to the program.

[122] 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).

The CH_4 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-100: 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)

[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.

Step 1.2: Estimate CH_4 Liberated from Degasification Systems

Coal mines use several types of degasification systems to remove CH_4, including pre-mining vertical and horizontal wells (to recover CH_4 before mining) and post-mining vertical wells and horizontal boreholes (to recover CH_4 during mining of the coal seam). Post-mining gob wells and cross-measure boreholes recover CH_4 from the overburden (i.e., gob area) after mining of the seam (primarily in longwall mines).

Twenty mines employed degasification systems in 2021, and all of these mines reported the CH_4 liberated through these systems to the EPA's GHGRP (EPA 2022). Twelve of the 20 mines with degasification systems had operational CH_4 recovery and use projects, including two mines with 2 recovery and use projects each, and the other eight reported emitting CH_4 from degasification systems to the atmosphere. Several of the mines venting CH_4 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 CH_4 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 CH_4 liberated from degasification systems. Data reported to EPA's GHGRP were used exclusively to estimate CH_4 liberated from degasification systems at 15 of the 20 mines that used degasification systems in 2021.

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.[123] 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 four mines with degasification systems that include pre-mining wells that were mined through in 2021, 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 2022; DMME 2022; WVGES 2022; JWR 2010; El Paso 2009; ERG 2022). For pre-mining wells, the cumulative CH_4 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 CH_4 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 CH_4 liberated as CH_4 destroyed and vice versa. Other errors include reporting CH_4 destroyed without reporting any CH_4 liberated by degasification systems. In the rare cases where GHGRP data are inaccurate and gas sales data are unavailable, estimates of CH_4 liberated are based on historical CH_4 liberation rates. No QA/QC issues or errors were identified in the 2021 subpart FF data.

Step 1.3: Estimate CH_4 Recovered from Ventilation and Degasification Systems, and Utilized or Destroyed (Emissions Avoided)

There were 12 active coal mines with operational CH_4 recovery and use projects in 2021, including two mines that had two recovery and use projects, each. Thirteen of these projects involved degasification systems, in place at twelve mines, and one involved ventilation air methane (VAM). Ten of these mines sold the recovered CH_4 to a pipeline, including one mine that used CH_4 to fuel a thermal coal dryer. One mine destroyed CH_4 using flares and one mine destroyed the recovered CH_4 (VAM) using Regenerative Thermal Oxidation (RTO) without energy recovery and enclosed flares. One mine used CH_4 to heat mine ventilation air, however data are unavailable for estimating CH_4 recovery at this mine.

The CH_4 recovered and used (or destroyed) at the twelve coal mines described above were estimated using the following methods:

- EPA's GHGRP data was exclusively used to estimate the CH_4 recovered and used from six mines that deployed degasification systems in 2021. Based on weekly measurements of gas flow and CH_4 concentrations, the GHGRP summary data for degasification destruction at each mine were added together to estimate the CH_4 recovered and used from degasification systems.
- State sales data were used to supplement the GHGRP data to estimate CH_4 recovered and used from five mines that deployed degasification systems in 2021 (DMME 2022; GSA 2022; ERG 2022; and WVGES 2022). Four of these mines intersected pre-mining wells in 2021. Supplemental information was used for these mines because estimating CH_4 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 2021 data came from state gas production databases (DMME 2022; GSA 2022; ERG 2022; and WVGES 2022), as well as mine-specific information on the timing of mined-through, pre-mining wells (JWR 2010; El Paso 2009, ERG 2019-2022). For pre-mining wells, the cumulative CH_4 production from the wells was totaled using gas sales data, and was considered to be CH_4 recovered and used from the mine's degasification system in the year in which the well was mined through.
- For the single mine that employed VAM for CH_4 recovery and use, the estimates of CH_4 recovered and used were obtained from the mine's offset verification statement (OVS) submitted to the California Air Resources Board (CARB) (McElroy OVS 2022).

Step 2: Estimate CH_4 Emitted from Surface Mines and Post-Mining Activities

Mine-specific data are not available for estimating CH_4 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*

[123] A well is "mined through" when coal mining development or the working face intersects the borehole or well.

Coal Report are multiplied by basin-specific gas contents and a 150 percent emission factor (to account for CH_4 from over- and under-burden) to estimate CH_4 emissions (King 1994; Saghafi 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 CH_4 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* CH_4 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 CH_4 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-101, which presents coal basin definitions by basin and by state.

The Energy Information Administration's *Annual Coal Report* (EIA 2022) 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-101. 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-102 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* CH_4 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; Saghafi 2013), the surface mining emission factor used was conservatively estimated to be 150 percent of the *in situ* CH_4 content of the basin. Furthermore, the post-mining emission factors used were estimated to be 25 to 40 percent of the average *in situ* CH_4 content in the basin. For this analysis, the post-mining emission factor was determined to be 32.5 percent of the *in situ* CH_4 content in the basin. Table A-103 presents the average *in situ* content for each basin, along with the resulting emission factor estimates.

Step 2.3: Estimate CH_4 Emitted

The total amount of CH_4 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-101 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-6, several coal basins span several states. Table A-102 shows annual underground, surface, and total coal production (in short tons) for each coal basin. Table A-103 shows the surface, post-surface, and post-underground emission factors used for estimating CH_4 emissions for each of the categories. For underground mines, Table A-104 presents annual estimates of CH_4 emissions for ventilation and degasification systems, and CH_4 recovered and used. Note: Totals may not sum due to independent rounding.

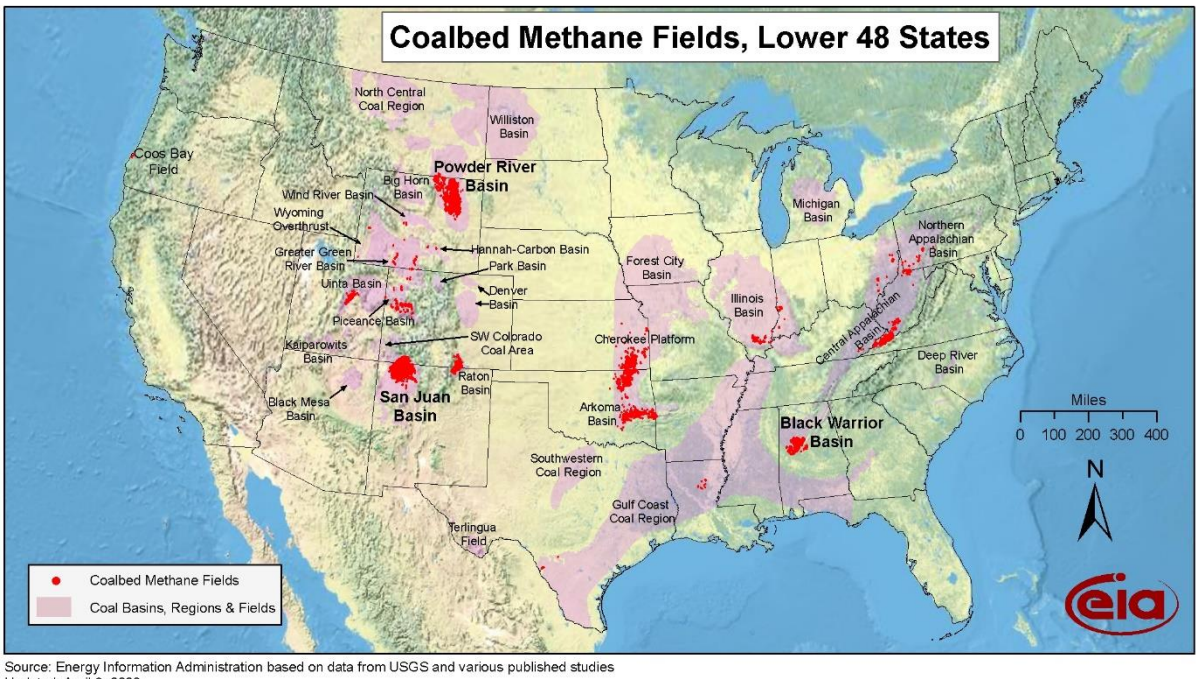
Table A-105 presents annual estimates of total CH_4 emissions from underground, post-underground, surface, and post-surface activities.

Table A-101: 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
South West 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	South West and Rockies Basin
Arkansas	West Interior Basin
California	South West and Rockies Basin

Colorado	South West 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	South West 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	South West 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-6: Locations of U.S. Coal Basins



Source: Energy Information Administration based on data from USGS and various published studies
Updated: April 8, 2009

Table A-102: Annual Coal Production (Thousand Short Tons)

Basin	1990	2005	2017	2018	2019	2020	2021
Underground Coal Production	**423,556**	**368,612**	**273,129**	**275,361**	**267,373**	**195,528**	**220,597**
N. Appalachia	103,865	111,151	97,741	97,070	97,905	71,998	84,265
Cent. Appalachia	198,412	123,082	46,053	45,306	39,957	30,249	34,562
Warrior	17,531	13,295	10,491	12,199	11,980	10,451	7,959
Illinois	69,167	59,180	80,855	85,416	81,061	54,334	62,667
S. West/Rockies	32,754	60,866	30,047	25,387	27,257	20,049	20,702
N. Great Plains	1,722	572	7,600	9,777	9,213	8,447	10,442
West Interior	105	465	343	206	0	0	0
Northwest	0	0	0	0	0	0	0
Surface Coal Production	**602,753**	**762,190**	**500,782**	**480,080**	**438,445**	**339,450**	**356,203**
N. Appalachia	60,761	28,873	9,396	9,219	8,476	6,215	6,677
Cent. Appalachia	94,343	112,222	31,796	33,799	32,742	17,921	20,299
Warrior	11,413	11,599	4,974	5,523	4,841	4,288	4,581
Illinois	72,000	33,703	22,427	21,405	18,591	13,098	9,713
S. West/Rockies	43,863	42,756	19,390	19,599	18,394	13,420	12,872
N. Great Plains	249,356	474,056	372,874	362,664	329,164	262,968	283,424
West Interior	64,310	52,262	38,966	26,969	25,261	20,519	17,595
Northwest	6,707	6,720	959	902	975	1,021	1,042
Total Coal Production	**1,026,309**	**1,130,802**	**773,911**	**755,442**	**705,818**	**534,978**	**576,800**
N. Appalachia	164,626	140,023	107,137	106,289	106,381	78,213	90,942
Cent. Appalachia	292,755	235,305	77,848	79,105	72,700	48,170	54,861
Warrior	28,944	24,894	15,464	17,723	16,822	14,739	12,540
Illinois	141,167	92,883	103,282	106,821	99,652	67,432	72,380
S. West/Rockies	76,617	103,622	49,437	44,987	45,652	33,469	33,574
N. Great Plains	251,078	474,629	380,474	372,441	338,376	271,415	293,866
West Interior	64,415	52,727	39,309	27,175	25,261	20,519	17,595
Northwest	6,707	6,720	959	902	975	1,021	1,042

Note: Totals may not sum due to independent rounding.

Table A-103: Coal Underground, Surface, and Post-Mining CH_4 Emission Factors (ft^3 per Short Ton)

Basin	Surface Average *In Situ* Content	Underground Average *In Situ* 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-104: Underground Coal Mining CH_4 Emissions (Billion Cubic Feet)

Activity	1990	2005	2017	2018	2019	2020	2021
Ventilation Output	112	75	78	73	62	60	57
Adjustment Factor for Mine Data	98%	98%	100%	100%	100%	100%	100%
Adjusted Ventilation Output	114	77	78	73	62	60	57
Degasification System Liberated	54	47	42	47	42	39	38
Total Underground Liberated	168	124	121	120	104	99	95
Recovered & Used	(14)	(37)	(36)	(39)	(33)	(34)	(34)
Total	**154**	**87**	**84**	**81**	**71**	**65**	**61**

Note: Totals may not sum due to independent rounding.

Table A-105: Total Coal Mining CH_4 Emissions (Billion Cubic Feet)

Activity	1990	2005	2017	2018	2019	2020	2021
Underground Mining	154	87	84	81	71	65	61
Surface Mining	22	25	15	15	13	10	11
Post-Mining (Underground)	19	16	11	11	11	8	9
Post-Mining (Surface)	5	5	3	3	3	2	2
Total	**200**	**133**	**114**	**110**	**98**	**86**	**83**

Note: Totals may not sum due to independent rounding.

Table A-106: Total Coal Mining CH_4 Emissions by State (Million Cubic Feet)

State	1990	2005	2017	2018	2019	2020	2021
Alabama	32,097	15,831	11,044	12,119	9,494	9,767	8,220
Alaska	50	42	28	26	28	30	30
Arizona	151	161	83	87	51	0	0
Arkansas	5	+	770	71	0	0	0
California	1	0	0	0	0	0	0
Colorado	10,187	13,441	1,940	1,616	1,730	1,380	1,392
Illinois	10,180	6,488	8,513	6,530	5,661	4,100	4,267
Indiana	2,232	3,303	6,036	6,729	6,807	6,067	6,388
Iowa	24	0	0	0	0	0	0
Kansas	45	11	0	0	0	0	0
Kentucky	10,018	6,898	4,636	4,636	2,264	1,765	2,164
Louisiana	64	84	42	129	36	14	6
Maryland	474	361	152	113	119	92	113
Mississippi	0	199	146	165	151	145	179
Missouri	166	37	15	16	12	10	3
Montana	1,373	1,468	1,102	1,172	1,038	775	816
New Mexico	363	2,926	1,728	1,360	1,446	723	1,661
North Dakota	299	306	294	303	276	270	271
Ohio	4,406	3,120	1,473	1,342	1,283	793	852
Oklahoma	226	825	2,407	2,317	116	367	+
Pennsylvania	21,864	18,605	19,662	20,695	23,528	18,931	19,100
Tennessee	276	115	14	23	17	7	0
Texas	1,119	922	730	498	468	395	346
Utah	3,587	4,787	678	629	811	845	770
Virginia	46,041	8,649	7,663	7,051	6,959	6,726	6,198
Washington	146	154	0	0	0	0	0
West Virginia	48,335	29,745	33,182	28,736	25,556	24,277	21,420
Wyoming	6,671	14,745	11,497	13,201	10,409	8,099	8,621
Total	**200,399**	**133,224**	**113,837**	**109,565**	**98,262**	**85,579**	**82,817**

+ 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 CH_4 liberated, minus CH_4 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.

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3.5. Methodology for Estimating CH_4, CO_2, and N_2O Emissions from Petroleum Systems

For details on the emissions, emission factors, activity data, data sources, and methodologies for each year from 1990 to 2021 please see the spreadsheet file annexes for the current (i.e., 1990 to 2021) Inventory, available at https://www.epa.gov/ghgemissions/stakeholder-process-natural-gas-and-petroleum-systems-1990-2021-inventory.

As described in the main body text on Petroleum Systems, the Inventory methodology involves the calculation of CH_4, CO_2, and N_2O 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.

TO BE UPDATED FOR FINAL INVENTORY REPORT

Emission Factors

Table 3.5-2, Table 3.5-7, and Table 3.5-10 show CH_4, CO_2, and N_2O 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 CH_4, CO_2, and N_2O 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 CH_4 and non-combustion-related CO_2 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 CH_4 emission factors for CH_4-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 2021a) 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. For chemical injection pumps, the estimate is calculated with an emission factor developed with GHGRP data, which is based on the previous GRI/EPA factor but takes into account operating hours. 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 CO_2 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. Produced Water CH_4 estimates are calculated using annual produced water quantities (Enverus DrillingInfo 2021 and EPA 2021b 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 2021a) and developed source level throughput-based emission factors from GHGRP data to estimate emissions in earlier time series years (1990-2009). 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 CH_4, CO_2, and N_2O emissions to GHGRP for all major activities since 2010. The national totals of these emissions for each activity were used for the 2010 to 2020

emissions. The national emission totals for each activity were divided by refinery feed rates for those four Inventory years (2010-2013) 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 2021a-d; EPA 2021a; EPA 2020). Emission factors are calculated for offshore facilities located in the Gulf of Mexico, Pacific, and Alaska regions.

When a CO_2-specific emission factor is not available for a source, the CO_2 emission factors were derived from the corresponding source CH_4 emission factors. The amount of CO_2 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 CO_2 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, CO_2 emission factors are estimated by multiplying the existing CH_4 emissions factors by a conversion factor, which is the ratio of CO_2 content to methane content for the particular stream. Ratios of CO_2 to CH_4 volume in emissions are presented in Table 3.5-1.

N_2O 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 N_2O 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, and chemical injection pumps, GHGRP Subpart W data were used to develop activity factors (i.e., 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 years 1990 to 1995. 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 GOM, 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 CO_2 and N_2O emission sources, the activity factors are the same as for CH_4 emission sources. In some instances, where recent time series data (e.g., year 2020) are not yet available, year 2019 or prior data were used as proxy.

Methodology for well counts and events

EPA used DrillingInfo and Prism, production databases maintained by Enverus Inc. (Enverus DrillingInfo 2021), 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. For more information on Enverus data processing, please see Annex 3.6 Methodology for Estimating CH_4, CO_2, and N_2O 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 CH_4, CO_2, and N_2O 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 CH_4, CO_2, and N_2O 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 1990-2020 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 CO_2 to CH_4 Volume in Emissions from Petroleum Production Field Operations
- Table 3.5-2: CH_4 Emissions (kt) for Petroleum Systems, by Segment and Source, for All Years
- Table 3.5-3: Average CH_4 Emission Factors (kg/unit activity) for Petroleum Systems Sources, for All Years
- Table 3.5-4: CH_4 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: CO_2 Emissions (kt) for Petroleum Systems, by Segment and Source, for All Years
- Table 3.5-8: Average CO_2 Emission Factors (kg/unit activity) for Petroleum Systems Sources, for All Years
- Table 3.5-9: CO_2 Emission Factors for Petroleum Systems, Data Sources/Methodology
- Table 3.5-10: N_2O Emissions (kt) for Petroleum Systems, by Segment and Source, for All Years
- Table 3.5-11: Average N_2O Emission Factors (kg/unit activity) for Petroleum Systems Sources, for All Years
- Table 3.5-12: N_2O Emission Factors for Petroleum Systems, Data Sources/Methodology
- Table 3.5-13: Annex 3.5 Electronic Tables – References

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3.6. Methodology for Estimating CH_4, CO_2, and N_2O Emissions from Natural Gas Systems

For details on the emissions, emission factors, activity data, data sources, and methodologies for each year from 1990 to 2020 please see the spreadsheet file annexes for the current (i.e., 1990 to 2020) Inventory, available at https://www.epa.gov/ghgemissions/stakeholder-process-natural-gas-and-petroleum-systems-1990-2021-inventory.

As described in the main body text on Natural Gas Systems, the Inventory methodology involves the calculation of CH_4, CO_2, and N_2O 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.

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Emission Factors

Table 3.6-1, Table 3.6-10, and Table 3.6-14 show CH_4, CO_2, and N_2O 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 CH_4, CO_2, and N_2O 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 CH_4 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 CH_4, CO_2, and N_2O 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 CH_4 and non-combustion-related CO_2 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 2021c), and others.

The EPA/GRI study developed over 80 CH_4 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 2021c) 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 EPA/GRI 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 EPA/GRI 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.

- For gas well completions without hydraulic fracturing, separate emissions estimates were developed for completions that vent and completions that flare.
- For liquids unloading, separate emissions estimates were developed for wells with plunger lifts and wells without plunger lifts.
- For condensate tanks, emissions estimates were developed for large and small tanks with flaring or vapor recovery control (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.
- Chemical injection pumps estimates are calculated with an emission factor developed with GHGRP data, which is based on the previous GRI/EPA factor but takes into account operating hours.

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 CO_2-specific emission factor is not available for a source, the CO_2 emission factors were derived from the corresponding source CH_4 emission factors using default gas composition data. CO_2 emission factors are estimated by multiplying the CH_4 emission factors by the ratio of the CO_2-to-CH_4 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).

N_2O 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 CO_2 was applied to calculate N_2O emission factors.

1990-2020 Inventory updates to emission factors

Summary information for emission factors for sources with revisions in this year's Inventory is below. The details are presented in memoranda,[124] *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2020: Update for Natural Gas Anomalous Leak Events*(EPA 2022a) and, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2020: Update for Post-Meter Emissions* (EPA 2022b), as well as the "Recalculations Discussion" section of the main body text.

EPA added well blowout emissions into the Inventory for three discrete well blowout events for this Inventory. The well blowouts occurred in Ohio in 2018 and in Texas and Louisiana in 2019.

The Inventory was updated to include an estimate for post-meter emissions. Post-meter emission factors are presented in the *2019 Refinement to the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories* under natural gas systems (IPCC 2019). Post-meter emission sources include certain leak emissions from residential and commercial appliances, industrial facilities and power plants, and natural gas fueled vehicles.

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 sources, either 2019 data were used as proxy for 2020 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.

[124] 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 DrillingInfo and Prism datasets from Enverus (Enverus 2021), 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 2012a).

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 applied a refracture rate of 1 percent (i.e., 1 percent of all wells with hydraulic fracturing are assumed to be refractured in a given year) to the total counts of wells with hydraulic fracturing from the Enverus datasets. 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-specific GHGRP data (applying year 2011 factors to earlier years). EPA assumed no REC use from 1990 through 2000, used a REC use percentage calculated from GHGRP data for 2011 forward, and then used linear interpolation between the 2000 and 2011 percentages. For flaring, EPA used an assumption of 10 percent (the average of the percent of completions and workovers that were flared in 2011 through 2013 GHGRP data) 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.

Reductions Data

As described under "Emission Factors" above, some sources in Natural Gas Systems rely on CH_4 emission factors developed from the 1996 EPA/GRI 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.

In 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 CH_4, CO_2, and N_2O 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 CH_4, CO_2, and N_2O emissions, respectively. As a final step for CH_4 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 CH_4 emissions for the Inventory. CH_4 potential emissions, reductions, and net emissions at a segment level are shown in Table 3.6-1. CO_2 emissions by segment and source are summarized in Table 3.6-10. N_2O emissions by segment and source are summarized in Table 3.6-14.

Refer to the 1990-2019 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: CH_4 Emissions (kt) for Natural Gas Systems, by Segment and Source, for All Years. Emissions presented here are net and include GasSTAR or Methane Challenge reductions.
- Table 3.6-2: Average CH_4 Emission Factors (kg/unit activity) for Natural Gas Systems Sources, for All Years
- Table 3.6-3: U.S. Production Sector CH_4 Content in Natural Gas by NEMS Region (General Sources)
- Table 3.6-4: U.S. Production Sector CH_4 Content in Natural Gas by NEMS Region (Gas Wells Without Hydraulic Fracturing)
- Table 3.6-5: U.S. Production Sector CH_4 Content in Natural Gas by NEMS Region (Gas Wells With Hydraulic Fracturing)
- Table 3.6-6: CH_4 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 CH_4 Reductions for Natural Gas Systems (kt)
- Table 3.6-10: CO_2 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 CO_2 Emission Factors (kg/unit activity) for Natural Gas Systems Sources, for All Years
- Table 3.6-13: CO_2 Emission Factors for Natural Gas Systems, Data Sources/Methodology
- Table 3.6-14: N_2O Emissions (kt) for Natural Gas Systems, by Segment and Source, for All Years
- Table 3.6-15: Average N_2O Emission Factors (kg/unit activity) for Natural Gas Systems Sources, for All Years
- Table 3.6-16: N_2O Emission Factors for Natural Gas Systems, Data Sources/Methodology
- Annex 3.6-17: Electronic Tables – References

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3.7. Methodology for Estimating CO_2, CH_4, and N_2O Emissions from the Incineration of Waste

Emissions of CO_2 from the combustion of waste include CO_2 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 CH_4 and N_2O. 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 CO_2 and non-CO_2 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 2021), 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 (CH_4) and nitrous oxide (N_2O) 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 CH_4 and N_2O for 2011 through 2021.

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).
- 2011-2021: MSW combustion tonnages are from EPA's GHGRP data.

Table A-107 provides the estimated tons of MSW combusted including and excluding tires.

Table A-107: Municipal Solid Waste Combusted (Short Tons)

Year	Waste Combusted *(excluding tires)*	Waste Combusted *(including tires)*
1990	33,344,839	33,766,239
2005	26,486,414	28,631,054
2017	28,574,258	30,310,598
2018	29,162,364	30,853,949
2019	28,174,311	29,821,141

2020	27,586,271	29,106,686
2021	27,867,446	29,261,446

Sources: *BioCycle*, EPA Facts and Figures, ERC, GHGRP, EIA, USTMA.

CO_2 Emissions from MSW Excluding Scrap Tires

Fossil CO_2 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 CO_2 emissions from GHGRP FLIGHT data for facilities classified as MSW combustors by the estimated tonnage from those facilities yielded an annual CO_2 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 CO_2 emission factor was proxied using an average of the CO_2 emission factors from years 2011 through 2021.

Finally, CO_2 emissions were calculated by multiplying the annual tonnage estimates, excluding tires, by the calculated emissions factor. Calculated fossil CO_2 emission factors are shown in Table A-108.

Table A-108: Calculated Fossil CO_2 Content per Ton Waste Combusted (kg CO_2/Short Ton Combusted)

	1990	2005	2017	2018	2019	2020	2021
CO_2 Emission Factors	366	366	360	361	363	377	365

CO_2 from Combustion of Synthetic Rubber and Carbon Black in Tires

Calculating emissions from tire combustion require two pieces of information: the amount of tires combusted and the C content of the tires. "2021 U.S. Scrap Tire Management Summary" (USTMA 2022) reports that 1,394 thousand of the 3,273 thousand tons of scrap tires generated in 2021 (approximately 43 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.[125] Table A-109 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 CO_2 emissions, as shown in Table A-110. 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-109 (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. Tire production and fuel use for 1990 through 2021 were taken from USTMA 2006; USTMA 2009; USTMA 2013; USTMA 2014; USTMA 2016; USTMA 2018; USTMA 2020; USTMA 2022. 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).

Table A-109: Elastomers Consumed in 2002 (kt)

Elastomer	Consumed	Carbon Content	Carbon Equivalent
Styrene butadiene rubber solid	**768**	**91%**	**700**
For Tires	660	91%	602

[125] The carbon content of tires (1,174 kt C) divided by the mass of rubber in tires (1,307 kt) equals 90 percent.

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-110: Scrap Tire Constituents and CO_2 Emissions from Scrap Tire Combustion in 2021

Material	Weight of Material (MMT)	Fraction Oxidized	Carbon Content	Emissions (MMT CO_2 Eq.)
Synthetic Rubber	0.3	98%	90%	1.0
Carbon Black	0.4	98%	100%	1.3
Total	**0.7**	**NA**	**NA**	**2.3**

NA (Not Applicable)

CH_4 and N_2O from the Combustion of Waste

Estimates of N_2O 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 2020a) and unpublished backup data (Schneider 2007). According to this methodology, emissions of N_2O from waste combustion are the product of the mass of waste combusted, an emission factor of N_2O emitted per unit mass of waste combusted, and an N_2O 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 N_2O/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 CH_4 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 CH_4 from waste combustion are the product of the mass of waste combusted and an emission factor of CH_4 emitted per unit mass of waste combusted. Similar to the N_2O emissions methodology, the mass of waste combusted including tires was derived following the methods previously outlined. An emission factor of 0.20 kg CH_4/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) for aviation and naval fuels. DLA Energy prepared a special report based on data in the Fuels Automated System (FAS) for calendar year 2021 fuel sales in the Continental United States (CONUS).[126] The following steps outline the methodology used for estimating emissions from international bunker fuels used by the U.S. Military.

Step 1: Omit Extra-Territorial Fuel Deliveries

Beginning with the complete FAS data set for each year, the first step in quantifying DoD-related emissions from international bunker fuels was to identify data that would be representative of international bunker fuel consumption as defined by decisions of the UNFCCC (i.e., fuel sold to a vessel, aircraft, or installation within the United States or its territories and used in international maritime or aviation transport). Therefore, fuel data were categorized by the location of fuel delivery in order to identify and omit all international fuel transactions/deliveries (i.e., sales abroad).

Step 2: Allocate Jet Fuel between Aviation and Land-based Vehicles

As a result of DoD[127] and NATO[128] policies on implementing the Single Fuel For the Battlefield concept, DoD activities have been increasingly replacing diesel fuel with jet fuel in compression ignition and turbine engines of land-based equipment. Based on this concept and examination of all data describing jet fuel used in land-based vehicles, it was determined that a portion of jet fuel consumption should be attributed to ground vehicle use. Based on available Military Service data and expert judgment, a small fraction of jet fuel use (i.e., between 1.78 and 2.7 times the quantity of diesel fuel used, depending on the Service) was reallocated from the aviation subtotal to a new land-based jet fuel category for 1997 and subsequent years. As a result of this reallocation, the jet fuel use reported for aviation was reduced and the fuel use for land-based equipment increased. DoD's total fuel use did not change. DoD has been undergoing a transition from JP-8 jet fuel to commercial specification Jet A fuel with additives (JAA) for non-naval aviation and ground assets. To account for this transition jet fuel used for ground-based vehicles was reallocated from JP8 prior to 2014 and from JAA in 2014 and subsequent years. The transition was completed in 2016.

Table A-111 displays DoD's consumption of transportation fuels, summarized by fuel type, that remain at the completion of Step 1, and reflects the adjustments for jet fuel used in land-based equipment, as described above.

Step 3: Omit Land-Based Fuels

Navy and Air Force land-based fuels (i.e., fuel not used by ships or aircraft) were omitted for the purpose of calculating international bunker fuels. The remaining fuels, listed below, were considered potential DoD international bunker fuels.

- **Aviation:** jet fuels (JP8, JP5, JP4, JAA, JA1, and JAB).
- **Marine:** naval distillate fuel (F76), marine gas oil (MGO), and intermediate fuel oil (IFO).

Step 4: Omit Fuel Transactions Received by Military Services that are not considered to be International Bunker Fuels

Only Navy and Air Force were deemed to be users of military international bunker fuels after sorting the data by Military Service and applying the following assumptions regarding fuel use by Service.

[126] 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.

[127] DoD Directive 4140.25-M-V1, Fuel Standardization and Cataloging, 2013; DoD Instruction 4140.25, DoD Management Policy for Energy Commodities and Related Services, 2015.

[128] NATO Standard Agreement NATO STANAG 4362, Fuels for Future Ground Equipment Using Compression Ignition or Turbine Engines, 2012.

- Only fuel delivered to a ship, aircraft, or installation in the United States was considered a potential international bunker fuel. Fuel consumed in international aviation or marine transport was included in the bunker fuel estimate of the country where the ship or aircraft was fueled. Fuel consumed entirely within a country's borders was not considered a bunker fuel.
- Based on previous discussions with the Army staff, only an extremely small percentage of Army aviation emissions, and none of Army watercraft emissions, qualified as bunker fuel emissions. The magnitude of these emissions was judged to be insignificant when compared to Air Force and Navy emissions. Based on this research, Army bunker fuel emissions were assumed to be zero.
- Marine Corps aircraft operating while embarked consumed fuel that was reported as delivered to the Navy. Bunker fuel emissions from embarked Marine Corps aircraft were reported in the Navy bunker fuel estimates. Bunker fuel emissions from other Marine Corps operations and training were assumed to be zero.
- Bunker fuel emissions from other DoD and non-DoD activities (i.e., other federal agencies) that purchased fuel from DLA Energy were assumed to be zero.

Step 5: Determine Bunker Fuel Percentages

It was necessary to determine what percent of the aviation and marine fuels were used as international bunker fuels. Military aviation bunkers include international operations (i.e., sorties that originate in the United States and end in a foreign country), operations conducted from naval vessels at sea, and operations conducted from U.S. installations principally over international water in direct support of military operations at sea (e.g., anti-submarine warfare flights). Methods for quantifying aviation and marine bunker fuel percentages are described below.

- **Aviation:** The Air Force Aviation bunker fuel percentage was determined to be 13.2 percent. A bunker fuel weighted average was calculated based on flying hours by major command. International flights were weighted by an adjustment factor to reflect the fact that they typically last longer than domestic flights. In addition, a fuel use correction factor was used to account for the fact that transport aircraft burn more fuel per hour of flight than most tactical aircraft. This percentage was multiplied by total annual Air Force aviation fuel delivered for U.S. activities, producing an estimate for international bunker fuel consumed by the Air Force.

  The Naval Aviation bunker fuel percentage was calculated to be 40.4 percent by using flying hour data from Chief of Naval Operations Flying Hour Projection System Budget for fiscal year 1998 and estimates of bunker fuel percent of flights provided by the fleet. This Naval Aviation bunker fuel percentage was then multiplied by total annual Navy aviation fuel delivered for U.S. activities, yielding total Navy aviation bunker fuel consumed.
- **Marine:** For marine bunkers, fuels consumed while ships were underway were assumed to be bunker fuels. The Navy maritime bunker fuel percentage was determined to be 79 percent because the Navy reported that 79 percent of vessel operations were underway, while the remaining 21 percent of operations occurred in port (i.e., pierside) in the year 2000.[129]

Table A-112 and Table A-113 display DoD bunker fuel use totals for the Navy and Air Force.

Step 6: Calculate Emissions from International Bunker Fuels

Bunker fuel totals were multiplied by appropriate emission factors to determine greenhouse gas (GHG) emissions. CO_2 emissions from Aviation Bunkers and distillate Marine Bunkers are the total of military aviation and marine bunker fuels, respectively.

The rows labeled "U.S. Military" and "U.S. Military Naval Fuels" in the tables in the International Bunker Fuels section of the Energy chapter were based on the totals provided in Table A-112 and Table A-113, below. CO_2 emissions from aviation bunkers and distillate marine bunkers are presented in Table A-117, and are based on emissions from fuels tallied in Table A-112 and Table A-113.

[129] Note that 79 percent is used because it is based on Navy data, but the percentage of time underway may vary from year-to-year depending on vessel operations. For example, for years prior to 2000, the bunker fuel percentage was 87 percent.

Table A-111: Transportation Fuels from Domestic Fuel Deliveries[a] (Million Gallons)

Vehicle Type/Fuel	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Aviation	**4,598.4**	**3,099.9**	**2,664.4**	**2,338.1**	**1,663.9**	**1,663.7**	**1,558.0**	**1,537.7**	**1,482.2**	**1,487.6**	**1,435.7**	**1,513.7**
Total Jet Fuels	**4,598.4**	**3,099.9**	**2,664.4**	**2,338.0**	**1,663.7**	**1,663.5**	**1,557.7**	**1,537.5**	**1,481.9**	**1,487.4**	**1,435.5**	**1,513.5**
JP8	285.7	2,182.8	2,122.7	1,838.8	1,100.1	126.6	(9.5)	(11.4)	1.9	4.7	(4.4)	3.02
JP5	1,025.4	691.2	472.1	421.6	399.3	316.4	320.4	316.3	304.1	314.4	309.0	308.6
Other Jet Fuels	3,287.3	225.9	69.6	77.6	164.3	1,220.5	1,246.9	1,232.7	1,175.9	1,168.2	1,130.9	1,201.8
Aviation Gasoline	**+**	**+**	**+**	**0.1**	**0.2**	**0.3**	**0.3**	**0.2**	**0.3**	**0.2**	**0.2**	**0.2**
Marine	**686.8**	**438.9**	**454.4**	**604.9**	**578.8**	**421.7**	**412.4**	**395.2**	**370.9**	**365.4**	**384.1**	**369.7**
Middle Distillate (MGO)	0.0	0.0	48.3	54.0	48.4	56.0	23.1	24.4	19.9	23.2	26.1	17.6
Naval Distillate (F76)	686.8	438.9	398.0	525.9	513.7	363.3	389.1	370.8	351.0	342.2	358.0	352.1
Intermediate Fuel Oil (IFO)[b]	0.0	0.0	8.1	25.0	16.7	2.4	0.1	0.0	0.0	0.0	0.0	0.0
Other[c]	**717.1**	**310.9**	**248.2**	**205.6**	**224.0**	**181.1**	**178.3**	**165.8**	**170.4**	**161.4**	**130.3**	**145.3**
Diesel	93.0	119.9	126.6	56.8	64.1	54.8	54.7	50.4	51.8	48.7	39.2	44.6
Gasoline	624.1	191.1	74.8	24.3	25.5	16.2	15.9	15.6	14.7	14.9	12.5	12.5
Jet Fuel[d]	0.0	0.0	46.7	124.4	134.4	110.1	107.6	99.9	104.0	97.7	78.6	88.2
Total (Including Bunkers)	**6,002.4**	**3,849.8**	**3,367.0**	**3,148.6**	**2,466.7**	**2,266.5**	**2,148.7**	**2,098.7**	**2,023.4**	**2,014.3**	**1,950.1**	**2,028.6**

+ Indicates value does not exceed 0.05 million gallons.

[a] Includes fuel distributed in the United States and U.S. Territories.

[b] Intermediate fuel oil (IFO 180 and IFO 380) is a blend of distillate and residual fuels. IFO is used by the Military Sealift Command.

[c] Prior to 2001, gasoline and diesel fuel totals were estimated using data provided by the Military Services for 1990 and 1996. The 1991 through 1995 data points were interpolated from the Service inventory data. The 1997 through 1999 gasoline and diesel fuel data were initially extrapolated from the 1996 inventory data. Growth factors used for other diesel and gasoline were 5.2 and -21.1 percent, respectively. However, prior diesel fuel estimates from 1997 through 2000 were reduced according to the estimated consumption of jet fuel that is assumed to have replaced the diesel fuel consumption in land-based vehicles. Datasets for other diesel and gasoline consumed by the military in 2000 were estimated based on ground fuels consumption trends. This method produced a result that was more consistent with expected consumption for 2000. Since 2001, other gasoline and diesel fuel totals were generated by DLA Energy.

[d] The fraction of jet fuel consumed in land-based vehicles was estimated based on DLA Energy data as well as Military Service and expert judgment.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values. The negative values in this table represent returned products.

Table A-112: Total U.S. Military Aviation Bunker Fuel (Million Gallons)

Fuel Type/Service	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Jet Fuels												
JP8	**56.7**	**300.4**	**307.6**	**285.6**	**182.5**	**17.2**	**2.4**	**2.5**	**2.9**	**1.2**	**0.6**	**1.5**
Navy	56.7	38.3	53.4	70.9	60.8	0.8	5.5	6.4	4.8	2.5	2.8	1.7
Air Force	+	262.2	254.2	214.7	121.7	16.4	(3.1)	(3.9)	(1.9)	(1.3)	(2.2)	(0.2)
JP5	**370.5**	**249.8**	**160.3**	**160.6**	**152.5**	**124.1**	**126.1**	**124.7**	**120.1**	**123.9**	**122.0**	**121.9**
Navy	365.3	246.3	155.6	156.9	149.7	122.6	124.7	123.4	118.9	122.5	120.7	120.8
Air Force	5.3	3.5	4.7	3.7	2.8	1.5	1.4	1.3	1.2	1.4	1.2	1.2
JP4	**420.8**	**21.5**	**+**	**+**	**0.1**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
Navy	+	+	0.0	+	+	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Air Force	420.8	21.5	+	+	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
JAA	**13.7**	**9.2**	**12.5**	**15.5**	**31.4**	**199.8**	**203.7**	**198.9**	**191.8**	**192.5**	**185.2**	**197.5**
Navy	8.5	5.7	7.9	11.6	13.7	71.7	72.9	67.8	68.1	71.2	66.1	70.7
Air Force	5.3	3.5	4.5	3.9	17.7	128.1	130.8	131.1	123.7	121.4	119.1	126.8
JA1	**+**	**+**	**+**	**0.5**	**0.3**	**0.3**	**0.5**	**0.2**	**0.5**	**0.3**	**0.3**	**0.2**
Navy	+	+	+	+	0.1	+	0.1	(+)	+	+	(+)	+
Air Force	+	+	+	0.5	0.1	0.3	0.5	0.2	0.5	0.3	0.3	0.2
JAB	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**
Navy	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
Air Force	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
Navy Subtotal	**430.5**	**290.2**	**216.9**	**239.4**	**224.4**	**195.0**	**203.2**	**197.5**	**191.8**	**196.1**	**189.6**	**193.2**
Air Force Subtotal	**431.3**	**290.7**	**263.5**	**222.9**	**142.4**	**146.4**	**129.5**	**128.8**	**123.5**	**121.8**	**118.5**	**127.8**
Total	**861.8**	**580.9**	**480.4**	**462.3**	**366.7**	**341.4**	**332.8**	**326.3**	**315.3**	**317.9**	**308.1**	**321.1**

+ Does not exceed 0.05 million gallons.

NO (Not Occurring)

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values. The negative values in this table represent returned products.

Table A-113: Total U.S. DoD Maritime Bunker Fuel (Million Gallons)

Marine Distillates	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Navy – MGO	0.0	0.0	23.8	38.0	32.9	37.8	5.7	13.2	8.5	10.6	13.5	7.1
Navy – F76	522.4	333.8	298.6	413.1	402.2	286.7	307.8	293.3	276.9	270.0	282.6	277.5
Navy – IFO	0.0	0.0	6.4	19.7	12.9	1.9	+	0.0	0.0	0.0	0.0	0.0
Total	**522.4**	**333.8**	**328.8**	**470.7**	**448.0**	**326.3**	**313.6**	**306.5**	**285.4**	**280.6**	**296.1**	**284.5**

+ Does not exceed 0.05 million gallons.

Note: Totals may not sum due to independent rounding.

Table A-114: Aviation and Marine Carbon Contents (MMT Carbon/QBtu) and Fraction Oxidized

Mode (Fuel)	Carbon Content Coefficient	Fraction Oxidized
Aviation (Jet Fuel)	Variable	1.00
Marine (Distillate)	Variable	1.00
Marine (Residual)	20.48	1.00

Source: EPA (2010) and IPCC (2006).

Table A-115: Annual Variable Carbon Content Coefficient for Jet Fuel (MMT Carbon/QBtu)

Fuel	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Jet Fuel	19.40	19.34	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70

Source: EPA (2010).

Table A-116: Annual Variable Carbon Content Coefficient for Distillate Fuel Oil (MMT Carbon/QBtu)

Fuel	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Distillate Fuel Oil	20.17	20.17	20.39	20.37	20.24	20.22	20.21	20.21	20.22	20.22	20.22	20.22

Source: EPA (2020).

Table A-117: Total U.S. DoD CO_2 Emissions from Bunker Fuels (MMT CO_2 Eq.)

Mode	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Aviation	8.2	5.7	4.8	4.6	3.6	3.4	3.3	3.3	3.2	3.2	3.1	3.2
Marine	5.4	3.4	3.4	4.9	4.6	3.4	3.2	3.1	2.9	2.9	3.0	2.9
Total	**13.6**	**9.1**	**8.2**	**9.5**	**8.3**	**6.8**	**6.6**	**6.4**	**6.1**	**6.1**	**6.1**	**6.1**

Note: Totals may not sum due to independent rounding.

References

DLA Energy (2022) Unpublished data from the Defense Fuels Automated Management System (DFAMS). Defense Energy Support Center, Defense Logistics Agency, U.S. Department of Defense. Washington, D.C.

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EPA (2020) EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019: Updated Gasoline and Diesel Fuel CO_2 Emission Factors – Memo.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

3.9. Methodology and QA/QC and Verification Details for Estimating HFC, PFC, and CO_2 Emissions from Substitution of Ozone Depleting Substances

3.9.1 Methodology for Estimating HFC, PFC, and CO_2 Emissions from Substitution of Ozone Depleting Substances

Emissions of HFCs, PFCs, and CO_2 from the substitution of ozone depleting substances (ODS) are developed using a country-specific modeling approach. The Vintaging Model[130] was developed as a tool for estimating the annual chemical emissions from industrial sectors that have historically used ODS in their products. Under the terms of the Montreal Protocol and the United States Clean Air Act Amendments of 1990, 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 (CO_2), 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 (i.e., HFC-emitting) end-use sectors: refrigeration and air-conditioning, foams, aerosols, solvents, and fire-extinguishing. Within these sectors, there are 78 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 or charge sizes and loss rates. 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 and 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), and conference proceedings from the International Conferences on Ozone Protection Technologies and Earth Technologies Forums. 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 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), C_4F_{10}, and PFC/PFPEs, the latter being a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications) are

[130] Vintaging Model version VM IO file_v5.1_10.05.22 was used for all Inventory estimates.

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 an unspecified mix of HFCs and PFCs.

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 Ref/AC 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 refrigeration and air-conditioning. 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 Ref/AC 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-1: Calculation of Emissions from Refrigeration and Air-conditioning Equipment First-fill

$$Ef_j = Qc_j \times I_f \times A_j$$

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.
I_f	=	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-2: Calculation of Emissions from Refrigeration and Air-conditioning Equipment Serviced

$$Es_j = (I_a + I_s) \times \sum Qc_{j-i+1} \quad for\ i = 1 \rightarrow k$$

where:

Es	=	Emissions from Equipment Serviced. Emissions in year *j* from normal leakage and servicing (including recharging) of equipment.
I_a	=	Annual Leak Rate. Average annual leak rate during normal equipment operation (expressed as a percentage of total chemical charge).
I_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-3: 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-4: Calculation of Total Emissions from Refrigeration and Air-conditioning Equipment

$$E_j = Ef_j + Es_j + Ed_j$$

where:

E	=	Total Emissions. Emissions from refrigeration and air conditioning equipment in year *j.*
Ef	=	Emissions from first Equipment Fill. Emissions in year *j* from filling new equipment.
Es	=	Emissions from Equipment Serviced. Emissions in year *j* from leakage and servicing (including recharging) of equipment.
Ed	=	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-118, below. 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-118: Refrigeration and Air-Conditioning Market Transition Assumptions

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Average 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	
Centrifugal Chillers													
CFC-11	HCFC-123	1993	1993	45%	HCFO-1233zd(E)	2016	2016	1%	None				1.6%
					R-514A	2017	2017	1%	None				
					HCFO-1233zd(E)	2017	2020	49%	None				
					R-514A	2018	2020	49%	None				
	HCFC-22	1991	1993	16%	HFC-134a	2000	2010	100%	R-450A	2017	2017	1%	
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
	HFC-134a	1992	1993	39%	R-450A	2017	2017	1%	None				
					R-513A	2017	2017	1%	None				
					R-450A	2018	2024	49%	None				
					R-513A	2018	2024	49%	None				
CFC-12	HFC-134a	1992	1994	53%	R-450A	2017	2017	1%	None				1.5%
					R-513A	2017	2017	1%	None				
					R-450A	2018	2024	49%	None				
					R-513A	2018	2024	49%	None				
	HCFC-22	1991	1994	16%	HFC-134a	2000	2010	100%	R-450A	2017	2017	1%	
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
	HCFC-123	1993	1994	31%	HCFO-1233zd(E)	2016	2016	1%	None				
					R-514A	2017	2017	1%	None				
					HCFO-1233zd(E)	2017	2020	49%	None				
					R-514A	2018	2020	49%	None				
R-500	HFC-134a	1992	1994	53%	R-450A	2017	2017	1%	None				1.5%
					R-513A	2017	2017	1%	None				
					R-450A	2018	2024	49%	None				
					R-513A	2018	2024	49%	None				
	HCFC-22	1991	1994	16%	HFC-134a	2000	2010	100%	R-450A	2017	2017	1%	
									R-513A	2017	2017	1%	

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Average 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	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
					HCFO-1233zd(E)	2016	2016	1%					
	HCFC-123	1993	1994	31%	R-514A	2017	2017	1%	None				
					HCFO-1233zd(E)	2017	2020	49%	None				
					R-514A	2018	2020	49%	None				
CFC-114	HFC-236fa	1993	1996	100%	HFC-134a	1998	2009	100%	None				1.4%
Cold Storage													
CFC-12	HCFC-22	1990	1993	65%	R-404A	1996	2010	75%	R-407F	2017	2023	100%	3.1%
					R-507	1996	2010	25%	R-407F	2017	2023	100%	
	R-404A	1994	1996	26%	R-407F	2017	2023	100%	None				
	R-507	1994	1996	9%	R-407F	2017	2023	100%	None				
HCFC-22	HCFC-22	1992	1993	100%	R-404A	1996	2009	8%	R-407F	2017	2023	100%	3.0%
					R-507	1996	2009	3%	R-407F	2017	2023	100%	
					R-404A	2009	2010	68%	R-407F	2017	2023	100%	
					R-507	2009	2010	23%	R-407F	2017	2023	100%	
R-502	HCFC-22	1990	1993	40%	R-404A	1996	2010	38%	R-407F	2017	2023	100%	2.6%
					R-507	1996	2010	12%	R-407F	2017	2023	100%	
					Non-ODP/GWP	1996	2010	50%	None				
	R-404A	1993	1996	45%	R-407F	2017	2023	100%	None				
	R-507	1994	1996	15%	R-407F	2017	2023	100%	None				
Commercial Unitary Air Conditioners (Large)													
HCFC-22	HCFC-22	1992	1993	100%	R-410A	2001	2005	5%	None				1.8%
					R-407C	2006	2009	1%	None				
					R-410A	2006	2009	9%	None				
					R-407C	2009	2010	5%	None				
					R-410A	2009	2010	81%	None				
Commercial Unitary Air Conditioners (Small)													
HCFC-22	HCFC-22	1992	1993	100%	R-410A	1996	2000	3%	None				2.0%
					R-410A	2001	2005	18%	None				
					R-410A	2006	2009	8%	None				

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Average 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	
					R-410A	2009	2010	71%	None				
Dehumidifiers													
HCFC-22	HFC-134a	1997	1997	89%	None								1.3%
	R-410A	2007	2010	11%	None								
Ice Makers													
CFC-12	HFC-134a	1993	1995	27%	None								2.1%
	R-404A	1993	1995	73%	R-410A	2013	2019	32%	None				
Industrial Process Refrigeration													
CFC-11	HCFC-123	1992	1994	70%	HCFO-1233zd(E)	2016	2016	2%	None				3.2%
					HCFO-1233zd(E)	2017	2020	98%	None				
	HFC-134a	1992	1994	15%	None								
	HCFC-22	1991	1994	15%	HFC-134a	1995	2010	100%	None				
CFC-12	HCFC-22	1991	1994	10%	HFC-134a	1995	2010	15%	None				3.1%
					R-404A	1995	2010	50%	None				
					R-410A	1999	2010	20%	None				
					R-507	1995	2010	15%	None				
	HCFC-123	1992	1994	35%	HCFO-1233zd(E)	2016	2016	2%	None				
					HCFO-1233zd(E)	2017	2020	98%	None				
	HFC-134a	1992	1994	50%	None								
	R-401A	1995	1996	5%	HFC-134a	1997	2000	100%	None				
HCFC-22	HFC-134a	1995	2009	2%	None								3.0%
	R-404A	1995	2009	5%	None								
	R-410A	1999	2009	2%	None								
	R-507	1995	2009	2%	None								
	HFC-134a	2009	2010	14%	None								
	R-404A	2009	2010	45%	None								
	R-410A	2009	2010	18%	None								
	R-507	2009	2010	14%	None								
Mobile Air Conditioners (Passenger Cars)													
CFC-12	HFC-134a	1992	1994	100%	HFO-1234yf	2012	2015	1%	None				0.3%
					HFO-1234yf	2016	2021	99%	None				

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Average 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	
Mobile Air Conditioners (Light Duty Trucks)													
CFC-12	HFC-134a	1993	1994	100%	HFO-1234yf	2012	2015	1%	None				1.4%
					HFO-1234yf	2016	2021	99%	None				
Mobile Air Conditioners (Heavy Duty Vehicles)													
CFC-12	HFC-134a	1993	1994	100%	None								0.8%
Mobile Air Conditioners (School and Tour Buses)													
CFC-12	HCFC-22	1994	1995	0.5%	HFC-134a	2006	2007	100%	None				0.3%
	HFC-134a	1994	1997	99.5%	None								
Mobile Air Conditioners (Transit Buses)													
HCFC-22	HFC-134a	1995	2009	100%	None								0.3%
Mobile Air Conditioners (Trains)													
HCFC-22	HFC-134a	2002	2009	50%	None								0.3%
	R-407C	2002	2009	50%	None								
Packaged Terminal Air Conditioners and Heat Pumps													
HCFC-22	R-410A	2006	2009	10%	None								3.0%
	R-410A	2009	2010	90%	None								
Positive Displacement Chillers (Reciprocating and Screw)													
CFC-12													
HCFC-22[c]	HFC-134a	2000	2009	9%	R-407C	2010	2020	60%	R-450A	2017	2017	1%	2.5%
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
					R-410A	2010	2020	40%	R-450A	2017	2017	1%	
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
	R-407C	2000	2009	1%	R-450A	2017	2017	1%	None				
					R-513A	2017	2017	1%	None				
					R-450A	2018	2024	49%	None				
					R-513A	2018	2024	49%	None				
	HFC-134a	2009	2010	81%	R-407C	2010	2020	60%	R-450A	2017	2017	1%	
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
					R-410A	2010	2020	40%	R-450A	2017	2017	1%	
									R-513A	2017	2017	1%	

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Average 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	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
	R-407C	2009	2010	9%	R-450A	2017	2017	1%	None				
					R-513A	2017	2017	1%	None				
					R-450A	2018	2024	49%	None				
					R-513A	2018	2024	49%	None				
HCFC-22	HFC-134a	2000	2009	9%	R-407C	2010	2020	60%	R-450A	2017	2017	1%	2.5%
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
					R-410A	2010	2020	40%	R-450A	2017	2017	1%	
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
	R-407C	2000	2009	1%	R-450A	2017	2017	1%	None				
					R-513A	2017	2017	1%	None				
					R-450A	2018	2024	49%	None				
					R-513A	2018	2024	49%	None				
	HFC-134a	2009	2010	81%	R-407C	2010	2020	60%	R-450A	2017	2017	1%	
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
					R-410A	2010	2020	40%	R-450A	2017	2017	1%	
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
	R-407C	2009	2010	9%	R-450A	2017	2017	1%	None				
					R-513A	2017	2017	1%	None				
					R-450A	2018	2024	49%	None				
					R-513A	2018	2024	49%	None				
Positive Displacement Chillers (Scroll)													
HCFC-22	HFC-134a	2000	2009	9%	R-407C	2010	2020	60%	R-452B	2024	2024	100%	2.5%
					R-410A	2010	2020	40%	R-452B	2024	2024	100%	
	R-407C	2000	2009	1%	R-452B	2024	2024	100%	None				
	HFC-134a	2009	2010	81%	R-407C	2010	2020	60%	R-452B	2024	2024	100%	
					R-410A	2010	2020	40%	R-452B	2024	2024	100%	
	R-407C	2009	2010	9%	R-452B	2024	2024	100%	None				

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Average 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	
Refrigerated Appliances													
CFC-12	HFC-134a	1994	1995	100%	Non-ODP/GWP	2019	2021	86%	None				1.7%
					R-450A	2021	2021	7%	None				
					R-513A	2021	2021	7%	None				
Refrigerated Food Processing and Dispensing Equipment													
CFC-12	HCFC-22	1990	1994	100%	HFC-134a	1995	1998	70%	None				2.1%
					R-404A	1995	1998	30%	R-448A	2021	2021	50%	
									R-449A	2021	2021	50%	
Residential Unitary Air Conditioners													
HCFC-22	HCFC-22	2006	2006	70%	R-410A	2007	2010	29%	None				2.8%
					R-410A	2010	2010	71%	None				
	R-410A	2000	2005	5%	R-410A	2006	2006	100%	None				
	R-410A	2000	2006	5%	None								
	R-410A	2006	2006	20%	None								
Retail Food (Large; Technology Transition)													
DX[d]	DX	2001	2006	67.5%	DX	2006	2015	62%	None				1.7%
					DR[e]	2000	2015	23%	None				
					SLS[f]	2000	2015	15%	None				
	DR	2000	2006	22.5%	None								
	SLS	2000	2006	10%	None								
Retail Food (Large; Refrigerant Transition)													
CFC-12	R-404A	1995	2000	17.5%	R-404A	2000	2000	3.3%	R-407A	2017	2017	100%	1.7%
R-502[g]					R-407A	2011	2015	63.3%	None				
					R-407A	2017	2017	33.3%	None				
	R-507	1995	2000	7.5%	R-404A	2006	2010	71%	R-407A	2017	2017	100%	
					R-407A	2006	2010	30%	None				
	HCFC-22	1995	2000	75%	R-404A	2006	2010	13.3%	R-407A	2011	2015	100%	
					R-407A	2001	2005	1.3%	None				
					R-404A	2001	2005	12%	R-407A	2017	2017	100%	
					R-507	2001	2005	6.7%	R-407A	2011	2015	100%	
					R-404A	2006	2010	34%	R-407A	2011	2015	100%	
					R-404A	2006	2010	7.3%	R-407A	2017	2017	100%	
					R-407A	2006	2010	25.3%	None				
Retail Food (Large Condensing Units)													
HCFC-22	R-402A	1995	2005	5%	R-404A	2006	2006	100%	R-407A	2018	2018	100%	1.5%

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Average 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	
	R-404A	1995	2005	25%	R-407A	2018	2018	100%	None				
	R-507	1995	2005	10%	R-407A	2018	2018	100%	None				
	R-404A	2008	2010	45%	R-407A	2018	2018	100%	None				
	R-507	2008	2010	15%	R-407A	2018	2018	100%	None				
Retail Food (Small Condensing Units)													
HCFC-22	R-401A	1995	2005	6%	HFC-134a	2006	2006	100%	None				1.6%
	R-402A	1995	2005	4%	HFC-134a	2006	2006	100%	None				
	HFC-134a	1993	2005	30%	None								
	R-404A	1995	2005	30%	R-407A	2018	2018	100%					
	R-404A	2008	2010	30%	R-407A	2018	2018	100%					
Retail Food (Small)													
CFC-12	HCFC-22	1990	1993	91%	HFC-134a	1993	1995	91%	CO_2	2012	2015	1%	2.2%
									Non-ODP/GWP	2012	2015	3.7%	
									Non-ODP/GWP	2014	2019	31%	
									Non-ODP/GWP	2016	2016	17.3%	
									R-450A	2016	2020	23%	
									R-513A	2016	2020	23%	
					HFC-134a	2000	2009	9%	Non-ODP/GWP	2014	2019	30%	
									R-450A	2016	2020	35%	
									R-513A	2016	2020	35%	
	R-404A	1990	1993	9%	Non-ODP/GWP	2016	2016	30%	None				
					R-448A	2019	2020	35%	None				
					R-449A	2019	2020	35%	None				
Transport Refrigeration (Road Transport)													
CFC-12	HFC-134a	1993	1995	10%	None								5.5%
	R-404A	1993	1995	60%	R-452A	2017	2021	5%					
					R-452A	2021	2022	95%					
	HCFC-22	1993	1995	30%	R-410A	2000	2003	5%	None				
					R-404A	2006	2010	95%	R-452A	2017	2021	5%	
									R-452A	2021	2022	95%	
Transport Refrigeration (Intermodal Containers)													
CFC-12	HFC-134a	1993	1993	60%	CO_2	2017	2021	5%	None				7.3%

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Average 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	
	R-404A	1993	1993	5%	CO_2	2017	2021	5%	None				
	HCFC-22	1993	1993	35%	HFC-134a	2000	2010	100%	CO_2	2017	2021	5%	
Transport Refrigeration (Merchant Fishing Transport)													
HCFC-22	HFC-134a	1993	1995	10%	None								5.7%
	R-507	1994	1995	10%	None								
	R-404A	1993	1995	10%	None								
	HCFC-22	1993	1995	70%	R-407C	2000	2005	3%	R-410A	2005	2007	100%	
					R-507	2006	2010	49%	None				
					R-404A	2006	2010	49%	None				
Transport Refrigeration (Reefer Ships)													
HCFC-22	HFC-134a	1993	1995	3.3%	None								4.2%
	R-507	1994	1995	3.3%	None								
	R-404A	1993	1995	3.3%	None								
	HCFC-22	1993	1995	90%	HFC-134a	2006	2010	25%	None				
					R-507	2006	2010	25%	None				
					R-404A	2006	2010	25%	None				
					R-407C	2006	2010	25%	None				
Transport Refrigeration (Vintage Rail Transport)													
CFC-12	HCFC-22	1993	1995	100%	HFC-134a	1996	2000	100%	None				-100%
Transport Refrigeration (Modern Rail Transport)													
HFC-134a	R-404A	1999	1999	50%	R-452A	2022	2022	50%	None				0.3%
	HFC-134a	2005	2005	50%	None								
Vending Machines													
CFC-12	HFC-134a	1995	1998	90%	CO_2	2012	2012	1%	Propane	100%	2019	2019	-0.03%
					Propane	2013	2017	39%	None				
					Propane	2014	2014	1%	None				
					Propane	2019	2019	49%	None				
					R-450A	2019	2019	5%	None				
					R-513A	2019	2019	5%	None				
	R-404A	1995	1998	10%	R-450A	2019	2019	50%	None				
					R-513A	2019	2019	50%	None				
Water-Source and Ground-Source Heat Pumps													
HCFC-22	R-407C	2000	2006	5%	None								1.3%
	R-410A	2000	2006	5%	None								
	HFC-134a	2000	2009	2%	None								
	R-407C	2006	2009	2.5%	None								

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Average 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	
	R-410A	2006	2009	4.5%	None								
	HFC-134a	2009	2010	18%	None								
	R-407C	2009	2010	22.5%	None								
	R-410A	2009	2010	40.5%	None								
Window Units													
HCFC-22	R-410A	2008	2009	10%	HFC-32	2015	2019	50%	None				2.6%
	R-410A	2009	2010	90%	HFC-32	2015	2019	50%	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 of the Vintaging Model to 2030.

[c] The CFC-12 reciprocating chillers market for new systems transitioned to HCFC-22 overnight in 1993. This transition is not shown in the table in order to provide the HFC transitions in greater detail.

[d] 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.

[e] 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.

[f] 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.

[g] The CFC-12 large retail food market for new systems transitioned to R-502 from 1988 to 1990, and subsequently transitioned to HCFC-22 from 1990 to 1993. These transitions are not shown in the table in order to provide the HFC transitions in greater detail.

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Table A-119 presents the average equipment lifetimes, HFC charge sizes, one-time HFC emissions rates (for first-fill and disposal), and annual HFC emission rates (for servicing and leaks) for each refrigeration and air-conditioning end-use assumed by the Vintaging Model.

Table A-119: Refrigeration and Air-Conditioning Lifetime Assumptions

End-Use	Lifetime (Years)	HFC Charge Size (kg)	HFC Emission Rates (First-fill)[a] (%)	HFC Emission Rates (Servicing and Leaks) (%)	HFC Emission Rates (Disposal)[b] (%)
Centrifugal Chillers	20 – 27	440-926	0.2	1 – 10.9	10
Cold Storage	20 – 25	0.01[c]	1	10.5 – 15.0	10
Commercial Unitary A/C (Large)	15	12.8–13.2	1	8.6	15 – 35
Commercial Unitary A/C (Small)	15	6.6	0.5	7.9	20 – 40
Condensing Units (Medium Retail Food)	20	2.6–25	0.5	7.8 – 14.8	10 – 20
Dehumidifiers	11	0.2	0.5	0.5	50
Ice Makers	8	2.6	1	3.0	49
Industrial Process Refrigeration	25	598 – 9100	1	3.6 – 12.3	10
Large Retail Food	18	408 – 1800	2	17 – 33	10
Mobile A/C (Heavy-duty Vehicles)	16	1.1	0.2	13-25	43
Mobile A/C (Light-duty Trucks)	16	0.8 – 1.1	0.2	6.4 – 37.3	43
Mobile A/C (Passenger Cars)	16	0.6 – 0.9	0.2	6.4 – 37.3	43
Mobile A/C (School & Tour Buses)	12	4.9	0.2	9.6	50
Mobile A/C (Trains)	5	18.6	0.2	2.3	50
Mobile A/C (Transit Buses)	12	7.2	0.2	9.6	50
Positive Displacement Chillers	20	240 – 300	0.2	0.5 – 1.5	10
PTAC/PTHP	12	0.6	1	3.9	40
Refrigerated Appliances	14	0.1	0.6	0.6 – 0.8	42
Refrigerated Food Processing and Dispensing Equipment	10	0.5	1	1	68
Residential Unitary A/C	15	2.6 – 3.7	0.2	5.3 – 11	20 – 40
Small Retail Food	10	0.4 – 0.5	1	1	19 – 65
Transport Refrigeration (Intermodal Containers)	15	4.5	0.2	19.4 – 31.4	32.5
Transport Refrigeration (Merchant Fishing)	25	176 – 385	1	33.2 – 44.1	10
Transport Refrigeration (Modern Rail)	9	7.5	0.2	33.2 – 36.4	18 – 33
Transport Refrigeration (Reefer Ships)	25	750	1	23 – 31	10
Transport Refrigeration (Road)	12	4.5	0.2	23 – 36	33
Transport Refrigeration (Vintage Rail)	40	15	N/A[d]	36.4	65
Vending Machines	10	4.5	0.5	1	68– 79
Water & Ground Source Heat Pumps	20	3.5 – 3.6	1	3.9	43
Window Units	12	0.3 – 0.6	0.5	0.6	50

[a] 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.

[b] 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 (%).

[c] Charge sizes for cold storage are modeled on a kilogram per cubic foot of refrigerated space basis.

[d] Vintage rail transport HFC systems are assumed to be retrofitted from CFC-12 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. Essential use exemptions granted to the United

States under the Montreal Protocol for CFC use in MDIs were 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-5: 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-120.

Table A-120: 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%		2001	2011	28%	Non-ODP/GWP	2012	2018	64%	
					HFC-134a								
									HFC-227ea	2015	2015	1%	
					Non-ODP/GWP	2001	2014	67%					
									None				
						2007	2013	5%	Non-ODP/GWP	2015	2018	44%	
					HFC-227ea								
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								
									HFO-1234ze(E)	2012	2016	10%	
	HCFC-22	1994	1994	50%	HFC-134a	2001	2010	100%					
	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-6: Calculation of Emissions from Solvents

$$E_j = I \times Qc_j$$

where:

E = Emissions. Total emissions of a specific chemical in year j from use in solvent applications, by weight.

I = Percent Leakage. The percentage of the total chemical that is leaked to the atmosphere, assumed to be 90 percent.

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-121.

Table A-121: Solvent Market Transition Assumptions

	Primary Substitute				Secondary Substitute				
Initial Market Segment	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	Growth Rate[b]
Adhesives									
CH_3CCl_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_3CCl_3	Non-ODP/GWP	1996	1997	99.8%	None				2.0%
	PFC/PFPE	1996	1997	0.2%	Non-ODP/GWP	2000	2003	90%	
					Non-ODP/GWP	2005	2009	10%	
Metals									
CH_3CCl_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_3CCl_3	Non-ODP/GWP	1995	1996	99.3%	None				2.0%

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	
	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 24-year lifetime 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-7: Calculation of Emissions from Fire Extinguishing

$$E_j = r \times \sum Qc_{j-i+1} \quad \text{for } i=1 \rightarrow k$$

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.
Qc = 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-122.

Table A-122: Fire Extinguishing Market Transition Assumptions

	Primary Substitute				Secondary Substitute				
Initial Market Segment	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	Growth Rate[b]
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_4F_{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				
	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-8: 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-9: Calculation of Emissions from Foam Blowing Lifetime Losses (Closed-cell Foams)

$$Eu_j = lu \times \sum Qc_{j-i+1} \quad for\ i=1 \rightarrow k$$

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-10: 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-11: Calculation of Emissions from Foam Blowing Post-disposal (Closed-cell Foams)

$$Ep_j = lp \times \sum Qc_{j-m} \quad for\ m=k \rightarrow k+26$$

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-12: 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-123. The emission profiles of these thirteen foam types are shown in Table A-124.

Table A-123: 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%	
Stand-alone Equipment Foam													
CFC-11	HCFC-141b	1990	1995	40%	HFC-245fa	2003	2005	80%	HCFO-1233zd(E)	2019	2020	25%	2.2%
					HFC-134a	2003	2005	40%	None				
					Non-ODP/GWP	2003	2005	40%	None				
	HCFC-22	1990	1995	56%	HFC-134a	2004	2008	46%	Non-ODP/GWP	2010	2018	32%	
									HCFO-1233zd(E)	2019	2020	36%	
					Non-ODP/GWP	2004	2008	54%	None				
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%	
									HCFO-1233zd(E)	2017	2020	20%	
	HCFC-142b	1989	1996	8%	CO_2	2002	2003	69%	None				
					HFC-134a	2002	2003	31%	CO_2	2017	2020	47%	
									HCFO-1233zd(E)	2017	2020	20%	
	HCFC-22	1989	1996	52%	CO_2	2002	2003	69%	None				
					HFC-134a	2002	2003	31%	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	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%

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-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				
					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%
									Non-ODP/GWP	2017	2017	6%	
									HFO-1336mzz(Z)	2017	2017	10%	
					Non-ODP/GWP	2003	2010	4%	None				
	CO_2	1996	2000	50%	None								
Flexible PU Foam: Slabstock Foam, Moulded Foam													
CFC-11	Non-ODP/GWP	1992	1992	100%	None								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	
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%
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%	
									HCFO-1233zd(E)	2015	2020	50%	
					HFC-245fa	2006	2009	10%	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%
					HFC-134a	2009	2010	10%	HFO-1234ze(E)	2018	2020	100%	
					HFC-152a	2009	2010	10%	None				
	HCFC-22	1989	1996	30%	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				
	Non-ODP/GWP	2001	2004	40%	None								
	HFC-134a	2002	2004	20%	Non-ODP/GWP	2015	2020	100%	None				
HCFC-22	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													
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/HFC-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%

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-134a	2002	2003	85%	HFO-1234ze	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													
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.

1

Table A-124: Emission Profile for the Foam End-Uses

Foam End-Use	Loss at Manufacturing (%)	Annual Leakage Rate (%)	Leakage Lifetime (years)	Loss at Disposal (%)	Post-life Loss (%)	Total[a] (%)
Flexible PU Foam: Slabstock Foam, Moulded Foam	100	0	1	0	0	100
Vending Machine Foam	4	0.25	10	93.5	0	100
Stand-alone Equipment Foam	4	0.25	10	93.5	0	100
Ice Machine Foam	4	0.25	8	94.0	0	100
Refrigerated Food Processing and Dispensing Equipment Foam	4	0.25	10	93.5	0	100
Small Walk-in Cooler Foam	4	0.25	20	91.0	0	100
Large Walk-in Cooler Foam	4	0.25	20	91.0	0	100
CFC-11 Display Case Foam	4	0.25	18	91.5	0	100
CFC-12 Display Case Foam	4	0.25	18	91.5	0	100
Road Transport Foam	4	0.25	12	93.0	0	100
Intermodal Container Foam	4	0.25	15	92.3	0	100
Rigid PU: High Pressure Two-Component Spray Foam	15	1.5	50	10.0	0	100
Rigid PU: Low Pressure Two-Component Spray Foam	15	1.5	50	10.0	0	100
Rigid PU: Slabstock and Other [a]	20	1	15	22.5	1.5	57.5
Phenolic Foam	28	0.875	32	44.0	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	56.25	0	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	37.2	2.0	50.7
Rigid PU: Domestic Refrigerator and Freezer Insulation (all others)[a]	3.75	0.25	14	39.9	2.0	47.15
PU and PIR Rigid: Boardstock[a]	10	1	40	22.5	1.5	72.5
PU Sandwich Panels: Continuous and Discontinuous [a]	15	0.5	75	22.5	1.25	75

PIR (Polyisocyanurate)
PU (Polyurethane)
XPS (Extruded Polystyrene)
[a] Total 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.

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-13: 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-125.

Table A-125: 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 CO_2 equivalent (MMT CO_2 Eq.). The conversion of metric tons of chemical to MMT CO_2 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-14: 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-9 provides the bank for ODS and ODS substitutes by chemical grouping in metric tons (MT) for 1990 to 2021.

3.9.2 Comparisons to Other Information on Supply and Emissions of HFCs

Comparison of Reported Consumption to Modeled Consumption of HFCs

As discussed in Section 4.24 of the Inventory report, EPA conducted a quality assurance check of the Vintaging Model used for estimating emissions of HFCs, PFCs, and CO_2 used as ODS Substitutes. We 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).

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).

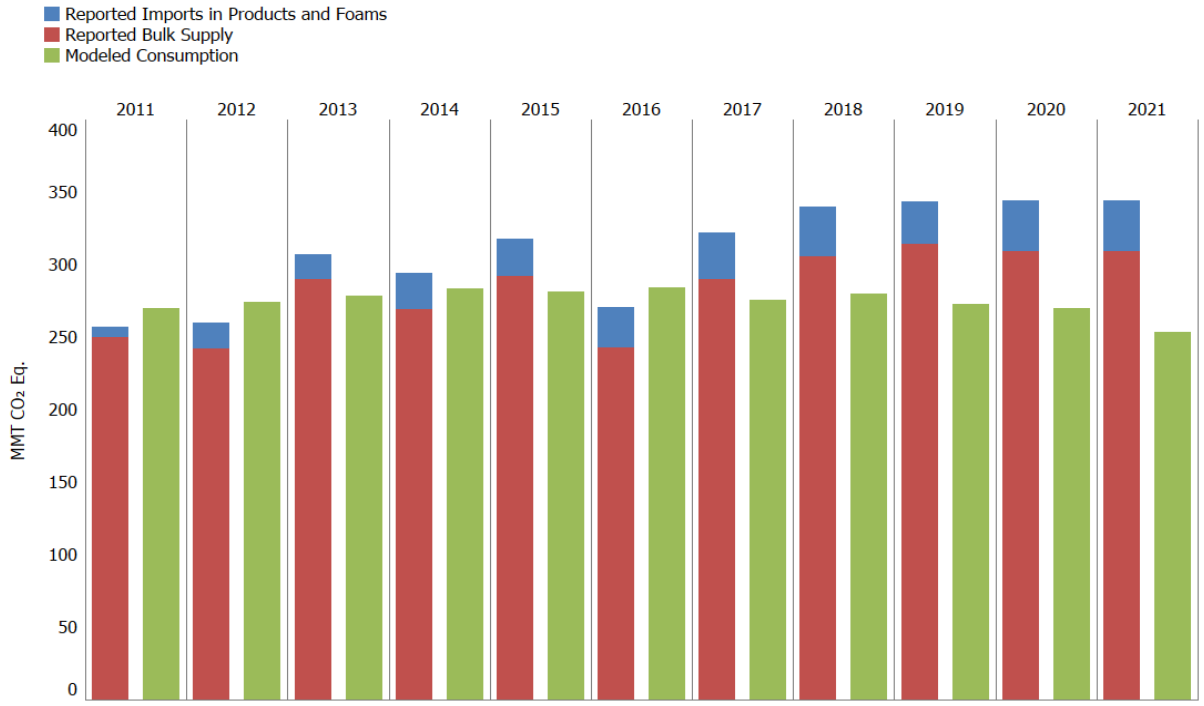
There are eleven saturated HFC species modeled in the Vintaging Model: HFC-23, HFC-32, HFC-125, HFC-134a, HFC-143a, HFC-152a, HFC-227ea, HFC-236fa, HFC-245fa, HFC-365mfc, and HFC-43-10mee. While some amounts of less-used saturated HFCs, including isomers of those included in the Vintaging Model, are reportable under EPA's GHGRP, the data are believed to represent an amount comparable to the modeled estimates as a quality assurance check.

Table A-126 and Figure A-7 compare the published net supply of saturated HFCs in MMT CO_2 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 2020 (EPA 2021; EPA 2022a) 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 is estimated using AR4 GWPs.

Table A-126: U.S. HFC Supply (MMT CO_2 Eq.)

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020
Reported Net Supply (GHGRP)	260	307	294	318	271	322	340	344	344
Industrial GHG Suppliers	242	290	269	292	243	290	306	314	309
HFCs in Products and Foams	18	17	25	26	28	32	34	30	35
Modeled Supply (Vintaging Model)	274	279	283	282	285	276	280	273	270
Percent Difference	**6%**	**-9%**	**-4%**	**-11%**	**5%**	**-14%**	**-18%**	**-21%**	**-22%**

Figure A-7: U.S. HFC Consumption (MMT CO_2 Eq.)



As shown, the estimates from the Vintaging Model are lower than the GHGRP estimates by an average of 9.8 percent across the time series (i.e., 2012 through 2020), with the difference growing to an average of 20 percent over the last three years (2018 through 2020). 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 exists amongst HFC suppliers in anticipation of current and recently promulgated controls on HFCs. Any such activity would increase the GHGRP 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 2020 (i.e., the years following agreement of the Kigali Amendment to the Montreal Protocol) 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; however, this data is not collected from suppliers under the GHGRP. Future reporting under the AIM Act may provide useful information in evaluating this issue.

- 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), EPA would expect the modeled estimates to be slightly lower than the corresponding GHGRP data due to this temporal effect. Regulations under the AIM Act require the reporting of chemical supplies held at the close of the calendar year; 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 CO_2 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 2021, 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. production and consumption baselines; this data is included in the totals presented above. Additional reporting under the AIM Act, if released, would likewise be included in the reported totals in the future.

- 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 or recovery from the recessions and 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 are 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 hence consumption would increase to meet that demand not satisfied by recovered quantities, increasing the GHGRP 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) 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. 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. To the extent lower-GWP isomers were used in lieu of the modeled chemicals (e.g., HFC-134 instead of HFC-134a), lower CO_2 Eq. amounts in the GHGRP 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 some years 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 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 CO_2 Eq. and 0.05 MMT CO_2 Eq. of HFCs in 2020, which is much less than the ODS substitute sector in that year (166.1 MMT CO_2 Eq.).

Comparison of Emissions Derived from Atmospheric Measurements to Modeled Emissions

As discussed in Section 4.24 of the Inventory report, EPA conducted another quality assurance check of the Vintaging Model estimated emissions. In this analysis, we compared the emissions of HFC-32, HFC-125, HFC-134a and HFC-143a as estimated by the bottom-up model to two sets of top-down estimates derived by the National Oceanic and Atmospheric Administration (NOAA) using atmospheric measurements.

Comparison of Results

Table A-127 lists the emissions NOAA derived for the contiguous United States from atmospheric measurements as described in Hu et al. (2017) and Hu et al. (2022), and those from EPA's Vintaging Model. Estimates from Hu et al. (2022) were available from two different models, the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model and the Stochastic Time-Inverted Lagrangian Transport (STILT) model. Figure A- 8 below show this information graphically for HFC-32, HFC-125, HFC-134a, and HFC-143a. The full time series of 2008 through 2020 is not yet available for each of the four HFCs from both models. In the Supplemental Information of Hu et al. (2017), uncertainty results were provided that represented one standard deviation of the spread of several inversion calculations. Uncertainty results representing one standard deviation were also provided in Hu et al. (2022). These 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 CO_2-equivalent emissions from HFCs, PFCs, and CO_2 used as alternatives to ODS) range from -4.2 percent to 14.7 percent (95 percent confidence interval), as shown in Section 4.24. The nature of the model and the uncertainty analysis, however, does not allow EPA to provide specific uncertainties to each species and hence comparisons below are to the EPA estimates without consideration of the uncertainty involved in those estimates.

Table A-127: U.S. Emissions of HFC-32, HFC-125, HFC-134a and HFC-143a (Gg)

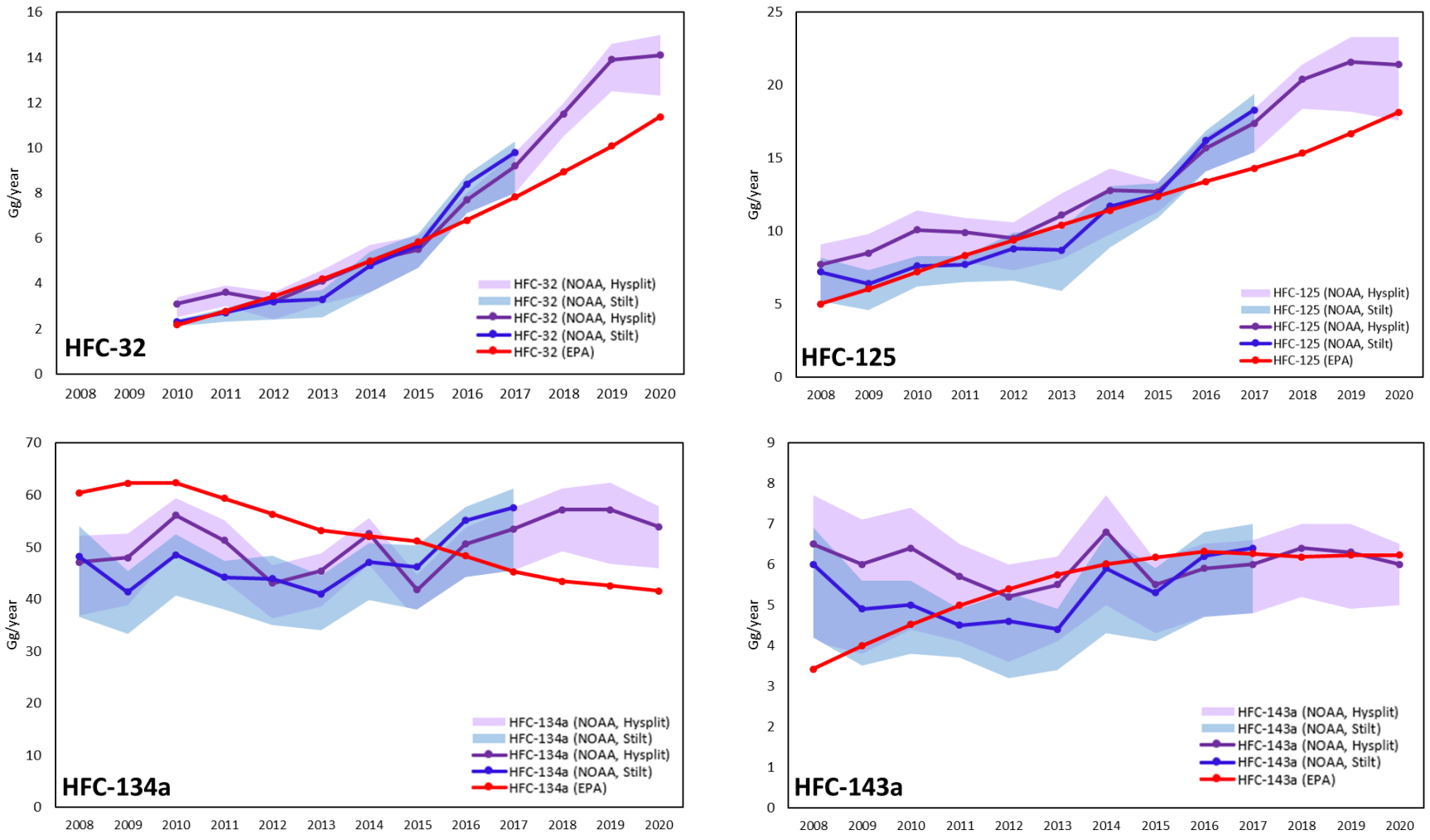
Gas	HFC-32			HFC-125			HFC-134a			HFC-143a		
Source	EPA	NOAA (HYSPLIT)	NOAA (STILT)	EPA	NOAA (HYSPLIT)	NOAA (STILT)	EPA	NOAA (HYSPLIT)	NOAA (STILT)	EPA	NOAA (HYSPLIT)	NOAA (STILT)
2008	1.2	1.7±0.34[a]	1.7±0.34[a]	5.0	7.7±1.4	7.2±1	60.4	47.1±5.1	48.2±5.8	3.4	6.5±1.2	6.0±0.9
2009	1.6	2.1±0.44[a]	2.1±0.44[a]	6.0	8.5±1.3	6.4±0.9	62.3	48.0±4.6	41.4±4	4.0	6.0±1.1	4.9±0.7
2010	2.2	3.1±0.3	2.3±0.1	7.2	10.1±1.3	7.6±0.7	62.3	56.1±3.3	48.5±3.9	4.5	6.4±1.0	5.0±0.6
2011	2.8	3.6±0.3	2.7±0.2	8.3	9.9±1	7.7±0.6	59.3	51.3±3.9	44.2±3.1	5.0	5.7±0.8	4.5±0.4
2012	3.4	3.2±0.4	3.2±0.3	9.4	9.5±1.1	8.8±1.1	56.3	43.1±3.4	43.9±4.4	5.4	5.2±0.8	4.6±0.7
2013	4.2	4.1±0.5	3.3±0.4	10.4	11.1±1.5	8.7±1.4	53.2	45.4±3.4	41.0±3.5	5.7	5.5±0.7	4.4±0.5
2014	5.0	5.0±0.7	4.8±0.6	11.4	12.8±1.5	11.7±1.4	52.1	52.6±3	47.1±3.6	6.0	6.8±0.9	5.9±0.8
2015	5.8	5.5±0.6	5.7±0.5	12.4	12.7±0.7	12.5±0.8	51.2	41.8±2.9	46.2±4.1	6.2	5.5±0.6	5.3±0.6
2016	6.8	7.7±0.3	8.4±0.4	13.4	15.7±0.8	16.2±0.7	48.3	50.6±3.2	55.1±2.6	6.3	5.9±0.6	6.2±0.6
2017	7.8	9.2±0.6	9.8±0.5	14.3	17.4±1	18.3±1.1	45.3	53.5±4	57.6±3.6	6.3	6.0±0.6	6.4±0.6
2018	8.9	11.5±0.5	NA	15.3	20.4±1	NA	43.4	57.2±4	NA	6.2	6.4±0.6	NA
2019	10.1	13.9±0.7	NA	16.7	21.6±1.7	NA	42.6	57.2±5.2	NA	6.2	6.3±0.7	NA
2020	11.4	14.1±0.9	NA	18.2	21.4±1.9	NA	41.6	53.9±4	NA	6.2	6.0±0.5	NA

[a]Estimates from Hu et al. (2017); all others from Hu et al. (2022)

Note: NOAA uncertainty values represent one standard deviation

NA is not available

Figure A- 8: U.S. Emissions of HFC-32, HFC-125, HFC-134a, and HFC-143a



As shown, modeled estimates of HFC-32 were comparable with those derived from atmospheric measurements for the years 2010 to 2016, with only small differences (in Gg y^{-1}), but estimates differed from both the HYSPLIT and STILT atmospheric-based estimates by more than two standard deviations (2 s.d.) in 2013, 2017, and 2018. Both atmosphere-derived and modeled estimates show a similar trend of increasing emissions after 2014, but modeled estimates of HFC-32 increase slower than both the HYSPLIT and STILT atmospheric measurements after 2015. Modeled emissions of HFC-134a were more than 2 s.d. higher than those seen through atmospheric measurements for the years 2008, 2009, and 2011 through 2013. On the other hand, the modeled emission estimates for this gas were more than 2 s.d. below the atmospheric measurements for the years 2017 to 2020. While the mean values from NOAA show year-to-year variability, the data with uncertain ranges may suggest a slight upward or constant trend in HFC-134a emissions through this entire period, unlike the modeled result; however, confidence in the trend from atmospheric measurements is limited because the magnitude of uncertainties are similar to the overall change and because increasing or decreasing trends of the mean values do not persist for more than four years. Modeled estimates for HFC-125 were consistently within 2 s.d. uncertainty of atmospheric measurements through 2015 but were smaller by more than 2 s.d. between 2016 and 2020. The modeled results suggest an upward year-on-year trend for HFC-125 emissions. NOAA results for HFC-125 similarly suggest an increase in emissions over time, and, as with HFC-32, the estimates from atmospheric measurement increase more quickly than the modeled estimates beginning in 2015. HFC-143a modeled emissions were comparable to the mean HYSPLIT and STILT atmospheric measurements, but uncertainties ranges were quite high. Considering these uncertainty ranges, HFC-143a modeled values agree within 2 s.d. with both sets of NOAA values for all years except 2013, where the modeled results were within 2 s.d. of just the HYSPLIT results, and 2008, where the modeled estimates are lower than 2 s.d. compared to both sets of NOAA results Modeled estimates for HFC-143a trend upward until 2015 and then remain relatively constant between 2016 and 2020. In the NOAA estimates, no secular trend is discernable from 2008 to 2020 for HFC-143a considering the annual mean uncertainties of approximately 12 percent; however, the mean values from the NOAA estimates are also relatively constant between 2016 and 2020.

Table A-128 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 were not within the given 1 s.d. uncertainty range in the NOAA results. Years when modeled estimates are within the uncertainty range reported by NOAA are not shown as those differences are assumed to be insignificant. We also look at the 2 s.d. range in the NOAA results, which for these results are twice 1 s.d. 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 2008 to 2011 and 2013 were greater than 1 s.d. uncertainty ranges for NOAA estimates the differences averaged only 0.48 Gg during these five years. These differences were insignificant at the twice uncertainty level for 2008 and 2009. Results were within the 1 s.d. uncertainty range of the NOAA estimates for 2012, 2014, 2015, 2019, and 2020. For 2016 to 2018, the modeled results were below the uncertainty range by an average of 18 percent compared to the mean values.

b. For HFC-125, the differences were within the uncertainty range of the NOAA estimates for 2011 to 2015. The results in 2009, 2010, and 2020 were within the twice uncertainty range. For 2008, the modeled results were below the uncertainty range by 33 percent compared to the mean, and the 2016 to 2019 modeled results were below the uncertainty range by an average of 21 percent compared to the mean values.

c. For HFC-134a, the differences ranged from 8 percent below the uncertainty range in 2016 to 40 percent above the uncertainty range in 2009. With the exception of 2014, all differences were greater than the NOAA estimates 1 s.d. uncertainty ranges. Furthermore, of these differences outside 1 s.d. uncertainty, only the 2016 estimates were within the NOAA estimates at twice the uncertainty.

d. For HFC-143a, the modeled results were within the uncertainty range in 2011, 2012, 2014, and again in 2016 to 2020. The 2009, 2010, 2013, and 2015 model results were within the twice uncertainty range. The most significant difference was in 2008, where the modeled results were below the NOAA estimates by 45 percent compared to the mean values.

Table A-128: Percentage Differences between EPA and NOAA HFC Emission Estimates

Year	HFC-32	HFC-125	HFC-134a	HFC-143a
2008	-0.43 (-26%)	**-2.4 (-33%)**	**12.8 (27%)**	**-2.8 (-45%)**
2009	-0.56 (-26%)	1.4 (-17%)	**17.6 (40%)**	-1.5 (-26%)
2010	**-0.53 (-18%)**	-1.6 (-17%)	**10.0 (20%)**	-1.2 (-19%)
2011	**-0.37 (-10%)**		**11.6 (25%)**	
2012			**12.8 (30%)**	
2013	**0.49 (15%)**		**10.0 (23%)**	0.8 (18%)
2014				
2015			**7.2 (17%)**	0.78 (14%)
2016	**-1.26 (-15%)**	**-2.6 (-16%)**	-4.5 (-8%)	
2017	**-1.7 (-17%)**	**-3.5 (-20%)**	**-10.3 (-18%)**	
2018	**-2.6 (-22%)**	**-5.1 (-25%)**	**-13.8 (-24%)**	
2019	**-3.8 (-27 %)**	**-4.9 (-23%)**	**-14.6 (-26%)**	
2020	**-2.7 (-19 %)**	-3.2 (-15%)	**-12.3 (-23%)**	
Average	-0.99 (-12%)	-2.0 (-13%)	2.2 (7%)	-0.27 (-4%)
Average of Absolute Values	0.17 (17%)	0.17 (17%)	0.19 (19%)	0.13 (13%)

Notes: Differences smaller than the 1 s.d. uncertainty on the annual NOAA-based estimates are not shown. Differences greater than 2 s.d. shown in bold font. Uncertainties associated with the Vintaging model have not been estimated by compound and year so are not included and could imply fewer differences than shown in this table.

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.

- When examining the NOAA estimates with twice the uncertainties provided, only a few of these larger differences from EPA model results are identified. In general, the uncertainties in the NOAA estimates are primarily driven by the frequency and spatial density of the atmospheric sampling, and the transport model simulations. There is also inherent uncertainty in the consistency of the setup of each gas chromatography measurement taken–e.g., variation in calibration, impurities in the carrier gas used, among others (Barwick 1999); however, that uncertainty is likely less than 1 percent for HFC-125, HFC-134a, and HFC-143a, and less than 5 percent for HFC-32. For HFC-134a and 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. In the case of HFC-32 and HFC-125, however, an increasing trend is seen. Although NOAA estimates are derived from thousands of individual sample analyses (approximately 5,000 per year), continued analysis and additional years will enable a better understanding of any secular trends in the NOAA-derived estimates, and hence whether the modeled results are showing similar changes over time. As discussed above, there is also uncertainty in the EPA estimates. Although these are not available by individual species, these uncertainties may also explain some of the differences seen. See Section 4.24 for a discussion of planned improvements to the modeled estimates that could address some of these discrepancies.
- 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, which changed between 2008 and 2014. Uncertainties were greatest in 2008 and 2009—i.e., early on in the North American sampling program (Hu et al. 2017)—due to a fewer number of tower sites and available measurements in those startup years. This may help explain why none of the EPA results for 2008 were within one standard deviation of the NOAA estimates, and only HFC-32 was within twice the uncertainty range. Also, changes in the number and location of measurement sites within the air sampling network containing over 25 sites can lead to biases in the year-to-year emission estimates. During the 2008 to 2014 period addressed by Hu et al. (2017), measurements at four network sites began only after 2008, while observations at two others were terminated. Uncertainties related to network changes were estimated with separate inversion runs in which sites were removed from the analysis and differences ascertained. These influences contribute to the uncertainties quoted in the NOAA estimates, as do the uncertainties related to meteorological models.
- 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. If available, calculations to reduce the bottom-up results could be made and the results compared again to the NOAA results.
- For HFC-125, the EPA model suggests lower emissions for 2008 to 2011 and 2014 through 2020 relative to the average of the atmosphere-derived estimates. For HFC-143a, the EPA model suggests lower emissions in 2008 through 2010, and slightly higher emissions in 2012 to 2014, 2016, 2017, and 2020 relative to the average of the atmosphere-derived estimates. Further research into the refrigeration market might improve the agreement in the estimates for these two gases. As stated in the Introduction above, emissions from the large retail food end-use (e.g., supermarkets), which uses both these gases, 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) or success in lowering emission rates could be used to improve the bottom-up model.
- The modeled emissions of HFC-32 agreed well with the atmospheric inversion results in absolute terms through 2016, with atmosphere-derived estimates higher in 2016 through 2020 than modeled estimates, although both data sets show the same year-on-year increasing trend. Irrespective of the uncertainties, slightly lower model results might imply that the actual emissions from R-410A 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 (a 50:50 by mass ratio of HFC-32 and HFC-125). EPA investigated the amount of "dry-charge" unitary air-conditioning imports by reviewing dry-shipped condensing unit estimates from air-conditioner manufacturer surveys to determine whether the Vintaging Model may be overestimating the number of dry-charged units. EPA determined that there were only small differences between survey results and Vintaging Model estimates for dry-shipped condensing unit shipments, which indicates that the way the Vintaging Model currently addresses dry-charged units is not the cause for the differences between Vintaging Model and NOAA emission estimates for HFC-32 and HFC-125. Therefore, updates to the Vintaging Model were not implemented (EPA 2022b). In addition, because the modeled results for both HFC-32 and HFC-125 are generally lower than the atmospheric inversion results, there could be an underestimate of R-410A emissions. This might 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.
- 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 on-going transition to HFO-1234yf) with concurrent increases in other sectors, 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 are not inconsistent with the slow rate of increase seen in the modeled emissions during 2008 through 2010. However, the NOAA results do not appear to show a subsequent decrease. If the 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 as modeled,

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 the 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, 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 slope of the EPA emission estimates for HFC-32, HFC-125, and HFC-143a, 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, or retirements, 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.

3.10. Methodology for Estimating CH_4 Emissions from Enteric Fermentation

The steps outlined in this annex were used to estimate methane emissions from enteric fermentation for the years 1990 through 2020. As explained in the Enteric Fermentation Chapter 5.1, a simplified approach was used to estimate emissions for 2021. The methodology used for 2021 relied on 2021 population estimates and 2020 implied emission factors and is explained in further detail within Chapter 5.1 Enteric Fermentation (CRF 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 CH_4 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 CH_4 conversion rates to estimate CH_4 emissions.[131] 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 2021a, USDA 2022). State-level cattle population estimates are shown by animal type for 2021 in Table A-129. 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-130, to ensure consistency. Cattle populations used in the Enteric Fermentation source category for the 1990 to 2020 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 2021, state populations were estimated by calculating ratios of 2020 state populations to the 2020 total national population, then applying those state-specific ratios to the 2021 national total population estimates. See the Enteric Fermentation chapter for more details about this approach.

Table A-129: 2021 Cattle Population Estimates, by Animal Type and State (1,000 head)

State	Dairy Calves	Dairy Cows	Dairy Repl. Heif. 7-11 Months	Dairy Repl. Heif. 12-23 Months	Bulls	Beef Calves	Beef Cows	Beef Repl. Heif. 7-11 Months	Beef Repl. Heif. 12-23 Months	Steer Stockers	Heifer Stockers	Feedlot
Alabama	3	5	1	1	44	348	686	27	64	21	18	6
Alaska	0	0	0	0	3	3	7	0	1	0	0	0
Arizona	106	207	33	79	20	106	209	8	19	136	9	305
Arkansas	3	5	1	3	59	461	910	36	86	53	36	13
California	892	1746	217	521	59	311	613	27	64	281	102	548
Colorado	92	180	31	75	54	391	771	39	94	382	270	1084

[131] Additional information on the Cattle Enteric Fermentation Model can be found in ICF (2006).

Conn.	10	20	3	6	0	2	4	0	1	1	1	0
Delaware	2	5	0	1	0	1	2	0	0	1	0	0
Florida	60	117	10	24	59	451	890	30	72	9	12	3
Georgia	42	82	9	21	32	246	486	21	50	17	14	5
Hawaii	1	2	0	1	4	37	73	3	6	5	2	1
Idaho	317	620	97	233	39	250	492	26	61	147	104	301
Illinois	44	86	13	31	25	200	394	16	39	113	45	254
Indiana	93	183	23	55	17	101	199	10	25	53	24	102
Iowa	113	222	36	86	69	459	905	36	86	640	266	1373
Kansas	83	163	49	116	93	754	1488	65	155	948	674	2541
Kentucky	27	54	13	31	69	502	990	28	66	104	62	17
Louisiana	6	11	1	3	29	226	447	19	46	12	11	3
Maine	15	29	4	10	1	5	11	1	2	2	1	0
Maryland	23	44	9	21	5	25	49	3	7	6	4	9
Mass.	5	11	2	4	1	3	7	0	1	1	0	0
Michigan	218	426	46	110	15	53	105	6	14	83	19	154
Minn.	232	454	73	175	34	182	360	22	52	223	81	432
Miss.	4	8	1	3	37	235	464	21	50	24	19	6
Missouri	42	82	11	27	123	1016	2004	78	185	182	97	100
Montana	6	12	2	5	98	714	1409	88	210	110	110	43
Nebraska	30	60	4	10	108	957	1889	85	202	1096	726	2881
Nevada	17	33	3	8	15	119	236	10	23	18	14	4
N.Hamp.	6	12	2	4	0	2	4	0	1	1	0	0
N.Jersey	3	6	1	2	1	5	9	1	1	1	0	0
N.Mexico	168	328	36	86	34	237	467	22	52	60	40	15
New York	322	631	96	229	18	52	102	9	22	22	21	23
N.Car.	22	43	6	14	29	181	357	14	33	16	9	4
N.Dakota	8	15	2	5	64	481	949	46	109	117	100	61
Ohio	130	255	36	86	29	151	299	16	39	99	26	154
Oklahoma	21	40	6	14	177	1060	2093	93	221	483	247	344
Oregon	64	126	19	45	39	264	521	26	61	74	55	94
Penn	260	510	83	199	25	111	219	15	36	62	26	101
R.Island	0	1	0	0	0	1	1	0	0	0	0	0
S.Car.	7	14	1	3	14	92	181	9	20	5	4	1
S.Dakota	63	123	11	27	103	897	1769	89	213	336	261	454
Tenn.	19	36	7	17	64	451	890	34	80	60	36	15
Texas	281	550	74	178	334	2296	4531	172	409	1252	802	2847
Utah	52	101	14	34	25	168	331	16	39	39	31	23
Vermont	65	127	16	38	3	7	14	1	2	2	3	1
Virginia	41	80	11	25	38	311	614	22	51	71	29	16
Wash.	144	283	35	84	20	113	224	13	31	92	57	237
W.Virg.	4	7	1	2	14	98	193	7	18	19	9	4
Wisconsin	655	1282	194	466	29	143	282	19	44	166	28	292
Wyoming	3	6	1	3	39	352	695	37	88	69	60	69

Table A-130: Cattle Population Estimates from the CEFM Transition Matrix for 1990–2021 (1,000 head)

Livestock Type	1990	1995	2000	2005	2010	2017	2018	2019	2020	2021[a]
Dairy										

Dairy Calves (0–6 months)	5,369	5,091	4,951	4,628	4,666	4,797	4,833	4,834	4,825	4,823
Dairy Cows	10,015	9,482	9,183	9,004	9,087	9,369	9,432	9,353	9,343	9,442
Dairy Replacements 7–11 months	1,214	1,216	1,196	1,257	1,351	1,416	1,400	1,391	1,364	1,342
Dairy Replacements 12–23 months	2,915	2,892	2,812	2,905	3,194	3,342	3,341	3,304	3,273	3,220
Beef										
Beef Calves (0–6 months)	16,909	18,177	17,431	16,918	16,067	15,931	16,221	15,892	15,635	15,631
Bulls	2,160	2,385	2,293	2,214	2,190	2,244	2,252	2,253	2,237	2,211
Beef Cows	32,455	35,190	33,575	32,674	31,440	31,171	31,466	31,691	31,339	30,844
Beef Replacements 7–11 months	1,269	1,493	1,313	1,363	1,238	1,479	1,420	1,380	1,366	1,364
Beef Replacements 12–23 months	2,967	3,637	3,097	3,171	3,050	3,594	3,444	3,321	3,254	3,250
Steer Stockers	10,321	11,716	8,724	8,185	8,234	7,904	7,633	7,745	7,600	7,714
Heifer Stockers	5,946	6,699	5,371	5,015	5,061	4,717	4,595	4,500	4,447	4,567
Feedlot Cattle	9,549	11,064	13,006	12,652	13,204	14,346	14,690	14,917	14,935	14,945

[a] Population estimates for 2021 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.[132] 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 CH_4 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 CH_4 emissions (e.g., beef versus dairy). Consequently, there is an 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-131**.

Table A-131: Cattle Population Categories Used for Estimating CH_4 Emissions

Dairy Cattle	Beef Cattle

[132] Mature animal populations are not assumed to have significant monthly fluctuations, and therefore the populations utilized are the January estimates downloaded from USDA (2021).

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 (2021). 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-132, 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-133. 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-132: 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-133: 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	1,163	1,154	1,378	1,618	1,552	1,541	2,515	4,711	8,199	6,637	3,089	1,542
5	1,155	1,379	1,619	1,553	1,541	2,516	4,712	8,202	6,640	3,091	1,544	1,151
4	1,426	1,660	1,598	1,580	2,556	4,754	8,243	6,688	3,135	1,588	1,194	1,184
3	1,662	1,599	1,581	2,557	4,755	8,246	6,690	3,136	1,588	1,194	1,185	1,459
2	1,600	1,582	2,558	4,757	8,249	6,693	3,138	1,589	1,195	1,186	1,460	1,698
1	1,584	2,560	4,760	8,253	6,695	3,139	1,590	1,195	1,186	1,461	1,699	1,635
0	2,562	4,763	8,257	6,698	3,140	1,590	1,196	1,187	1,462	1,700	1,636	1,618

Note: As highlighted in grey as an example, the cohort starting at age 0 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 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 (2021).

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-134) 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-134.

Table A-134: 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	185	180	104	37	15	9	8	8	6	3	1	0
22	320	146	49	19	12	9	9	9	6	3	17	181
21	260	69	25	14	11	11	11	8	6	68	218	313
20	123	35	19	14	14	13	10	8	133	331	387	254
19	63	27	19	17	16	13	10	196	472	615	318	120
18	48	27	23	20	16	13	241	610	900	514	149	61
17	47	33	27	19	15	295	709	1,179	759	237	129	47
16	58	38	26	19	363	828	1,380	1,000	348	340	47	46
15	67	36	25	452	977	1,619	1,172	456	603	47	46	57
14	65	36	599	1,172	1,921	1,378	534	862	47	46	57	66
13	64	845	1,478	2,309	1,639	629	1,117	47	46	57	66	63
12	982	1,602	2,556	1,858	755	1,512	214	46	57	66	63	63
11	1,814	2,770	2,056	855	1,872	277	138	76	89	81	80	1,016
10	3,133	2,255	945	2,241	385	189	184	231	209	185	1,135	2,445
9	2,545	1,062	2,502	484	335	341	420	372	371	1,292	2,786	5,299
8	1,200	2,951	664	482	557	759	658	649	1,503	3,247	5,984	4,877
7	3,381	800	794	956	1,160	1,109	1,100	1,876	3,666	6,504	5,243	2,353

Note: As highlighted 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 (2021). 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.[133] 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).[134] 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 2021a) 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-135.

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-136, and weight gain was held constant starting in 2000. Table A-136 provides weight gains that vary by year in the CEFM.

[133] Mature beef weight is held constant after 2007 but future inventory submissions will incorporate known trends through 2007 and extrapolate to future years, as noted in the Planned Improvements section of 5.1 Enteric Fermentation.

[134] Mature dairy weight is based solely on Holstein weight, so could be higher than the national average. Future Inventory submissions will consider other dairy breeds, as noted in the Planned Improvements section of 5.1 Enteric Fermentation.

Table A-135: Typical Animal Mass (lbs) [135]

Year/Cattle Type	Calves	Dairy Cows[a]	Dairy Replacements[b]	Bulls[a]	Beef Cows[a]	Beef Replacements[b]	Steer Stockers[b]	Heifer Stockers[b]	Steer Feedlot[b]	Heifer Feedlot[b]
1990	269	1499	899	1830	1220	819	691	651	923	845
1991	270	1499	897	1836	1224	821	694	656	933	855
1992	269	1499	897	1893	1262	840	714	673	936	864
1993	270	1499	898	1918	1279	852	721	683	929	863
1994	270	1499	897	1918	1279	853	720	688	943	875
1995	270	1499	897	1921	1281	857	735	700	947	879
1996	269	1499	898	1926	1284	858	739	707	939	878
1997	270	1499	899	1927	1285	860	736	707	938	876
1998	270	1499	896	1942	1295	865	736	709	956	892
1999	270	1499	899	1936	1291	861	730	708	959	894
2000	270	1499	896	1906	1271	849	719	702	960	898
2001	270	1499	897	1906	1271	850	725	707	963	900
2002	270	1499	896	1912	1275	851	725	707	981	915
2003	270	1499	899	1960	1307	871	718	701	972	904
2004	270	1499	896	1983	1322	877	719	702	966	904
2005	270	1499	894	1989	1326	879	717	706	974	917
2006	270	1499	897	2010	1340	889	724	712	983	925
2007	270	1499	896	2020	1347	894	720	706	991	928
2008	270	1499	897	2020	1347	894	720	704	999	938
2009	270	1499	895	2020	1347	894	730	715	1007	947
2010	270	1499	897	2020	1347	896	726	713	996	937
2011	270	1499	897	2020	1347	891	721	712	989	932
2012	270	1499	899	2020	1347	892	714	706	1003	945
2013	270	1499	898	2020	1347	892	718	709	1016	958
2014	270	1499	895	2020	1347	888	720	713	1021	960
2015	270	1499	896	2020	1347	890	717	714	1037	982
2016	270	1499	898	2020	1347	892	721	718	1047	991
2017	270	1499	896	2020	1347	894	714	709	1037	977
2018	270	1499	898	2020	1347	894	708	701	1030	972
2019	270	1499	897	2020	1347	893	710	698	1032	972
2020	271	1499	899	2020	1347	893	711	699	1046	984

[a] Input into the model.

[b] Annual average calculated in model based on age distribution.

[135] This table has not been updated for the current (1990 through 2021) Inventory. It will be updated for the next (1990 through 2022) Inventory submission.

Table A-136: 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-137) 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-137 provides a summary of the reported feedlot placement statistics for 2020.

Table A-137: Feedlot Placements in the United States for 2020 (Number of animals placed/1,000 Head) [136]

Weight Placed When:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
< 600 lbs	390	340	310	295	380	430	420	405	445	570	520	460
600 – 700 lbs	455	320	220	180	310	310	315	335	360	495	460	435
700 – 800 lbs	535	465	410	315	485	360	435	470	500	465	400	425
> 800 lbs	575	591	617	642	877	698	723	847	922	662	523	524
Total	**1,955**	**1,716**	**1,557**	**1,432**	**2,052**	**1,798**	**1,893**	**2,057**	**2,227**	**2,192**	**1,903**	**1,844**

Note: Totals may not sum due to independent rounding.
Source: USDA (2021).

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 the percentage of all mature animals that are pregnant each month, as well as milk production, to estimate CH_4 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

[136] This table has not been updated for the current (1990 through 2021) Inventory. It will be updated for the next (1990 through 2022) Inventory submission.

for daily milk production by beef cows are shown in Table A-138. Annual estimates for dairy cows were taken from USDA milk production statistics. Dairy lactation estimates for 1990 through 2020 are shown in Table A-139. 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-138: 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-139: Dairy Lactation Rates by State (lbs/ year/cow) [137]

State/Year	1990	2000	2005	2010	2016	2017	2018	2019	2020
Alabama	12,214	13,920	14,000	14,182	13,429	15,000	14,600	12,000	15,000
Alaska	13,300	14,500	12,273	11,833	11,667	9,667	9,333	4,455	5,333
Arizona	17,500	21,820	22,679	23,452	24,065	24,197	23,909	24,096	24,568
Arkansas	11,841	12,436	13,545	12,750	13,667	13,333	12,333	13,400	12,800
California	18,456	21,130	21,404	23,025	22,968	22,755	23,301	23,533	23,987
Colorado	17,182	21,618	22,577	23,664	25,654	25,858	25,892	25,844	26,142
Connecticut	15,606	17,778	19,200	19,158	21,526	22,105	22,474	22,526	23,053
Delaware	13,667	14,747	16,622	16,981	19,100	18,560	19,063	17,976	18,553
Florida	14,033	15,688	16,591	18,711	20,293	20,129	19,833	20,224	20,257
Georgia	12,973	16,284	17,259	17,658	21,786	21,905	21,277	21,598	21,877
Hawaii	13,604	14,358	12,889	13,316	14,542	16,913	16,950	4,455	5,333
Idaho	16,475	20,816	22,332	22,647	24,647	24,388	24,870	25,011	25,180
Illinois	14,707	17,450	18,827	18,400	20,340	20,742	20,867	20,810	21,530
Indiana	14,590	16,568	20,295	20,094	22,527	22,754	22,754	22,899	23,661
Iowa	15,118	18,298	20,641	20,676	23,634	23,757	23,955	24,271	24,651
Kansas	12,576	16,923	20,505	20,983	22,801	23,020	23,321	23,429	23,694
Kentucky	10,947	12,841	12,896	14,769	18,052	18,607	18,345	18,840	19,542
Louisiana	11,605	12,034	12,400	11,750	14,167	13,417	13,818	13,500	13,400
Maine	14,619	17,128	18,030	18,344	21,000	21,000	20,600	21,414	21,963
Maryland	13,461	16,083	16,099	18,537	20,021	19,917	20,556	19,535	20,905
Massachusetts	14,871	17,091	17,059	17,286	18,417	17,583	18,364	19,300	19,900
Michigan	15,394	19,017	21,635	23,277	25,957	26,302	26,409	26,725	27,170
Minnesota	14,127	17,777	18,091	19,366	20,967	21,544	21,784	22,147	22,705
Mississippi	12,081	15,028	15,280	13,118	14,300	15,222	14,333	15,750	16,375
Missouri	13,632	14,662	16,026	14,596	14,847	14,600	14,386	14,103	14,276
Montana	13,542	17,789	19,579	20,643	21,071	22,154	22,833	21,583	21,167
Nebraska	13,866	16,513	17,950	19,797	23,317	24,067	24,000	24,293	24,746
Nevada	16,400	19,000	21,680	23,714	22,000	22,156	22,938	23,091	24,677
New Hampshire	15,100	17,333	18,875	19,600	20,500	21,000	20,750	21,727	21,273
New Jersey	13,538	15,250	16,000	17,500	17,429	19,833	18,333	20,000	19,800
New Mexico	18,815	20,944	21,192	24,551	24,479	24,960	25,106	25,113	24,755
New York	14,658	17,378	18,639	20,807	23,834	23,925	23,888	24,118	24,500
North Carolina	15,220	16,746	18,741	19,682	20,978	21,156	21,295	21,476	21,829
North Dakota	12,624	14,292	14,182	18,286	21,500	21,563	22,267	21,733	21,867
Ohio	13,767	17,027	17,567	19,446	21,140	21,284	21,359	21,614	22,118
Oklahoma	12,327	14,440	16,480	17,125	18,703	18,200	18,125	17,829	17,452
Oregon	16,273	18,222	18,876	20,331	20,744	20,395	20,577	20,913	21,032
Pennsylvania	14,726	18,081	18,722	19,847	20,439	20,749	20,534	20,629	21,320
Rhode Island	14,250	15,667	17,000	17,727	17,625	16,250	16,429	17,667	21,800

[137] This table has not been updated for the current (1990 through 2021) Inventory. It will be updated for the next (1990 through 2022) Inventory submission.

South Carolina	12,771	16,087	16,000	17,875	16,667	16,533	17,286	17,167	18,900
South Dakota	12,257	15,516	17,741	20,478	22,139	22,376	22,364	22,480	23,111
Tennessee	11,825	14,789	15,743	16,346	16,571	17,325	17,135	17,219	18,067
Texas	14,350	16,503	19,646	21,375	22,585	23,406	23,948	24,513	24,926
Utah	15,838	17,573	18,875	21,898	22,989	23,073	23,220	23,061	23,198
Vermont	14,528	17,199	18,469	18,537	20,977	21,155	21,126	21,405	21,328
Virginia	14,213	15,833	16,990	18,095	19,144	19,954	19,699	19,867	20,293
Washington	18,532	22,644	23,270	23,514	24,094	23,836	24,318	24,225	24,346
West Virginia	11,250	15,588	14,923	15,700	14,889	15,875	15,857	15,000	14,833
Wisconsin	13,973	17,306	18,500	20,630	23,542	23,735	24,002	24,123	24,408
Wyoming	12,337	13,571	14,878	20,067	23,300	23,033	23,700	24,433	25,173

Source: USDA (2021).

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 CH_4 conversion rate values (Y_m, the fraction of gross energy converted to CH_4) for each of the cattle population categories, data were collected on diets considered representative of different regions. For both grazing animals and animals being fed mixed rations, 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-140. 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-141. 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-140: 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 Hampshire		North Carolina
Oregon		Wyoming	Ohio	New Jersey		South Carolina
Utah			Wisconsin	New York		Tennessee
Washington				Pennsylvania		Virginia
				Rhode Island		
				Vermont		
				West Virginia		

Source: USDA (1996).

Table A-141: Regions used for Characterizing the Diets of Foraging Cattle from 2007–2020

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 2007-2020 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 (1999), which represents physiological processes in the ruminant animals, as well as diet characteristics from USDA (1996). The Donovan and Baldwin model 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-liner 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 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 Ym value. The resulting Y_m equation (incorporating both 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-140 (California, Northern Great Plains, Midwestern, Northeast, Southcentral, Southeast) and Table A-141 (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-142. 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-143 and Table A-144 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.[138] 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-145.

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-146 shows the regional DE and Y_m for U.S. cattle in each region for 2020.

[138] 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-145.

Table A-142: Feed Components and Digestible Energy Values Incorporated into Forage Diet Composition Estimates

Forage Type	DE (% of GE)	Grass pasture - Spring	Grass pasture - Summer	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 Andropagon spp, fresh, early vegetative	73.17				x						
Bluestem Andropagon 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					x		
Buffalograss, Buchloe dactyloides, fresh	64.02				x	x					
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		x						
Corn, Dent Yellow Zea mays indentata, aerial part without ears, without husks, sun-cured, (stover)(straw)	55.28			x							
Dropseed, Sand Sporobolus cryptandrus, fresh, stem cured	64.69				x	x	x			x	
Fescue Festuca spp, hay, sun-cured, early vegetative	67.39	x									
Fescue Festuca spp, hay, sun-cured, early bloom	53.57			x							
Grama Bouteloua spp, fresh, early vegetative	67.02	x									
Grama Bouteloua spp, fresh, mature	63.38		x	x						x	
Millet, Foxtail Setaria italica, fresh	68.20	x			x						
Napiergrass Pennisetum purpureum, fresh, late bloom	57.24		x	x							
Needleandthread Stipa comata, fresh, stem cured	60.36					x	x	x			
Orchardgrass Dactylis glomerata, fresh, early vegetative	75.54	x									

Forage Type	DE (% of GE)	Grass pasture - Spring	Grass pasture - Summer	Grass pasture - Fall	Range June	Range July	Range August	Range September	Range Winter	Meadow - Spring	Meadow - Fall
Orchardgrass Dactylis glomerata, fresh, midbloom	60.13		x								
Pearlmillet Pennisetum glaucum, fresh	68.04	x									
Prairie plants, Midwest, hay, sun-cured	55.53			x							x
Rape Brassica napus, fresh, early bloom	80.88	x									
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**	**67.11**	**62.70**	**60.62**	**58.59**	**52.07**	**64.03**	**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-143: 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 #030	66.29							35%
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	Table 8, feed #147	60.13							40%
Soybean Meal Supplement		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**	**68.0**
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-144: DE Values and Representative Regional Diets for the Supplemental Diet of Grazing Beef Cattle for 2007–2020[139]

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%
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).

[139] This table has not been updated for the current (1990 through 2021) Inventory. It will be updated for the next (1990 through 2022) Inventory submission.

Table A-145: Foraging Animal DE (% of GE) and Y_m Values for Each Region and Animal Type for 2007–2020[140]

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-141.

[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.

Table A-146: Regional DE (% of GE) and Y_m Rates for Dairy and Feedlot Cattle by Animal Type for 2020[141]

Animal Type	Data	California[a]	West	Northern Great 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%

[a] Emissions are currently calculated on a state-by-state basis, but diets are applied in Table A-140 by the regions shown in the table above. To see the regional designation for foraging cattle per state, please see Table A-140.

[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 CH_4 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)

[140] This table has not been updated for the current (1990 through 2021) Inventory. It will be updated for the next (1990 through 2022) Inventory submission.

[141] This table has not been updated for the current (1990 through 2021) Inventory. It will be updated for the next (1990 through 2022) Inventory submission.

- Net Energy for Activity (C_a, MJ/day)[142]
- Standard Reference Weight (kg)[143]
- Milk Production (kg/day)
- Milk Fat (percent of fat in milk)[144]
- Pregnancy (percent of population that is pregnant)
- DE (percent of GE intake digestible)
- Y_m (the fraction of GE converted to CH_4)
- Population

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 2020 are shown by state and animal type in Table A-147.

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)

[142] 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).

[143] 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.

[144] Average milk fat varies by year and is derived from USDA's Economic Research Service Dairy Data set (USDA 2021b).

Table A-147: Calculated Annual GE by Animal Type and State, for 2020 (1,000 GJ)[145]

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	18	488	27	97	4,166	3,121	56,024	1,431	3,950	1,024	1,055	320
Alaska	1	18	1	5	347	37	662	16	43	15	10	4
Arizona	870	30,802	1,537	5,573	1,779	939	16,671	324	890	6,735	388	12,037
Arkansas	22	552	40	145	5,165	4,104	73,653	1,804	4,979	2,616	1,679	666
California	7,661	265,333	10,160	36,828	5,336	3,171	56,285	1,557	4,274	15,185	5,428	25,489
Colorado	839	30,890	1,537	5,573	4,447	3,732	66,253	2,011	5,520	19,104	14,733	52,866
Conn.	87	2,947	127	460	42	25	444	24	67	34	36	11
Delaware	17	506	24	87	33	10	178	8	23	59	12	11
Florida	515	16,574	468	1,696	4,999	4,054	72,767	1,563	4,315	569	600	180
Georgia	360	12,097	401	1,454	2,666	2,328	41,777	1,082	2,987	978	720	263
Hawaii	3	41	13	48	356	365	6,471	143	392	245	129	54
Idaho	2,842	102,143	4,412	15,991	3,558	2,372	42,106	1,686	4,630	7,348	5,170	14,633
Illinois	364	11,892	602	2,181	1,629	1,652	29,746	703	1,944	5,324	2,104	11,328
Indiana	782	27,022	1,003	3,634	1,303	848	15,266	480	1,328	2,396	1,052	4,956
Iowa	955	33,860	1,537	5,573	4,887	3,954	71,217	1,699	4,698	28,841	14,029	60,891
Kansas	742	25,662	1,872	6,784	6,923	6,305	113,554	2,930	8,099	46,145	36,241	121,781
Kentucky	218	6,861	535	1,938	5,832	4,579	82,185	1,503	4,149	4,892	2,639	802
Louisiana	44	1,128	40	145	2,499	2,041	36,625	986	2,722	569	480	162
Maine	124	4,109	187	678	125	49	888	42	117	114	84	31
Maryland	187	5,986	348	1,260	292	211	3,794	133	366	262	192	283
Mass.	44	1,385	87	315	84	25	444	24	67	46	24	11
Michigan	1,896	71,540	2,340	8,480	1,222	406	7,318	270	745	3,882	748	7,788
Minn.	1,976	66,624	3,142	11,388	2,443	1,595	28,723	1,113	3,078	11,536	3,741	18,881
Miss.	36	1,019	67	242	3,249	2,162	38,799	1,082	2,987	1,320	1,031	363
Missouri	342	8,938	468	1,696	9,774	9,101	163,917	3,926	10,853	9,096	5,144	5,192
Montana	53	1,723	67	242	9,339	6,913	122,710	5,059	13,890	6,123	5,945	2,360
Nebraska	258	9,156	401	1,454	9,774	8,398	151,248	4,336	11,987	52,801	35,072	122,725
Nevada	138	4,885	134	485	1,334	1,205	21,397	571	1,567	980	853	142
N. Hamp.	49	1,584	87	315	42	18	323	16	43	34	17	8
N. Jersey	21	649	41	150	84	42	751	27	73	46	29	12

[145] This table has not been updated for the current (1990 through 2021) Inventory; however, the title has been corrected to indicate that units are in 1000 GJ. It will be updated for the next (1990 through 2022) Inventory submission.

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
N. Mexico	1,466	52,107	1,872	6,784	2,668	2,324	41,247	1,038	2,849	2,449	2,068	648
New York	2,776	98,052	4,612	16,718	1,671	472	8,475	483	1,332	1,255	962	1,038
N. Car.	182	6,115	241	872	2,583	1,655	29,703	758	2,091	910	552	227
N. Dakota	67	2,196	107	388	5,701	4,347	78,299	2,133	5,896	6,101	5,378	1,982
Ohio	1,119	37,139	1,604	5,815	2,443	1,302	23,450	820	2,268	4,881	1,520	8,024
Oklahoma	182	5,289	267	969	14,163	9,458	169,764	4,450	12,281	22,980	12,713	16,049
Oregon	564	18,166	936	3,392	3,558	2,580	45,802	1,362	3,740	3,551	3,102	4,484
Penn.	2,132	69,210	3,676	13,326	1,671	990	17,758	724	1,997	3,081	1,323	4,720
R. Island	3	88	7	24	8	5	97	6	17	11	5	3
S. Car.	49	1,512	53	194	1,083	803	14,409	313	863	273	264	83
S. Dakota	564	19,220	602	2,181	8,959	7,790	140,310	4,219	11,663	15,751	10,755	20,769
Tenn.	138	4,158	334	1,211	4,999	4,077	73,170	1,503	4,149	3,527	2,039	863
Texas	2,576	92,122	3,743	13,568	29,160	20,495	367,861	9,621	26,553	60,293	37,179	140,662
Utah	431	14,714	668	2,423	2,224	1,733	30,764	1,103	3,027	1,959	1,551	944
Vermont	551	17,883	735	2,665	251	58	1,049	54	150	91	132	34
Virginia	329	10,584	441	1,599	3,333	2,807	50,390	1,118	3,087	3,754	1,535	944
Wash.	1,252	44,068	1,698	6,154	1,779	1,104	19,592	739	2,030	5,021	3,515	11,328
W. Virg.	27	710	40	145	1,253	895	16,063	410	1,132	1,004	529	189
Wisconsin	5,596	197,212	9,225	33,436	2,443	1,354	24,395	1,055	2,916	7,543	1,169	11,328
Wyoming	27	957	53	194	4,002	3,505	62,214	2,076	5,698	3,796	3,257	3,304

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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

$$DayEmit = \frac{GE \times Y_m}{55.65}$$

where,

DayEmit = Emission factor (kg CH_4/head/day)
GE = Gross energy intake (MJ/head/day)
Y_m = CH_4 conversion rate, which is the fraction of GE in feed converted to CH_4 (%)
55.65 = A factor for the energy content of methane (MJ/kg CH_4)

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-148. State-level emission factors are shown by animal type for 2020 in Table A-149.

Table A-148: Calculated Annual National Enteric Fermentation Emission Factors for Cattle by Animal Type, for 2020 (kg CH_4/head/year) [146]

Cattle Type	1990	1995	2000	2005	2010	2016	2017	2018	2019	2020
Dairy										
Calves	12	12	12	12	12	12	12	12	12	12
Cows	121	122	129	130	138	144	145	147	148	150
Replacements 7–11 months	48	46	46	45	46	46	46	46	45	45
Replacements 12–23 months	73	69	70	67	69	69	69	69	69	69
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	94	94	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	44	43	43	43	43

Note: To convert to a daily emission factor, the yearly emission factor can be divided by 365 (the number of days in a year).

[146] This table has not been updated for the current (1990 through 2021) Inventory. It will be updated for the next (1990 through 2022) Inventory submission.

Table A-149: Enteric Fermentation Emission Factors for Cattle by Animal Type and State, for 2020 (kg CH_4/head/year) [147]

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	138	53	80	97	10	94	60	69	58	60	35
Alaska	12	57	45	69	104	11	100	64	74	62	65	32
Arizona	12	153	45	69	104	11	100	64	74	62	65	33
Arkansas	12	115	49	74	97	10	94	60	69	58	60	35
California	12	150	45	69	104	11	100	64	74	62	65	34
Colorado	12	150	43	65	104	11	100	64	74	62	65	34
Conn.	12	156	48	73	98	11	94	60	69	58	60	35
Delaware	12	137	48	73	98	11	94	60	69	58	60	35
Florida	12	162	53	80	97	10	94	60	69	58	60	36
Georgia	12	169	53	80	97	10	94	60	69	58	60	35
Hawaii	12	57	45	69	104	11	100	64	74	62	65	35
Idaho	12	155	45	69	104	11	100	64	74	62	65	34
Illinois	12	133	43	65	95	10	92	58	68	56	59	33
Indiana	12	141	43	65	95	10	92	58	68	56	59	34
Iowa	12	145	43	65	95	10	92	58	68	56	59	34
Kansas	12	141	43	65	95	10	92	58	68	56	59	34
Kentucky	12	158	53	80	97	10	94	60	69	58	60	34
Louisiana	12	118	49	74	97	10	94	60	69	58	60	34
Maine	12	151	48	73	98	11	94	60	69	58	60	36
Maryland	12	147	48	73	98	11	94	60	69	58	60	30
Mass.	12	143	48	73	98	11	94	60	69	58	60	35
Michigan	12	154	43	65	95	10	92	58	68	56	59	34
Minn.	12	138	43	65	95	10	92	58	68	56	59	33
Miss.	12	144	53	80	97	10	94	60	69	58	60	35
Missouri	12	107	43	65	95	10	92	58	68	56	59	34
Montana	12	132	43	65	104	11	100	64	74	62	65	35
Nebraska	12	145	43	65	95	10	92	58	68	56	59	33
Nevada	12	153	45	69	104	11	100	64	74	62	65	31
N. Hamp.	12	148	48	73	98	11	94	60	69	58	60	35
N. Jersey	12	142	48	73	98	11	94	60	69	58	60	35
N. Mexico	12	154	45	69	104	11	100	64	74	62	65	34
New York	12	162	48	73	98	11	94	60	69	58	60	34

[147] This table has not been updated for the current (1990 through 2021) Inventory. It will be updated for the next (1990 through 2022) Inventory submission.

N. Car.	12	169	53	80	97	10	94	60	69	58	60	36
N. Dakota	12	135	43	65	95	10	92	58	68	56	59	31
Ohio	12	136	43	65	95	10	92	58	68	56	59	35
Oklahoma	12	135	49	74	97	10	94	60	69	58	60	34
Oregon	12	139	45	69	104	11	100	64	74	62	65	34
Penn.	12	148	48	73	98	11	94	60	69	58	60	34
R. Island	12	150	48	73	98	11	94	60	69	58	60	36
S. Car.	12	156	53	80	97	10	94	60	69	58	60	36
S. Dakota	12	139	43	65	95	10	92	58	68	56	59	34
Tenn.	12	152	53	80	97	10	94	60	69	58	60	36
Texas	12	166	49	74	97	10	94	60	69	58	60	34
Utah	12	148	45	69	104	11	100	64	74	62	65	33
Vermont	12	149	48	73	98	11	94	60	69	58	60	34
Virginia	12	162	53	80	97	10	94	60	69	58	60	36
Wash.	12	152	45	69	104	11	100	64	74	62	65	34
W. Virg.	12	122	48	73	98	11	94	60	69	58	60	34
Wisconsin	12	144	43	65	95	10	92	58	68	56	59	32
Wyoming	12	147	43	65	104	11	100	64	74	62	65	34

Note: To convert to a daily emission factor, the yearly emission factor can be divided by 365 (the number of days in a year).

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For quality assurance purposes, U.S. emission factors for each animal type were compared to estimates provided by the other Annex I member countries of the United Nations Framework Convention on Climate Change (UNFCCC) (the most recently available summarized results for Annex I countries are through 2012 only). Results, presented in Table A-150, indicate that U.S. emission factors are comparable to those of other Annex I countries. Results in Table A-150 are presented along with Tier I emission factors provided by IPCC (2006). Throughout the time series, beef cattle in the United States generally emit more enteric CH_4 per head than other Annex I member countries, while dairy cattle in the United States generally emit comparable enteric CH_4 per head.

Table A-150: Annex I Countries' Implied Enteric Fermentation Emission Factors for Cattle by Year (kg CH_4/head/year)[148, 149]

	Dairy Cattle		Beef Cattle	
Year	United States Implied Emission Factor	Mean of Implied Emission Factors for Annex I countries (excluding U.S.)	United States Implied Emission Factor	Mean of Implied Emission Factors for Annex I 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	121	NA	74	NA
Tier I EFs For North America, from IPCC (2006)		**121**		**53**

NA (Not Applicable)

[148] Excluding calves.

[149] This table has not been updated for the current (1990 through 2021) Inventory. It will be updated for the next (1990 through 2021) Inventory submission.

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

$$Emissions_{state} = DayEmit_{state} \times Days/Month \times SubPop_{state}$$

where,

$Emissions_{state}$ = Emissions for state during the month (kg CH_4)
$DayEmit_{state}$ = Emission factor for the subcategory and state (kg CH_4/head/day)
Days/Month = Number of days in the month
$SubPop_{state}$ = 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-151 (in kt) and Table A-153 (in MMT CO_2 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-151: Enteric Fermentation CH_4 Emissions from Cattle (kt)

Cattle Type	1990	1995	2000	2005	2010	2017	2018	2019	2020	2021
Dairy	**1,547**	**1,471**	**1,492**	**1,473**	**1,594**	**1,715**	**1,737**	**1,732**	**1,744**	**1,754**
Calves (4–6 months)	62	59	59	54	57	58	59	59	59	59
Cows	1,214	1,156	1,182	1,167	1,253	1,363	1,385	1,383	1,398	1,413
Replacements 7–11 months	58	56	55	56	62	65	64	63	62	61
Replacements 12–23 months	212	201	196	196	222	230	230	227	225	221
Beef	**4,742**	**5,396**	**5,050**	**4,986**	**4,963**	**5,033**	**5,042**	**5,062**	**5,013**	**4,967**
Calves (4–6 months)	196	225	215	214	215	220	221	221	219	217
Bulls	182	193	186	179	169	168	171	168	165	165
Cows	2,862	3,199	3,037	3,035	2,955	2,941	2,972	2,994	2,963	2,916
Replacements 7–11 months	69	85	74	80	75	89	86	83	82	82
Replacements 12–23 months	188	241	204	217	213	251	240	232	227	227
Steer Stockers	563	662	509	473	476	458	442	449	440	446
Heifer Stockers	306	375	323	299	302	284	277	271	267	275
Feedlot Cattle	375	416	502	488	560	621	633	644	649	638
Total	**6,289**	**6,866**	**6,541**	**6,460**	**6,557**	**6,748**	**6,779**	**6,794**	**6,757**	**6,721**

Table A-152: Enteric Fermentation CH_4 Emissions from Cattle (MMT CO_2 Eq.)

Cattle Type	1990	1995	2000	2005	2010	2017	2018	2019	2020	2021
Dairy	**43.3**	**41.2**	**41.8**	**41.3**	**44.6**	**48.0**	**48.6**	**48.5**	**48.8**	**49.1**
Calves (4–6 months)	1.7	1.6	1.6	1.5	1.6	1.6	1.6	1.7	1.7	1.7
Cows	34.0	32.4	33.1	32.7	35.1	38.2	38.8	38.7	39.1	39.6
Replacements 7–11 months	1.6	1.6	1.5	1.6	1.7	1.8	1.8	1.8	1.7	1.7
Replacements 12–23 months	5.9	5.6	5.5	5.5	6.2	6.4	6.4	6.3	6.3	6.2
Beef	**132.8**	**151.1**	**141.4**	**139.6**	**139.0**	**140.9**	**141.2**	**141.7**	**140.4**	**139.1**
Calves (4–6 months)	5.1	5.4	5.2	5.0	4.7	4.7	4.8	4.7	4.6	4.6
Bulls	5.5	6.3	6.0	6.0	6.0	6.2	6.2	6.2	6.1	6.1
Cows	80.1	89.6	85.0	85.0	82.8	82.3	83.2	83.8	83.0	81.7
Replacements 7–11 months	1.9	2.4	2.1	2.3	2.1	2.5	2.4	2.3	2.3	2.3
Replacements 12–23 months	5.3	6.7	5.7	6.1	6.0	7.0	6.7	6.5	6.4	6.4
Steer Stockers	15.8	18.5	14.2	13.2	13.3	12.8	12.4	12.6	12.3	12.5
Heifer Stockers	8.6	10.5	9.1	8.4	8.4	8.0	7.7	7.6	7.5	7.7
Feedlot Cattle	10.5	11.6	14.0	13.7	15.7	17.4	17.7	18.0	18.2	17.9
Total	**176.1**	**192.3**	**183.2**	**180.9**	**183.6**	**189.0**	**189.8**	**190.2**	**189.2**	**188.1**

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 2022) or the Census of Agriculture (USDA 2019). The Manure Management Annex 3.11 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-153 shows the emission factors used for these other livestock. National enteric fermentation emissions from all livestock types are shown in Table A-154 and Table A-155. Enteric fermentation emissions from most livestock types, broken down by state, for 2021 are shown in Table A-156 through Table A-159. Livestock populations are shown in Table A-129.

Table A-153: Enteric Fermentation Emission Factors for Other Livestock (kg CH_4/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-154: CH_4 Emissions from Enteric Fermentation (kt)

Livestock Type	1990	1995	2000	2005	2010	2017	2018	2019	2020	2021
Beef Cattle	4,742	5,396	5,050	4,986	4,963	5,033	5,042	5,062	5,013	4,967
Dairy Cattle	1,547	1,471	1,492	1,473	1,594	1,715	1,737	1,732	1,744	1,754
Swine	81	88	88	92	97	108	110	115	116	111
Horses	40	47	61	70	68	51	48	46	43	40
Sheep	102	81	63	55	51	47	47	47	47	47
Goats	23	21	22	26	26	24	24	25	25	23
American Bison	4	9	16	17	15	15	15	16	16	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**	**6,998**	**7,028**	**7,046**	**7,007**	**6,962**

Note: Totals may not sum due to independent rounding.

Table A-155: CH_4 Emissions from Enteric Fermentation (MMT CO_2 Eq.)

Livestock Type	1990	1995	2000	2005	2010	2017	2018	2019	2020	2021
Beef Cattle	132.8	151.1	141.4	139.6	139.0	140.9	141.2	141.7	140.4	139.1
Dairy Cattle	43.3	41.2	41.8	41.3	44.6	48.0	48.6	48.5	48.8	49.1
Swine	2.3	2.5	2.5	2.6	2.7	3.0	3.1	3.2	3.2	3.1
Horses	1.1	1.3	1.7	2.0	1.9	1.4	1.4	1.3	1.2	1.1
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	0.4	0.4	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**	**195.9**	**196.8**	**197.3**	**196.2**	**194.9**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table A-156: CH_4 Emissions from Enteric Fermentation from Cattle (metric tons), by State, for 2021[150]

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	25	558	30	110	4,807	3,645	64,403	1,670	4,609	1,214	1,266	282	82,618
Alaska	2	17	1	5	400	44	761	18	50	17	12	3	1,331
Arizona	1,242	30,273	1,498	5,430	2,053	1,097	19,164	378	1,039	7,984	465	11,562	82,185
Arkansas	32	583	42	152	5,961	4,792	84,668	2,105	5,809	3,102	2,014	599	109,858
California	10,931	260,770	9,901	35,886	6,158	3,703	64,703	1,817	4,987	18,001	6,511	23,566	446,932
Colorado	1,198	28,721	1,419	5,142	5,132	4,358	76,162	2,346	6,441	22,646	17,673	48,293	219,532
Conn.	124	3,067	131	475	48	29	510	28	78	41	43	10	4,583
Delaware	24	527	25	90	39	12	204	10	27	70	14	10	1,051
Florida	735	18,953	529	1,918	5,769	4,734	83,651	1,824	5,035	674	719	158	124,699
Georgia	513	13,833	454	1,644	3,077	2,718	48,025	1,263	3,486	1,160	863	231	77,266
Hawaii	4	41	13	47	411	426	7,438	167	457	290	155	49	9,498
Idaho	4,055	100,386	4,299	15,582	4,105	2,770	48,404	1,968	5,403	8,710	6,201	13,410	215,293
Illinois	520	11,057	555	2,012	1,880	1,929	34,195	820	2,268	6,312	2,524	10,593	74,665
Indiana	1,115	25,124	925	3,354	1,504	990	17,550	561	1,550	2,840	1,262	4,543	61,318
Iowa	1,362	31,482	1,419	5,142	5,639	4,617	81,868	1,983	5,481	34,189	16,827	56,706	246,717
Kansas	1,058	23,860	1,727	6,260	7,989	7,362	130,537	3,418	9,451	54,702	43,471	111,357	401,193
Kentucky	310	7,846	605	2,192	6,730	5,347	94,477	1,754	4,841	5,799	3,165	734	133,800
Louisiana	63	1,191	42	152	2,884	2,383	42,103	1,151	3,176	674	575	148	54,542
Maine	177	4,277	193	699	145	58	1,021	49	136	135	101	26	7,018
Maryland	266	6,231	358	1,299	337	247	4,361	155	427	311	231	292	14,515
Mass.	63	1,442	90	325	96	29	510	28	78	54	29	10	2,754
Michigan	2,706	66,516	2,159	7,825	1,410	474	8,413	314	869	4,602	897	7,069	103,256
Minn.	2,820	61,945	2,899	10,508	2,820	1,862	33,019	1,299	3,591	13,675	4,487	17,590	156,516
Miss.	51	1,165	76	274	3,750	2,524	44,601	1,263	3,486	1,564	1,237	319	60,310
Missouri	488	8,310	432	1,565	11,279	10,627	188,433	4,581	12,664	10,783	6,170	4,713	260,044
Montana	76	1,602	62	224	10,777	8,072	141,063	5,904	16,208	7,258	7,131	2,089	200,465
Nebraska	368	8,513	370	1,341	11,279	9,806	173,869	5,059	13,987	62,592	42,069	115,168	444,420
Nevada	196	4,801	130	472	1,540	1,408	24,597	666	1,829	1,161	1,023	141	37,965

[150]Because a simplified calculation approach was used for 2021 emissions, state-level emissions for 2021 were estimated by calculating ratios of 2020 state-level emissions to the 2020 total national emissions, then applying those state-specific ratios to the 2021 national total emissions estimate.

N. Hamp.	70	1,649	90	325	48	21	371	18	50	41	20	7	2,710
N. Jersey	30	676	43	155	96	49	863	31	85	54	35	10	2,127
N. Mexico	2,091	51,211	1,824	6,611	3,079	2,713	47,416	1,211	3,325	2,903	2,480	601	125,466
New York	3,960	102,054	4,755	17,234	1,928	552	9,743	563	1,554	1,488	1,155	962	145,948
N. Car.	260	6,993	272	986	2,980	1,932	34,145	884	2,440	1,079	662	198	52,832
N. Dakota	95	2,041	99	358	6,579	5,076	90,010	2,489	6,880	7,232	6,451	2,003	129,313
Ohio	1,597	34,530	1,480	5,366	2,820	1,520	26,958	957	2,646	5,786	1,823	7,238	92,722
Oklahoma	260	5,584	280	1,013	16,344	11,045	195,154	5,192	14,330	27,241	15,249	14,771	306,460
Oregon	805	17,854	912	3,305	4,105	3,013	52,652	1,589	4,364	4,210	3,721	4,105	100,635
Penn.	3,042	72,034	3,790	13,738	1,928	1,156	20,414	845	2,331	3,652	1,587	4,373	128,890
R. Island	4	91	7	25	10	6	111	7	19	14	6	2	302
S. Car.	70	1,729	60	219	1,250	937	16,564	365	1,007	324	316	71	22,912
S. Dakota	805	17,870	555	2,012	10,339	9,097	161,294	4,923	13,609	18,672	12,901	19,095	271,172
Tenn.	196	4,755	378	1,370	5,769	4,760	84,113	1,754	4,841	4,180	2,446	750	115,313
Texas	3,675	97,255	3,913	14,184	33,650	23,933	422,879	11,226	30,983	71,473	44,596	128,067	885,835
Utah	615	14,461	651	2,361	2,566	2,024	35,365	1,287	3,532	2,323	1,860	904	67,948
Vermont	786	18,613	758	2,748	289	68	1,206	63	175	108	159	31	25,005
Virginia	469	12,103	499	1,808	3,846	3,278	57,926	1,305	3,602	4,450	1,841	826	91,954
Wash.	1,787	43,311	1,654	5,997	2,053	1,289	22,523	863	2,369	5,952	4,217	10,398	102,411
W. Virg.	38	739	41	150	1,446	1,045	18,466	479	1,321	1,190	635	175	25,725
Wisconsin	7,984	183,362	8,512	30,854	2,820	1,582	28,043	1,231	3,402	8,942	1,402	10,887	289,021
Wyoming	38	890	49	179	4,619	4,093	71,519	2,422	6,649	4,500	3,907	3,012	101,877

Table A-157: CH_4 Emissions from Enteric Fermentation from Cattle (MMT CO_2 Eq.), by State, for 2021[151]

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	0.001	0.016	0.001	0.003	0.135	0.102	1.803	0.047	0.129	0.034	0.035	0.008	2.313
Alaska	0.000	0.000	0.000	0.000	0.011	0.001	0.021	0.001	0.001	0.000	0.000	0.000	0.037
Arizona	0.035	0.848	0.042	0.152	0.057	0.031	0.537	0.011	0.029	0.224	0.013	0.324	2.301
Arkansas	0.001	0.016	0.001	0.004	0.167	0.134	2.371	0.059	0.163	0.087	0.056	0.017	3.076

[151]Because a simplified calculation approach was used for 2021 emissions, state-level emissions for 2021 were estimated by calculating ratios of 2020 state-level emissions to the 2020 total national emissions, then applying those state-specific ratios to the 2021 national total emissions estimate.

California	0.306	7.302	0.277	1.005	0.172	0.104	1.812	0.051	0.140	0.504	0.182	0.660	12.514
Colorado	0.034	0.804	0.040	0.144	0.144	0.122	2.133	0.066	0.180	0.634	0.495	1.352	6.147
Conn.	0.003	0.086	0.004	0.013	0.001	0.001	0.014	0.001	0.002	0.001	0.001	0.000	0.128
Delaware	0.001	0.015	0.001	0.003	0.001	0.000	0.006	0.000	0.001	0.002	0.000	0.000	0.029
Florida	0.021	0.531	0.015	0.054	0.162	0.133	2.342	0.051	0.141	0.019	0.020	0.004	3.492
Georgia	0.014	0.387	0.013	0.046	0.086	0.076	1.345	0.035	0.098	0.032	0.024	0.006	2.163
Hawaii	0.000	0.001	0.000	0.001	0.011	0.012	0.208	0.005	0.013	0.008	0.004	0.001	0.266
Idaho	0.114	2.811	0.120	0.436	0.115	0.078	1.355	0.055	0.151	0.244	0.174	0.375	6.028
Illinois	0.015	0.310	0.016	0.056	0.053	0.054	0.957	0.023	0.064	0.177	0.071	0.297	2.091
Indiana	0.031	0.703	0.026	0.094	0.042	0.028	0.491	0.016	0.043	0.080	0.035	0.127	1.717
Iowa	0.038	0.881	0.040	0.144	0.158	0.129	2.292	0.056	0.153	0.957	0.471	1.588	6.908
Kansas	0.030	0.668	0.048	0.175	0.224	0.206	3.655	0.096	0.265	1.532	1.217	3.118	11.233
Kentucky	0.009	0.220	0.017	0.061	0.188	0.150	2.645	0.049	0.136	0.162	0.089	0.021	3.746
Louisiana	0.002	0.033	0.001	0.004	0.081	0.067	1.179	0.032	0.089	0.019	0.016	0.004	1.527
Maine	0.005	0.120	0.005	0.020	0.004	0.002	0.029	0.001	0.004	0.004	0.003	0.001	0.196
Maryland	0.007	0.174	0.010	0.036	0.009	0.007	0.122	0.004	0.012	0.009	0.006	0.008	0.406
Mass.	0.002	0.040	0.003	0.009	0.003	0.001	0.014	0.001	0.002	0.002	0.001	0.000	0.077
Michigan	0.076	1.862	0.060	0.219	0.039	0.013	0.236	0.009	0.024	0.129	0.025	0.198	2.891
Minn.	0.079	1.734	0.081	0.294	0.079	0.052	0.925	0.036	0.101	0.383	0.126	0.493	4.382
Miss.	0.001	0.033	0.002	0.008	0.105	0.071	1.249	0.035	0.098	0.044	0.035	0.009	1.689
Missouri	0.014	0.233	0.012	0.044	0.316	0.298	5.276	0.128	0.355	0.302	0.173	0.132	7.281
Montana	0.002	0.045	0.002	0.006	0.302	0.226	3.950	0.165	0.454	0.203	0.200	0.058	5.613
Nebraska	0.010	0.238	0.010	0.038	0.316	0.275	4.868	0.142	0.392	1.753	1.178	3.225	12.444
Nevada	0.006	0.134	0.004	0.013	0.043	0.039	0.689	0.019	0.051	0.033	0.029	0.004	1.063
N. Hamp.	0.002	0.046	0.003	0.009	0.001	0.001	0.010	0.001	0.001	0.001	0.001	0.000	0.076
N. Jersey	0.001	0.019	0.001	0.004	0.003	0.001	0.024	0.001	0.002	0.002	0.001	0.000	0.060
N. Mexico	0.059	1.434	0.051	0.185	0.086	0.076	1.328	0.034	0.093	0.081	0.069	0.017	3.513
New York	0.111	2.858	0.133	0.483	0.054	0.015	0.273	0.016	0.044	0.042	0.032	0.027	4.087
N. Car.	0.007	0.196	0.008	0.028	0.083	0.054	0.956	0.025	0.068	0.030	0.019	0.006	1.479
N. Dakota	0.003	0.057	0.003	0.010	0.184	0.142	2.520	0.070	0.193	0.203	0.181	0.056	3.621
Ohio	0.045	0.967	0.041	0.150	0.079	0.043	0.755	0.027	0.074	0.162	0.051	0.203	2.596
Oklahoma	0.007	0.156	0.008	0.028	0.458	0.309	5.464	0.145	0.401	0.763	0.427	0.414	8.581
Oregon	0.023	0.500	0.026	0.093	0.115	0.084	1.474	0.045	0.122	0.118	0.104	0.115	2.818
Penn.	0.085	2.017	0.106	0.385	0.054	0.032	0.572	0.024	0.065	0.102	0.044	0.122	3.609
R. Island	0.000	0.003	0.000	0.001	0.000	0.000	0.003	0.000	0.001	0.000	0.000	0.000	0.008
S. Car.	0.002	0.048	0.002	0.006	0.035	0.026	0.464	0.010	0.028	0.009	0.009	0.002	0.642
S. Dakota	0.023	0.500	0.016	0.056	0.289	0.255	4.516	0.138	0.381	0.523	0.361	0.535	7.593
Tenn.	0.006	0.133	0.011	0.038	0.162	0.133	2.355	0.049	0.136	0.117	0.068	0.021	3.229
Texas	0.103	2.723	0.110	0.397	0.942	0.670	11.841	0.314	0.868	2.001	1.249	3.586	24.803

Utah	0.017	0.405	0.018	0.066	0.072	0.057	0.990	0.036	0.099	0.065	0.052	0.025	1.903
Vermont	0.022	0.521	0.021	0.077	0.008	0.002	0.034	0.002	0.005	0.003	0.004	0.001	0.700
Virginia	0.013	0.339	0.014	0.051	0.108	0.092	1.622	0.037	0.101	0.125	0.052	0.023	2.575
Wash.	0.050	1.213	0.046	0.168	0.057	0.036	0.631	0.024	0.066	0.167	0.118	0.291	2.867
W. Virg.	0.001	0.021	0.001	0.004	0.040	0.029	0.517	0.013	0.037	0.033	0.018	0.005	0.720
Wisconsin	0.224	5.134	0.238	0.864	0.079	0.044	0.785	0.034	0.095	0.250	0.039	0.305	8.093
Wyoming	0.001	0.025	0.001	0.005	0.129	0.115	2.003	0.068	0.186	0.126	0.109	0.084	2.853

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Table A-158: CH_4 Emissions from Enteric Fermentation from Other Livestock (metric tons), by State, for 2021[152]

State	Swine	Horses	Sheep	Goats	American Bison	Mules and Asses	Total
Alabama	17	792	165	452	8	107	1,540
Alaska	3	27	6	8	118	0	162
Arizona	203	1,334	950	489	8	26	3,010
Arkansas	181	687	151	302	10	73	1,405
California	142	1,416	5,160	1,157	109	52	8,036
Colorado	967	1,723	3,847	513	912	59	8,021
Connecticut	6	149	47	56	38	9	305
Delaware	10	57	12	11	14	1	106
Florida	19	1,388	164	596	5	114	2,285
Georgia	55	778	166	620	5	109	1,733
Hawaii	14	81	182	163	7	3	449
Idaho	46	780	2,082	308	2,223	27	5,466
Illinois	7,678	611	498	350	57	45	9,239
Indiana	6,222	1,271	516	382	41	43	8,475
Iowa	35,316	843	1,367	864	218	32	38,640
Kansas	3,028	777	661	474	416	42	5,398
Kentucky	662	2,036	561	512	181	119	4,071
Louisiana	9	652	88	170	6	62	987
Maine	7	124	105	50	18	4	309
Maryland	27	518	156	140	3	20	865
Massachusetts	13	213	104	63	1	12	406
Michigan	1,777	957	769	273	258	38	4,072
Minnesota	13,126	674	1,041	339	223	32	15,436
Mississippi	158	566	111	307	20	81	1,244
Missouri	5,412	1,275	905	544	57	111	8,304
Montana	295	1,290	1,810	150	1,755	32	5,331
Nebraska	5,394	751	706	277	2,488	18	9,635
Nevada	4	175	588	76	0	5	848
New Hampshire	5	110	64	34	25	5	244
New Jersey	11	399	119	111	3	15	657
New Mexico	2	747	860	335	387	25	2,355
New York	99	1,067	788	241	92	29	2,315
North Carolina	13,270	804	272	470	19	114	14,948
North Dakota	206	382	679	69	1,098	9	2,442
Ohio	3,902	1,668	1,141	577	86	79	7,453
Oklahoma	3,096	2,023	471	907	68	171	6,736
Oregon	13	1,154	1,494	471	175	40	3,347
Pennsylvania	2,010	1,331	869	484	98	95	4,886
Rhode Island	2	33	14	9	-	1	60
South Carolina	270	691	84	375	3	62	1,486
South Dakota	2,927	823	2,263	167	2,239	21	8,440
Tennessee	374	1,556	444	909	28	191	3,501
Texas	1,546	5,590	6,653	7,278	754	913	22,735
Utah	1,431	945	2,580	199	80	14	5,249
Vermont	6	127	136	83	14	0	367

[152] Because a simplified calculation approach was used for 2021 emissions, state-level emissions for 2021 were estimated by calculating ratios of 2020 state-level emissions to the 2020 total national emissions, then applying those state-specific ratios to the 2022 national total emissions estimate.

Virginia	446	1,013	661	428	44	79	2,671
Washington	24	873	453	276	79	30	1,735
West Virginia	4	415	299	233	9	38	998
Wisconsin	575	1,106	733	1,110	553	37	4,115
Wyoming	137	876	3,078	154	792	34	5,069

"-" Indicates there are no emissions, as there is no significant population of this animal type.

Table A-159: CH_4 Emissions from Enteric Fermentation from Other Livestock (MMT CO_2 Eq.), by State, for 2021[153]

State	Swine	Horses	Sheep	Goats	American Bison	Mules and Asses	Total
Alabama	0.0005	0.0208	0.0046	0.0127	0.0002	0.0030	0.0419
Alaska	0.0001	0.0007	0.0002	0.0002	0.0034	+	0.0046
Arizona	0.0059	0.0351	0.0265	0.0138	0.0002	0.0007	0.0822
Arkansas	0.0053	0.0181	0.0042	0.0085	0.0003	0.0021	0.0384
California	0.0042	0.0372	0.1436	0.0326	0.0031	0.0015	0.2222
Colorado	0.0282	0.0453	0.1071	0.0144	0.0261	0.0017	0.2229
Connecticut	0.0002	0.0039	0.0013	0.0016	0.0011	0.0003	0.0083
Delaware	0.0003	0.0015	0.0003	0.0003	0.0004	+	0.0029
Florida	0.0005	0.0365	0.0046	0.0168	0.0001	0.0032	0.0618
Georgia	0.0016	0.0205	0.0046	0.0175	0.0002	0.0031	0.0474
Hawaii	0.0004	0.0021	0.0051	0.0046	0.0002	0.0001	0.0125
Idaho	0.0013	0.0205	0.0580	0.0087	0.0637	0.0008	0.1529
Illinois	0.2242	0.0161	0.0139	0.0098	0.0016	0.0013	0.2669
Indiana	0.1817	0.0334	0.0144	0.0108	0.0012	0.0012	0.2426
Iowa	1.0311	0.0222	0.0381	0.0243	0.0062	0.0009	1.1228
Kansas	0.0884	0.0204	0.0184	0.0133	0.0119	0.0012	0.1537
Kentucky	0.0193	0.0535	0.0156	0.0144	0.0052	0.0034	0.1115
Louisiana	0.0003	0.0171	0.0024	0.0048	0.0002	0.0018	0.0266
Maine	0.0002	0.0033	0.0029	0.0014	0.0005	0.0001	0.0084
Maryland	0.0008	0.0136	0.0044	0.0040	0.0001	0.0006	0.0234
Massachusetts	0.0004	0.0056	0.0029	0.0018	+	0.0004	0.0110
Michigan	0.0519	0.0252	0.0214	0.0077	0.0074	0.0011	0.1146
Minnesota	0.3833	0.0177	0.0290	0.0095	0.0064	0.0009	0.4468
Mississippi	0.0046	0.0149	0.0031	0.0086	0.0006	0.0023	0.0341
Missouri	0.1580	0.0335	0.0252	0.0153	0.0016	0.0031	0.2368
Montana	0.0086	0.0339	0.0504	0.0042	0.0503	0.0009	0.1483
Nebraska	0.1575	0.0197	0.0197	0.0078	0.0713	0.0005	0.2765
Nevada	0.0001	0.0046	0.0164	0.0021	+	0.0001	0.0234
New Hampshire	0.0002	0.0029	0.0018	0.0010	0.0007	0.0001	0.0067
New Jersey	0.0003	0.0105	0.0033	0.0031	0.0001	0.0004	0.0177
New Mexico	0.0001	0.0196	0.0239	0.0094	0.0111	0.0007	0.0648
New York	0.0029	0.0281	0.0219	0.0068	0.0026	0.0008	0.0631
North Carolina	0.3875	0.0211	0.0076	0.0132	0.0005	0.0032	0.4332
North Dakota	0.0060	0.0100	0.0189	0.0020	0.0315	0.0003	0.0686
Ohio	0.1139	0.0439	0.0318	0.0162	0.0025	0.0023	0.2105
Oklahoma	0.0904	0.0532	0.0131	0.0255	0.0020	0.0049	0.1890
Oregon	0.0004	0.0303	0.0416	0.0133	0.0050	0.0011	0.0917
Pennsylvania	0.0587	0.0350	0.0242	0.0136	0.0028	0.0027	0.1370
Rhode Island	0.0001	0.0009	0.0004	0.0002	-	+	0.0016

[153] Because a simplified calculation approach was used for 2021 emissions, state-level emissions for 2021 were estimated by calculating ratios of 2020 state-level emissions to the 2020 total national emissions, then applying those state-specific ratios to the 2021 national total emissions estimate.

South Carolina	0.0079	0.0182	0.0023	0.0106	0.0001	0.0018	0.0408
South Dakota	0.0855	0.0216	0.0630	0.0047	0.0641	0.0006	0.2395
Tennessee	0.0109	0.0409	0.0123	0.0256	0.0008	0.0054	0.0960
Texas	0.0452	0.1470	0.1852	0.2049	0.0216	0.0260	0.6298
Utah	0.0418	0.0249	0.0718	0.0056	0.0023	0.0004	0.1467
Vermont	0.0002	0.0033	0.0038	0.0024	0.0004	+	0.0101
Virginia	0.0130	0.0266	0.0184	0.0120	0.0013	0.0023	0.0736
Washington	0.0007	0.0230	0.0126	0.0078	0.0023	0.0009	0.0471
West Virginia	0.0001	0.0109	0.0083	0.0065	0.0003	0.0011	0.0273
Wisconsin	0.0168	0.0291	0.0204	0.0313	0.0159	0.0010	0.1145
Wyoming	0.0040	0.0230	0.0857	0.0043	0.0227	0.0010	0.1407

"-" Indicates there are no emissions, as there is no significant population of this animal type.
"+" Indicates emissions fall below 0.00005 MMT CO_2 eq.

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3.11. Methodology for Estimating CH_4 and N_2O Emissions from Manure Management[154]

The following steps were used to estimate methane (CH_4) and nitrous oxide (N_2O) emissions from the management of livestock manure for the years 1990 through 2020. As explained in the Manure Management section (Section 5.2 Manure Management (IPCC Source Category 3B)), a simplified approach was used to estimate emissions for 2021.

Step 1: Livestock Population Characterization Data

Annual animal population data for 1990 through 2020 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 2021). 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, 2018a, 2018b, 2019a, 2019b, 2019c, 2021b, and 2021c). 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 Enteric Fermentation). 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 2020 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 through

[154] Note that direct N_2O 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 N_2O 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.

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 2020 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 2020 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 2020 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 2020 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, 2014a, 2014b, 2015a, 2015b, 2016a, 2016b, 2017a, 2017b, 2018a, 2018b, 2019b, 2019c, 2021b, and 2021c). 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 CH_4 and N_2O emissions is presented in Table A-160.

Step 2: Waste Characteristics Data

Methane and N_2O emissions calculations are based on the following animal characteristics for each relevant livestock population:

- Volatile solids (VS) excretion rate;
- Maximum methane producing capacity (B_0) for U.S. animal waste;
- Nitrogen excretion rate (Nex); and
- Typical animal mass (TAM).

Table A-161 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 Nex for most non-cattle animal groups across the time series of the Inventory, as shown in Table A-162 (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 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 CH_4 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

$$\text{VS production (kg)} = \left[\left(\text{GE - DE}\right) + \left(\text{UE} \times \text{GE}\right)\right] \times \frac{1 - ASH}{18.45}$$

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).
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

$$Nex_{(T)} = N_{intake} \times \left(1 - N_{retention\_fract(T)}\right)$$

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 *T* (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

$$N_{intake(T)} = \frac{GE}{18.45} \bullet \left(\frac{\frac{CP\%}{100}}{6.25} \right)$$

where,

$N_{intake(T)}$	=	Daily N consumed per animal of category T (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 T (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-163 presents the state-specific VS and

Nex production rates used for cattle in 2020. As shown in Table A-163, 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-164 and Table A-165 summarize 2020 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-166.

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 drylots. Therefore, for these animal groups, the percent of manure deposited in drylots is assumed to be 100 percent. 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 (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 drylots; this percentage ranges from 0.4 to 1.3 percent (ERG 2000a). The percentage of manure generating emissions from beef feedlots is therefore greater than 100 percent. 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. 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 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 2020. WMS for 1997 through 2015 were interpolated between the data sources used for the 1990-1997 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 2021). 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 2018 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.

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 2021).

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, 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 2020 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. It was also assumed that system usage in 2000 through 2020 was equal to that estimated for 1999. 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. As with dairy and swine, using information about AD WMS from EPA's AgSTAR database (EPA 2021), 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. 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 2021).

Step 4: Emission Factor and Other Parameter Calculations

Methane conversion factors (MCFs) and N_2O 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-167. 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 CH_4 Based on Temperature (van't Hoff-Arrhenius *f* factor)

$$f = \exp\left[\frac{E(T_2 - T_1)}{RT_1T_2}\right]$$

where,

f = van't Hoff-Arrhenius *f* factor, the proportion of VS that are biologically available for conversion to CH_4 based on the temperature of the system

T_1 = 303.15K

T_2 = Ambient temperature (K) for climate zone (in this case, a weighted value for each state)

E = Activation energy constant (15,175 cal/mol)
R = 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 2020 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 CH_4 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 CH_4 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 CH_4 generated during the month is equal to the monthly VS consumed multiplied by B_0.

The annual MCF is then calculated as:

Equation A-32: MCF for Anaerobic Lagoons and Liquid Systems

$$MCF_{annual} = \frac{CH_4 \text{ generated}_{annual}}{VS \text{ produced}_{annual} \times B_o}$$

where,

MCF_{annual} = Methane conversion factor
$VS \text{ produced}_{annual}$ = 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 CH_4. 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-168 by state, WMS, and animal group for 2020.

Nitrous Oxide Emission Factors and Other Parameters

Direct N_2O: Direct N_2O EFs for manure management systems (kg N_2O-N/kg excreted N) were set equal to the most recent default IPCC factors (IPCC 2006), presented in Table A-169.

Indirect N_2O: Indirect N_2O EFs account for two fractions of nitrogen losses: volatilization of ammonia (NH_3) and NO_X ($Frac_{gas}$) and runoff/leaching ($Frac_{runoff/leach}$). IPCC default indirect N_2O EFs were used to estimate indirect N_2O emissions. These factors are 0.010 kg N_2O-N/kg N for volatilization and 0.0075 kg N_2O/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 NH_3. 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 NH_3 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-170.

Step 5: CH_4 Emission Calculations

To calculate CH_4 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

$$\text{VS excreted}_{\text{State,Animal,WMS}} = \text{Population}_{\text{State,Animal}} \times \frac{\text{TAM}}{1000} \times \text{VS} \times \text{WMS} \times 365.25$$

where,

	$\text{VS excreted}_{\text{State, Animal, WMS}}$	=	Amount of VS excreted in manure managed in each WMS for each animal type (kg/yr)
	$\text{Population}_{\text{State, Animal}}$	=	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,

	$\text{VS excreted}_{\text{State, Animal, WMS}}$	=	Amount of VS excreted in manure managed in each WMS for each animal type (kg/yr)
	$\text{Population}_{\text{State, Animal}}$	=	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 CH_4 emissions using the following equation:

Equation A-35: CH_4 Emissions for All Animal Types

$$CH_4 = \sum_{State, Animal, WMS} \left(VS\ excreted_{State, Animal, WMS} \times B_o \times MCF \times 0.662 \right)$$

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 CH_4 emitted from AD systems utilizing CH_4 capture and combustion technology. First, AD systems were assumed to produce 90 percent of B_0 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 CH_4 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 CH_4 production from some systems and underestimating CH_4 production in other systems. The CH_4 production of AD systems is calculated using the equation below:

Equation A-36: CH_4 Production from AD Systems

$$CH_4\ ProductionAD_{ADSystem} = ProductionAD_{ADSystem} \times \frac{TAM}{1000} \times VS \times B_0 \times 0.662 \times 365.25 \times 0.90$$

where,

	CH_4 Production $AD_{AD\ system}$	=	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 CH_4 produced by AD is calculated only as a means to estimate the emissions from AD; i.e., only the estimated amount of CH_4 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 CH_4 DE from flaring or burning in an engine was assumed to be 98 percent; therefore, the amount of CH_4 that would not be flared or combusted was assumed to be 2 percent (EPA 2008). The amount of CH_4 produced by systems with AD was calculated with the following equation:

Equation A-37: CH_4 Emissions from AD Systems

$$CH_4\ Emissions\ AD = \sum_{State, Animal, ADSystems} \left(\begin{array}{l} \left[CH_4\ Production\ AD_{ADsystem} \times CE_{ADsystem} \times (1 - DE) \right] \\ + \left[CH_4\ Production\ AD_{ADsystem} \times (1 - CE_{ADsystem}) \right] \end{array} \right)$$

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: N_2O Emission Calculations

Total N_2O emissions from manure management systems were calculated by summing direct and indirect N_2O emissions. The first step in estimating direct and indirect N_2O 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,

	$\text{N excreted}_{\text{State, Animal, WMS}}$	=	Amount of N excreted in manure managed in each WMS for each animal type (kg/yr)
	$\text{Population}_{\text{state}}$	=	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,

	$\text{N excreted}_{\text{State, Animal, WMS}}$	=	Amount of N excreted in manure managed in each WMS for each animal type (kg/yr)
	$\text{Population}_{\text{state}}$	=	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 N_2O emissions were calculated as follows:

Equation A-40: Direct N_2O emissions from All Animal Types

$$\text{Direct } N_2O = \sum_{\text{State, Animal, WMS}} \left(\text{N excreted}_{\text{State, Animal, WMS}} \times EF_{\text{WMS}} \times \frac{44}{28} \right)$$

where,

	Direct N_2O	=	Direct N_2O emissions (kg N_2O/yr)
	$\text{N excreted}_{\text{State, Animal, WMS}}$	=	Amount of N excreted in manure managed in each WMS for each animal type (kg/yr)
	EF_{WMS}	=	Direct N_2O emission factor from IPCC guidelines (kg N_2O-N /kg N)
	44/28	=	Conversion factor of N_2O-N to N_2O

Indirect N_2O emissions were calculated for all animals with the following equation:

Equation A-41: Indirect N_2O Emissions from All Animal Types

$$\text{Indirect } N_2O = \sum_{\text{State, Animal, WMS}} \left(\left[\text{N excreted}_{\text{State, Animal, WMS}} \times \frac{\text{Frac}_{\text{gas, WMS}}}{100} \times \text{EF}_{\text{volatiliza tion}} \times \frac{44}{28} \right] + \left[\text{N excreted}_{\text{State, Animal, WMS}} \times \frac{\text{Frac}_{\text{runoff/leach, WMS}}}{100} \times \text{EF}_{\text{runnoff/leach}} \times \frac{44}{28} \right] \right)$$

where,

Indirect N_2O	=	Indirect N_2O emissions (kg N_2O/yr)
N excreted $_{\text{State, Animal, WMS}}$	=	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_2O-N/kg N)
$EF_{runoff/leach}$	=	Emission factor for runoff/leaching (0.0075 kg N_2O-N/kg N)
44/28	=	Conversion factor of N_2O-N to N_2O

Emission estimates of CH_4 and N_2O by animal type are presented for all years of the inventory in Table A-171 and Table A-173 respectively. Emission estimates for 2020 are presented by animal type and state in Table A-175 and Table A-177 respectively.

Table A-160: Livestock Population (1,000 Head)

Animal Type	1990	1995	2005	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Dairy Cattle	**19,512**	**18,681**	**17,793**	**18,442**	**18,587**	**18,505**	**18,517**	**18,812**	**18,857**	**18,923**	**19,006**	**18,849**	**18,804**	**18,828**
Dairy Cows	*10,015*	*9,482*	*9,004*	*9,156*	*9,236*	*9,221*	*9,209*	*9,312*	*9,312*	*9,369*	*9,432*	*9,353*	*9,343*	*9,442*
Dairy Heifer	*4,129*	*4,108*	*4,162*	*4,577*	*4,581*	*4,523*	*4,571*	*4,727*	*4,785*	*4,757*	*4,741*	*4,677*	*4,637*	*4,562*
Dairy Calves	*5,369*	*5,091*	*4,628*	*4,709*	*4,770*	*4,761*	*4,737*	*4,774*	*4,760*	*4,797*	*4,833*	*4,818*	*4,825*	*4,823*
Swine[a]	**53,941**	**58,899**	**61,073**	**65,572**	**66,363**	**65,437**	**64,195**	**68,178**	**70,065**	**72,125**	**73,430**	**76,898**	**77,267**	**74,100**
Market <50 lb.	*18,359*	*19,656*	*20,228*	*19,285*	*19,472*	*19,002*	*18,939*	*19,843*	*20,572*	*20,973*	*21,359*	*22,278*	*22,047*	*21,219*
Market 50-119 lb.	*11,734*	*12,836*	*13,519*	*16,904*	*17,140*	*16,834*	*16,559*	*17,577*	*18,175*	*18,767*	*19,039*	*20,195*	*20,153*	*19,318*
Market 120-179 lb.	*9,440*	*10,545*	*11,336*	*12,514*	*12,714*	*12,674*	*12,281*	*13,225*	*13,575*	*13,982*	*14,311*	*14,852*	*15,143*	*14,457*
Market >180 lb.	*7,510*	*8,937*	*9,997*	*11,078*	*11,199*	*11,116*	*10,525*	*11,555*	*11,714*	*12,282*	*12,418*	*13,138*	*13,604*	*12,918*
Breeding	*6,899*	*6,926*	*5,993*	*5,791*	*5,839*	*5,812*	*5,892*	*5,978*	*6,030*	*6,122*	*6,303*	*6,435*	*6,321*	*6,187*
Beef Cattle[b]	**81,576**	**90,361**	**82,193**	**78,937**	**76,858**	**76,010**	**74,966**	**76,149**	**79,323**	**81,385**	**81,722**	**82,049**	**80,812**	**80,525**
Feedlot Steers	*6,357*	*7,233*	*8,116*	*8,771*	*8,586*	*8,613*	*8,696*	*8,594*	*9,017*	*9,560*	*9,605*	*9,706*	*9,685*	*9,691*
Feedlot Heifers	*3,192*	*3,831*	*4,536*	*4,830*	*4,742*	*4,655*	*4,518*	*4,334*	*4,433*	*4,786*	*5,085*	*5,210*	*5,250*	*5,253*
NOF Bulls	*2,160*	*2,385*	*2,214*	*2,165*	*2,100*	*2,074*	*2,038*	*2,109*	*2,137*	*2,244*	*2,252*	*2,253*	*2,237*	*2,211*
Beef Calves	*16,909*	*18,177*	*16,918*	*15,817*	*15,288*	*14,805*	*14,737*	*14,998*	*15,546*	*15,931*	*16,221*	*16,146*	*15,635*	*15,631*
NOF Heifers	*10,182*	*11,829*	*9,550*	*8,874*	*8,687*	*8,780*	*8,730*	*9,291*	*9,892*	*9,790*	*9,460*	*9,257*	*9,066*	*9,181*
NOF Steers	*10,321*	*11,716*	*8,185*	*7,568*	*7,173*	*7,451*	*7,291*	*7,491*	*8,133*	*7,904*	*7,633*	*7,786*	*7,600*	*7,714*
NOF Cows	*32,455*	*35,190*	*32,674*	*30,913*	*30,282*	*29,631*	*28,956*	*29,332*	*30,164*	*31,171*	*31,466*	*31,691*	*31,339*	*30,844*
Sheep	**11,358**	**8,989**	**6,135**	**5,470**	**5,375**	**5,360**	**5,235**	**5,270**	**5,295**	**5,270**	**5,265**	**5,230**	**5,200**	**5,170**
Sheep On Feed	*1,180*	*1,769*	*2,976*	*2,691*	*2,669*	*2,658*	*2,588*	*2,587*	*2,624*	*2,618*	*2,623*	*2,616*	*2,611*	*2,596*
Sheep NOF	*10,178*	*7,220*	*3,159*	*2,779*	*2,706*	*2,702*	*2,647*	*2,683*	*2,671*	*2,652*	*2,642*	*2,614*	*2,589*	*2,574*
Goats	**2,516**	**2,357**	**2,897**	**2,725**	**2,622**	**2,637**	**2,652**	**2,668**	**2,683**	**2,699**	**2,714**	**2,729**	**2,745**	**2,753**
Poultry[c]	**1,537,074**	**1,826,977**	**2,150,410**	**2,095,951**	**2,168,697**	**2,106,502**	**2,116,333**	**2,134,445**	**2,173,216**	**2,214,462**	**2,256,552**	**2,276,951**	**2,269,691**	**2,254,998**
Hens >1 yr.	*273,467*	*299,071*	*348,203*	*338,944*	*346,965*	*361,403*	*370,637*	*351,656*	*377,299*	*388,006*	*402,536*	*403,102*	*391,010*	*393,078*
Pullets	*73,167*	*81,369*	*96,809*	*102,233*	*104,460*	*106,646*	*106,490*	*118,114*	*112,061*	*117,173*	*124,729*	*121,971*	*119,898*	*123,179*
Chickens	*6,545*	*7,637*	*8,289*	*6,922*	*6,827*	*6,853*	*6,403*	*7,211*	*6,759*	*6,859*	*6,626*	*7,130*	*7,371*	*6,447*
Broilers	*1,066,209*	*1,331,940*	*1,613,091*	*1,565,018*	*1,625,945*	*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*
Turkeys	*117,685*	*106,960*	*84,018*	*82,833*	*84,500*	*80,000*	*79,167*	*77,700*	*81,333*	*81,733*	*79,333*	*76,167*	*74,667*	*72,167*
Horses	**2,212**	**2,632**	**3,875**	**3,703**	**3,621**	**3,467**	**3,312**	**3,157**	**3,002**	**2,847**	**2,692**	**2,538**	**2,383**	**2,233**
Mules and Asses	**63**	**101**	**212**	**291**	**293**	**298**	**303**	**308**	**313**	**318**	**323**	**328**	**333**	**337**
American Bison	**47**	**104**	**212**	**169**	**162**	**166**	**171**	**175**	**179**	**184**	**188**	**193**	**197**	**201**

[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-161: 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-163	CEFM	0.24	Morris 1976	Table A-163	CEFM
Dairy Heifers	406-408	CEFM	Table A-163	CEFM	0.17	Bryant et al. 1976	Table A-163	CEFM
Feedlot Steers	419-457	CEFM	Table A-163	CEFM	0.33	Hashimoto 1981	Table A-163	CEFM
Feedlot Heifers	384-430	CEFM	Table A-163	CEFM	0.33	Hashimoto 1981	Table A-163	CEFM
NOF Bulls	831-917	CEFM	Table A-163	CEFM	0.17	Hashimoto 1981	Table A-163	CEFM
NOF Calves	118	ERG 2003b	Table A-162	USDA 1996, 2008	0.17	Hashimoto 1981	Table A-162	USDA 1996, 2008
NOF Heifers	296-407	CEFM	Table A-163	CEFM	0.17	Hashimoto 1981	Table A-163	CEFM
NOF Steers	314-335	CEFM	Table A-163	CEFM	0.17	Hashimoto 1981	Table A-163	CEFM
NOF Cows	554-611	CEFM	Table A-163	CEFM	0.17	Hashimoto 1981	Table A-163	CEFM
American Bison	578.5	Meagher 1986	Table A-163	CEFM	0.17	Hashimoto 1981	Table A-163	CEFM
Market Swine <50 lbs.	13	ERG 2010a	Table A-162	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-162	USDA 1996, 2008
Market Swine <60 lbs.	16	Safley 2000	Table A-162	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-162	USDA 1996, 2008
Market Swine 50-119 lbs.	39	ERG 2010a	Table A-162	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-162	USDA 1996, 2008
Market Swine 60-119 lbs.	41	Safley 2000	Table A-162	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-162	USDA 1996, 2008
Market Swine 120-179 lbs.	68	Safley 2000	Table A-162	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-162	USDA 1996, 2008
Market Swine >180 lbs.	91	Safley 2000	Table A-162	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-162	USDA 1996, 2008
Breeding Swine	198	Safley 2000	Table A-162	USDA 1996, 2008	0.48	Hashimoto 1984	Table A-162	USDA 1996, 2008
Feedlot Sheep	25	EPA 1992	Table A-162	ASAE 1998, USDA 2008	0.36	EPA 1992	Table A-162	ASAE 1998, USDA 2008
NOF Sheep	80	EPA 1992	Table A-162	ASAE 1998, USDA 2008	0.19	EPA 1992	Table A-162	ASAE 1998, USDA 2008
Goats	64	ASAE 1998	Table A-162	ASAE 1998	0.17	EPA 1992	Table A-162	ASAE 1998
Horses	450	ASAE 1998	Table A-162	ASAE 1998, USDA 2008	0.33	EPA 1992	Table A-162	ASAE 1998, USDA 2008
Mules and Asses	130	IPCC 2006	Table A-162	IPCC 2006	0.33	EPA 1992	Table A-162	IPCC 2006
Hens >/= 1 yr	1.8	ASAE 1998	Table A-162	USDA 1996, 2008	0.39	Hill 1982	Table A-162	USDA 1996, 2008
Pullets	1.8	ASAE 1998	Table A-162	USDA 1996, 2008	0.39	Hill 1982	Table A-162	USDA 1996, 2008
Other Chickens	1.8	ASAE 1998	Table A-162	USDA 1996, 2008	0.39	Hill 1982	Table A-162	USDA 1996, 2008
Broilers	0.9	ASAE 1998	Table A-162	USDA 1996, 2008	0.36	Hill 1984	Table A-162	USDA 1996, 2008
Turkeys	6.8	ASAE 1998	Table A-162	USDA 1996, 2008	0.36	Hill 1984	Table A-162	USDA 1996, 2008

[a] Nex and VS values vary by year; Table A-163 shows state-level values for 2020 only.

Table A-162: 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)[1]

Animal Type	1990	1995	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
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	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	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	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	5.4
Swine, Breeding	2.6	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	6.4	7.4	7.5	7.6	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	9.2	8.6	8.5	8.4	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	9.5
Hens >1yr.	10.1	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	10.1	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	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	15.0	16.5	16.7	16.8	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	9.7	8.8	8.7	8.6	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	10.0	7.3	6.9	6.5	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	7.2
Nex																		
Swine, Market <50 lbs.	0.60	0.60	0.84	0.87	0.89	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	0.42	0.51	0.52	0.53	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	0.42	0.51	0.52	0.53	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	0.42	0.51	0.52	0.53	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	0.24	0.21	0.21	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
NOF Cattle Calves	0.30	0.30	0.41	0.43	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
Sheep	0.42	0.42	0.44	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
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	0.45
Hens >1yr.	0.70	0.70	0.77	0.77	0.78	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	0.70	0.77	0.77	0.78	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	0.83	1.03	1.06	1.08	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	1.10	1.00	0.98	0.97	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	0.74	0.65	0.64	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

Animal Type	1990		1995		2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Horses	0.30		0.30		0.26	0.26	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	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	0.30

[1] This table has not been updated for the current (1990 through 2021) Inventory. It will be updated for the next (1990 through 2022) Inventory submission.

1

Table A-163: Estimated Volatile Solids (VS) and Total Nitrogen Excreted (Nex) Production Rates by State for Cattle (other than Calves) and American Bison[a] for 2020 (kg/animal/year)[1]

	Volatile Solids									Nitrogen Excreted								
State	Dairy Cow	Dairy Heifers	Beef NOF Cow	Beef NOF Heifers	Beef NOF Steer	Beef OF Heifers	Beef OF Steer	Beef NOF Bull	American Bison	Dairy Cow	Dairy Heifers	Beef NOF Cow	Beef NOF Heifers	Beef NOF Steer	Beef OF Heifers	Beef OF Steer	Beef NOF Bull	American Bison
Alabama	2,267	1,255	1,663	1,099	973	689	671	1,721	1,721	136	69	73	50	41	58	60	83	83
Alaska	1,099	1,255	1,890	1,263	1,119	689	672	1,956	1,956	84	69	59	41	33	59	60	69	69
Arizona	2,923	1,255	1,890	1,251	1,119	689	672	1,956	1,956	162	69	59	41	33	59	60	69	69
Arkansas	2,054	1,255	1,663	1,095	973	689	671	1,721	1,721	125	69	73	50	41	58	60	83	83
California	2,861	1,255	1,890	1,222	1,119	689	671	1,956	1,956	159	69	59	39	33	59	60	69	69
Colorado	3,040	1,255	1,890	1,201	1,119	689	671	1,956	1,956	167	69	59	38	33	59	60	69	69
Connecticut	2,810	1,255	1,672	1,092	979	689	671	1,731	1,731	157	69	74	50	42	58	60	84	84
Delaware	2,476	1,255	1,672	1,093	979	689	671	1,731	1,731	143	69	74	50	42	58	60	84	84
Florida	2,657	1,255	1,663	1,107	973	689	671	1,721	1,721	152	69	73	51	41	58	60	83	83
Georgia	2,778	1,255	1,663	1,100	973	689	671	1,721	1,721	158	69	73	50	41	58	60	83	83
Hawaii	1,099	1,255	1,890	1,257	1,119	689	671	1,956	1,956	84	69	59	41	33	58	60	69	69
Idaho	2,968	1,255	1,890	1,226	1,119	689	671	1,956	1,956	164	69	59	39	33	59	60	69	69
Illinois	2,697	1,255	1,587	1,016	926	689	671	1,643	1,643	152	69	75	50	43	59	60	85	85
Indiana	2,856	1,255	1,587	1,023	926	689	671	1,643	1,643	159	69	75	50	43	59	60	85	85
Iowa	2,929	1,255	1,587	991	926	689	671	1,643	1,643	162	69	75	48	43	59	60	85	85
Kansas	2,858	1,255	1,587	983	926	689	671	1,643	1,643	159	69	75	47	43	59	60	85	85
Kentucky	2,604	1,255	1,663	1,081	973	689	671	1,721	1,721	150	69	73	49	41	59	60	83	83
Louisiana	2,098	1,255	1,663	1,104	973	689	671	1,721	1,721	127	69	73	51	41	59	60	83	83
Maine	2,730	1,255	1,672	1,085	979	689	670	1,731	1,731	154	69	74	50	42	58	60	84	84
Maryland	2,651	1,255	1,672	1,092	979	689	673	1,731	1,731	150	69	74	50	42	59	61	84	84
Massachusetts	2,576	1,255	1,672	1,100	979	689	671	1,731	1,731	147	69	74	51	42	58	60	84	84
Michigan	3,116	1,255	1,587	1,017	926	689	671	1,643	1,643	170	69	75	50	43	59	60	85	85
Minnesota	2,785	1,255	1,587	1,013	926	689	671	1,643	1,643	156	69	75	49	43	59	60	85	85
Mississippi	2,369	1,255	1,663	1,094	973	689	671	1,721	1,721	140	69	73	50	41	58	60	83	83
Missouri	2,159	1,255	1,587	1,035	926	689	671	1,643	1,643	129	69	75	51	43	59	60	85	85
Montana	2,670	1,255	1,890	1,252	1,119	689	671	1,956	1,956	151	69	59	41	33	58	60	69	69
Nebraska	2,936	1,255	1,587	991	926	689	671	1,643	1,643	163	69	75	48	43	59	60	85	85
Nevada	2,931	1,255	1,890	1,246	1,119	689	672	1,956	1,956	162	69	59	40	33	59	61	69	69
New Hampshire	2,678	1,255	1,672	1,099	979	689	671	1,731	1,731	152	69	74	51	42	58	60	84	84
New Jersey	2,569	1,255	1,672	1,099	979	689	671	1,731	1,731	147	69	74	51	42	58	60	84	84
New Mexico	2,937	1,255	1,890	1,238	1,119	689	671	1,956	1,956	163	69	59	40	33	59	60	69	69
New York	2,918	1,255	1,672	1,085	979	689	671	1,731	1,731	162	69	74	50	42	59	60	84	84
North Carolina	2,774	1,255	1,663	1,099	973	689	670	1,721	1,721	158	69	73	50	41	58	60	83	83
North Dakota	2,722	1,255	1,587	1,020	926	689	672	1,643	1,643	153	69	75	50	43	59	61	85	85
Ohio	2,741	1,255	1,587	1,027	926	689	671	1,643	1,643	154	69	75	51	43	58	60	85	85

	Volatile Solids									Nitrogen Excreted								
State	Dairy Cow	Dairy Heifers	Beef NOF Cow	Beef NOF Heifers	Beef NOF Steer	Beef OF Heifers	Beef OF Steer	Beef NOF Bull	American Bison	Dairy Cow	Dairy Heifers	Beef NOF Cow	Beef NOF Heifers	Beef NOF Steer	Beef OF Heifers	Beef OF Steer	Beef NOF Bull	American Bison
Oklahoma	2,399	1,255	1,663	1,069	973	689	671	1,721	1,721	140	69	73	48	41	59	60	83	83
Oregon	2,660	1,255	1,890	1,235	1,119	689	671	1,956	1,956	151	69	59	40	33	59	60	69	69
Pennsylvania	2,682	1,255	1,672	1,087	979	689	671	1,731	1,731	152	69	74	50	42	59	60	84	84
Rhode Island	2,717	1,255	1,672	1,104	979	689	670	1,731	1,731	153	69	74	51	42	58	60	84	84
South Carolina	2,557	1,255	1,663	1,097	973	689	670	1,721	1,721	148	69	73	50	41	58	60	83	83
South Dakota	2,815	1,255	1,587	1,020	926	689	671	1,643	1,643	157	69	75	50	43	59	60	85	85
Tennessee	2,495	1,255	1,663	1,087	973	689	670	1,721	1,721	146	69	73	50	41	58	60	83	83
Texas	2,954	1,255	1,663	1,061	973	689	671	1,721	1,721	164	69	73	48	41	59	60	83	83
Utah	2,821	1,255	1,890	1,248	1,119	689	672	1,956	1,956	158	69	59	40	33	59	60	69	69
Vermont	2,682	1,255	1,672	1,080	979	689	671	1,731	1,731	152	69	74	50	42	59	60	84	84
Virginia	2,660	1,255	1,663	1,087	973	689	670	1,721	1,721	153	69	73	50	41	58	60	83	83
Washington	2,907	1,255	1,890	1,213	1,119	689	671	1,956	1,956	161	69	59	39	33	59	60	69	69
West Virginia	2,200	1,255	1,672	1,095	979	689	671	1,731	1,731	131	69	74	51	42	59	60	84	84
Wisconsin	2,911	1,255	1,587	1,038	926	689	672	1,643	1,643	162	69	75	51	43	59	60	85	85
Wyoming	2,968	1,255	1,890	1,245	1,119	689	671	1,956	1,956	164	69	59	40	33	59	60	69	69

[a] Beef NOF Bull values were used for American bison Nex and VS.

[1] This table has not been updated for the current (1990 through 2021) Inventory. It will be updated for the next (1990 through 2022) Inventory submission.

Source: CEFM.

1 **Table A-164: 2020 Manure Distribution Among Waste Management Systems by Operation for Cattle (Percent)[1]**

	Beef Feedlots		Beef Not on Feed Operations	Dairy Cow Farms[a]							Dairy Heifer Facilities			
State	Dry Lot	Liquid/ Slurry[b]	Pasture, Range, Paddock	Pasture, Range, Paddock	Daily Spread	Dry Lot	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Daily Spread[b]	Dry Lot[b]	Liquid/ Slurry[b]	Pasture, Range, Paddock[b]
Alabama	100	1	100	48	0	0	14	2	22	14	17	38	0	45
Alaska	100	1	100	25	12	0	26	5	9	22	6	90	1	4
Arizona	100	0	100	10	0	11	42	6	30	2	10	90	0	0
Arkansas	100	1	100	47	0	0	13	3	23	14	15	28	0	57
California	100	1	100	5	0	3	26	3	54	9	11	88	1	1
Colorado	100	0	100	11	0	11	41	5	30	2	1	98	0	1
Connecticut	100	1	100	15	3	0	16	6	33	28	43	51	0	6
Delaware	100	1	100	14	2	0	18	7	29	31	44	50	0	6
Florida	100	1	100	48	0	0	7	0	40	4	22	61	1	17
Georgia	100	1	100	48	0	0	9	1	36	6	18	42	0	40
Hawaii	100	1	100	4	0	4	27	2	54	9	0	99	1	1
Idaho	100	0	100	5	0	3	26	2	53	10	1	99	0	0

	Beef Feedlots		Beef Not on Feed Operations	Dairy Cow Farms[a]							Dairy Heifer Facilities			
State	Dry Lot	Liquid/ Slurry[b]	Pasture, Range, Paddock	Pasture, Range, Paddock	Daily Spread	Dry Lot	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Daily Spread[b]	Dry Lot[b]	Liquid/ Slurry[b]	Pasture, Range, Paddock[b]
Illinois	100	1	100	24	0	0	23	3	33	18	8	87	0	5
Indiana	100	1	100	21	0	0	21	2	41	16	13	79	0	8
Iowa	100	1	100	20	0	0	21	3	41	16	10	83	0	6
Kansas	100	1	100	14	0	0	16	1	55	13	5	92	0	3
Kentucky	100	1	100	51	0	0	14	2	23	11	14	24	0	61
Louisiana	100	1	100	48	0	0	13	3	23	12	14	26	0	60
Maine	100	1	100	18	4	0	16	5	30	28	45	48	0	7
Maryland	100	1	100	21	4	0	16	6	23	29	44	49	0	7
Massachusetts	100	1	100	25	5	0	17	6	17	30	45	47	0	7
Michigan	100	1	100	11	3	0	22	6	36	22	6	91	0	3
Minnesota	100	1	100	16	6	0	24	6	26	23	10	84	0	6
Mississippi	100	1	100	50	0	0	14	2	23	11	15	28	0	57
Missouri	100	1	100	29	0	0	25	2	26	17	14	77	0	8
Montana	100	0	100	19	0	0	21	4	38	18	4	93	0	3
Nebraska	100	1	100	15	0	0	18	2	50	15	6	90	0	4
Nevada	100	0	100	11	0	0	14	2	61	13	0	99	0	0
New Hampshire	100	1	100	21	4	0	17	5	22	31	44	49	0	7
New Jersey	100	1	100	27	5	0	16	6	16	29	45	47	0	8
New Mexico	100	0	100	10	0	11	42	6	30	2	10	90	0	0
New York	100	1	100	14	3	0	15	5	38	25	45	48	0	7
North Carolina	100	1	100	48	0	0	10	2	31	9	15	31	0	54
North Dakota	100	1	100	18	0	0	19	3	44	16	11	83	0	6
Ohio	100	1	100	24	0	0	23	2	35	17	14	78	0	8
Oklahoma	100	0	100	11	0	8	41	5	23	12	6	94	0	0
Oregon	100	1	100	9	0	3	24	4	50	11	0	80	1	20
Pennsylvania	100	1	100	27	6	0	16	5	18	29	47	44	0	9
Rhode Island	100	1	100	29	6	0	17	5	14	30	47	44	0	9
South Carolina	100	1	100	45	0	0	10	2	33	11	15	31	0	54
South Dakota	100	1	100	14	0	0	16	2	54	14	8	87	0	5
Tennessee	100	1	100	48	0	0	12	2	26	11	15	26	0	59
Texas	100	0	100	11	0	10	41	5	30	3	8	92	0	0
Utah	100	0	100	12	0	9	40	5	28	7	1	98	0	1
Vermont	100	1	100	14	3	0	16	5	36	26	44	49	0	7
Virginia	100	1	100	49	0	0	12	2	26	11	15	28	0	57
Washington	100	1	100	8	0	3	25	3	51	10	0	83	1	17
West Virginia	100	1	100	29	6	0	17	5	13	30	45	48	0	7

	Beef Feedlots		Beef Not on Feed Operations	Dairy Cow Farms[a]							Dairy Heifer Facilities			
State	Dry Lot	Liquid/ Slurry[b]	Pasture, Range, Paddock	Pasture, Range, Paddock	Daily Spread	Dry Lot	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Daily Spread[b]	Dry Lot[b]	Liquid/ Slurry[b]	Pasture, Range, Paddock[b]
Wisconsin	100	1	100	15	5	0	24	6	27	23	12	82	0	7
Wyoming	100	0	100	16	0	0	18	2	49	15	12	81	0	7

[1] This table has not been updated for the current (1990 through 2021) Inventory. It will be updated for the next (1990 through 2022) Inventory submission.

Source(s): See Step 3: Waste Management System Usage Data.

[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.

[b] Deep pit systems are their own manure management systems in the U.S. but are included under Liquid Systems in the UNFCCC CRF tables due to lack of a separate allocation for those systems within the tables. For Dairy Cows, solid storage and dry lot systems calculated separately in Table A-164, but are reported as "NE" in the UNFCCC CRF tables due to lack of a separate allocation for those systems within the tables.

1

Table A-165: 2020 Manure Distribution Among Waste Management Systems by Operation for Livestock Other Than Cattle (Percent)[1]

	Swine Operations[a]						Layer Operations		Broiler and Turkey Operations		Sheep	
State	Pasture, Range, Paddock	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Deep Pit (<1 month)	Anaerobic Lagoon	Poultry without Litter	Pasture, Range, Paddock	Poultry with Litter	Dry Lot	Pasture, Range, Paddock
Alabama	15	0	29	30	12	14	42	58	1	99	95	5
Alaska	57	0	3	2	34	4	25	75	1	99	31	69
Arizona	19	0	28	29	11	13	60	40	1	99	28	72
Arkansas	6	0	60	26	5	2	0	100	1	99	83	18
California	15	0	28	29	13	14	12	88	1	99	31	69
Colorado	2	0	53	0	23	22	60	40	1	99	28	72
Connecticut	66	0	2	2	26	4	5	95	1	99	95	5
Delaware	29	0	4	5	56	5	5	95	1	99	95	5
Florida	53	0	20	14	9	5	42	58	1	99	95	5
Georgia	13	0	56	28	3	1	42	58	1	99	95	5
Hawaii	42	0	22	18	11	7	25	75	1	99	31	69
Idaho	16	0	16	3	57	8	60	40	1	99	28	72
Illinois	2	0	15	7	71	5	2	98	1	99	83	18
Indiana	1	0	3	12	78	7	0	100	1	99	83	18
Iowa	1	0	10	4	80	5	0	100	1	99	83	18
Kansas	1	0	13	35	21	30	2	98	1	99	83	18
Kentucky	8	0	19	21	31	21	5	95	1	99	95	5
Louisiana	67	0	17	9	6	2	60	40	1	99	83	18
Maine	74	0	2	1	20	4	5	95	1	99	95	5
Maryland	37	0	10	2	44	6	5	95	1	99	95	5
Massachusetts	60	0	2	2	31	4	5	95	1	99	95	5
Michigan	3	0	12	6	69	9	2	98	1	99	83	18
Minnesota	1	0	3	2	88	5	0	100	1	99	83	18
Mississippi	2	0	31	36	13	18	60	40	1	99	95	5
Missouri	2	0	16	33	34	15	0	100	1	99	83	18
Montana	3	0	21	2	64	9	60	40	1	99	28	72
Nebraska	2	0	9	22	49	19	2	98	1	99	83	18
Nevada	12	0	29	32	12	15	0	100	1	99	28	72
New Hampshire	65	0	2	2	27	4	5	95	1	99	95	5
New Jersey	54	0	3	3	36	4	5	95	1	99	95	5
New Mexico	67	0	17	9	6	2	60	40	1	99	28	72
New York	41	0	6	3	44	5	5	95	1	99	95	5

	Swine Operations[a]						Layer Operations		Broiler and Turkey Operations		Sheep	
State	Pasture, Range, Paddock	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit	Deep Pit (<1 month)	Anaerobic Lagoon	Poultry without Litter	Pasture, Range, Paddock	Poultry with Litter	Dry Lot	Pasture, Range, Paddock
North Carolina	1	0	33	49	1	16	42	58	1	99	95	5
North Dakota	2	0	21	2	65	9	2	98	1	99	83	18
Ohio	1	0	10	9	67	13	0	100	1	99	95	5
Oklahoma	1	0	11	53	3	32	60	40	1	99	83	18
Oregon	51	0	20	15	9	5	25	75	1	99	31	69
Pennsylvania	1	0	8	5	77	9	0	100	1	99	95	5
Rhode Island	64	0	2	2	28	4	5	95	1	99	95	5
South Carolina	6	0	30	34	13	16	60	40	1	99	95	5
South Dakota	1	0	17	11	57	14	2	98	1	99	83	18
Tennessee	7	0	30	33	13	16	5	95	1	99	95	5
Texas	6	0	31	34	13	17	12	88	1	99	28	72
Utah	1	0	22	2	65	9	60	40	1	99	28	72
Vermont	69	0	2	1	24	4	5	95	1	99	95	5
Virginia	6	0	14	29	15	35	5	95	1	99	95	5
Washington	35	0	12	2	45	7	12	88	1	99	31	69
West Virginia	82	0	1	0	13	3	5	95	1	99	95	5
Wisconsin	15	0	23	1	57	4	2	98	1	99	83	18
Wyoming	3	0	21	2	64	9	60	40	1	99	28	72

[1] This table has not been updated for the current (1990 through 2021) Inventory. It will be updated for the next (1990 through 2022) Inventory submission.

[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 systems are their own manure management systems in the U.S. but are included under Liquid Systems in the UNFCCC CRF tables due to lack of a separate allocation for those systems within the tables.

[b] Because manure from beef feedlots and dairy heifers may be managed for long periods of time in multiple systems (i.e., both drylot and runoff collection pond), the percent of manure that generates emissions is greater than 100 percent.

Source(s): See *Step 3: Waste Management System Usage Data.*

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Table A-166: Manure Management System Descriptions

Manure Management System	Description[a]
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_2O 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_2O emissions are accounted for under Manure Management. Direct N_2O 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.
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-167: Methane Conversion Factors (percent) for Dry Systems

Waste Management System	Cool Climate MCF	Temperate Climate 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-168: Methane Conversion Factors by State for Liquid Systems for 2020 (Percent)[1]

	Dairy		Swine		Beef	Poultry
State	Anaerobic Lagoon	Liquid/Slurry and Deep Pit	Anaerobic Lagoon	Liquid/Slurry and Pit Storage	Liquid/Slurry	Anaerobic Lagoon
Alabama	76	40	76	40	42	76
Alaska	49	15	49	15	15	49
Arizona	81	64	79	51	48	77
Arkansas	75	35	76	37	36	75
California	75	34	75	34	45	76
Colorado	66	23	70	25	25	66
Connecticut	71	26	71	26	27	71
Delaware	75	34	75	34	33	75
Florida	78	60	78	58	54	78
Georgia	76	43	76	41	49	76
Hawaii	77	60	77	60	60	77
Idaho	68	24	64	21	21	64
Illinois	72	29	72	29	28	73
Indiana	71	27	71	27	28	71
Iowa	70	26	70	26	26	70
Kansas	74	32	74	32	32	74
Kentucky	74	32	74	33	32	74
Louisiana	78	50	78	48	51	77
Maine	64	21	64	22	21	65
Maryland	74	31	75	33	32	74
Massachusetts	69	25	70	26	26	70
Michigan	68	24	69	25	25	68
Minnesota	68	24	68	25	24	67
Mississippi	77	44	76	42	47	77

State	Dairy		Swine		Beef	Poultry
	Anaerobic Lagoon	Liquid/Slurry and Deep Pit	Anaerobic Lagoon	Liquid/Slurry and Pit Storage	Liquid/Slurry	Anaerobic Lagoon
Missouri	74	32	73	30	31	74
Montana	60	19	63	20	20	62
Nebraska	72	28	72	28	27	72
Nevada	72	27	72	27	24	74
New Hampshire	65	22	66	23	22	66
New Jersey	73	30	74	30	29	73
New Mexico	75	34	72	29	32	73
New York	67	23	68	24	24	68
North Carolina	74	34	76	40	34	74
North Dakota	66	23	66	22	23	66
Ohio	71	27	71	28	28	71
Oklahoma	76	38	75	36	36	76
Oregon	65	22	64	21	22	64
Pennsylvania	71	27	71	27	28	72
Rhode Island	71	27	71	27	27	71
South Carolina	76	41	76	42	39	76
South Dakota	69	25	70	26	25	69
Tennessee	74	33	75	36	34	74
Texas	77	41	77	44	41	78
Utah	68	23	66	22	24	68
Vermont	64	21	64	21	21	64
Virginia	72	29	75	35	29	73
Washington	64	21	64	21	22	65
West Virginia	71	27	71	27	27	71
Wisconsin	67	23	68	24	24	68
Wyoming	62	20	64	21	22	63

Note: MCFs developed using Tier 2 methods described in *2006 IPCC Guidelines*, Section 10.4.2.

[1] This table has not been updated for the current (1990 through 2021) Inventory. It will be updated for the next (1990 through 2022) Inventory submission.

Table A-169: Direct Nitrous Oxide Emission Factors (kg N_2O-N/kg N excreted)

Waste Management System	Direct N_2O Emission Factor
Aerobic Treatment (forced aeration)	0.005
Aerobic Treatment (natural aeration)	0.01
Anaerobic Digester	0
Anaerobic Lagoon	0
Cattle Deep Bed (active mix)	0.07
Cattle Deep Bed (no mix)	0.01
Composting_in vessel	0.006
Composting_intensive	0.1
Composting_passive	0.01
Composting_static	0.006
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	0.005

Source: IPCC (2006).

Table A-170: 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	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
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
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-171: Total Methane Emissions from Livestock Manure Management (kt)[a]

Animal Type	1990	1995	2005	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Dairy Cattle	**572**	**665**	**943**	**1,114**	**1,158**	**1,140**	**1,159**	**1,203**	**1,232**	**1,248**	**1,278**	**1,237**	**1,269**	**1,283**
Dairy Cows	*564*	*657*	*935*	*1,106*	*1,149*	*1,131*	*1,150*	*1,193*	*1,223*	*1,239*	*1,269*	*1,228*	*1,260*	*1,273*
Dairy Heifer	*7*	*7*	*7*	*8*	*9*	*8*	*8*	*9*	*9*	*9*	*9*	*8*	*9*	*8*
Dairy Calves	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*
Swine	**621**	**762**	**812**	**791**	**821**	**755**	**718**	**807**	**846**	**840**	**882**	**891**	**895**	**858**
Market Swine	*482*	*607*	*665*	*653*	*678*	*623*	*585*	*665*	*699*	*697*	*730*	*740*	*748*	*715*
Market <50 lbs.	*101*	*121*	*128*	*94*	*98*	*88*	*86*	*95*	*101*	*100*	*105*	*106*	*103*	*99*
Market 50-119 lbs.	*101*	*123*	*131*	*142*	*149*	*136*	*130*	*145*	*154*	*153*	*160*	*163*	*163*	*156*
Market 120-179 lbs.	*136*	*170*	*184*	*185*	*193*	*179*	*169*	*192*	*203*	*200*	*211*	*211*	*215*	*206*
Market >180 lbs.	*144*	*193*	*221*	*231*	*238*	*219*	*200*	*232*	*241*	*244*	*254*	*260*	*267*	*254*
Breeding Swine	*139*	*155*	*147*	*138*	*143*	*133*	*133*	*143*	*146*	*143*	*152*	*151*	*147*	*144*
Beef Cattle	**63**	**69**	**67**	**67**	**66**	**65**	**64**	**65**	**68**	**70**	**70**	**71**	**71**	**71**
Feedlot Steers	*14*	*14*	*15*	*17*	*16*	*16*	*16*	*16*	*17*	*18*	*18*	*18*	*19*	*19*
Feedlot Heifers	*7*	*8*	*9*	*9*	*9*	*9*	*9*	*9*	*9*	*9*	*10*	*10*	*10*	*10*
NOF Bulls	*2*	*2*	*2*	*2*	*2*	*2*	*2*	*2*	*2*	*2*	*2*	*2*	*2*	*2*
Beef Calves	*2*	*3*	*3*	*3*	*3*	*3*	*3*	*3*	*3*	*3*	*3*	*3*	*3*	*3*
NOF Heifers	*5*	*6*	*5*	*5*	*5*	*5*	*5*	*5*	*6*	*6*	*5*	*5*	*5*	*5*
NOF Steers	*5*	*6*	*4*	*4*	*4*	*4*	*4*	*4*	*4*	*4*	*4*	*4*	*4*	*4*
NOF Cows	*27*	*30*	*28*	*27*	*27*	*26*	*26*	*26*	*27*	*28*	*28*	*28*	*28*	*27*
Sheep	**3**	**3**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**
Goats	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Poultry	**131**	**128**	**130**	**127**	**128**	**128**	**130**	**134**	**134**	**136**	**139**	**144**	**142**	**141**
Hens >1 yr.	*73*	*69*	*66*	*64*	*63*	*65*	*66*	*68*	*67*	*69*	*70*	*73*	*72*	*[b]*
Total Pullets	*25*	*22*	*22*	*23*	*24*	*24*	*24*	*26*	*26*	*26*	*28*	*29*	*28*	*[b]*
Chickens	*4*	*4*	*3*	*3*	*3*	*3*	*3*	*3*	*3*	*3*	*3*	*3*	*3*	*[b]*
Broilers	*19*	*23*	*31*	*31*	*32*	*31*	*31*	*31*	*32*	*32*	*33*	*33*	*33*	*[b]*
Turkeys	*10*	*9*	*6*	*6*	*6*	*6*	*6*	*6*	*6*	*6*	*6*	*6*	*6*	*[b]*
Horses	**4**	**5**	**5**	**4**	**4**	**4**	**4**	**4**	**3**	**3**	**3**	**3**	**3**	**3**
Mules and Asses	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
American Bison	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**

+ Does not exceed 0.5 kt.

[a] Accounts for CH_4 reductions due to capture and destruction of CH_4 at facilities using anaerobic digesters.

[b] Disaggregated poultry values (e.g., Broilers, Turkeys, etc.) have not been estimated for the current (1990 through 2021) Inventory. These values will be updated for the next (1990 through 2022) Inventory submission.

Table A-172: Total Methane Emissions from Livestock Manure Management (MMT CO_2 Eq.)[a]

Animal Type	1990	1995	2005	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Dairy Cattle	**16.0**	**18.6**	**26.4**	**31.2**	**32.4**	**31.9**	**32.5**	**33.7**	**34.5**	**35.0**	**35.8**	**34.6**	**35.5**	**35.9**
Dairy Cows	*15.8*	*18.4*	*26.2*	*31.0*	*32.2*	*31.7*	*32.2*	*33.4*	*34.2*	*34.7*	*35.5*	*34.4*	*35.3*	*35.7*
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*	*0.2*
Dairy Calves	*+*	*+*	*+*	*+*	*+*	*+*	*+*	*+*	*+*	*+*	*+*	*+*	*+*	*+*
Swine	**17.4**	**21.3**	**22.7**	**22.1**	**23.0**	**21.2**	**20.1**	**22.6**	**23.7**	**23.5**	**24.7**	**25.0**	**25.1**	**24.0**
Market Swine	13.5	17.0	18.6	18.3	19.0	17.4	16.4	18.6	19.6	19.5	20.4	20.7	21.0	20.0
Market <50 lbs.	*2.8*	*3.4*	*3.6*	*2.6*	*2.7*	*2.5*	*2.4*	*2.7*	*2.8*	*2.8*	*2.9*	*3.0*	*2.9*	*2.8*
Market 50-119 lbs.	*2.8*	*3.5*	*3.7*	*4.0*	*4.2*	*3.8*	*3.6*	*4.1*	*4.3*	*4.3*	*4.5*	*4.6*	*4.6*	*4.4*
Market 120-179 lbs.	*3.8*	*4.8*	*5.1*	*5.2*	*5.4*	*5.0*	*4.7*	*5.4*	*5.7*	*5.6*	*5.9*	*5.9*	*6.0*	*5.8*
Market >180 lbs.	*4.0*	*5.4*	*6.2*	*6.5*	*6.7*	*6.1*	*5.6*	*6.5*	*6.7*	*6.8*	*7.1*	*7.3*	*7.5*	*7.1*
Breeding Swine	3.9	4.3	4.1	3.9	4.0	3.7	3.7	4.0	4.1	4.0	4.3	4.2	4.1	4.0
Beef Cattle	**1.8**	**1.9**	**1.9**	**1.9**	**1.8**	**1.8**	**1.8**	**1.8**	**1.9**	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**
Feedlot Steers	*0.4*	*0.4*	*0.4*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*
Feedlot Heifers	*0.2*	*0.2*	*0.2*	*0.3*	*0.3*	*0.3*	*0.2*	*0.2*	*0.2*	*0.3*	*0.3*	*0.3*	*0.3*	*0.3*
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*	*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*	*0.1*
NOF Heifers	*0.1*	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.2*	*0.2*	*0.2*	*0.1*	*0.1*	*0.1*
NOF Steers	*0.1*	*0.2*	*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*	*0.8*	*0.8*	*0.8*	*0.7*	*0.7*	*0.7*	*0.7*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*
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**	**0.1**
Goats	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Poultry	**3.7**	**3.6**	**3.6**	**3.6**	**3.6**	**3.6**	**3.6**	**3.8**	**3.7**	**3.8**	**3.9**	**4.0**	**4.0**	**3.9**
Hens >1 yr.	*2.0*	*1.9*	*1.9*	*1.8*	*1.8*	*1.8*	*1.8*	*1.9*	*1.9*	*1.9*	*2.0*	*2.0*	*2.0*	[b]
Total Pullets	*0.7*	*0.6*	*0.6*	*0.6*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.8*	*0.8*	*0.8*	[b]
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*	[b]
Broilers	*0.5*	*0.7*	*0.9*	*0.9*	*0.9*	*0.9*	*0.9*	*0.9*	*0.9*	*0.9*	*0.9*	*0.9*	*0.9*	[b]
Turkeys	*0.3*	*0.3*	*0.2*	*0.2*	*0.2*	*0.2*	*0.2*	*0.2*	*0.2*	*0.2*	*0.2*	*0.2*	*0.2*	[b]
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**	**0.1**
Mules and Asses	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
American Bison	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Accounts for CH_4 reductions due to capture and destruction of CH_4 at facilities using anaerobic digesters.

[b] Disaggregated poultry values (e.g., Broilers, Turkeys, etc.) have not been estimated for the current (1990 through 2021) Inventory. These values will be updated for the next (1990 through 2022) Inventory submission.

Table A-173: Total (Direct and Indirect) Nitrous Oxide Emissions from Livestock Manure Management (kt)

Animal Type	1990	1995	2005	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Dairy Cattle	**17.5**	**18.0**	**18.1**	**19.0**	**19.3**	**19.3**	**19.4**	**19.9**	**20.2**	**20.3**	**20.6**	**20.5**	**20.6**	**20.6**
Dairy Cows	*10.4*	*10.5*	*10.3*	*10.7*	*10.9*	*10.9*	*11.0*	*11.2*	*11.3*	*11.6*	*11.8*	*11.8*	*11.9*	*12.1*
Dairy Heifer	*7.1*	*7.5*	*7.8*	*8.4*	*8.5*	*8.3*	*8.4*	*8.7*	*8.8*	*8.8*	*8.8*	*8.7*	*8.7*	*8.5*
Dairy Calves	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
Swine	**4.0**	**4.5**	**5.5**	**5.9**	**6.0**	**6.0**	**5.8**	**6.2**	**6.3**	**6.6**	**6.7**	**7.0**	**7.1**	**6.8**
Market Swine	3.0	3.5	4.6	5.2	5.2	5.2	5.0	5.4	5.6	5.7	5.8	6.1	6.2	*5.9*
Market <50 lbs.	*0.6*	*0.6*	*0.9*	*0.8*	*0.8*	*0.7*	*0.7*	*0.8*	*0.8*	*0.8*	*0.8*	*0.9*	*0.9*	*0.8*
Market 50-119 lbs.	*0.6*	*0.7*	*0.9*	*1.2*	*1.2*	*1.2*	*1.1*	*1.2*	*1.2*	*1.3*	*1.3*	*1.4*	*1.4*	*1.3*
Market 120-179 lbs.	*0.9*	*1.0*	*1.3*	*1.5*	*1.5*	*1.5*	*1.5*	*1.6*	*1.6*	*1.7*	*1.7*	*1.8*	*1.8*	*1.7*
Market >180 lbs.	*0.9*	*1.1*	*1.5*	*1.8*	*1.8*	*1.8*	*1.7*	*1.8*	*1.9*	*2.0*	*2.0*	*2.1*	*2.2*	*2.1*
Breeding Swine	*1.0*	*1.1*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*0.9*	*0.8*	*0.8*
Beef Cattle	**19.8**	**21.8**	**24.0**	**25.9**	**25.8**	**26.0**	**26.0**	**26.8**	**28.4**	**29.9**	**30.5**	**31.0**	**31.4**	**31.4**
Feedlot Steers	*13.4*	*14.4*	*15.5*	*16.9*	*16.7*	*17.0*	*17.3*	*17.9*	*19.1*	*20.1*	*20.1*	*20.3*	*20.5*	*20.6*
Feedlot Heifers	*6.4*	*7.4*	*8.5*	*9.1*	*9.0*	*9.0*	*8.7*	*8.9*	*9.2*	*9.8*	*10.4*	*10.7*	*10.9*	*10.9*
Sheep	**+**	**0.7**	**1.2**	**1.1**	**1.1**	**1.1**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**
Goats	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Poultry	**4.7**	**5.1**	**5.4**	**5.2**	**5.3**	**5.2**	**5.2**	**5.2**	**5.4**	**5.5**	**5.6**	**5.6**	**5.5**	**5.5**
Hens >1 yr.	*1.0*	*1.0*	*1.3*	*1.3*	*1.3*	*1.3*	*1.4*	*1.3*	*1.4*	*1.4*	*1.5*	*1.5*	*1.4*	[a]
Total Pullets	+	+	+	+	+	+	+	+	+	+	+	+	+	[a]
Chickens	+	+	+	+	+	+	+	+	+	+	+	+	+	[a]
Broilers	*2.2*	*2.7*	*3.0*	*2.8*	*2.9*	*2.7*	*2.7*	*2.8*	*2.8*	*2.9*	*2.9*	*2.9*	*3.0*	[a]
Turkeys	*1.2*	*1.1*	*0.8*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.6*	[a]
Horses	**0.3**	**0.4**	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3+**	**0.3**
Mules and Asses	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
American Bison	**NA**	**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)

[a] Disaggregated poultry values (e.g., Broilers, Turkeys, etc.) have not been estimated for the current (1990 through 2021) Inventory. These values will be updated for the next (1990 through 2022) Inventory submission.

Table A-174: Total (Direct and Indirect) Nitrous Oxide Emissions from Livestock Manure Management (MMT CO_2 Eq.)

Animal Type	1990	1995	2005	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Dairy Cattle	**4.6**	**4.8**	**4.8**	**5.0**	**5.1**	**5.1**	**5.1**	**5.3**	**5.3**	**5.4**	**5.4**	**5.4**	**5.5**	**5.5**
Dairy Cows	*2.7*	*2.8*	*2.7*	*2.8*	*2.9*	*2.9*	*2.9*	*3.0*	*3.0*	*3.1*	*3.1*	*3.1*	*3.2*	*3.2*
Dairy Heifer	*1.9*	*2.0*	*2.1*	*2.2*	*2.2*	*2.2*	*2.2*	*2.3*	*2.3*	*2.3*	*2.3*	*2.3*	*2.3*	*2.3*
Dairy Calves	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
Swine	**1.1**	**1.2**	**1.4**	**1.6**	**1.6**	**1.6**	**1.5**	**1.6**	**1.7**	**1.7**	**1.8**	**1.9**	**1.9**	**1.8**
Market Swine	0.8	0.9	1.2	1.4	1.4	1.4	1.3	1.4	1.5	1.5	1.5	1.6	1.7	1.6
Market <50 lbs.	*0.1*	*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*
Market 50-119 lbs.	*0.2*	*0.2*	*0.2*	*0.3*	*0.3*	*0.3*	*0.3*	*0.3*	*0.3*	*0.3*	*0.3*	*0.4*	*0.4*	*0.4*
Market 120-179 lbs.	*0.2*	*0.3*	*0.3*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.5*	*0.5*	*0.5*	*0.5*
Market >180 lbs.	*0.2*	*0.3*	*0.4*	*0.5*	*0.5*	*0.5*	*0.4*	*0.5*	*0.5*	*0.5*	*0.5*	*0.6*	*0.6*	*0.5*
Breeding Swine	*0.3*	*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**	**5.8**	**6.4**	**6.9**	**6.8**	**6.9**	**6.9**	**7.1**	**7.5**	**7.9**	**8.1**	**8.2**	**8.3**	**8.3**
Feedlot Steers	*3.5*	*3.8*	*4.1*	*4.5*	*4.4*	*4.5*	*4.6*	*4.7*	*5.1*	*5.3*	*5.3*	*5.4*	*5.4*	*5.4*
Feedlot Heifers	*1.7*	*2.0*	*2.2*	*2.4*	*2.4*	*2.4*	*2.3*	*2.3*	*2.4*	*2.6*	*2.8*	*2.8*	*2.9*	*2.9*
Sheep	**0.1**	**0.2**	**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	**1.2**	**1.4**	**1.4**	**1.4**	**1.4**	**1.4**	**1.4**	**1.4**	**1.4**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**
Hens >1 yr.	*0.3*	*0.3*	*0.3*	*0.3*	*0.3*	*0.4*	*0.4*	*0.3*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	[a]
Total Pullets	*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*	[a]
Chickens	*+*	*+*	*+*	*+*	*+*	*+*	*+*	*+*	*+*	*+*	*+*	*+*	*+*	[a]
Broilers	*0.6*	*0.7*	*0.8*	*0.7*	*0.8*	*0.7*	*0.7*	*0.7*	*0.7*	*0.8*	*0.8*	*0.8*	*0.8*	[a]
Turkeys	*0.3*	*0.3*	*0.2*	*0.2*	*0.2*	*0.2*	*0.2*	*0.2*	*0.2*	*0.2*	*0.2*	*0.2*	*0.2*	[a]
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**	**0.1**
Mules and Asses	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
American Bison	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**

+ Does not exceed 0.05 MMT CO_2 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.

[a] Disaggregated poultry values (e.g., Broilers, Turkeys, etc.) have not been estimated for the current (1990 through 2021) Inventory. These values will be updated for the next (1990 through 2022) Inventory submission.

Table A-175: Methane Emissions by State from Livestock Manure Management for 2021 (kt)[a,b]

State	Beef Cattle[b]	Dairy Cattle[b]	Swine[b]	Poultry[b]	Sheep	Goats	Horses	Mules and Asses	American Bison	Total
Alabama	0.8125	0.3599	0.2652	14.7198	0.0123	0.0070	0.0469	0.0046	0.0001	16.2282
Alaska	0.0134	0.0050	0.0052	0.0035	0.0002	0.0001	0.0015	+	0.0015	0.0304
Arizona	0.9966	23.4247	2.4403	1.7632	0.0371	0.0076	0.0789	0.0011	0.0001	28.7496
Arkansas	1.0922	0.4039	1.7514	5.2257	0.0103	0.0047	0.0406	0.0031	0.0001	8.5320
California	2.7562	323.0222	1.4203	4.3432	0.2105	0.0179	0.0837	0.0022	0.0014	331.8577
Colorado	3.1745	20.9705	5.5459	4.9704	0.1226	0.0074	0.0945	0.0023	0.0120	34.9000
Connecticut	0.0079	2.7281	0.0136	0.1865	0.0024	0.0008	0.0082	0.0004	0.0004	2.9483
Delaware	0.0040	0.5347	0.0651	1.0918	0.0006	0.0002	0.0031	+	0.0002	1.6996
Florida	1.0095	14.9550	0.1333	8.8616	0.0123	0.0092	0.0821	0.0049	0.0001	25.0680
Georgia	0.6054	10.9026	0.6449	22.2759	0.0124	0.0096	0.0460	0.0046	0.0001	34.5015
Hawaii	0.0995	0.0645	0.1475	0.1156	0.0074	0.0025	0.0048	0.0001	0.0001	0.4420
Idaho	1.2816	105.7955	0.1903	0.6988	0.0663	0.0044	0.0428	0.0011	0.0292	108.1099
Illinois	0.8948	10.2961	54.7801	0.4229	0.0233	0.0050	0.0335	0.0018	0.0006	66.4581
Indiana	0.4284	15.5371	46.5341	1.8016	0.0242	0.0055	0.0697	0.0017	0.0004	64.4027
Iowa	3.6466	34.2068	215.8725	1.9100	0.0640	0.0124	0.0462	0.0013	0.0024	255.7621
Kansas	6.9297	35.4499	34.7837	0.1182	0.0309	0.0068	0.0426	0.0017	0.0046	77.3680
Kentucky	1.2161	4.4761	6.0783	1.6469	0.0282	0.0074	0.1117	0.0047	0.0021	13.5715
Louisiana	0.5254	0.8997	0.0478	2.8371	0.0060	0.0026	0.0386	0.0027	0.0001	4.3599
Maine	0.0168	3.1449	0.0114	0.1573	0.0053	0.0007	0.0068	0.0002	0.0002	3.3436
Maryland	0.0718	5.1270	0.1493	1.3693	0.0079	0.0020	0.0284	0.0008	+	6.7564
Massachusetts	0.0083	0.4177	0.0366	0.0148	0.0052	0.0009	0.0117	0.0005	+	0.4958
Michigan	0.4355	64.9945	11.0382	1.0654	0.0360	0.0039	0.0525	0.0015	0.0028	77.6304
Minnesota	1.2549	43.3187	70.5794	1.4579	0.0487	0.0049	0.0370	0.0013	0.0025	116.7051
Mississippi	0.5890	0.6259	2.0967	10.2208	0.0083	0.0048	0.0335	0.0035	0.0002	13.5827
Missouri	2.5116	7.0403	48.3527	1.9507	0.0424	0.0078	0.0699	0.0044	0.0006	59.9804
Montana	2.0740	1.2438	1.3460	0.9375	0.0577	0.0021	0.0707	0.0013	0.0230	5.7562
Nebraska	7.5531	11.2037	45.0874	0.5302	0.0331	0.0040	0.0412	0.0007	0.0274	64.4808
Nevada	0.3341	7.0013	0.0358	0.0007	0.0187	0.0011	0.0096	0.0002	+	7.4015
New Hampshire	0.0058	1.0829	0.0135	0.0338	0.0032	0.0005	0.0061	0.0002	0.0003	1.1462
New Jersey	0.0122	0.4490	0.0446	0.2477	0.0060	0.0016	0.0219	0.0006	+	0.7835
New Mexico	0.6665	40.2367	0.0076	0.1577	0.0274	0.0048	0.0410	0.0010	0.0051	41.1478
New York	0.2028	87.3303	0.3550	0.6195	0.0396	0.0035	0.0585	0.0011	0.0011	88.6113
North Carolina	0.4405	5.0729	163.1506	17.1607	0.0203	0.0073	0.0475	0.0049	0.0002	185.9050
North Dakota	1.2542	2.2544	1.1102	0.0410	0.0318	0.0010	0.0209	0.0003	0.0121	4.7260

State	Beef Cattle[b]	Dairy Cattle[b]	Swine[b]	Poultry[b]	Sheep	Goats	Horses	Mules and Asses	American Bison	Total
Ohio	0.6877	31.8047	28.1332	1.6689	0.0574	0.0083	0.0915	0.0031	0.0009	62.4557
Oklahoma	3.5639	4.0923	41.3493	3.6594	0.0321	0.0140	0.1196	0.0073	0.0008	52.8387
Oregon	0.9299	8.6644	0.0585	0.8784	0.0489	0.0068	0.0633	0.0016	0.0023	10.6541
Pennsylvania	0.4975	43.9632	13.2523	1.8838	0.0437	0.0069	0.0730	0.0037	0.0011	59.7254
Rhode Island	0.0018	0.0520	0.0056	0.0078	0.0007	0.0001	0.0018	+	+	0.0698
South Carolina	0.2067	1.3996	3.4253	5.1236	0.0063	0.0058	0.0409	0.0026	+	10.2108
South Dakota	2.9274	23.3986	19.9356	0.2723	0.1060	0.0024	0.0452	0.0008	0.0247	46.7130
Tennessee	1.0931	3.0969	4.3940	0.9534	0.0332	0.0141	0.0920	0.0081	0.0003	9.6851
Texas	13.4426	77.1905	17.7303	8.2182	0.2597	0.1126	0.3305	0.0390	0.0087	117.3321
Utah	0.5317	9.5031	7.4454	4.7090	0.0822	0.0029	0.0519	0.0005	0.0011	22.3277
Vermont	0.0211	12.0337	0.0116	0.0176	0.0068	0.0012	0.0070	+	0.0002	12.0992
Virginia	0.7740	7.2078	4.7956	1.7154	0.0333	0.0061	0.0556	0.0031	0.0005	14.5914
Washington	0.8556	44.0113	0.0861	1.3765	0.0148	0.0040	0.0479	0.0012	0.0010	46.3984
West Virginia	0.2458	0.4200	0.0066	0.5340	0.0150	0.0033	0.0228	0.0015	0.0001	1.2492
Wisconsin	0.8691	130.2341	2.8725	0.7716	0.0343	0.0159	0.0607	0.0015	0.0061	134.8657
Wyoming	1.1067	0.9912	0.6647	0.0324	0.0981	0.0022	0.0480	0.0013	0.0104	2.9550

+ Does not exceed 0.00005 kt.

[a] Accounts for CH_4 reductions due to capture and destruction of CH_4 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 2021) Inventory. Disaggregated animal types will be estimated for the next (1990 through 2022) Inventory submission.

Table A-176: Methane Emissions by State from Livestock Manure Management for 2021 (MMT CO_2 Eq.)[a]

State	Beef Cattle[b]	Dairy Cattle[b]	Swine[b]	Poultry[b]	Sheep	Goats	Horses	Mules and Asses	American Bison	Total
Alabama	0.0227	0.0101	0.0074	0.4122	0.0003	0.0002	0.0013	0.0001	+	0.4544
Alaska	0.0004	0.0001	0.0001	0.0001	+	+	+	+	+	0.0008
Arizona	0.0279	0.6559	0.0683	0.0494	0.0010	0.0002	0.0022	+	+	0.8050
Arkansas	0.0306	0.0113	0.0490	0.1463	0.0003	0.0001	0.0011	0.0001	+	0.2389
California	0.0772	9.0446	0.0398	0.1216	0.0059	0.0005	0.0023	0.0001	+	9.2920
Colorado	0.0889	0.5872	0.1553	0.1392	0.0034	0.0002	0.0026	0.0001	0.0003	0.9772
Connecticut	0.0002	0.0764	0.0004	0.0052	0.0001	+	0.0002	+	+	0.0825
Delaware	0.0001	0.0150	0.0018	0.0306	+	+	0.0001	+	+	0.0476

State	Beef Cattle[b]	Dairy Cattle[b]	Swine[b]	Poultry[b]	Sheep	Goats	Horses	Mules and Asses	American Bison	Total
Florida	0.0283	0.4187	0.0037	0.2481	0.0003	0.0003	0.0023	0.0001	+	0.7019
Georgia	0.0170	0.3053	0.0181	0.6237	0.0003	0.0003	0.0013	0.0001	+	0.9660
Hawaii	0.0028	0.0018	0.0041	0.0032	0.0002	0.0001	0.0001	+	+	0.0124
Idaho	0.0359	2.9623	0.0053	0.0196	0.0019	0.0001	0.0012	+	0.0008	3.0270
Illinois	0.0251	0.2883	1.5338	0.0118	0.0007	0.0001	0.0009	0.0001	+	1.8608
Indiana	0.0120	0.4350	1.3030	0.0504	0.0007	0.0002	0.0020	+	+	1.8032
Iowa	0.1021	0.9578	6.0444	0.0535	0.0018	0.0003	0.0013	+	0.0001	7.1613
Kansas	0.1940	0.9926	0.9739	0.0033	0.0009	0.0002	0.0012	+	0.0001	2.1663
Kentucky	0.0341	0.1253	0.1702	0.0461	0.0008	0.0002	0.0031	0.0001	0.0001	0.3800
Louisiana	0.0147	0.0252	0.0013	0.0794	0.0002	0.0001	0.0011	0.0001	+	0.1221
Maine	0.0005	0.0881	0.0003	0.0044	0.0001	+	0.0002	+	+	0.0936
Maryland	0.0020	0.1436	0.0042	0.0383	0.0002	0.0001	0.0008	+	+	0.1892
Massachusetts	0.0002	0.0117	0.0010	0.0004	0.0001	+	0.0003	+	+	0.0138
Michigan	0.0122	1.8198	0.3091	0.0298	0.0010	0.0001	0.0015	+	0.0001	2.1736
Minnesota	0.0351	1.2129	1.9762	0.0408	0.0014	0.0001	0.0010	+	0.0001	3.2677
Mississippi	0.0165	0.0175	0.0587	0.2862	0.0002	0.0001	0.0009	0.0001	+	0.3803
Missouri	0.0703	0.1971	1.3539	0.0546	0.0012	0.0002	0.0020	0.0001	+	1.6794
Montana	0.0581	0.0348	0.0377	0.0263	0.0016	0.0001	0.0020	+	0.0006	0.1611
Nebraska	0.2115	0.3137	1.2624	0.0148	0.0009	0.0001	0.0012	+	0.0008	1.8054
Nevada	0.0094	0.1960	0.0010	0.0000	0.0005	+	0.0003	+	+	0.2072
New Hampshire	0.0002	0.0303	0.0004	0.0009	0.0001	+	0.0002	+	+	0.0321
New Jersey	0.0003	0.0126	0.0012	0.0069	0.0002	+	0.0006	+	+	0.0219
New Mexico	0.0187	1.1266	0.0002	0.0044	0.0008	0.0001	0.0011	+	0.0001	1.1521
New York	0.0057	2.4452	0.0099	0.0173	0.0011	0.0001	0.0016	+	+	2.4811
North Carolina	0.0123	0.1420	4.5682	0.4805	0.0006	0.0002	0.0013	0.0001	+	5.2053
North Dakota	0.0351	0.0631	0.0311	0.0011	0.0009	+	0.0006	+	0.0003	0.1323
Ohio	0.0193	0.8905	0.7877	0.0467	0.0016	0.0002	0.0026	0.0001	+	1.7487
Oklahoma	0.0998	0.1146	1.1578	0.1025	0.0009	0.0004	0.0033	0.0002	+	1.4795
Oregon	0.0260	0.2426	0.0016	0.0246	0.0014	0.0002	0.0018	+	0.0001	0.2983
Pennsylvania	0.0139	1.2310	0.3711	0.0527	0.0012	0.0002	0.0020	0.0001	+	1.6723
Rhode Island	0.0000	0.0015	0.0002	0.0002	+	+	0.0001	+	+	0.0019
South Carolina	0.0058	0.0392	0.0959	0.1435	0.0002	0.0002	0.0011	0.0001	+	0.2859
South Dakota	0.0820	0.6552	0.5582	0.0076	0.0030	0.0001	0.0013	+	0.0007	1.3079
Tennessee	0.0306	0.0867	0.1230	0.0267	0.0009	0.0004	0.0026	0.0002	+	0.2712
Texas	0.3764	2.1613	0.4964	0.2301	0.0073	0.0032	0.0093	0.0011	0.0002	3.2853

State	Beef Cattle[b]	Dairy Cattle[b]	Swine[b]	Poultry[b]	Sheep	Goats	Horses	Mules and Asses	American Bison	Total
Utah	0.0149	0.2661	0.2085	0.1319	0.0023	0.0001	0.0015	+	+	0.6251
Vermont	0.0006	0.3369	0.0003	0.0005	0.0002	+	0.0002	+	+	0.3387
Virginia	0.0217	0.2018	0.1343	0.0480	0.0009	0.0002	0.0016	0.0001	+	0.4085
Washington	0.0240	1.2323	0.0024	0.0385	0.0004	0.0001	0.0013	+	+	1.2991
West Virginia	0.0069	0.0118	0.0002	0.0150	0.0004	0.0001	0.0006	+	+	0.0349
Wisconsin	0.0243	3.6466	0.0804	0.0216	0.0010	0.0004	0.0017	+	0.0002	3.7762
Wyoming	0.0310	0.0278	0.0186	0.0009	0.0027	0.0001	0.0013	+	0.0003	0.0827

+ Does not exceed 0.00005 MMT CO_2 Eq.

[a] Accounts for CH_4 reductions due to capture and destruction of CH_4 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 2021) Inventory. Disaggregated animal types will be estimated for the next (1990 through 2022) Inventory submission.

1 **Table A-177: Total (Direct and Indirect) Nitrous Oxide Emissions by State from Livestock Manure Management for 2021 (kt)**

State	Beef Cattle[a]	Dairy Cattle	Dairy Heifer	Swine[a]	Poultry[a]	Sheep	Goats	Horses	Mules and Asses	American Bison	Total
Alabama	0.0140	0.0024	0.0018	0.0014	0.4590	0.0069	0.0016	0.0044	0.0004	NA	0.4919
Alaska	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	+	0.0001	+	NA	0.0009
Arizona	0.5696	0.3689	0.2376	0.0119	0.0089	0.0115	0.0017	0.0074	0.0001	NA	1.2176
Arkansas	0.0297	0.0028	0.0020	0.0110	0.5226	0.0055	0.0011	0.0038	0.0003	NA	0.5789
California	1.1721	2.4669	1.5498	0.0088	0.1824	0.0706	0.0041	0.0078	0.0002	NA	5.4627
Colorado	2.3705	0.3623	0.2577	0.0644	0.0295	0.0466	0.0018	0.0095	0.0002	NA	3.1426
Connecticut	0.0005	0.0212	0.0116	0.0001	0.0080	0.0020	0.0002	0.0008	+	NA	0.0443
Delaware	0.0005	0.0039	0.0022	0.0004	0.0879	0.0005	+	0.0003	+	NA	0.0956
Florida	0.0078	0.0708	0.0500	0.0006	0.0800	0.0069	0.0021	0.0077	0.0005	NA	0.2263
Georgia	0.0115	0.0527	0.0295	0.0038	0.5487	0.0070	0.0022	0.0043	0.0004	NA	0.6601
Hawaii	0.0024	0.0005	0.0023	0.0006	0.0013	0.0025	0.0006	0.0004	+	NA	0.0106
Idaho	0.6584	0.9377	0.7450	0.0022	0.0043	0.0252	0.0011	0.0043	0.0001	NA	2.3783
Illinois	0.5226	0.0829	0.0899	0.4682	0.0316	0.0179	0.0012	0.0034	0.0002	NA	1.2179
Indiana	0.2238	0.1875	0.1359	0.3823	0.2311	0.0186	0.0013	0.0070	0.0002	NA	1.1876
Iowa	2.7968	0.2363	0.2201	2.1285	0.2547	0.0493	0.0030	0.0047	0.0001	NA	5.6934
Kansas	5.4848	0.1829	0.2946	0.2091	0.0087	0.0238	0.0017	0.0043	0.0002	NA	6.2100
Kentucky	0.0364	0.0314	0.0230	0.0408	0.1278	0.0235	0.0018	0.0112	0.0005	NA	0.2964
Louisiana	0.0074	0.0056	0.0018	0.0002	0.0721	0.0032	0.0006	0.0036	0.0003	NA	0.0948
Maine	0.0013	0.0285	0.0161	0.0001	0.0072	0.0044	0.0002	0.0007	+	NA	0.0585

Maryland	0.0146	0.0409	0.0305	0.0012	0.1057	0.0065	0.0005	0.0029	0.0001	NA	0.2028
Massachusetts	0.0005	0.0090	0.0074	0.0003	0.0007	0.0044	0.0002	0.0012	0.0001	NA	0.0237
Michigan	0.3480	0.5462	0.3633	0.1084	0.0847	0.0277	0.0010	0.0053	0.0002	NA	1.4846
Minnesota	0.8676	0.4918	0.4534	0.7227	0.1703	0.0375	0.0012	0.0037	0.0001	NA	2.7483
Mississippi	0.0158	0.0048	0.0033	0.0105	0.2731	0.0047	0.0011	0.0031	0.0003	NA	0.3167
Missouri	0.2320	0.0631	0.0622	0.3096	0.2097	0.0326	0.0019	0.0070	0.0005	NA	0.9186
Montana	0.1023	0.0125	0.0106	0.0168	0.0061	0.0219	0.0005	0.0071	0.0001	NA	0.1780
Nebraska	5.6833	0.0650	0.0620	0.3225	0.0392	0.0254	0.0010	0.0041	0.0001	NA	6.2027
Nevada	0.0070	0.0350	0.0227	0.0003	0.0001	0.0071	0.0003	0.0010	+	NA	0.0734
New Hampshire	0.0004	0.0108	0.0076	0.0001	0.0015	0.0027	0.0001	0.0006	+	NA	0.0239
New Jersey	0.0005	0.0041	0.0035	0.0003	0.0103	0.0050	0.0004	0.0022	0.0001	NA	0.0264
New Mexico	0.0296	0.6248	0.2891	0.0001	0.0009	0.0104	0.0012	0.0041	0.0001	NA	0.9602
New York	0.0478	0.6942	0.3973	0.0035	0.0282	0.0330	0.0008	0.0059	0.0001	NA	1.2108
North Carolina	0.0098	0.0276	0.0129	0.8765	0.4869	0.0114	0.0017	0.0044	0.0005	NA	1.4316
North Dakota	0.0994	0.0158	0.0152	0.0122	0.0039	0.0245	0.0002	0.0021	+	NA	0.1732
Ohio	0.3562	0.2567	0.2165	0.2433	0.2058	0.0475	0.0020	0.0092	0.0003	NA	1.3374
Oklahoma	0.7254	0.0619	0.0428	0.1919	0.0816	0.0169	0.0032	0.0112	0.0007	NA	1.1355
Oregon	0.2041	0.1617	0.1283	0.0005	0.0162	0.0204	0.0017	0.0064	0.0002	NA	0.5394
Pennsylvania	0.2171	0.4287	0.2930	0.1230	0.2186	0.0364	0.0017	0.0073	0.0004	NA	1.3262
Rhode Island	0.0001	0.0005	0.0005	+	0.0004	0.0006	+	0.0002	+	NA	0.0023
South Carolina	0.0035	0.0072	0.0029	0.0203	0.1289	0.0035	0.0013	0.0038	0.0003	NA	0.1717
South Dakota	0.9409	0.1383	0.0901	0.1774	0.0248	0.0815	0.0006	0.0045	0.0001	NA	1.4582
Tennessee	0.0371	0.0196	0.0155	0.0263	0.0715	0.0186	0.0032	0.0086	0.0008	NA	0.2012
Texas	6.2846	1.0842	0.5899	0.1049	0.3432	0.0806	0.0254	0.0308	0.0038	NA	8.5473
Utah	0.0445	0.1673	0.1115	0.0883	0.0397	0.0312	0.0007	0.0052	0.0001	NA	0.4885
Vermont	0.0015	0.1297	0.0643	0.0001	0.0009	0.0057	0.0003	0.0007	+	NA	0.2032
Virginia	0.0408	0.0489	0.0215	0.0295	0.1481	0.0277	0.0015	0.0056	0.0003	NA	0.3239
Washington	0.5169	0.3948	0.2432	0.0010	0.0386	0.0062	0.0010	0.0048	0.0001	NA	1.2066
West Virginia	0.0087	0.0046	0.0035	0.0001	0.0417	0.0125	0.0008	0.0023	0.0002	NA	0.0742
Wisconsin	0.5382	1.4621	1.2950	0.0324	0.0634	0.0264	0.0039	0.0061	0.0002	NA	3.4275
Wyoming	0.1478	0.0067	0.0074	0.0075	0.0002	0.0373	0.0005	0.0048	0.0001	NA	0.2125

+ Does not exceed 0.00005 kt.

[a] Disaggregated animal type (E.g., Market Swine and Breeding Swine animal types, versus "Swine") nitrous oxide emissions were not estimated by state for the current (1990 through 2021) Inventory. Disaggregated animal types will be estimated for the next (1990 through 2022) Inventory submission.

Table A-178: Total (Direct and Indirect) Nitrous Oxide Emissions by State from Livestock Manure Management for 2021 (MMT CO_2 Eq.)

State	Beef Cattle[a]	Dairy Cow	Dairy Heifer	Swine[a]	Poultry[a]	Sheep	Goats	Horses	Mules and Asses	American Bison	Total
Alabama	0.0037	0.0006	0.0005	0.0004	0.1216	0.0018	0.0004	0.0012	0.0001	NA	0.1304
Alaska	+	+	0.0001	+	+	+	+	+	+	NA	0.0001
Arizona	0.1510	0.0978	0.0630	0.0032	0.0024	0.0030	0.0005	0.0020	+	NA	0.3226
Arkansas	0.0079	0.0008	0.0005	0.0029	0.1385	0.0015	0.0003	0.0010	0.0001	NA	0.1534
California	0.3106	0.6537	0.4107	0.0023	0.0483	0.0187	0.0011	0.0021	0.0001	NA	1.4476
Colorado	0.6282	0.0960	0.0683	0.0171	0.0078	0.0123	0.0005	0.0025	0.0001	NA	0.8328
Connecticut	0.0001	0.0056	0.0031	+	0.0021	0.0005	0.0001	0.0002	+	NA	0.0117
Delaware	0.0001	0.0010	0.0006	0.0001	0.0233	0.0001	+	0.0001	+	NA	0.0253
Florida	0.0021	0.0188	0.0133	0.0002	0.0212	0.0018	0.0006	0.0020	0.0001	NA	0.0600
Georgia	0.0030	0.0140	0.0078	0.0010	0.1454	0.0018	0.0006	0.0011	0.0001	NA	0.1749
Hawaii	0.0006	0.0001	0.0006	0.0002	0.0003	0.0007	0.0002	0.0001	+	NA	0.0028
Idaho	0.1745	0.2485	0.1974	0.0006	0.0011	0.0067	0.0003	0.0011	+	NA	0.6302
Illinois	0.1385	0.0220	0.0238	0.1241	0.0084	0.0048	0.0003	0.0009	+	NA	0.3227
Indiana	0.0593	0.0497	0.0360	0.1013	0.0612	0.0049	0.0004	0.0019	+	NA	0.3147
Iowa	0.7411	0.0626	0.0583	0.5640	0.0675	0.0131	0.0008	0.0012	+	NA	1.5087
Kansas	1.4535	0.0485	0.0781	0.0554	0.0023	0.0063	0.0004	0.0011	+	NA	1.6456
Kentucky	0.0096	0.0083	0.0061	0.0108	0.0339	0.0062	0.0005	0.0030	0.0001	NA	0.0785
Louisiana	0.0020	0.0015	0.0005	0.0001	0.0191	0.0008	0.0002	0.0010	0.0001	NA	0.0251
Maine	0.0003	0.0075	0.0043	+	0.0019	0.0012	+	0.0002	+	NA	0.0154
Maryland	0.0039	0.0108	0.0081	0.0003	0.0280	0.0017	0.0001	0.0008	+	NA	0.0537
Massachusetts	0.0001	0.0024	0.0020	0.0001	0.0002	0.0012	0.0001	0.0003	+	NA	0.0063
Michigan	0.0922	0.1447	0.0963	0.0287	0.0224	0.0073	0.0003	0.0014	+	NA	0.3934
Minnesota	0.2299	0.1303	0.1201	0.1915	0.0451	0.0099	0.0003	0.0010	+	NA	0.7283
Mississippi	0.0042	0.0013	0.0009	0.0028	0.0724	0.0012	0.0003	0.0008	0.0001	NA	0.0839
Missouri	0.0615	0.0167	0.0165	0.0820	0.0556	0.0086	0.0005	0.0019	0.0001	NA	0.2434
Montana	0.0271	0.0033	0.0028	0.0045	0.0016	0.0058	0.0001	0.0019	+	NA	0.0471
Nebraska	1.5061	0.0172	0.0164	0.0855	0.0104	0.0067	0.0003	0.0011	+	NA	1.6437
Nevada	0.0018	0.0093	0.0060	0.0001	+	0.0019	0.0001	0.0003	+	NA	0.0194
New Hampshire	0.0001	0.0029	0.0020	+	0.0004	0.0007	+	0.0002	+	NA	0.0063
New Jersey	0.0001	0.0011	0.0009	0.0001	0.0027	0.0013	0.0001	0.0006	+	NA	0.0070
New Mexico	0.0078	0.1656	0.0766	+	0.0002	0.0028	0.0003	0.0011	+	NA	0.2544
New York	0.0127	0.1840	0.1053	0.0009	0.0075	0.0087	0.0002	0.0016	+	NA	0.3208
North Carolina	0.0026	0.0073	0.0034	0.2323	0.1290	0.0030	0.0004	0.0012	0.0001	NA	0.3794

North Dakota	0.0263	0.0042	0.0040	0.0032	0.0010	0.0065	0.0001	0.0006	+	NA	0.0459
Ohio	0.0944	0.0680	0.0574	0.0645	0.0545	0.0126	0.0005	0.0024	0.0001	NA	0.3544
Oklahoma	0.1922	0.0164	0.0113	0.0509	0.0216	0.0045	0.0008	0.0030	0.0002	NA	0.3009
Oregon	0.0541	0.0428	0.0340	0.0001	0.0043	0.0054	0.0004	0.0017	+	NA	0.1429
Pennsylvania	0.0575	0.1136	0.0776	0.0326	0.0579	0.0096	0.0005	0.0019	0.0001	NA	0.3514
Rhode Island	+	0.0001	0.0001	+	0.0001	0.0002	+	+	+	NA	0.0005
South Carolina	0.0009	0.0019	0.0008	0.0054	0.0342	0.0009	0.0004	0.0010	0.0001	NA	0.0455
South Dakota	0.2493	0.0367	0.0239	0.0470	0.0066	0.0216	0.0002	0.0012	+	NA	0.3864
Tennessee	0.0098	0.0052	0.0041	0.0070	0.0190	0.0049	0.0008	0.0023	0.0002	NA	0.0533
Texas	1.6654	0.2873	0.1563	0.0278	0.0909	0.0213	0.0067	0.0082	0.0010	NA	2.2650
Utah	0.0118	0.0443	0.0296	0.0234	0.0105	0.0083	0.0002	0.0014	+	NA	0.1294
Vermont	0.0004	0.0344	0.0170	+	0.0002	0.0015	0.0001	0.0002	+	NA	0.0538
Virginia	0.0108	0.0130	0.0057	0.0078	0.0392	0.0073	0.0004	0.0015	0.0001	NA	0.0858
Washington	0.1370	0.1046	0.0645	0.0003	0.0102	0.0016	0.0003	0.0013	+	NA	0.3197
West Virginia	0.0023	0.0012	0.0009	+	0.0110	0.0033	0.0002	0.0006	+	NA	0.0196
Wisconsin	0.1426	0.3875	0.3432	0.0086	0.0168	0.0070	0.0010	0.0016	+	NA	0.9083
Wyoming	0.0392	0.0018	0.0020	0.0020	0.0001	0.0099	0.0001	0.0013	+	NA	0.0563

+ Does not exceed 0.00005 MMT CO_2 Eq.

[a] Disaggregated animal type (E.g., Market Swine and Breeding Swine animal types, versus "Swine") nitrous oxide emissions were not estimated by state for the current (1990 through 2021) Inventory. Disaggregated animal types will be estimated for the next (1990 through 2022) Inventory submission.

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3.12. Methodologies for Estimating Soil Organic C Stock Changes, Soil N_2O Emissions, and CH_4 Emissions and from Agricultural Lands (Cropland and Grassland)

This annex provides a detailed description of Tier 1 and 3 methods that are used to estimate direct N_2O emissions from cropland and grassland soils, as well as indirect N_2O emissions associated with volatilization, leaching, and runoff of N from croplands and grasslands. See Annex 3.12 in the previous Inventory (EPA 2022) for information on soil organic C stock changes for Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland and Land Converted to Grassland, in addition to CH_4 emissions from rice cultivation.

Nitrous oxide (N_2O) is produced in soils through the microbial processes of nitrification and denitrification.[155] Management influences these processes by modifying the availability of mineral nitrogen (N), which is a key control on the N_2O emissions rates (Mosier et al. 1998; Paustian et al. 2016). Emissions can occur directly in the soil where the N is made available or can be transported to another location following volatilization, leaching, or runoff, and then converted into N_2O.

A combination of Tier 1 and 3 approaches are used to estimate direct and indirect soil N_2O emissions for agricultural croplands and grasslands. The methodologies used to estimate soil N_2O 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, 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 N_2O emissions associated with management of cropland and grassland simulated with DayCent;

3) A Tier 1 method to estimate direct and indirect N_2O 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 N 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 N_2O emissions due to partial or complete drainage of organic soils in croplands and grasslands.

The Tier 3 approach to estimate direct soil N_2O emissions is applied to most agricultural lands in the United States, and 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 N_2O emissions and C stock changes at finer spatial scales, as opposed to a single emission factor for the entire country for soil N_2O;

2) The model uses a more detailed characterization of spatially-mapped soil properties that influence soil N 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;

[155] Nitrification and denitrification are driven by the activity of microorganisms in soils. Nitrification is the aerobic microbial oxidation of ammonium (NH_4^+) to nitrate (NO_3^-), and denitrification is the anaerobic microbial reduction of nitrate to N_2. Nitrous oxide is a gaseous intermediate product in the reaction sequence of nitrification and denitrification.

4) The legacy effects of past management can be addressed with the Tier 3 approach such as ongoing effects of N fertilization that may continue to stimulate N_2O emissions in years after the application; and

5) Soil N_2O emissions 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. The splicing method is described in Box 5-4 of Chapter 5.4 Agricultural Soil Management.

Inventory Compilation Steps

There are five steps involved in this inventory to estimate direct N_2O emissions from cropland and grassland soils, and indirect N_2O emissions from volatilization, leaching, and runoff from croplands and grasslands. First, the activity data are compiled from a combination of land-use, livestock, crop, and grassland management surveys, as well as expert knowledge. In the second, third, and fourth steps, direct and indirect N_2O emissions are estimated using Tier 1 and 3 methods. In the fifth step, total emissions are calculated by summing all components for N_2O 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 direct and indirect N_2O emissions. The activity data requirements include: (1) land base and history data, (2) crop-specific mineral N fertilizer rates and timing,[156] (3) crop-specific manure amendment N rates and timing, (4) other N inputs, (5) tillage practices, (6) cover crop management, (7) planting and harvesting dates for crops, (8) irrigation data, (9) Enhanced Vegetation Index (EVI), (10) daily weather data, and (11) edaphic characteristics.[157]

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 and grassland.[158] The NRI program have data available from 1979 through 2017 (USDA-NRCS 2018a), and extended through 2020 using the USDA-NASS Crop Data Layer (CDL) (USDA-NASS 2021, Johnson and Mueller 2010). The time series will be further extended as new data are released by the USDA NRI program and CDL.

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). In principle, the expansion factors represent 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 expansion factors. 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.

[156] 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.

[157] Edaphic characteristics include such factors as soil texture and pH.

[158] Note that the Inventory does not include estimates of N_2O emissions for federal grasslands with the exception of soil N_2O from PRP manure N, 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 2016 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 2018-2020, the time series is extended with the crop data provided in USDA-NASS CDL. CDL data have a 30 to 58 m spatial resolution, depending on the year. NRI survey locations are overlaid on the CDL in a geographic information system, and the crop types are extracted to extend the crop histories for the inventory analysis.

NRI survey locations are included in the land base for the agricultural soil organic C and N_2O emissions inventories if they are identified as cropland or grassland[159] 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).[160] 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, 525,495 survey locations in this NRI are designated as agricultural land on non-federal lands in the conterminous United States and Hawaii.

The Tier 3 method using the DayCent model is applied to estimate N_2O emissions for 364,334 NRI survey locations that occur on mineral soils. Parcels of land that are not simulated with DayCent are allocated to the Tier 1 method (IPCC 2006) to estimate soil N_2O emissions[161] (Table A-179). The land base for the Tier 1 method includes 161,161 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. DayCent has not been fully tested or developed to simulate biogeochemical processes in soils used to produce some annual (e.g., lettuce), horticultural (e.g., flowers), or perennial (e.g., vineyards, orchards) crops and agricultural use of organic soils. In addition, DayCent has not been adequately tested for soils with a high gravel, cobble, or shale content.

Table A-179: Total Cropland and Grassland Area Estimated with Tier 1 and 3 Inventory Approaches (Million Hectares)

	Land Areas (million ha)				
	Mineral			Organic	
Year	Tier 1	Tier 3	Total	Tier 1	Total[162]
1990	137.66	323.33	460.99	1.37	**463.06**
1991	136.96	323.63	460.58	1.35	**462.64**
1992	136.24	323.91	460.15	1.35	**462.21**
1993	135.41	324.38	459.79	1.35	**461.85**
1994	134.62	324.80	459.42	1.35	**461.47**
1995	133.52	325.26	458.79	1.34	**460.82**
1996	132.55	325.76	458.31	1.33	**460.33**
1997	131.53	326.26	457.79	1.33	**459.81**
1998	130.66	326.75	457.42	1.32	**459.42**
1999	129.63	327.26	456.89	1.31	**458.88**
2000	129.12	327.56	456.68	1.31	**458.67**

[159] Includes only non-federal lands because federal lands are not classified into land uses as part of the NRI survey (i.e., they are only designated as federal lands).

[160] Land use for 2021 has not been incorporated into the inventory analysis, but will be updated in a future inventory.

[161] The Tier 1 method for soil N_2O 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.

[162] 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 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.

2001	128.45	327.89	456.34	1.31	**458.33**
2002	127.77	328.20	455.97	1.31	**457.97**
2003	127.17	328.19	455.36	1.29	**457.30**
2004	126.65	328.18	454.84	1.31	**456.79**
2005	126.07	328.20	454.27	1.31	**456.22**
2006	125.52	328.23	453.75	1.30	**455.70**
2007	125.00	328.26	453.26	1.29	**455.20**
2008	124.64	328.21	452.86	1.29	**454.79**
2009	124.24	328.25	452.49	1.29	**454.43**
2010	123.93	328.19	452.12	1.29	**454.06**
2011	123.51	328.22	451.74	1.29	**453.67**
2012	123.12	328.25	451.37	1.29	**453.31**
2013	122.92	328.03	450.96	1.28	**452.89**
2014	122.66	327.80	450.46	1.28	**452.38**
2015	122.29	327.74	450.03	1.27	**451.95**
2016	121.92	327.62	449.54	1.27	**451.45**
2017	121.39	327.59	448.98	1.26	**450.88**
2018	121.41	327.24	448.66	1.25	**450.56**
2019	121.37	327.04	448.41	1.25	**450.30**
2020	121.59	326.64	448.23	1.26	**450.13**

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.

Step 1b: Obtain Management Activity Data to estimate Soil N_2O 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, 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.

These data are combined with other datasets in an imputation analysis to generate a time series from 1950 to 2020. The imputation analysis is comprised of three steps: a) determine the trends in management activity across the time series by combining information from several datasets (discussed below); b) use gradient boosting (Friedman, J.H. 2001) to determine the likely management practice at a given NRI survey location; and c) assign management practices from the CEAP survey to the specific NRI locations using a predictive mean matching method for certain variables that are adapted to reflect the trending information (Little 1988, van Buuren 2012). Gradient boosting is a machine learning technique used in regression and classification tasks, among others. It 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 predictive mean matching method identifies the most similar management activity recorded in the CEAP survey that matches the prediction from the gradient boosting algorithm. The matching ensures that imputed management activities are realistic for each NRI survey location, and not odd or physically unrealizable results that could be generated by the gradient boosting algorithm. The final imputation product includes six complete imputations of the management activity data in order to adequately capture the uncertainty. The sections below provide additional information for each of the management practices.

Synthetic and Manure N Fertilizer Applications: Data on synthetic mineral N 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 is now compiled as part of Agricultural Resource Management Surveys (ARMS), which started in 1996 (USDA-ERS 2020). In these surveys, data on inorganic N 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).[163] The time series is extended through 2020 using a linear 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 N_2O 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 fertilization[164] is reduced by 3 percent (the same adjustments are also made for leaching and volatilization losses of N that are used to estimate indirect N_2O emissions). This method ensures that the simulated amount of mineral fertilization using bottom-up data from the ARMS and CEAP surveys are adjusted so that they do not exceed 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 3.11), 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-180.

PRP Manure N: Another key source of N for grasslands is PRP manure N (i.e., manure deposited by grazing livestock on pasture, range or paddock). The total amount of PRP manure N is estimated using methods described in the Manure Management section (Section 5.2) and annex (Annex 3.11). Nitrogen from PRP animal waste deposited on non-federal grasslands in a county is generated by multiplying the total PRP N (based on animal type and population data in a county) by the fraction of non-federal grassland area in the county. PRP manure N input rates for the Tier 3 DayCent simulations are estimated by dividing the total PRP manure N amount by the land area associated with non-federal grasslands in the county from the NRI survey data. During the simulations, the PRP N input is subdivided equally between urine and solid manure (i.e., 50:50 split), and C 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 N added to soils is found in Table A-180.

Residue N Inputs: Crop residue N, fixation by legumes, and N residue inputs from senesced grass litter are included as sources of N to the soil, and these sources of N 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 N from crop residues to the soil profile based on simulating the growth of the crop and senescence. This includes the total N inputs of above- and below-ground N and fixed N in residues that are not harvested or burned (DayCent simulations assume that 3 percent of non-harvested above ground residues for crops are burned),[165] and the resulting amounts can be found in Table A-180.

[163] 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).

[164] See Step 2A for the approach that is used to disaggregate N_2O emissions from DayCent into the sources of N inputs (e.g., mineral fertilizer inputs).

[165] Another improvement is to reconcile the amount of crop residues burned with the Field Burning of Agricultural Residues source category (Section 5.5).

Other N Inputs: Other N 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 N 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 N 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 N input from soil organic matter mineralization and asymbiotic N fixation are provided in Table A-180.

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 Product[166] for 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 C (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 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 are based on USDA CEAP data (USDA-NRCS 2018, 2022), USDA Census of Agriculture (USDA-NASS 2012, 2017) and the OpTIS data product[167] (Hagen et al. 2020). 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 esitmated from the CEAP survey in 2000.

[166] OpTIS data on tillage practices provided by Regrow Agriculture, Inc.
[167] OpTIS data on cover crop management provided by Regrow Agriculture, Inc.

Cover crops percentages are modeled by state and crop from 1991 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, 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.

Irrigation: NRI (USDA-NRCS 2020) 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 at an NRI survey location drains to 60 percent of field capacity in the DayCent model simulation. The amount of NRI survey locations is 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 from 1981 through 2020 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: corn, soybeans, sorghum, cotton, wheat, and other close-grown crops such as barley and oats.[168]

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. 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 cropland area prior to 2009. 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 these cases, 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.

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 C 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 condition in soils are associated with poor drainage, and hence prone to have a high-water table for part of the year in their native (pre-cultivation) condition. Non-hydric soils are moderately to well-drained.[169] 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).[170]

[168] Additional crops and grassland will be used with the NASA-CASA method in the future, as a planned improvement.

[169] Artificial drainage (e.g., ditch- or tile-drainage) is simulated as a management variable.

[170] 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.

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 N_2O Emissions from Mineral Soils

Synthetic N Fertilizer: A process-of-elimination approach is used to estimate synthetic N 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 N 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 N 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-180.

Managed Livestock Manure and Other Organic Fertilizers: Managed manure N 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 3.11). Managed manure N applied to croplands for the Tier 1 method is calculated using a process of elimination approach. Specifically, the amount of managed manure N that is amended to soils in the DayCent model simulations is subtracted from total managed manure N available for application to soils. The difference is assumed to be applied to croplands that are not included in the DayCent model simulations. The fate of manure available for application to soils is summarized in Table A-180.

Estimates of total national annual N additions from other commercial organic fertilizers are derived from organic fertilizer statistics (TVA 1991 through 1994; AAPFCO 1995 through 2022).[171] 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 N by multiplying the consumption values by the average organic fertilizer N 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 N applications to soils for dried manure and biosolids (i.e., treated sewage sludge) that are included as commercial fertilizers because these N inputs are already addressed in the manure dataset (See Manure Management Section 5.2 and Annex 3.11) and biosolids (See Biosolids below) that are estimated for this Inventory. Therefore, the amounts of dried manure and biosolids in other commercial organic fertilizer, which are provided in the reports[172] (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-180.

PRP Manure N: Soil N_2O emissions from PRP manure N deposited on federal grasslands are estimated with a Tier 1 method. PRP manure N data are derived using methods described in the Manure Management section (Section 5.2) and Annex 3.11. PRP N deposited on federal grasslands is calculated using a process of elimination approach. Specifically, the amount of PRP N included in the DayCent model simulations of non-federal grasslands is subtracted from total PRP N. This difference was assumed to be deposited on federal grasslands. The total PRP manure N added to soils is found in Table A-180.

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

[171] 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).

[172] The amount of reported dried manure and biosolids in other organic fertilizers must be converted into units of N. While the amounts of dried manure and biosolids are provided in each report (TVA 1991 through 1994; AAPFCO 1995 through 2022), the N contents of dried manure and biosolids are only provided in AAPFCO (2000). The values are 0.5 and 6.0 percent, respectively, for dried manure and biosolids.

facilities, such as landfills. In this Inventory, all biosolids that are amended to agricultural soils are assumed to be applied to grasslands[173]. Estimates of the amounts of biosolids N applied to agricultural lands are derived from national data on biosolids generation, disposition, and N content. Total biosolids generation data for 1990 through 2004, in dry mass units, are obtained from AAPFCO (1995 through 2004). Values for 2005 through 2021 are not available so a "least squares line" statistical extrapolation using the previous 16 years of data to impute an approximate value. The total sludge generation estimates are then converted to units of N by applying an average N content (the N content of biosolids used in estimating the total N 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). 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 N applied to agricultural land are used to estimate N_2O emissions from agricultural soil management; the estimates of biosolids N applied to other land and surface-disposed are used in estimating N_2O 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-180.

Residue N Inputs: Soil N_2O emissions for residue N 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 2022). 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 N. 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. N inputs are estimated by multiplying above- and below-ground biomass by respective N concentrations and by the portion of cropland that is not simulated by DayCent. All ratios and equations used to calculate residue N 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 N fractions. The resulting annual residue N inputs are presented in Table A-180.

Table A-180: Sources of Soil Nitrogen (kt N)

N Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
1. Synthetic Fertilizer N: Cropland	9,816	10,003	10,089	9,982	11,145	10,303	10,874	10,856	10,836	10,974
2. Synthetic Fertilizer N: Grassland	7	8	14	43	23	8	7	15	56	15
3. Managed Manure N: Cropland	2,449	2,481	2,490	2,476	2,538	2,571	2,563	2,583	2,602	2,606
4. Managed Manure N: Grassland	+	+	+	+	+	+	+	+	+	+
5. Pasture, Range, & Paddock Manure N	4,084	4,091	4,251	4,341	4,414	4,515	4,482	4,380	4,337	4,275
6. N from Crop Residue Decomposition[a]	4,761	4,882	4,584	4,930	4,571	5,034	4,776	4,779	4,637	5,380
7. N from Grass Residue Decomposition[a]	9,589	9,449	9,782	10,018	9,092	10,181	9,691	9,791	9,002	10,577
8. Min. SOM / Asymbiotic N-Fixation: Cropland[b]	12,759	12,052	12,167	12,828	12,044	12,583	11,989	12,163	13,407	12,381
9. Min. SOM / Asymbiotic N-Fixation: Grassland[b]	19,211	19,630	19,765	19,922	18,623	19,593	19,513	20,292	20,014	19,001
10. Treated Sewage Sludge N: Grassland	52	55	58	62	65	68	72	75	78	81
11. Other Organic Amendments: Cropland[c]	4	8	6	5	8	10	13	14	12	11
Total	**62,733**	**62,659**	**63,206**	**64,609**	**62,521**	**64,867**	**63,981**	**64,949**	**64,982**	**65,301**

N Source	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
1. Synthetic Fertilizer N: Cropland	10,797	10,068	10,551	10,603	11,332	10,728	10,459	11,496	10,932	9,943
2. Synthetic Fertilizer N: Grassland	19	24	18	23	35	14	14	13	23	15
3. Managed Manure N: Cropland	2,640	2,627	2,660	2,669	2,593	2,626	2,704	2,726	2,701	2,677
4. Managed Manure N: Grassland	+	+	+	+	+	+	+	+	+	+
5. Pasture, Range, & Paddock Manure N	4,182	4,178	4,186	4,191	4,144	4,195	4,248	4,139	4,099	4,066
6. N from Crop Residue Decomposition[a]	5,005	4,955	4,976	5,046	4,656	4,882	4,776	4,783	4,629	4,746
7. N from Grass Residue Decomposition[a]	9,368	9,899	9,688	10,048	9,259	10,170	9,743	10,195	10,102	9,622
8. Min. SOM / Asymbiotic N-Fixation: Cropland[b]	12,647	13,400	12,747	13,076	14,007	13,136	13,028	13,589	13,490	13,942

[173] A portion of biosolids may be applied to croplands, but there is no national dataset to disaggregate the amounts between cropland and grassland.

9. Min. SOM / Asymbiotic N-Fixation: Grassland[b]	18,575	18,991	18,877	19,583	21,610	20,207	19,650	20,850	20,258	20,628
10. Treated Sewage Sludge N: Grassland	84	86	89	91	94	98	101	104	107	110
11. Other Organic Amendments: Cropland[c]	9	7	8	8	9	10	12	15	12	10
Total	**63,324**	**64,236**	**63,800**	**65,340**	**67,740**	**66,065**	**64,736**	**67,910**	**66,352**	**65,761**

N Source	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
1. Synthetic Fertilizer N: Cropland	10,785	11,260	11,907	11,906	11,708	11,489	11,392	11,506	11,301	11,244
2. Synthetic Fertilizer N: Grassland	10	13	12	9	10	11	6	5	10	13
3. Managed Manure N: Cropland	2,666	2,694	2,721	2,701	2,693	2,756	2,821	2,893	2,937	2,970
4. Managed Manure N: Grassland	+	+	+	+	+	+	+	+	+	+
5. Pasture, Range, & Paddock Manure N	4,015	3,919	3,832	3,791	3,730	3,809	3,938	4,005	4,002	4,007
6. N from Crop Residue Decomposition[a]	5,176	5,129	5,058	4,985	5,006	4,664	4,746	4,922	5,314	4,915
7. N from Grass Residue Decomposition[a]	10,110	9,593	10,082	9,431	9,505	8,834	9,378	9,751	9,290	9,672
8. Min. SOM / Asymbiotic N-Fixation: Cropland[b]	14,622	13,141	12,279	14,305	14,858	15,380	15,531	14,813	15,716	15,450
9. Min. SOM / Asymbiotic N-Fixation: Grassland[b]	20,743	18,840	17,745	20,621	20,545	21,074	20,820	20,198	20,816	20,922
10. Treated Sewage Sludge N: Grassland	113	116	119	122	124	127	130	133	136	139
11. Other Organic Amendments: Cropland[c]	10	12	13	13	11	12	20	22	16	14
Total	**68,249**	**64,717**	**63,768**	**67,885**	**68,190**	**68,156**	**68,784**	**68,248**	**69,538**	**69,346**

N Source	2020	2021
1. Synthetic Fertilizer N: Cropland	11,205	11,624
2. Synthetic Fertilizer N: Grassland	10	8
3. Managed Manure N: Cropland	2,988	2,922
4. Managed Manure N: Grassland	+	+
5. Pasture, Range, & Paddock Manure N	3,947	3,917
6. N from Crop Residue Decomposition[a]	5,503	4,719
7. N from Grass Residue Decomposition[a]	9,979	9,155
8. Min. SOM / Asymbiotic N-Fixation: Cropland[b]	13,835	15,020
9. Min. SOM / Asymbiotic N-Fixation: Grassland[b]	18,344	20,271
10. Treated Sewage Sludge N: Grassland	142	145
11. Other Organic Amendments: Cropland[c]	13	12
Total	**65,965**	**67,791**

+ Does not exceed 0.5 kt

[a] Residue N inputs include unharvested fixed N from legumes as well as crop and grass residue N.

[b] Mineralization of soil organic matter and the asymbiotic fixation of nitrogen gas.

[c] Includes dried blood, tankage, 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 available for 2021 and so the activity data provided in this table are estimated based on emissions derived from data splicing methods and the implied emission factors for 2020. 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 Activity Data for Indirect N_2O Emissions

A portion of the N that is applied as synthetic fertilizer, livestock manure, and biosolids (i.e., treated sewage sludge) volatilizes as NH_3 and NO_x. In turn, the volatilized N is eventually returned to soils through atmospheric deposition, thereby increasing mineral N availability and enhancing N_2O production. Additional N is lost from soils through leaching of mostly NO_3^- as water percolates through a soil profile and through runoff with overland water flow. N losses from leaching and runoff enter groundwater and waterways, from which a portion is emitted as N_2O. However, leaching is assumed to be an insignificant source of indirect N_2O in cropland and grassland systems where the amount of precipitation plus irrigation does not exceed 80 percent of the potential evapotranspiration. These areas are typically semi-arid to arid regions in the Western United States, and nitrate leaching to groundwater is a relatively uncommon

event. Moreover IPCC (2006) recommends limiting the amount of nitrate leaching assumed to be a source of indirect N_2O emissions based on precipitation, irrigation and potential evapotranspiration.

The activity data for synthetic fertilizer, livestock manure, residue N inputs, biosolids N, and other N inputs are the same as those used in the calculation of direct emissions from agricultural mineral soils, and may be found in Table A-180.

Using the DayCent model and N sources contributing to indirect emissions described in IPCC (2006) guidelines, volatilization and leaching/surface run-off of N from soils is estimated in the simulations for crops and non-federal grasslands in the Tier 3 method. DayCent simulates the processes leading to these losses of N based on environmental conditions (i.e., weather patterns and soil characteristics), management impacts (e.g., plowing, irrigation, harvest), soil N availability, and has been shown to represent observed leaching patterns (Del Grosso et al. 2005, 2008a; David et al. 2009). Note that the DayCent model accounts for losses of N from all anthropogenic activity, not just the inputs of N from mineral fertilization and organic amendments[174], which are addressed in the Tier 1 methodology. In addition, DayCent is a mass balance model and ensures that are all N inputs are tracked through the flows in the ecosystem with no double counting of losses. Volatilized losses of N are summed for each day in the annual cycle to provide an estimate of the amount of N subject to indirect N_2O emissions. Consistent with the IPCC guidelines (2006), indirect emissions are not estimated for leaching and runoff of N 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 N even in drier climates). For non-arid regions, the daily losses of N through leaching and runoff in overland flow are summed for the annual cycle. Uncertainty in the estimated losses is derived from the measured of variability in the fertilizer and organic amendment activity data, in addition to uncertainty in the DayCent model predictions.

To estimate volatilized N losses for land areas that are not included in the DayCent simulations, 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 N ranges from 0.03-0.3 kg NH_3-N+NO_x-N/kg N for synthetic fertilizer and 0.05-0.5 kg NH_3-N+NO_x-N/kg N for organic amendments (IPCC 2006). To estimate leaching/runoff losses of N from land areas that are not included in the DayCent simulations, the N 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 NO_3-N/kg N (IPCC 2006). However, leaching is assumed to be an insignificant source of indirect N_2O emissions if the amount of precipitation did not exceed 80 percent of the potential evapotranspiration, consistent with the Tier 3 method (Note: Irrigated systems are always assumed to have leaching of N even in drier climates). PDFs are derived for each of the N inputs in the same manner as direct N_2O emissions, discussed in Steps 1a and 1c.

Volatilized N is summed for losses from croplands and grasslands. Similarly, the annual amounts of N lost from soil profiles through leaching and surface runoff are summed to obtain the total losses for this pathway.

Step 2: Estimate Direct N_2O Emissions for Mineral Soils

In this step, direct N_2O emissions are estimated for cropland and non-federal grasslands, and this involves two methods. The DayCent process-based model is used for the croplands and non-federal grasslands included in the Tier 3 method. A Tier 1 methodology is used to estimate N_2O emissions from crops that are not simulated by DayCent and PRP manure N deposition on federal grasslands.

Step 2a: Estimate Direct Soil N_2O 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 all non-federal grasslands in the United States.

[174] 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 N Fertilizer Applications in Step 1b for more information.

The methodology description is divided into two sub-steps. First, the DayCent model is used to establish the initial conditions and C stocks for 1979, which is the first year of the NRI survey. In the second sub-step, DayCent is used to simulate direct soil N_2O emissions, in addition to leaching and volatilization losses of N contributing to indirect N_2O emissions 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 C among the pools represented in the model (e.g., Structural, Metabolic, Active, Slow, and Passive). Each pool has a different turnover rate (representing the heterogeneous nature of soil organic matter), and the amount of C in each pool at any point in time influences the forward trajectory of the total soil organic C storage and the soil N dynamics that influence direct soil N_2O emissions. There is currently no national set of soil C measurements subdivided by the pools that can be used for establishing initial conditions in the model. Sensitivity analysis of the soil organic C algorithms showed that the rate of change of soil organic matter is relatively insensitive to the *amount* of total soil organic C but is highly sensitive to the relative *distribution* of C 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 2018), 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 5,000 years in the pre-settlement era in order to achieve a steady-state condition.

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).

NRI History Simulations: After model initialization, DayCent is used to simulate the NRI land use and management histories from 1979 through 2020. The simulations address the influence of soil management on direct soil N_2O emissions, and losses of N from the profile through leaching/runoff and volatilization. The NRI histories, supplemented with CDL 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 N 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 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 set of run executive programs.

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). 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). There are 90 experimental sites available with about 850 observations to evaluate structural uncertainty in the N_2O emission predictions from DayCent. 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 soil N_2O emissions 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). 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 expansion factors and replicate weights provided with the NRI dataset. The expansion factors 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 for the expansion factor. Briefly, each set of replicate weights is used to compute one weighted estimate. The empirical variation across the weighted estimates from all replicates is an estimate of the theoretical scaling uncertainty due to the complex sampling design.

A Monte Carlo approach is used to propagate uncertainty from the three components through the analysis with 1,000 iterations for each NRI survey location. In each iteration, there is a random selection of management activity data from the imputation product; a random draw of parameter values for the uncertainty estimator (Ogle et al. 2010); and a random draw of a set of replicate weights to scale the emissions from the individual NRI survey locations to the entire domain of the inventory analysis. Note that parameter values for the statistical equations (i.e., fixed effects) are selected from their joint probability distribution, as well as random error associated with the time series and data collected from the same site, and the residual/unexplained error. The randomly selected parameter values for soil N_2O emissions and associated management information are then used as input into the linear mixed-effect model, and adjusted values are computed for each N_2O emissions estimate. After completing the Monte Carlo stochastic simulation, the median of the final distribution from the 1,000 replicates is used as the estimate of total emissions, and a 95 percent confidence interval is based on 2.5 and 97.5 percentile values.

In DayCent, the model cannot distinguish among the original sources of N after the mineral N 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 N inputs, such as crop residues. It is desirable, however, to report emissions associated with specific sources of N inputs. Thus, for each NRI survey location, the N inputs in a simulation are determined for anthropogenic practices discussed in IPCC (2006), including synthetic mineral N fertilization, organic amendments, and crop residue N added to soils (including N-fixing crops). The percentage of N input for anthropogenic practices is divided by the total N input, and this proportion is used to determine the amount of N_2O emissions assigned to each of the N sources. For example, if 70 percent of the mineral N 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 N fixation from the atmosphere. Mineralization of soil organic matter is significant source of N, but is typically less than half of the amount of N made available in cropland soils compared to application of synthetic fertilizers and manure amendments, along with symbiotic fixation. Mineralization of soil organic matter accounts for the majority of available N in grassland soils. Asymbiotic N fixation by soil bacteria is a minor source of N, typically not exceeding 10 percent of total N inputs to agroecosystems. Accounting for the influence of “other N inputs” is necessary because the processes leading to these inputs of N are influenced by management.

This attribution of N_2O emissions to the individual N sources is required for reporting emissions based on UNFCCC reporting guidelines. However, this method is a simplification of reality to allow partitioning of N_2O emissions, as it assumes that all N inputs have an identical chance of being converted to N_2O. It is important to realize that sources such as synthetic fertilization may have a larger impact on N_2O emissions than would be suggested by the associated level of N 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 N_2O emissions are provided in Table A-181 and Table A-182.

Step 2b: Soil N_2O Emissions from Agricultural Lands on Mineral Soils Approximated with the Tier 1 Approach

To estimate direct N_2O emissions from N additions to crops in the Tier 1 method, the amount of N in applied synthetic fertilizer, manure, and other commercial organic fertilizers (i.e., dried blood, tankage, compost, and other) is added to N inputs from crop residues, and the resulting annual totals are multiplied by the IPCC default emission factor of 0.01 kg N_2O-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 N_2O-N/kg N (IPCC 2006). For flooded rice soils, the IPCC default emission factor is 0.003 kg N_2O-N/kg N and the uncertainty range is 0.000–0.006 kg N_2O-N/kg N (IPCC 2006).[175] Uncertainties in the emission factor and fertilizer additions are combined with uncertainty in the equations used to calculate residue N additions from above- and below-ground biomass dry matter and N concentration to derive overall uncertainty.

The Tier 1 method is also used to estimate emissions from manure N deposited by livestock on federal lands (i.e., PRP manure N), and from biosolids (i.e., treated sewage sludge) application to grasslands. These two sources of N inputs to soils are multiplied by the IPCC (2006) default emission factors (0.01 kg N_2O-N/kg N for sludge and horse, sheep, and goat manure, and 0.02 kg N_2O-N/kg N for cattle, swine, and poultry manure) to estimate N_2O 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 N_2O-N/kg N (IPCC 2006).

The results for direct soil N_2O emissions using the Tier 1 method are provided in Table A-181 and Table A-182.

Table A-181: Direct Soil N_2O Emissions from Mineral Soils in Cropland (MMT CO_2 Eq.)

Land Use Category	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Cropland Mineral Soil Emission	**169.2**	**161.8**	**160.3**	**169.4**	**173.1**	**168.8**	**174.6**	**167.8**	**167.5**	**169.8**
Tier 3 Cropland	153.4	147.2	144.8	154.5	157.1	153.1	158.1	152.4	151.7	153.2
Inorganic N Fertilizer Application	52.6	53.4	52.0	54.0	60.8	54.3	58.9	57.0	54.2	55.1
Managed Manure Additions	4.1	4.0	4.1	4.0	4.1	3.9	4.2	4.8	4.5	3.9
Crop Residue N	23.1	23.1	21.4	24.1	22.4	24.4	24.3	22.9	21.2	26.1
Min. SOM / Asymbiotic N-Fixation[a]	73.6	66.7	67.3	72.4	69.8	70.5	70.7	67.7	71.8	68.1
Tier 1 Cropland	15.7	14.5	15.6	14.9	16.1	15.8	16.5	15.4	15.8	16.5
Inorganic N Fertilizer Application	5.5	4.2	5.3	4.8	5.4	5.2	6.1	5.6	5.8	6.0
Managed Manure Additions	6.9	7.1	7.1	7.1	7.4	7.6	7.4	6.7	7.0	7.6
Other Organic Amendments[b]	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0
Crop Residue N	3.3	3.1	3.2	3.0	3.2	3.0	3.0	2.9	3.0	2.9
Implied Emission Factor for Croplands[c] (kt N_2O-N/kt N)	0.014	0.013	0.013	0.014	0.014	0.014	0.014	0.014	0.013	0.013

Land Use Category	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Cropland Mineral Soil Emission	**166.7**	**172.5**	**172.8**	**174.9**	**175.6**	**172.5**	**170.0**	**176.7**	**174.0**	**174.2**
Tier 3 Cropland	151.8	158.0	158.9	160.5	161.2	158.8	155.7	163.1	160.2	162.7
Inorganic N Fertilizer Application	56.0	53.4	55.9	56.0	57.9	56.5	55.6	59.6	57.1	55.6
Managed Manure Additions	4.7	5.7	7.1	6.2	5.8	6.2	5.5	7.0	7.4	7.3
Crop Residue N	23.4	24.0	24.6	25.1	21.7	23.6	23.2	22.9	21.9	23.1
Min. SOM / Asymbiotic N-Fixation[a]	67.6	74.8	71.4	73.3	75.7	72.5	71.4	73.6	73.8	76.7
Tier 1 Cropland	15.0	14.6	13.9	14.4	14.5	13.8	14.3	13.6	13.8	11.5
Inorganic N Fertilizer Application	5.2	5.5	5.7	5.6	5.9	5.3	5.2	5.6	6.1	3.8
Managed Manure Additions	6.8	6.2	5.5	6.1	5.8	5.8	6.6	5.4	5.2	5.1
Other Organic Amendments[b]	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0
Crop Residue N	2.9	2.8	2.6	2.7	2.7	2.6	2.5	2.5	2.5	2.5
Implied Emission Factor for Croplands[c] (kt N_2O-N/kt N)	0.013	0.014	0.014	0.014	0.013	0.013	0.013	0.013	0.013	0.014

[175] Due to lack of data, uncertainties are not addressed for managed manure N production, PRP manure N production, other commercial organic fertilizer amendments, indirect losses of N in the DayCent simulations, and biosolids (i.e., treated sewage sludge), but these sources of uncertainty will be included in future Inventories.

Land Use Category	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Cropland Mineral Soil Emission	**173.6**	**176.6**	**172.1**	**188.4**	**194.5**	**185.0**	**179.8**	**185.1**	**192.6**	**181.8**
Tier 3 Cropland	161.7	164.0	159.1	174.9	181.4	172.2	167.7	172.0	180.0	168.1
Inorganic N Fertilizer Application	54.7	59.8	61.4	62.9	63.4	59.5	58.4	60.7	60.7	57.1
Managed Manure Additions	7.4	8.0	8.0	8.3	8.4	8.0	7.7	8.1	7.9	7.6
Crop Residue N	23.8	25.2	24.4	24.3	25.0	22.0	21.3	23.6	25.7	22.5
Min. SOM / Asymbiotic N-Fixation[a]	75.7	71.0	65.3	79.4	84.5	82.8	80.2	79.7	85.6	81.0
Tier 1 Cropland	11.9	12.6	13.0	13.4	13.1	12.8	12.1	13.1	12.6	13.7
Inorganic N Fertilizer Application	4.8	5.5	5.9	6.3	5.8	5.2	4.3	5.0	4.1	4.9
Managed Manure Additions	4.6	4.7	4.7	4.6	4.7	4.9	5.1	5.4	5.6	5.9
Other Organic Amendments[b]	0.0	0.0	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.1
Crop Residue N	2.5	2.4	2.4	2.5	2.6	2.6	2.6	2.6	2.8	2.8
Implied Emission Factor for Croplands[c] (kt N_2O-N/kt N)	0.013	0.013	0.013	0.014	0.014	0.013	0.013	0.013	0.013	0.013

Land Use Category	2020	2021
Total Cropland Mineral Soil Emission	**174.3**	**175.4**
Tier 3 Cropland	159.5	161.1
Inorganic N Fertilizer Application	54.6	54.0
Managed Manure Additions	7.8	8.0
Crop Residue N	25.9	21.7
Min. SOM / Asymbiotic N-Fixation[a]	71.3	77.4
Tier 1 Cropland	14.8	14.3
Inorganic N Fertilizer Application	6.0	5.5
Managed Manure Additions	5.9	5.9
Other Organic Amendments[b]	0.1	0.0
Crop Residue N	2.9	2.8
Implied Emission Factor for Croplands[c] (kt N_2O-N/kt N)	0.013	0.012

[a] Mineralization of soil organic matter and the asymbiotic fixation of nitrogen gas.

[b] Includes dried blood, tankage, compost, other. Excludes dried manure and bio-solids (i.e., treated sewage sludge) used as commercial fertilizer to avoid double counting.

[c] Annual Implied Emission Factor (kt N_2O-N/kt N) is calculated by dividing total estimated emissions by total activity data for N applied.

Note: Emissions in 2021 are estimated with a data splicing method for most sources of N input to soils. 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. Quality control uncovered minor errors in the estimates that will be corrected in the final version of this Inventory.

Table A-182: Direct Soil N_2O Emissions from Mineral Soils in Grassland (MMT CO_2 Eq.)

Land Use Change Category	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Grassland Mineral Soil Emission	**77.6**	**76.1**	**75.6**	**77.2**	**75.5**	**76.8**	**78.2**	**78.0**	**79.2**	**74.5**
Tier 3 Grassland	72.5	71.2	70.6	72.3	70.6	72.0	73.6	73.7	74.9	70.5
Inorganic N Fertilizer Application	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.0
Managed Manure Additions	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pasture, Range, & Paddock N Deposition	7.3	7.2	7.3	7.6	8.1	7.9	8.3	7.8	8.2	7.5
Grass Residue N	21.4	20.5	20.8	21.6	20.4	21.9	21.5	21.3	20.5	22.5
Min. SOM / Asymbiotic N-Fixation[a]	43.8	43.5	42.5	43.0	42.0	42.2	43.8	44.5	46.1	40.4
Tier 1 Grassland	5.1	5.0	5.0	5.0	4.9	4.8	4.6	4.3	4.3	4.0
Pasture, Range, & Paddock N Deposition	4.9	4.7	4.8	4.7	4.6	4.5	4.3	4.0	3.9	3.7
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_2O-N/kt N)	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.005

Land Use Change Category	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Grassland Mineral Soil Emission	**73.4**	**76.7**	**77.2**	**77.1**	**81.7**	**77.8**	**77.5**	**78.0**	**77.4**	**79.8**
Tier 3 Grassland	69.5	73.0	73.7	73.6	78.3	74.5	74.2	74.9	74.4	76.9
Inorganic N Fertilizer Application	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0
Managed Manure Additions	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pasture, Range, & Paddock N Deposition	7.7	8.0	8.2	7.8	7.9	7.7	8.1	7.7	7.7	8.1
Grass Residue N	20.4	22.3	22.0	22.4	20.8	22.4	21.9	22.2	22.4	22.1
Min. SOM / Asymbiotic N-Fixation[a]	41.4	42.7	43.4	43.4	49.4	44.3	44.2	45.1	44.3	46.7
Tier 1 Grassland	3.9	3.7	3.6	3.5	3.4	3.4	3.3	3.0	3.0	2.9
Pasture, Range, & Paddock N Deposition	3.5	3.3	3.2	3.1	3.0	3.0	2.9	2.6	2.5	2.5
Treated Sewage Sludge Additions	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5
Implied Emission Factor for Grassland[b] (kt N_2O-N/kt N)	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.005	0.006	0.006

Land Use Change Category	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Grassland Mineral Soil Emission	**79.8**	**75.9**	**72.1**	**81.6**	**82.2**	**82.1**	**80.2**	**79.9**	**84.1**	**81.4**
Tier 3 Grassland	77.0	73.1	69.4	79.0	79.6	79.6	77.7	77.4	81.6	78.9
Inorganic N Fertilizer Application	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Managed Manure Additions	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pasture, Range, & Paddock N Deposition	7.8	7.9	7.3	7.7	7.8	8.0	7.9	8.0	8.8	8.1
Grass Residue N	22.7	22.1	22.3	22.4	22.6	20.9	21.4	22.7	22.3	22.5
Min. SOM / Asymbiotic N-Fixation[a]	46.5	43.1	39.8	48.8	49.2	50.6	48.3	46.6	50.5	48.3
Tier 1 Grassland	2.9	2.8	2.7	2.7	2.6	2.6	2.5	2.5	2.5	2.5
Pasture, Range, & Paddock N Deposition	2.4	2.3	2.2	2.2	2.1	2.0	2.0	1.9	2.0	2.0
Treated Sewage Sludge Additions	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.6
Implied Emission Factor for Grassland[b] (kt N_2O-N/kt N)	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006

Land Use Change Category	2020	2021
Total Grassland Mineral Soil Emission	**74.1**	**77.0**
Tier 3 Grassland	71.5	74.3
Inorganic N Fertilizer Application	0.0	0.0
Managed Manure Additions	0.0	0.0
Pasture, Range, & Paddock N Deposition	7.8	8.1
Grass Residue N	22.7	20.8
Min. SOM / Asymbiotic N-Fixation[a]	41.0	45.3
Tier 1 Grassland	2.6	2.7
Pasture, Range, & Paddock N Deposition	2.0	2.1
Treated Sewage Sludge Additions	0.6	0.6
Implied Emission Factor for Grassland[b] (kt N_2O-N/kt N)	0.006	0.006

[a] Mineralization of soil organic matter and the asymbiotic fixation of nitrogen gas.

[b] Annual Implied Emission Factor (kt N_2O-N/kt N) is calculated by dividing total estimated emissions by total activity data for N applied.

Note: Emissions in 2021 are estimated with a data splicing method for most sources of N input to soils. 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. Quality control uncovered minor errors in the estimates that will be corrected in the final version of this inventory.

Step 3: Estimate Direct N_2O Emissions from Organic Soils

In this step, direct N_2O emissions are estimated for organic soils that are drained for agricultural production in croplands and grasslands. The area of drained organic soils in croplands and grasslands 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 N_2O-N/ha cultivated) of IPCC (2006) default emission factors for temperate (8 kg N_2O-N/ha cultivated) and tropical (16 kg N_2O-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 N_2O-N/ha (IPCC 2006). Table A-183 lists the direct N_2O emissions associated with drainage of organic soils in cropland and grassland.

Table A-183: Direct Soil N_2O Emissions from Drainage of Organic Soils (MMT CO_2 Eq.)

Land Use	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Organic Soil Emissions	**5.7**	**5.7**	**5.7**	**5.7**	**5.7**	**5.7**	**5.6**	**5.7**	**5.6**	**5.5**
Cropland	3.4	3.4	3.4	3.3	3.3	3.3	3.3	3.3	3.3	3.3
Grassland	2.3	2.3	2.3	2.3	2.4	2.3	2.3	2.4	2.3	2.3

Land Use	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Total Organic Soil Emission	**5.6**	**5.6**	**5.6**	**5.4**	**5.5**	**5.5**	**5.5**	**5.4**	**5.4**	**5.4**
Cropland	3.3	3.3	3.3	3.2	3.3	3.2	3.2	3.1	3.1	3.0
Grassland	2.3	2.2	2.3	2.2	2.2	2.2	2.3	2.2	2.3	2.3

Land Use	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Organic Soil Emission	**5.4**	**5.4**	**5.3**	**5.3**	**5.3**	**5.3**	**5.3**	**5.2**	**5.2**	**5.2**
Cropland	3.0	3.1	3.1	3.1	3.0	3.0	3.0	3.0	3.0	2.9
Grassland	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.2	2.2

Land Use	2020	2021
Total Organic Soil Emission	**5.2**	**5.2**
Cropland	2.9	2.9
Grassland	2.3	2.3

Step 4: Estimate Indirect Soil N_2O Emissions for Croplands and Grasslands

In this step, soil N_2O emissions are estimated for the two indirect emission pathways (N_2O emissions due to volatilization, and N_2O emissions due to leaching and runoff of N), which are summed to yield total indirect N_2O emissions from croplands and grasslands.

Step 4a: Indirect Soil N_2O Emissions Due to Volatilization

Indirect emissions from volatilization of N inputs from synthetic fertilizer, manure amendments, and PRP manure, are calculated according to the amount of mineral N that is volatilized from the soil profile and later emitted as soil N_2O following atmospheric deposition. See Step 1d for additional information about the methods used to compute N losses due to volatilization. The estimated N volatilized is multiplied by the IPCC default emission factor of 0.01 kg N_2O-N/kg N (IPCC 2006) to estimate total indirect soil N_2O emissions from volatilization. The uncertainty is estimated using simple error propagation methods (IPCC 2006), by combining uncertainties in the amount of N volatilized, with uncertainty in the default emission factor ranging from 0.002–0.05 kg N_2O-N/kg N (IPCC 2006). See the following peer-reviewed publications on the use of DayCent for estimating the N losses that lead to indirect soil N_2O 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-184 and Table A-185 for cropland and grassland, respectively.

Step 4b: Indirect Soil N_2O Emissions Due to Leaching and Runoff

The amounts of mineral N from synthetic fertilizers, manure amendments, PRP manure, crop residue, N mineralization, asymbiotic fixation that is transported from the soil profile in water flows are used to calculate indirect emissions from leaching of mineral N from soils and losses in runoff associated with overland flow. See Step 1d for additional information about the methods used to estimate N losses from soils due to leaching and runoff in overland water flows. The total amount of N transported from soil profiles through leaching and surface runoff is multiplied by the IPCC default emission factor of 0.0075 kg N_2O-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 N_2O-N/kg N (IPCC 2006). The emission estimates are provided in Table A-184 and Table A-185 for cropland and grassland, respectively.

Table A-184: Indirect Soil N_2O Emissions for Cropland from Volatilization and Atmospheric Deposition, and from Leaching and Runoff (MMT CO_2 Eq.)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Cropland Indirect Emissions	**19.9**	**18.1**	**19.8**	**22.0**	**17.2**	**20.2**	**19.6**	**19.0**	**21.4**	**19.6**
Volatilization & Atmospheric Deposition	6.3	6.0	6.0	6.2	6.4	6.4	6.4	6.3	6.6	6.6
Leaching & Runoff	13.6	12.1	13.8	15.8	10.9	13.8	13.2	12.7	14.7	13.0
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 Cropland Indirect Emissions	**18.2**	**20.4**	**18.3**	**19.2**	**21.6**	**19.1**	**19.7**	**20.8**	**21.3**	**20.7**
Volatilization & Atmospheric Deposition	6.7	6.6	6.5	6.6	6.7	6.6	6.7	6.5	6.5	6.4
Leaching & Runoff	11.5	13.8	11.8	12.6	14.9	12.5	13.0	14.3	14.8	14.3
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 Cropland Indirect Emissions	**21.1**	**20.2**	**16.4**	**22.1**	**22.1**	**24.0**	**21.4**	**22.4**	**23.7**	**23.5**
Volatilization & Atmospheric Deposition	6.7	6.5	6.2	6.8	7.1	7.0	7.1	7.1	7.6	6.7
Leaching & Runoff	14.4	13.7	10.1	15.3	15.0	16.9	14.3	15.3	16.1	16.7
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	2021
Total Cropland Indirect Emissions	**20.0**	**21.9**
Volatilization & Atmospheric Deposition	7.2	7.1
Leaching & Runoff	12.9	14.8
Volatilization Implied Emission Factor	0.0100	0.0100
Leaching & Runoff Implied Emission Factor	0.0075	0.0075

Note: Estimates after 2021 are based on a data splicing method. 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. Quality control uncovered minor errors in the estimates that will be corrected in the final version of this Inventory.

Table A-185: Indirect Soil N_2O Emissions for Grassland from Volatilization and Atmospheric Deposition, and from Leaching and Runoff (MMT CO_2 Eq.)

Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Total Grassland Indirect Emissions	**5.9**	**5.8**	**6.0**	**6.2**	**5.7**	**6.0**	**5.8**	**5.9**	**6.4**	**5.7**
Volatilization & Atmospheric Deposition	3.5	3.5	3.5	3.4	3.4	3.5	3.6	3.5	3.6	3.4
Leaching & Runoff	2.4	2.4	2.5	2.7	2.3	2.5	2.2	2.4	2.8	2.3
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	**5.2**	**6.0**	**5.8**	**5.6**	**6.3**	**5.7**	**5.6**	**6.1**	**6.0**	**6.0**

Volatilization & Atmospheric Deposition	3.2	3.3	3.4	3.5	3.7	3.5	3.5	3.4	3.4	3.4
Leaching & Runoff	2.0	2.7	2.4	2.1	2.7	2.2	2.2	2.7	2.6	2.6
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	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Grassland Indirect Emissions	**5.8**	**5.7**	**5.3**	**6.1**	**5.6**	**6.3**	**5.8**	**5.9**	**6.4**	**6.3**
Volatilization & Atmospheric Deposition	3.4	3.2	3.1	3.5	3.5	3.4	3.4	3.4	3.5	3.3
Leaching & Runoff	2.5	2.5	2.1	2.6	2.1	2.9	2.4	2.4	3.0	3.0
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

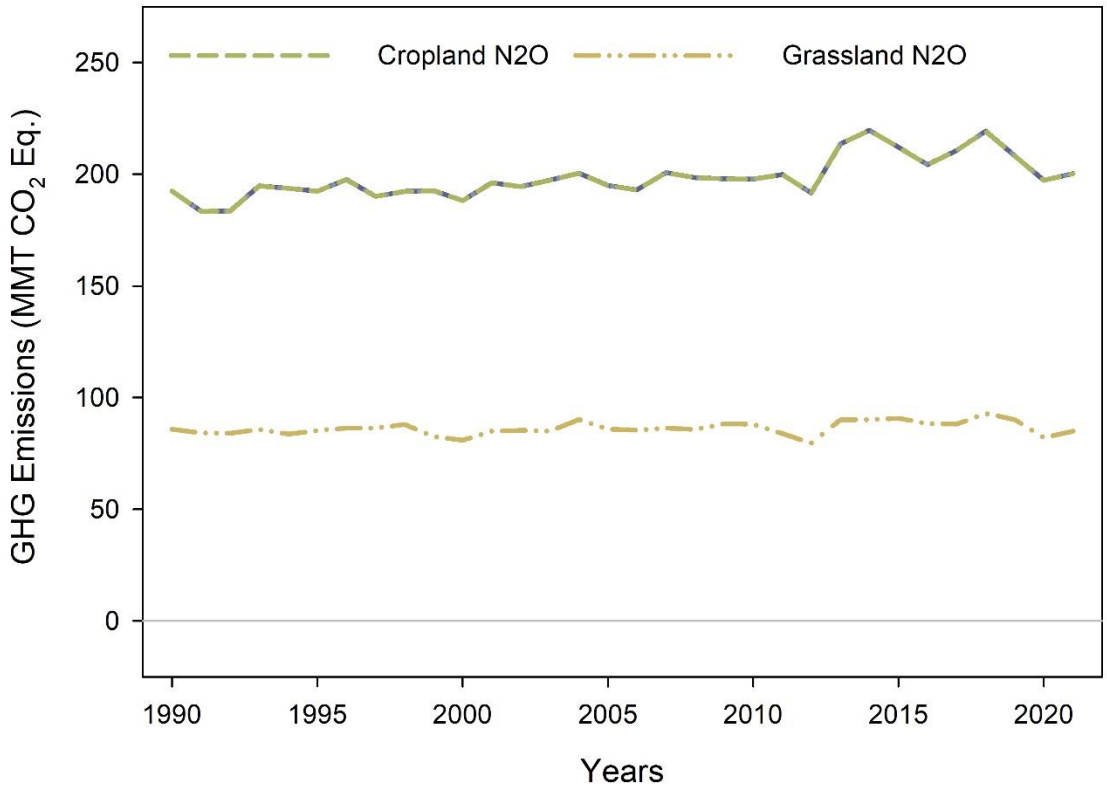
Source	2020	2021
Total Grassland Indirect Emissions	**5.6**	**5.7**
Volatilization & Atmospheric Deposition	3.1	3.2
Leaching & Runoff	2.6	2.5
Volatilization Implied Emission Factor	0.0100	0.0100
Leaching & Runoff Implied Emission Factor	0.0075	0.0075

Note: Estimates after 2021 are based on a data splicing method. 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. Quality control uncovered minor errors in the estimates that will be corrected in the final version of this Inventory.

Step 5: Estimate Total Soil N_2O Emissions for U.S. Agricultural Soils

Total N_2O emissions are estimated by summing total direct and indirect emissions for croplands and grasslands (both organic and mineral soils). The results are provided in Figure A-9. In general, N_2O emissions from agricultural soil management have been relatively stable for grasslands and increasing slightly for croplands from 1990 to 2021.

Figure A-9: GHG Emissions and Removals for Cropland & Grassland



Direct and indirect simulated emissions of soil N_2O vary regionally in croplands and grasslands as a function of N input, other management practices, weather, and soil type. The top-10 highest total N_2O emissions for 2020[176] occur in Texas, Iowa, Kansas, Nebraska, Illinois, Minnesota, South Dakota, North Dakota, Montana and Missouri (Table A-186). 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 N inputs.

Table A-186: Total Soil N_2O Emissions (Direct and Indirect) from Agricultural Lands by State in 2020 (MMT CO_2 Eq.)

State	Croplands			Grasslands			Total Emissions
	Tier 1	Tier 3	Total	Tier 1	Tier 3	Total	
AL	0.29	1.00	1.28	0.03	0.90	0.93	2.21
AK	0.00	0.00	0.00	0.01	0.00	0.01	0.01
AZ	0.48	0.22	0.70	0.12	2.93	3.05	3.75
AR	0.15	4.16	4.32	0.10	1.07	1.17	5.49
CA	3.73	1.58	5.31	0.64	1.92	2.56	7.87
CO	0.22	2.96	3.18	0.20	3.26	3.46	6.64
CT	0.03	0.04	0.07	0.01	0.01	0.02	0.10
DE	0.07	0.18	0.24	0.00	0.02	0.02	0.26
DC	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FL	1.82	0.19	2.01	0.77	1.26	2.03	4.04

[176] 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.

GA	0.42	1.33	1.75	0.09	0.63	0.73	2.48
HI	0.01	0.00	0.01	0.07	0.00	0.07	0.08
ID	0.63	2.86	3.49	0.38	1.04	1.43	4.92
IL	0.27	14.74	15.01	0.03	0.73	0.76	15.78
IN	0.52	7.31	7.83	0.05	0.45	0.51	8.34
IA	1.15	16.50	17.65	-0.11	1.64	1.53	19.18
KS	0.25	13.51	13.76	-0.27	4.08	3.81	17.57
KY	0.18	2.72	2.90	0.02	1.52	1.54	4.44
LA	0.59	2.36	2.94	0.11	0.78	0.89	3.83
ME	0.03	0.12	0.15	0.01	0.04	0.05	0.20
MD	0.03	0.60	0.62	0.02	0.12	0.14	0.76
MA	0.06	0.04	0.09	0.02	0.02	0.04	0.14
MI	0.48	3.44	3.93	0.25	0.53	0.78	4.71
MN	0.57	12.11	12.68	0.79	1.02	1.81	14.49
MS	0.05	2.80	2.85	0.03	0.75	0.78	3.62
MO	0.34	7.63	7.97	0.08	2.40	2.48	10.46
MT	0.03	5.43	5.46	0.15	6.05	6.20	11.66
NE	0.77	11.98	12.74	-0.33	3.68	3.35	16.10
NV	0.04	0.19	0.23	0.18	0.73	0.91	1.14
NH	0.01	0.03	0.04	0.01	0.02	0.03	0.07
NJ	0.07	0.11	0.18	0.03	0.03	0.06	0.24
NM	0.28	0.44	0.72	0.13	4.18	4.31	5.03
NY	0.05	1.94	2.00	0.06	0.75	0.81	2.80
NC	1.03	1.77	2.80	0.08	0.46	0.53	3.34
ND	0.60	10.83	11.43	-0.03	2.02	1.99	13.42
OH	0.46	5.56	6.03	0.05	0.60	0.65	6.68
OK	0.83	3.10	3.93	0.28	3.68	3.96	7.89
OR	0.75	1.21	1.96	0.36	1.22	1.58	3.54
PA	0.01	1.97	1.98	0.04	0.54	0.59	2.57
RI	0.01	0.00	0.01	0.00	0.00	0.01	0.02
SC	0.07	0.84	0.91	0.02	0.27	0.28	1.20
SD	0.71	9.08	9.79	-0.15	4.09	3.93	13.72
TN	0.17	2.09	2.26	-0.03	1.22	1.18	3.44
TX	1.74	8.88	10.62	0.07	12.43	12.50	23.12
UT	0.16	0.64	0.80	0.26	0.97	1.23	2.03
VT	0.09	0.21	0.31	0.00	0.10	0.11	0.41
VA	0.13	1.10	1.23	0.01	0.86	0.87	2.10
WA	0.91	2.63	3.55	0.16	0.89	1.05	4.60
WV	0.04	0.18	0.22	0.01	0.35	0.36	0.58
WI	0.14	5.78	5.91	0.33	0.97	1.30	7.21
WY	0.72	0.70	1.42	0.24	3.35	3.59	5.02

[a] N_2O 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] N_2O emissions are not reported for District of Columbia except from biosolids application, which are estimated with the Tier 1 method.

Note: Quality control uncovered minor errors in the estimates that will be corrected in the final version of this Inventory.

Tier 3 Model Description, Parameterization and Evaluation

The DayCent ecosystem model (Parton et al. 1998; Del Grosso et al. 2001, 2011) simulates biogeochemical C and N 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 N_2O emissions than IPCC Tier 1 or 2 methods by accounting for a broader suite of environmental drivers that influence emissions. These drivers include soil characteristics, weather patterns, crop and forage characteristics, and management practices. The DayCent model utilizes the soil C 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 N dynamics are linked in plant-soil systems through biogeochemical processes of microbial decomposition and plant production (McGill and Cole 1981). Representing these processes in the inventory analysis captures interactions between C and N cycling in soils that influence soil N_2O emissions, and the method ensures conservation of mass. For example, plant growth is controlled by nutrient availability, water, and temperature stress. Plant growth determines C inputs to soils and influences availability of N for microbial processes of nitrification and denitrification that generate N_2O 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 greater N_2O emissions by enhancing mineral N 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 N_2O 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).

2) The model is designed to simulate management practices that influence direct N_2O 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 1 method is used to estimate N_2O 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 N_2O 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 N_2O emissions associated with these practices are addressed with the Tier 1 method.

DayCent Model Description

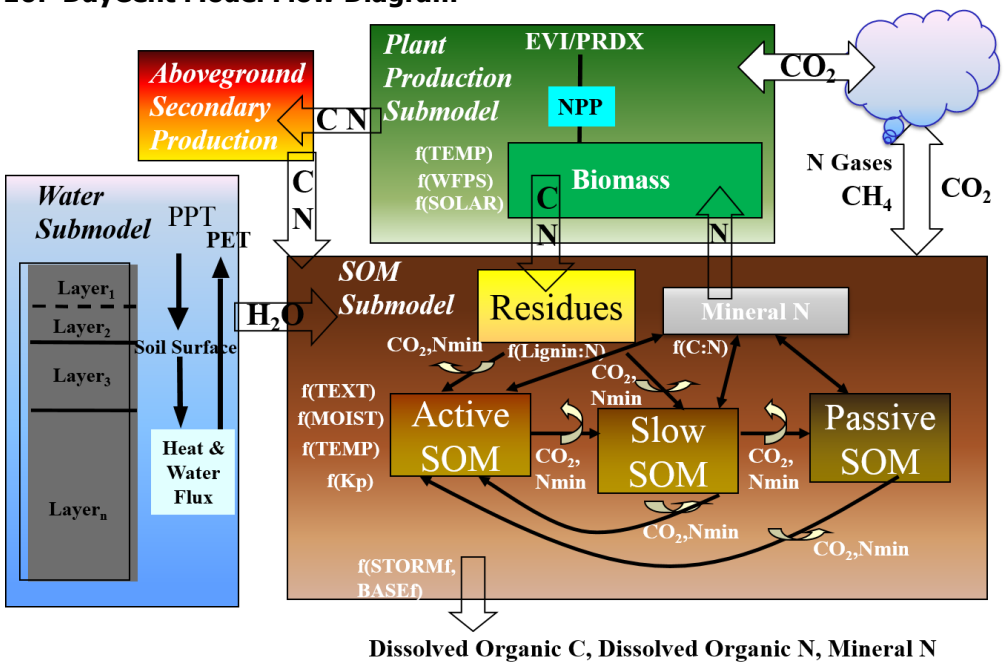
Key processes simulated by DayCent include (1) plant growth; (2) organic matter formation and decomposition; (3) soil water and temperature regimes by layer; (4) nitrification and denitrification processes; and (5) methanogenesis (Figure A-10). Each submodel is described below.

1) The plant-growth submodel simulates C assimilation through photosynthesis; N uptake; dry matter production; partitioning of C 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.[177] 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. If the NASA-CASA algorithm is not used in the simulation, then production is further subject to nutrient limitations (i.e., nitrogen). Model evaluation has shown that the NASA-CASA algorithm improves the precision of

[177] It is a planned improvement to estimate NPP for additional crops and grass forage with the NASA-CASA method in the future.

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-11.

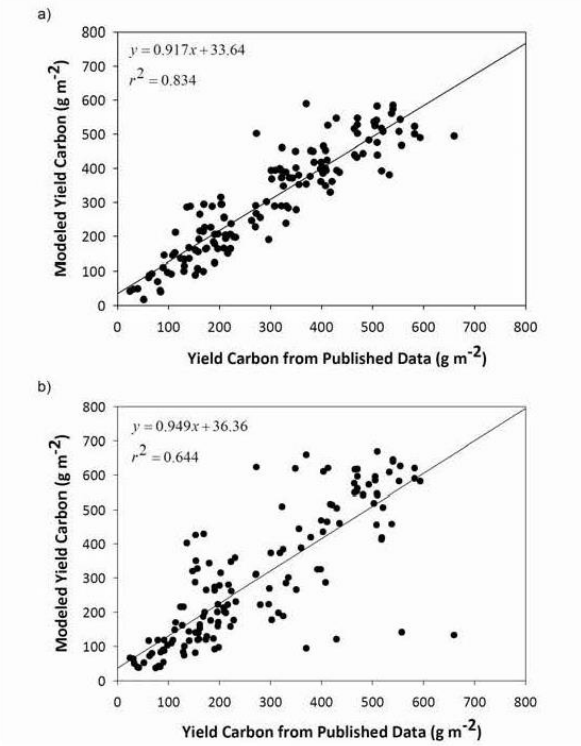
Figure A-10: DayCent Model Flow Diagram



2) Dynamics of soil organic C and N (Figure A-10) are simulated for the surface and belowground litter pools and soil organic matter in the top 30 cm of the soil profile; mineral N dynamics are simulated through the whole soil profile. Organic C and N 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 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 C from the soil organic matter pools.

3) The soil-water submodel 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-11: 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 N dynamics are modeled based on N inputs from fertilizer inputs (synthetic and organic), residue N inputs, soil organic matter mineralization in addition to symbiotic and asymbiotic N fixation. Mineral N 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 N 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).

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 Metherell et al. (1993), and archived copies of the model source code are available.

Box A-2: DayCent Model Simulation of N Gas losses and Nitrate Leaching

The DayCent model simulates the two biogeochemical processes, nitrification and denitrification, that result in N_2O and NOx 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 N_2O emissions from nitrification and denitrification are described below.

Nitrification is controlled by soil ammonium (NH_4^+) concentration, temperature (t), Water Filled Pore Space (WFPS) and pH according to the following equation:

Equation A-42: Soil Nitrification Rate

$$Nit = NH_{4+} \times K_{max} \times F(t) \times F(WFPS) \times F(pH)$$

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-12a)
F(WFPS)	=	the effect of soil water content and soil texture on nitrification (Figure A-12b)
F(pH)	=	the effect of soil pH on nitrification (Figure A-12c)

The current parameterization used in the model assumes that 1.2 percent of nitrified N is converted to N_2O.

The model assumes that denitrification rates are controlled by the availability of soil NO_3^- (electron acceptor), labile C compounds (electron donor) and oxygen (competing electron acceptor). Heterotrophic soil respiration is used as a proxy for labile C 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 NO_3^- and CO_2 functions to establish a maximum potential denitrification rate. These rates vary for particular levels of electron acceptor and C substrate, and account for limitations of oxygen availability to estimate daily denitrification rates according to the following equation:

Equation A-43: Soil Denitrification Rate

$$Den = \min[F(CO_2), F(NO_3)] \times F(WFPS)$$

where,

Den	=	the soil denitrification rate (μg N/g soil/day)
F(NO_3)	=	a function relating N gas flux to nitrate levels Figure A-13a)
F(CO_2)	=	a function relating N gas flux to soil respiration (Figure A-13b)
F(WFPS)	=	a dimensionless multiplier (Figure A-13c)

The x inflection point of F(WFPS) is a function of respiration and soil gas diffusivity at field capacity (D_{FC}):

Equation A-44: Inflection Point Calculation

$$x\ inflection = 0.90 - M(CO_2)$$

where,

M	=	a multiplier that is a function of D_{FC}. In technical terms, the inflection point is the domain where either F(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-12b). 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 N gas flux, the ratio of N_2/N_2O is estimated so that total N gas emissions can be partitioned between N_2O and N_2:

Equation A-45: Ratio of Nitrogen Gas (N_2) to Nitrous Oxide

$$R_{N2/N2O} = F_r(NO_3/CO_2) \times F_r(WFPS).$$

where,

$R_{N2/N2O}$ = the ratio of N_2/N_2O
$F_r(NO_3/CO_2)$ = a function estimating the impact of the availability of electron donor relative to substrate
$F_r(WFPS)$ = a multiplier to account for the effect of soil water on N_2:N_2O.

For $F_r(NO_3/CO_2)$, as the ratio of electron donor to substrate increases, a higher portion of N gas is assumed to be in the form of N_2O. For $F_r(WFPS)$, as WFPS increases, a higher portion of N gas is assumed to be in the form of N_2.

After calculating and summing N_2O emissions from nitrification and dentification, NOx emissions are calculated using a NOx/N_2O ratio function based on soil gas diffusivity. The NOx/N_2O 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 N gas losses. A soil texture specific portion of N 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 % of harvested or senesced biomass N 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 N2O 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 N demand, precipitation event size, and other factors.

1

Figure A-12: Effect of Soil Temperature (a), Water-Filled Pore Space (b), and pH (c) on Nitrification Rates

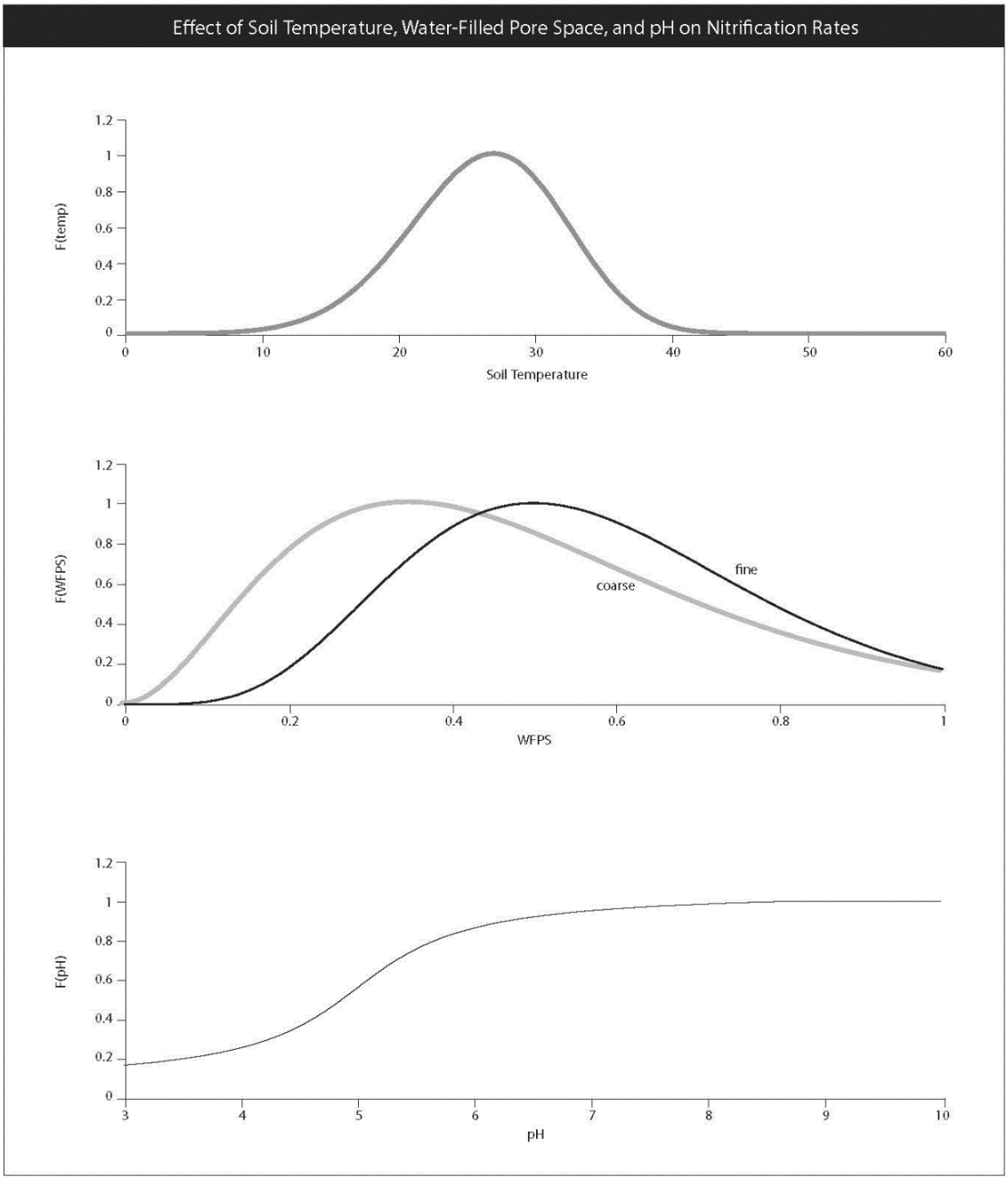
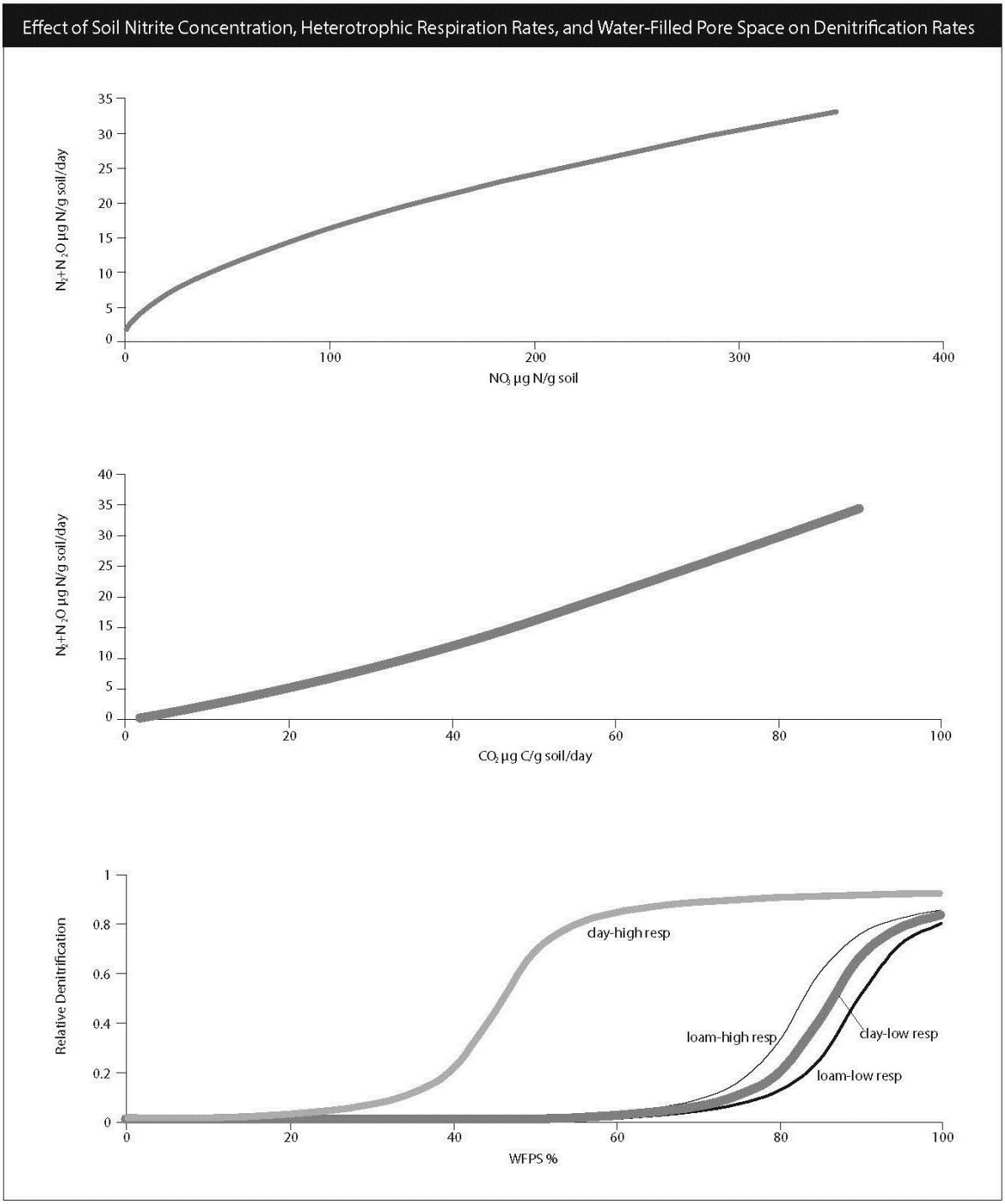


Figure A-13: Effect of Soil Nitrite Concentration (a), Heterotrophic Respiration Rates (b), and Water-Filled Pore Space (c) on Denitrification Rates



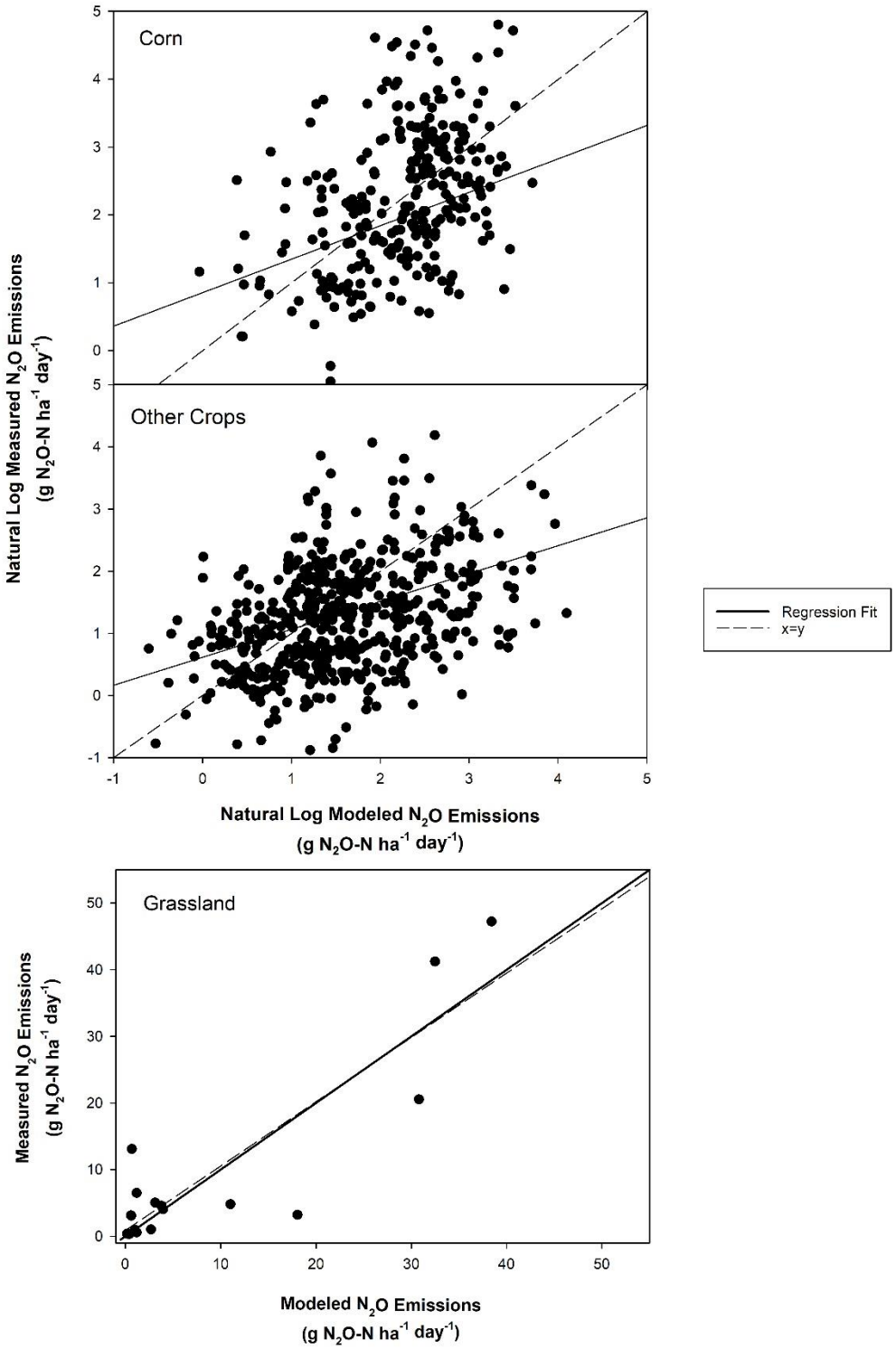
Pulses of N_2O emissions can occur during freeze-thaw events in soils of cold climates, and these events can contribute a substantial portion of annual emissions in northern temperate and boreal regions (Butterbach-Bahl et al. 2017, Wagner-Riddle et al. 2017, Del Grosso et al. 2022). The mechanisms responsible 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 sensitives of the enzymatic processes that control the amounts of N_2 and

N_2O 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 N_2O 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 N_2O from denitrification is amplified by an amount proportional to cumulative freezing degree days during the winter season. DayCent was evaluated using annual high frequency N_2O 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 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). DayCent model results have been compared to trace gas N_2O fluxes for a number of native and managed systems including 90 experimental sites with about 850 observations (Figure A-13). 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 N_2O 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 N_2O 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 N_2O emissions. Furthermore, DayCent also simulated NO_3^- 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 N_2O emissions is the only component that has not been thoroughly tested, which is due to a lack of measurement data.

Figure A- 14: Comparisons of Results from DayCent Model and Measurements of Soil Nitrous Oxide Emissions



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3.13. 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-CO_2 Emissions from Forest Fires

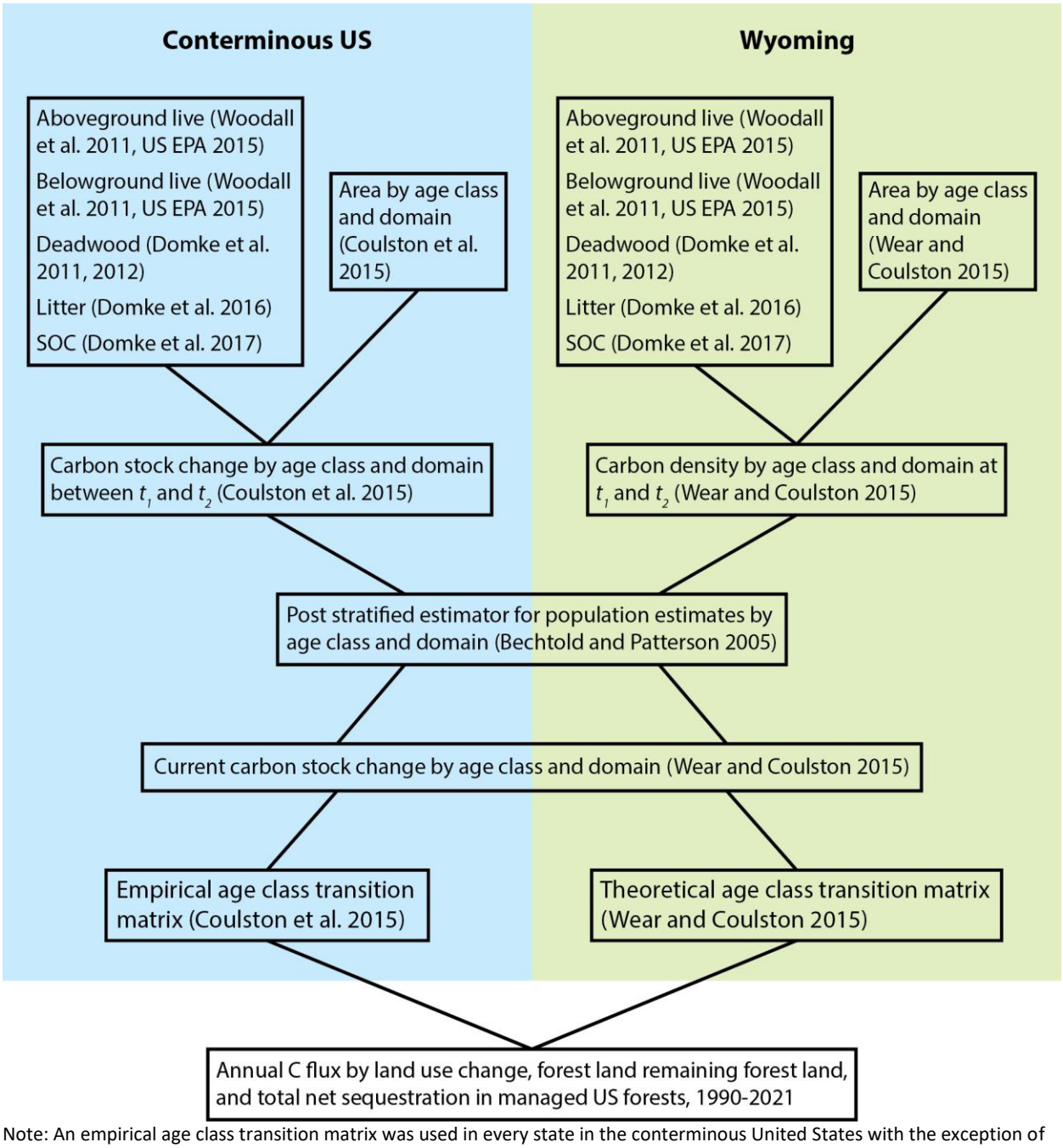
This sub-annex expands on the methodology used to estimate net changes in carbon (C) stocks in forest ecosystems and harvested wood products for Forest Land Remaining Forest Land and Land Converted to Forest Land as well as non-CO_2 emissions from forest fires. Full details of the C conversion factors and procedures may be found in the cited references. For details on the methods used to estimate changes in mineral soil C stocks in the Land Converted to Forest Land section please refer to Annex 3.12.

Carbon stocks and net stock change in forest ecosystems

The inventory-based methodologies for estimating forest C 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 gain-loss (used for Alaska) methods. Estimates of ecosystem C are based on data from the network of annual national 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 C per hectare in forest ecosystem C pools (i.e., above- and belowground biomass, dead wood, litter, and soil organic carbon (SOC)). For the conterminous United States, 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 C 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 in this Inventory are described in Coulston et al. (2015). The annual NFI data in the conterminous United States 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-15). 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 C stocks and fluxes on plots that have yet to be measured as part of the NFI.

The following subsections of this annex describe the estimation system used this year (Figure A-15), including the methods for estimating individual pools of forest ecosystem C in addition to the approaches used to inform land use and stand age transitions.

Figure A-15: Flowchart of the inputs necessary in the estimation framework, including the methods for estimating individual pools of forest C in the conterminous United States



Note: An empirical age class transition matrix was used in 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

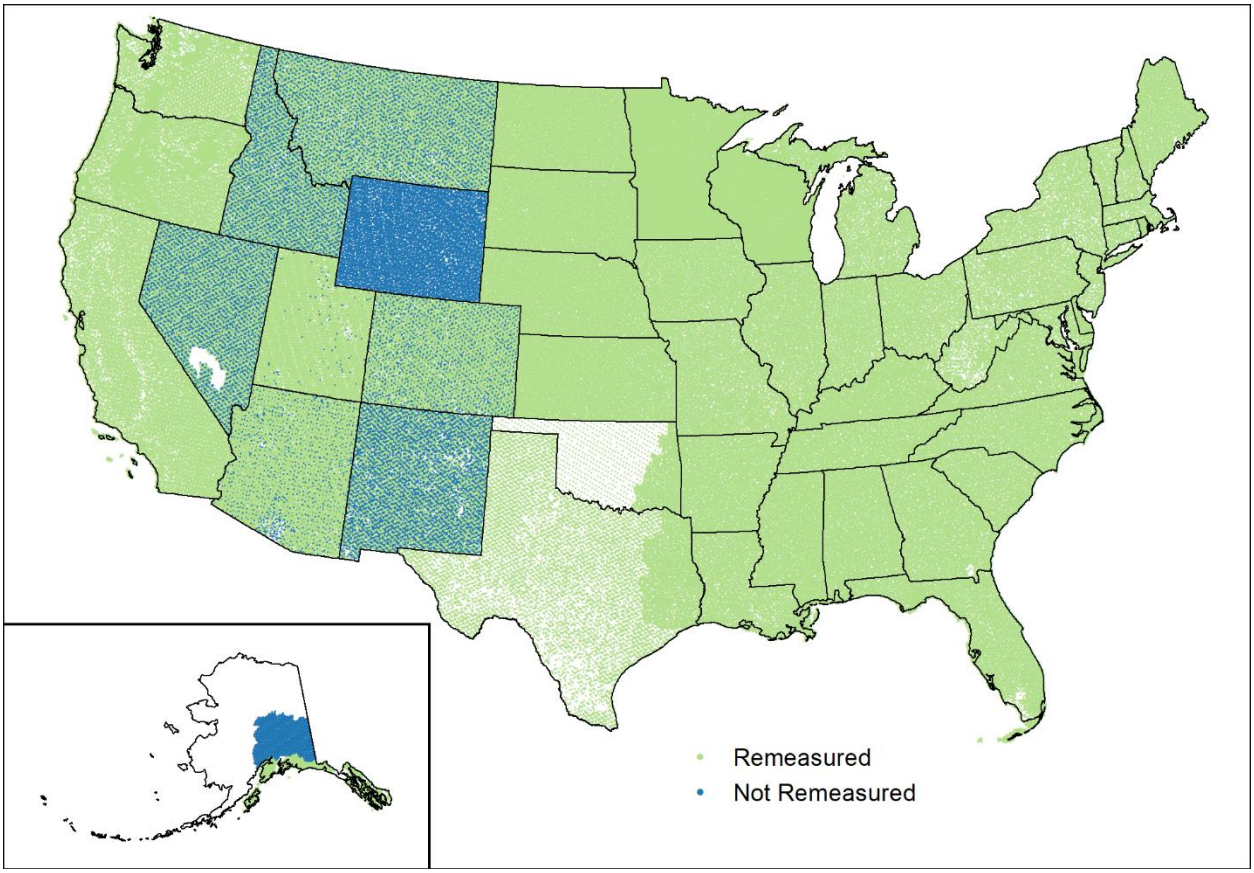
regenerating or capable of attaining such condition in the near future. Forest land also includes transition zones, such as areas between forest and non-forest lands that have at least 10 percent cover (or equivalent stocking) with live trees and forest areas adjacent to urban and built-up lands. Unimproved 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 C 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 C 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 2022a; USDA Forest Service 2022b). 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 C stocks from these data are ongoing (Woodall et al. 2015a) with the latest research incorporated on an annual basis (see Domke et al. 2022). The field protocols are thoroughly documented and available for download from the USDA Forest Service (2022c). Bechtold and Patterson (2005) provide the estimation procedures for NFI population estimation. The data are freely available for download at USDA Forest Service (2011b) as the FIA Database (FIADB) Version 8.0 (USDA Forest Service 2022b; USDA Forest Service 2022c); these are the primary sources of NFI data used to estimate forest C 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 m^2. 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 the U.S. 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 2022a) were introduced by FIA with most new annual NFIs beginning after 1998. These are the only NFIs used in the compilation of estimates for this Inventory. These NFIs involve the sampling of all forest land including reserved and lower productivity lands. All conterminous states in the U.S. have annualized NFI data available with substantial remeasurement (with the exception of Wyoming; Figure A-16). 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 C stocks are affected by the redundancy in the data used to generate the annual updates of C 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 C 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 C 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., 2022) 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-187 and this list can be compared with the full set of summaries available for download (USDA Forest Service 2022b).

Figure A-16: Annual 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 C estimates provided here represent C 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.[178] 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. 2014) and the FIADB (USDA Forest Service 2015b) due to a refined modelling approach developed specifically for Inventory reporting (Coulston et al. 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.

[178] See the Grassland Remaining Grassland and Land Converted to Grassland sections for details.

Table A-187: Specific Annual Forest Inventories by State Used in Development of Forest C Stock and Stock Change Estimate

Remeasured Annual Plots			Split Annual Cycle Plots[1]		
State	Time 1 Year Range	Time 2 Year Range	State	Time 1 Year Range	Time 2 Year Range
Alabama	2006 - 2017	2014 - 2021	Wyoming	2000	2011 - 2020
Arizona	2001 - 2009	2011 - 2019			
Arkansas	2012 - 2016	2017 - 2021	Alaska (Coastal)	2004 - 2021	
California	2001 - 2009	2011 - 2019	Alaska (Interior)	2014, 2016 - 2021	
Colorado	2002 - 2009	2012 - 2019			
Connecticut	2008 - 2013	2013 - 2019			
Delaware	2008 - 2013	2013 - 2019			
Florida	2010 - 2016	2015 - 2019			
Georgia	2011 - 2017	2016 - 2020			
Idaho	2004 - 2009	2014 - 2019			
Illinois	2007 - 2013	2012 - 2019			
Indiana	2009 - 2013	2014 - 2020			
Iowa	2009 - 2014	2015 - 2021			
Kansas	2009 - 2013	2014 - 2020			
Kentucky	2005 - 2012	2012 - 2018			
Louisiana	2001 - 2012	2009 - 2018			
Maine	2012 - 2016	2017 - 2021			
Maryland	2008 - 2013	2013 - 2019			
Massachusetts	2008 - 2013	2013 - 2019			
Michigan	2008 - 2013	2013 - 2019			
Minnesota	2010 - 2014	2015 - 2019			
Mississippi	2009 - 2015	2016 - 2020			
Missouri	2009 - 2013	2014 - 2020			
Montana	2003 - 2009	2013 - 2019			
Nebraska	2009 - 2013	2014 - 2020			
Nevada	2004 - 2009	2014 - 2019			
New Hampshire	2009 - 2014	2014 - 2020			
New Jersey	2009 - 2014	2015 - 2019			
New Mexico	2005 - 2009	2015 - 2019			
New York	2008 - 2013	2013 - 2019			
North Carolina	2009 - 2015	2016 - 2021			
North Dakota	2009 - 2014	2015 - 2021			
Ohio	2008 - 2013	2013 - 2019			
Oklahoma	2009 - 2014	2015 - 2019			
Oregon	2001 - 2009	2011 - 2019			
Pennsylvania	2008 - 2013	2013 - 2019			
Rhode Island	2008 - 2013	2013 - 2019			
South Carolina	2007 - 2016	2014 - 2020			
South Dakota	2009 - 2013	2014 - 2020			
Tennessee	2005 - 2014	2012 - 2018			
Texas (East)	2009 - 2017	2015 - 2020			
Texas (West)	2004 - 2013	2014 - 2018			
Utah	2000 - 2009	2010 - 2019			
Vermont	2009 - 2013	2014 - 2020			
Virginia	2009 - 2015	2015 - 2020			
Washington	2002 - 2009	2012 - 2019			

West Virginia	2008 - 2013	2013 - 2019
Wisconsin	2009 - 2013	2014 - 2020

[1] Plots in 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 spilt annual cycle plots represent a single inventory cycle of plots that are split where remeasurements have yet to occur.

Estimating Forest Inventory Plot-Level C-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 C density for each forest ecosystem C 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 C estimates (Smith et al. 2010; Heath et al. 2011) were initially developed as an extension of the forest C 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 C variables for individual forest C 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 C density (T per hectare) for each forest ecosystem C pool. Carbon density for live trees, standing dead trees, understory vegetation, downed dead wood, litter, and SOC are estimated. All non-soil C pools except litter and downed dead wood can be separated into aboveground and belowground components. The live tree and understory C 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. C stocks and fluxes for Forest Land Remaining Forest Land and Land Converted to Forest Land are reported in forest ecosystem C pools following IPCC (2006).

Live tree C pools

Live tree C 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. If inventory plots include data on individual trees, tree C is based on Woodall et al. (2011), which is also known as the component ratio method (CRM), and is a function of volume, species, diameter, and, in some regions, tree height and site quality. The estimated sound volume (i.e., after rotten/missing deductions) provided in the tree table of the FIADB is the principal input to the CRM biomass calculation for each tree (Woodall et al. 2011). The estimated volumes of wood and bark are converted to biomass based on the density of each. Additional components of the trees such as tops, branches, and coarse roots, are estimated according to adjusted component estimates from Jenkins et al. (2003). Live trees with dbh of less than 12.7 cm do not have estimates of sound volume in the FIADB, and CRM biomass estimates follow a separate process (see Woodall et al. 2011 for details). An additional component of foliage, which was not explicitly included in Woodall et al. (2011), was added to each tree following the same CRM method. Carbon is estimated by multiplying the estimated oven-dry biomass by a C fraction of 0.5 because biomass is 50 percent C by dry weight (USDA Forest Service 2022d). Further discussion and example calculations are provided in Woodall et al. (2011) and Domke et al. (2012).

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 C 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 C 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 C Density to Live Tree C 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 C 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-188. Regions and forest types are the same classifications described in Smith et al. (2003). As an example, the basic calculation for understory C in aspen-birch forests in the Northeast is:

Equation A-47: Understory C 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-201 column "maximum ratio"); this also applies to stands with zero tree C, 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-188) are set to coefficient A, which is a C density (T C/ha) for these types only.

Table A-188: Coefficients for Estimating the Ratio of C 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
	Nonstocked	4.430	4.430	4.773
RMS	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
	Ponderosa Pine	3.214	1.732	4.820
	Nonstocked	4.243	4.243	4.797
SC	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
	Planted Pine	1.489	1.037	4.124
	Upland Hardwood	2.089	1.235	4.170
	Nonstocked	4.044	4.044	4.170
SE	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 C to live tree C is based on the model: Ratio=exp(A − B × ln(tree_C_density)), where "ratio" is the ratio of understory C density to live tree (above-and below- ground) C density, and "tree_C_density" is live tree (above-and below- ground) C density in T C/ha. Note that this ratio is multiplied by tree C 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 (Domke et al. 2011; Woodall et al. 2011). This C pool includes aboveground and belowground (coarse root) mass and includes trees of at least 12.7 cm dbh. Calculations follow the basic CRM method applied to live trees (Woodall et al. 2011) with additional modifications to account for decay and structural loss. In addition to the lack of foliage, two characteristics of standing dead trees that can substantially affect C mass are decay, which affects density and thus specific C fraction (Domke et al. 2011; Harmon et al. 2011), and structural loss such as branches and bark (Domke et al. 2011). A C fraction of 0.5 is used for standing dead trees (USDA forest Service 2022d).

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 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-189. 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 C density at age zero and first order decay; initial densities and decay coefficients are provided in Table A-190. 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 C density and Table A-189 (SC, Natural Pine)

Equation A-48: C 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-189 (SC, softwood)

Equation A-49: Logging Residue C 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 C Density of Downed Dead Wood

$$\text{C density} = (5.67 + 1.37) \times 0.886 = 6.24 \text{ (T C/ha)}$$

Table A-189: 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
SE	Bottomland Hardwood	0.064
	Misc. Conifer	0.081
	Natural Pine	0.081
	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 C density on a plot to produce downed dead wood C density (T C/ha).

Table A-190: 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 C is the pool of organic C (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 C density based on plot/site variables for plots that lacked litter information (Domke et al. 2016):

Equation A-51: Litter C density

$$P(FFCFull) = f(lat, lon, elev, fortypgrp, above, ppt, tmax, gmi) + u \quad (3)$$

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 C predictions are expressed as density (T 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 subplots 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 C

$$\sum SOC_{FIA\_TOTAL} = C_i \cdot BD_i \cdot t_i \cdot ucf \quad (4)$$

where,

$\sum SOC_{FIA\_TOTAL}$ = total mass (Mg C ha-1) of the mineral and organic soil C over all *i*th layers,

C_i = percent organic C in the *i*th layer,

BD_i = bulk density calculated as weight per unit volume of soil (g·cm-3) at the *i*th soil layer,

t_i = thickness (cm) of the *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 C at midpoint depth

$$\log_{10} SOC_i = I + \log_{10} Depth \quad (5)$$

where,

$\log_{10} SOC_i$ = SOC density (Mg C ha-1 cm depth-1) at the midpoint depth,

I = intercept,

$\log_{10} Depth$ = profile midpoint depth (cm).

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 C density

$$SOC_{100} = SOC_{FIA\_TOTAL} + SOC_{20\text{–}100} \quad (6)$$

where,

SOC_{100} = total estimated SOC density from 0-100 cm for each forest condition with a soil sample in the FIA database,

SOC_{FIA_TOTAL} as previously defined in model (4), $SOC_{20\text{-}100}$ = predicted SOC from 20.32 to 100 cm from model (5).

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

$$P(SOC) = f(lat, lon, elev, fortypgrp, ppt, t\,max, g\,mi, order, surfgeo) \quad (7)$$

where,

P(SOC)	= predicted soil organic carbon per hectare to a depth of 100 cm
lat	= latitude,
lon	= longitude,
elev	= elevation,
fortypgrp	= forest type group,
ppt	= mean annual precipitation,
t max	= average maximum temperature,
g mi	= the ratio of precipitation to potential evapotranspiration,
order	= soil order,
surfgeo	= surficial geological description

Compilation of population estimates using NFI plot data

Methods for the conterminous United States

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 C parameters back to 1990. To facilitate the C 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 (i.e., disturbances such as wind, fire, and floods identified by foresters on inventory plots). The land use dynamics module assesses C stock transfers associated with afforestation and deforestation (e.g., Woodall et al. 2015b). Both modules are developed from land use area statistics and C stock change or C stock transfer by age class. The required inputs are estimated from more than 625,000 forest and nonforest observations in the NFI database (U.S. Forest Service 2022a-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 C 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 C 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 2021. This prediction approach requires simulating changes in the age-class distribution resulting from forest aging and disturbance events and then applying C 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 2021.

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 C 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 (**T**) is an n x 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 **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

$$\boldsymbol{T} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 \end{pmatrix} \quad (8)$$

where all forest area progresses to the next age class and forests within the terminal age class are retained forever. With this version of **T**, after five time steps all forests would be in the terminal age class. Relaxing these assumptions changes the structure of **T**. If all disturbances, including harvesting and fire, that result in stand regeneration are accounted for and stochastic elements in forest aging are allowed, **T** defines a traditional Lefkovitch matrix population model (e.g., Caswell 2001) and becomes,

$$\boldsymbol{T} = \begin{pmatrix} 1-t_1-d_1 & d_2 & d_3 & d_4 & d_5 \\ t_1 & 1-t_2-d_2 & 0 & 0 & 0 \\ 0 & t_2 & 1-t_3-d_3 & 0 & 0 \\ 0 & 0 & t_3 & 1-t_4-d_4 & 0 \\ 0 & 0 & 0 & t_4 & 1-d_5 \end{pmatrix} \quad (9)$$

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 West Oklahoma and Wyoming

Projections of forest C in Wyoming are based on a life stage model:

Equation A-57: C 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 **T** is an age transition matrix that shifts the age distribution of the forest **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 C density by age class (**Den**) to estimate C stock change of forest remaining forest between *t* and *t+s*. Land-use change is accounted for by the addition of $\mathbf{L}_t$·**Den,** where **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 **F** and **Den**, while inventory observations and modeling assumptions are used to estimate **T**. By expanding **Den** to a matrix of C contained in all the constituent pools of forest C, projections for all pools are generated.

Land-use change is incorporated as a 1 x n vector **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 **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 C 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 (B):

Equation A-58: Backcasting Age Class Distribution

$$\boldsymbol{F}_{t-s} = \boldsymbol{F}_t \cdot \boldsymbol{B} \quad (11)$$

B is constructed based on similar logic used for creating **T**. The matrix cannot simply be derived as the inverse of **T** ($\boldsymbol{F}_{\boldsymbol{t-s}} = \boldsymbol{F}_{\boldsymbol{t}}\boldsymbol{T}^{\boldsymbol{-1}}$) because of the accumulating final age class (i.e., **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).[179] However, **B** can be constructed using observed changes from the inventory and assumptions about transition/accumulation including nonstationary elements of the transition model:

Equation A-59: Age Transition Model

$$\boldsymbol{B} = \begin{pmatrix} 1-\sum_q d_q & \mathrm{b}_2 & 0 & 0 & 0 \\ d_1 & 1-b_2 & \mathrm{b}_3 & 0 & 0 \\ d_2 & 0 & 1-b_3 & \mathrm{b}_4 & 0 \\ d_3 & 0 & 0 & 1-b_4 & \mathrm{b}_r \\ d_4 & 0 & 0 & 0 & 1-\mathrm{b}_r \end{pmatrix} \quad (12)$$

Forest area changes need to be accounted for in the backcasts as well:

Equation A-60: Forest Area Change

$$\boldsymbol{F}_{t-s} = \boldsymbol{F}_{\boldsymbol{t}}\boldsymbol{B} - \boldsymbol{L}_{\boldsymbol{t}} \quad (13)$$

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 **T** and **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 (**T**), the average of implied disturbance for the previous two periods was applied. For the backcast (**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)

For all states in the conterminous United States (with the exception of Wyoming) remeasured plots were available. When remeasured data are available, the previously described approach is extended to estimate change more directly; in this case $\Delta Ct = Ft \cdot \delta C$, where ΔC is net stock change by pool within the analysis area, F is as previously defined, and δC is an *n* x cp matrix of per unit area forest C stock change per year by pool (cp) arrayed by forest age class. Inter-period

[179] Simulation experiments show that a population that evolves as a function of **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.

forest C dynamics are previously described, and the age transition matrix (T) is estimated from the observed data directly. Forest C change at the end of the next period is defined as: ΔCt+s = Ft·T·δC. 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 x n identity matrix and *δCd* is a C stock transfer rate by age. Paired measurements for all plots in the inventory provide direct estimates of all elements of $\delta C, T_d, \text{and } A_{td}$ matrices.

Predictions are developed by specifying either Ft+s or At+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 2022d). This relationship allowed for the modification of Fcut such that it followed trends described by Oswalt et al. (2019).

Methods for Alaska

Inventory and sampling

The NFI has been measuring plots in southeast and southcentral coastal Alaska as part of the annual NFI since 2004. 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, 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 2021 from the Interior Alaska NFI were used (n = 1031) with base-intensity annual NFI plots from coastal AK (n = 3060) in this analysis.

A spatially balanced sampling design was used to identify field sample locations across all of Alaska following standard FIA procedures with a tessellation of hexagons and one sample plot selected per hexagon – 1/5 intensity in interior Alaska and base-intensity in coastal Alaska (Bechtold and Patterson 2005). The sampling locations were classified as forest or non-forest using the NLCD from 2001 and 2011. 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 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 2021).

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-201) 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.

Forest Land Remaining Forest Land Area Estimates

Forest land area estimates in section 6.2 Forest Land Remaining Forest Land (CRF 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 (CRF Category 4.1). The Forest Land area estimates in section 6.2 do not include Hawaii as insufficient data is available from the NFI to compile area estimates over the entire time series. 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. 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 (CRF 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-199). 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 C sinks and emissions (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). These methods are based on IPCC (2006) guidance for estimating HWP C. The *2006 IPCC Guidelines* provide methods that allow Parties to report 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 C 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 C to and from the atmosphere within national boundaries. Carbon removal due to forest growth is accounted for in the producing country while C emissions to the atmosphere from oxidation of wood products are accounted for in the consuming country.
- **Default approach**: Assumes no change in C stocks in HWP. IPCC (2006) requests that such an assumption be justified if this is how a Party is choosing to report.

The United States uses the production accounting approach (as in previous years) to report HWP Contribution (Table A-191) but estimates for all three approaches are provides in Table A-192. Annual estimates of change are calculated by tracking the additions to and removals from 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-193. The HWP variables estimated are:

(1A) Annual change of C in wood and paper products in use in the United States,

(1B) Annual change of C in wood and paper products in SWDS in the United States,

(2A) Annual change of C 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 C 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-191: Harvested Wood Products from Wood Harvested in the United States—Annual Additions of C to Stocks and Total Stocks under the Production Approach

	Net C additions per year (MMT C per year)			Total C stocks (MMT C)		
		Products in use	Products in SWDS			
Year	Total	Total	Total	Total	Products in use	Products in SWDS
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	(14.9)	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	1008
2012	(20.9)	(3.7)	(17.1)	2,500	1,475	1025
2013	(22.6)	(5.3)	(17.3)	2,521	1,479	1042
2014	(23.4)	(6.1)	(17.4)	2,543	1,484	1059
2015	(24.9)	(7.4)	(17.5)	2,567	1,490	1076
2016	(25.9)	(8.3)	(17.7)	2,592	1,498	1094
2017	(27.3)	(9.5)	(17.8)	2,618	1,506	1112
2018	(25.6)	(7.9)	(17.8)	2,645	1,516	1129
2019	(24.4)	(6.8)	(17.6)	2,671	1,523	1147
2020	(26.3)	(8.7)	(17.6)	2,695	1,530	1165
2021	(28.0)	(10.3)	(17.7)	2,721	1,539	1182

Note: Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere).

Table A-192: Comparison of Net Annual Change in Harvested Wood Products C Stocks Using Alternative Accounting Approaches (MMT CO_2 Eq.)

Inventory Year	Stock-Change Approach	Atmospheric Flow Approach	Production Approach
1990	(116.6)	(131.4)	(123.8)
1991	(120.2)	(131.6)	(123.8)
1992	(127.1)	(127.8)	(120.7)
1993	(130.3)	(129.9)	(122.5)
1994	(126.0)	(128.0)	(118.4)
1995	(122.3)	(122.5)	(112.2)
1996	(131.3)	(127.4)	(117.3)
1997	(137.2)	(122.8)	(114.2)
1998	(147.1)	(127.2)	(119.0)
1999	(141.2)	(120.2)	(112.9)
2000	(125.0)	(100.3)	(93.4)
2001	(130.7)	(103.3)	(98.2)
2002	(125.8)	(98.5)	(93.7)
2003	(143.2)	(107.9)	(104.1)
2004	(142.1)	(109.7)	(105.4)
2005	(136.4)	(112.0)	(106.0)
2006	(113.5)	(109.9)	(100.3)
2007	(72.1)	(88.3)	(76.1)
2008	(41.9)	(70.1)	(54.5)
2009	(48.3)	(79.9)	(60.8)
2010	(51.5)	(92.3)	(69.1)
2011	(59.1)	(95.2)	(71.0)
2012	(72.4)	(103.0)	(76.5)
2013	(85.9)	(109.5)	(82.7)
2014	(92.8)	(113.2)	(85.9)
2015	(104.5)	(119.0)	(91.5)
2016	(109.0)	(122.7)	(95.1)
2017	(113.6)	(128.7)	(100.3)
2018	(111.2)	(124.1)	(94.0)
2019	(109.1)	(116.8)	(89.6)
2020	(128.8)	(139.2)	(96.6)
2021	(134.3)	(147.4)	(102.8)

Note: Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere).

Table A-193: Harvested Wood Products Sectoral Background Data

	1A	1B	2A	2B	3	4	5	6	7	8
Inventory year	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	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
	ΔCHWP IU DC	ΔCHWP SWDS DC	ΔC HWP IU DH	ΔCHWP SWDS DH	PIM	PEX	H	↑CHWP DC	↑CHWP 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	13.9	25.0	102.7	77.5	83.9	(69.1)
2017	13.6	17.4	9.5	17.8	18.0	22.2	126.8	91.7	99.4	(100.3)
2018	12.8	17.5	7.9	17.8	15.6	19.1	126.1	92.2	100.4	(94.0)
2019	12.2	17.5	6.8	17.6	15.9	18.0	122.0	90.1	97.6	(89.6)
2020	17.2	18.0	8.7	17.6	16.5	19.3	125.5	87.6	99.2	(96.6)
2021	18.4	18.3	10.3	17.7	17.1	20.7	129.1	88.9	101.1	(102.8)

Note: Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere).

Annual estimates of variables 1A, 1B, 2A and 2B were calculated by tracking the additions to and removals 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 removals 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; FAO 2021).

The rate of removals 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 (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-194. The first criterion is that the WOODCARB II model estimate of C in houses standing in 2001 needed to match an independent estimate of C 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-195. 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-191. The decline in net additions to HWP C 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 C 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 C additions to HWP in use and in landfills combined.

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 Land Converted to Forest Land – Soil C Methods.

Table A-194: 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-195: 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-196: Net CO_2 Flux from Forest Pools in Forest Land Remaining Forest Land and Harvested Wood Pools (MMT CO_2 Eq.)

Carbon Pool	1990	1995	2000	2005	2010	2017	2018	2019	2020	2021
Forest	**(697.7)**	**(690.4)**	**(664.9)**	**(608.2)**	**(628.3)**	**(610.4)**	**(610.5)**	**(559.8)**	**(610.8)**	**(592.5)**
Aboveground Biomass	(499.1)	(485.0)	(468.7)	(443.8)	(440.8)	(425.9)	(428.0)	(410.8)	(419.0)	(409.1)
Belowground Biomass	(101.8)	(98.6)	(95.1)	(89.8)	(88.6)	(84.5)	(85.1)	(81.6)	(83.1)	(81.1)
Dead Wood	(100.8)	(101.8)	(101.1)	(97.9)	(101.1)	(100.0)	(102.7)	(98.2)	(102.3)	(101.1)
Litter	0.9	(7.7)	(1.9)	22.5	2.6	(2.0)	1.6	30.4	(1.9)	1.9
Soil (Mineral)	3.2	2.7	1.8	0.5	(0.9)	(0.1)	0.6	0.7	(5.4)	(4.0)
Soil (Organic)	(0.8)	(0.7)	(0.6)	(0.4)	(0.2)	1.4	2.3	(1.1)	0.1	0.1
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)**	**(100.3)**	**(94.0)**	**(89.6)**	**(96.6)**	**(102.8)**
Products in Use	(54.8)	(51.7)	(31.9)	(42.6)	(7.4)	(34.9)	(28.9)	(25.1)	(32.0)	(37.8)
SWDS	(69.0)	(60.5)	(61.5)	(63.4)	(61.7)	(65.3)	(65.1)	(64.5)	(64.6)	(65.1)
Total Net Flux	**(821.4)**	**(802.6)**	**(758.3)**	**(714.2)**	**(697.3)**	**(710.7)**	**(704.4)**	**(649.3)**	**(707.4)**	**(695.4)**

[a] These estimates include C stock changes from drained organic soils from both Forest Land Remaining Forest Land and Land Converted to Forest Land.

Note: Parentheses indicate negative values.

Table A-197: Net C Flux from Forest Pools in Forest Land Remaining Forest Land and Harvested Wood Pools (MMT C)

Carbon Pool	1990	1995	2000	2005	2010	2017	2018	2019	2020	2021
Forest	**(190.3)**	**(188.3)**	**(181.3)**	**(165.9)**	**(171.3)**	**(166.5)**	**(166.5)**	**(152.7)**	**(166.6)**	**(161.6)**
Aboveground Biomass	(136.1)	(132.3)	(127.8)	(121.0)	(120.2)	(116.1)	(116.7)	(112.0)	(114.3)	(111.6)
Belowground Biomass	(27.8)	(26.9)	(25.9)	(24.5)	(24.2)	(23.0)	(23.2)	(22.3)	(22.7)	(22.1)
Dead Wood	(27.5)	(27.8)	(27.6)	(26.7)	(27.6)	(27.3)	(28.0)	(26.8)	(27.9)	(27.6)
Litter	0.2	(2.1)	(0.5)	6.1	0.7	(0.6)	0.4	8.3	(0.5)	0.5
Soil (Mineral)	0.9	0.7	0.5	0.1	(0.2)	(0.0)	0.2	0.2	(1.5)	(1.1)
Soil (Organic)	(0.2)	(0.2)	(0.2)	(0.1)	(0.1)	0.4	0.6	(0.3)	0.0	0.0
Drained Organic Soil[a]	0.21	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)**	**(27.3)**	**(25.6)**	**(24.4)**	**(26.3)**	**(28.0)**
Products in Use	(14.9)	(14.1)	(8.7)	(11.6)	(2.0)	(9.5)	(7.9)	(6.8)	(8.7)	(10.3)
SWDS	(18.8)	(16.5)	(16.8)	(17.3)	(16.8)	(17.8)	(17.8)	(17.6)	(17.6)	(17.7)
Total Net Flux	**(224.0)**	**(218.9)**	**(206.8)**	**(194.8)**	**(190.2)**	**(193.8)**	**(192.1)**	**(177.1)**	**(192.9)**	**(189.6)**

[a] These estimates include C stock changes from drained organic soils from both Forest Land Remaining Forest Land and Land Converted to Forest Land.

Note: Parentheses indicate negative values.

Table A-198: Forest area (1,000 ha) and C Stocks in Forest Land Remaining Forest Land and Harvested Wood Pools (MMT C)

	1990	1995	2000	2005	2010	2017	2018	2019	2020	2021	2022
Forest Area (1000 ha)	***282,150***	***281,956***	***281,709***	***281,096***	***280,844***	***280,544***	***280,467***	***280,299***	***280,120***	***279,962***	***279,800***
Carbon Pools											
Forest Ecosystem	**51,354**	**52,308**	**53,237**	**54,098**	**54,952**	**56,137**	**56,303**	**56,470**	**56,623**	**56,790**	**56,951**
Aboveground Biomass	11,899	12,573	13,226	13,849	14,453	15,290	15,406	15,523	15,635	15,749	15,861
Belowground Biomass	2,344	2,481	2,614	2,740	2,862	3,029	3,052	3,076	3,098	3,121	3,143
Dead Wood	1,948	2,086	2,224	2,359	2,496	2,689	2,717	2,745	2,771	2,799	2,827
Litter	3,929	3,936	3,943	3,922	3,913	3,896	3,896	3,896	3,888	3,888	3,888
Soil (Mineral)	25,920	25,916	25,913	25,911	25,911	25,914	25,914	25,914	25,914	25,915	25,916
Soil (Organic)	5,315	5,316	5,317	5,318	5,318	5,318	5,318	5,317	5,317	5,317	5,317
Harvested Wood	**1,895**	**2,061**	**2,218**	**2,353**	**2,462**	**2,618**	**2,645**	**2,671**	**2,695**	**2,721**	**2,749**
Products in Use	1,249	1,326	1,395	1,447	1,471	1,506	1,516	1,523	1,530	1,539	1,549
SWDS	646	735	823	906	991	1,112	1,129	1,147	1,165	1,182	1,200
Total Stock	**53,249**	**54,369**	**55,455**	**56,451**	**57,414**	**58,754**	**58,948**	**59,141**	**59,318**	**59,511**	**59,701**

Table A-199: Forest Land Area Estimates and Differences Between Estimates in 6.1 Representation of the U.S. Land Base (CRF Category 4.1) and 6.2 Forest Land Remaining Forest Land (CRF 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	281,232	282,150	(918)
1995	280,998	281,956	(958)
2000	280,691	281,709	(1,018)
2005	280,457	281,096	(639)
2010	280,183	280,844	(662)
2017	279,841	280,544	(703)
2018	279,778	280,467	(689)
2019	279,616	280,299	(683)
2020	279,446	280,120	(674)
2021	279,298	279,962	(664)

Note: Parentheses indicate negative values.

Table A-200: State-level Net C Flux from all Forest Pools in Forest Land Remaining Forest Land (MMT C) with Uncertainty Range Relative to Flux Estimate, 2021

State	Stock Change	Lower Bound	Lower Bound (%)	Upper Bound	Upper Bound (%)
Alabama	(12.8)	(14.6)	14%	(11.0)	14%
Alaska	(3.1)	(10.2)	-227%	4.0	227%
Arizona	0.7	0.3	-60%	1.1	60%
Arkansas	(9.7)	(11.2)	-16%	(8.1)	16%
California	(6.8)	(14.8)	-117%	1.2	117%
Colorado	3.2	(5.3)	-263%	11.8	263%
Connecticut	(0.9)	(1.2)	-32%	(0.6)	32%
Delaware	(0.0)	(0.1)	-75%	(0.0)	75%
Florida	(3.6)	(4.3)	-19%	(2.9)	19%
Georgia	(8.9)	(9.4)	-6%	(8.4)	6%
Idaho	1.1	(2.4)	-324%	4.6	324%
Illinois	(1.1)	(2.1)	-88%	(0.1)	88%
Indiana	(1.3)	(2.9)	-123%	0.3	123%
Iowa	(0.7)	(1.0)	-45%	(0.4)	45%
Kansas	(0.6)	(1.0)	-71%	(0.2)	71%
Kentucky	(5.2)	(6.7)	-30%	(3.6)	30%
Louisiana	(7.2)	(7.7)	-7%	(6.8)	7%
Maine	(3.7)	(6.7)	-81%	(0.7)	81%
Maryland	(1.1)	(1.6)	-49%	(0.5)	49%
Massachusetts	(1.2)	(1.6)	-30%	(0.9)	30%
Michigan	(3.7)	(7.3)	-97%	(0.1)	97%
Minnesota	(3.5)	(5.9)	-65%	(1.2)	65%
Mississippi	(16.3)	(19.1)	-18%	(13.4)	18%
Missouri	(3.2)	(5.7)	-82%	(0.6)	82%
Montana	2.8	(5.2)	-286%	10.8	286%
Nebraska	(0.2)	(0.3)	-24%	(0.2)	24%
Nevada	0.0	(0.2)	-708%	0.3	708%
New Hampshire	(1.4)	(2.0)	-43%	(0.8)	43%
New Jersey	(0.5)	(0.6)	-17%	(0.4)	17%
New Mexico	1.2	(0.8)	-165%	3.1	165%
New York	(6.2)	(8.5)	-37%	(3.9)	37%
North Carolina	(8.2)	(9.5)	-15%	(6.9)	15%

North Dakota	(0.1)	(0.2)	-99%	(0.0)	99%
Ohio	(1.5)	(3.6)	-139%	0.6	139%
Oklahoma	(2.2)	(2.8)	-28%	(1.6)	28%
Oregon	(9.6)	(11.7)	-22%	(7.5)	22%
Pennsylvania	(5.0)	(9.4)	-90%	(0.5)	90%
Rhode Island	(0.1)	(0.2)	-177%	0.1	177%
South Carolina	(4.1)	(4.7)	-13%	(3.6)	13%
South Dakota	0.2	(0.1)	-142%	0.6	142%
Tennessee	(7.4)	(8.9)	-20%	(5.9)	20%
Texas	(7.7)	(8.2)	-7%	(7.2)	7%
Utah	1.0	(0.4)	-142%	2.4	142%
Vermont	(1.7)	(2.4)	-41%	(1.0)	41%
Virginia	(10.2)	(12.9)	-27%	(7.5)	27%
Washington	(4.3)	(8.9)	-107%	0.3	107%
West Virginia	(3.8)	(5.6)	-45%	(2.1)	45%
Wisconsin	(4.4)	(4.9)	-10%	(4.0)	10%
Wyoming	1.3	0.7	-48%	2.0	48%
49 States	**(161.8)**	**(181.7)**	**-12%**	**(141.9)**	**12%**

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 C pools for Land Converted to Forest Land. Forest Inventory and Analysis data and IPCC (2006) defaults for reference C stocks were used to compile separate estimates for the five C 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 2022b, 2022c). 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 C 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 C pools

Live tree C pools include aboveground and belowground (coarse root) biomass of live trees with a 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. If inventory plots include data on individual trees, tree C is based on Woodall et al. (2011), which is also known as the component ratio method (CRM), and is a function of volume, species, diameter, and, in some regions, tree height and site quality. The estimated sound volume (i.e., after rotten/missing deductions) provided in the tree table of the FIADB is the principal input to the CRM biomass calculation for each tree (Woodall et al. 2011). The estimated volumes of wood and bark are converted to biomass based on the density of each. Additional components of the trees such as tops, branches, and coarse roots, are estimated according to adjusted component estimates from Jenkins et al. (2003). Live trees with dbh of less than 12.7 cm do not have estimates of sound volume in the FIADB, and CRM biomass estimates follow a separate process (see Woodall et al. 2011 for details). An additional component of foliage, which was not explicitly included in Woodall et al. (2011), was added to each tree following the same CRM method. Carbon is estimated by multiplying the estimated oven-dry biomass by a C constant of 0.5 because biomass is 50 percent of dry weight (USDA Forest Service 2022d). Further discussion and example calculations are provided in Woodall et al. 2011 and Domke et al. 2012.

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 C 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 C density are based on information in Birdsey (1996), which was applied to FIA 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 C density (T C/ha) to live tree C 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-188. Regions and forest types are the same classifications described in Smith et al. (2003). An example calculation for understory C 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 C, 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-188) are set to coefficient A, which is a C density (T C/ha) for these types only.

Dead wood

The standing dead tree estimates are primarily based on plot-level measurements (Domke et al. 2011; Woodall et al. 2011). This C pool includes aboveground and belowground (coarse root) mass and includes trees of at least 12.7 cm dbh. Calculations follow the basic CRM method applied to live trees (Woodall et al. 2011) with additional modifications to account for decay and structural loss. In addition to the lack of foliage, two characteristics of standing dead trees that can significantly affect C mass are decay, which affects density and thus specific C content (Domke et al. 2011; Harmon et al. 2011), and structural loss such as branches and bark (Domke et al. 2011). Dry weight to C mass conversion is by multiplying by 0.5 (USDA Forest Service 2022d).

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-189. 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 C density at age zero and first order decay; initial densities and decay coefficients are provided in Table A-190. 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 FIA plots. Litter C is the pool of organic C (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 FIA plots, a model was developed to predict C density based on plot/site attributes for plots that lacked litter information (Domke et al. 2016).

As the litter, or forest floor, estimates are based on an entirely new model this year, a more detailed overview of the methods is provided here. The first step in model development was to evaluate all relevant variables—those that may influence the formation, accumulation, and decay of forest floor organic matter—from annual inventories collected on FIADB plots (P2) using all available estimates of forest floor C (n = 4,530) from the P3 plots (hereafter referred to as the research dataset) compiled from 2000 through 2014 (Domke et al. 2016).

Random forest, a machine learning tool (Domke et al. 2016), was used to evaluate the importance of all relevant forest floor C predictors available from P2 plots in the research dataset. Given many of the variables were not available due to regional differences in sampling protocols during periodic inventories, the objective was to reduce the random forest regression model to the minimum number of relevant predictors without substantial loss in explanatory power. The model (3) and parameters are described in the Forest Land Remaining Forest Land section of the Annex.

Due to data limitation in certain regions and inventory periods a series of reduced random forest regression models were used rather than replacing missing variables with imputation techniques in random forest. Database records used to compile estimates for this report were grouped by variable availability and the approaches described herein were applied to replace forest floor model predictions from Smith and Heath (2002). Forest floor C predictions are expressed in T•ha−1.

Soil organic carbon

A Tier 2 method is applied to estimate mineral soil C 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 C 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 C 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 3.12 for more information about this method (Methodology for Estimating N_2O Emissions, CH_4 Emissions and Soil Organic C Stock Changes from Agricultural Soil Management).

Table A-201 summarizes the annual change in mineral soil C 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 3.12). Table A-202 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 (CRF 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 (CRF Category 4.1). The Forest Land area estimates in section 6.3 do not include Hawaii as insufficient data is available from the NFI to compile area estimates over the entire time series. 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 is included in that section. 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 (CRF 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-203). 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-201: 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	2017	2018	2019	2020	2021
Cropland Converted to Forest Land	0.08 (0.03 to 0.13)	0.07 (0.03 to 0.12)	0.07 (0.02 to 0.12)	0.07 (0.02 to 0.13)	0.06 (0.01 to 0.11)	0.06 (-0.02 to 0.13)	0.06 (-0.02 to 0.13)	0.06 (-0.02 to 0.13)	0.06 (-0.02 to 0.13)	0.06 (-0.02 to 0.13)
Grassland Converted to Forest Land	-0.05 (-0.08 to -0.01)	-0.05 (-0.1 to -0.01)	-0.07 (-0.12 to -0.01)	-0.08 (-0.14 to -0.02)	-0.08 (-0.15 to -0.02)	-0.08 (-0.18 to 0.02)	-0.08 (-0.17 to 0.02)	-0.07 (-0.17 to 0.02)	-0.07 (-0.17 to 0.03)	-0.07 (-0.17 to 0.03)
Other Lands Converted to Forest Land	0.17 (0.13 to 0.21)	0.22 (0.14 to 0.25)	0.24 (0.17 to 0.29)	0.30 (0.22 to 0.36)	0.32 (0.22 to 0.38)	0.31 (0.13 to 0.5)	0.31 (0.12 to 0.5)	0.31 (0.12 to 0.51)	0.31 (0.11 to 0.51)	0.31 (0.11 to 0.52)
Settlements Converted to Forest Land	0.01 (0 to 0.02)	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	**0.22**	**0.25**	**0.26**	**0.30**	**0.31**	**0.31**	**0.31**	**0.31**	**0.31**	**0.31**

Note: The range is a 95 percent confidence interval from 50,000 simulations (Ogle et al. 2003, 2006).

Table A-202: Total land areas (hectares) by land use/land-use change subcategory for mineral soils between 1990 to 2015

Conversion Land Areas (Hectares x10^6)	1990	1995	2000	2005	2007	2008	2009	2010	2011	2012	2013	2014	2015
Cropland Converted to Forest Land	0.17	0.16	0.17	0.16	0.16	0.15	0.15	0.15	0.15	0.14	0.14	0.14	0.14
Grassland Converted to Forest Land	0.75	0.81	0.80	0.81	0.82	0.84	0.84	0.84	0.83	0.84	0.84	0.83	0.80
Other Lands Converted to Forest Land	0.05	0.06	0.07	0.08	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Settlements Converted to Forest Land	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
Wetlands Converted to Forest Land	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Total Lands Converted to Forest Lands	**0.99**	**1.06**	**1.05**	**1.08**	**1.09**	**1.11**	**1.11**	**1.10**	**1.10**	**1.10**	**1.10**	**1.09**	**1.06**

Note: Estimated with a Tier 2 approach and based on analysis of USDA National Resources Inventory data (USDA-NRCS 2018).

Table A-203: Land Converted to Forest Land area estimates and differences between estimates in the Representation of the U.S. Land Base (CRF Category 4.1) and Land Converted to Forest Land (CRF Category 4A1) (kha)

Year	Cropland Converted to Forest Land - 6.1 Represent-ation of the U.S. Land Base (CRF Category 4.1)	Cropland Converted to Forest Land - 6.3 Land Converted to Forest Land (CRF Category 4A2)	Difference between estimates	Grassland Converted to Forest Land - 6.1 Represent-ation of the U.S. Land Base (CRF Category 4.1)	Grassland Converted to Forest Land - 6.3 Land Converted to Forest Land (CRF Category 4A2)	Difference between estimates	Other Lands Converted to Forest Land - 6.1 Represent-ation of the U.S. Land Base (CRF Category 4.1)	Other Lands Converted to Forest Land - 6.3 Land Converted to Forest Land (CRF Category 4A2)	Difference between estimates	Settlemen-ts Converted to Forest Land - 6.1 Represent-ation of the U.S. Land Base (CRF Category 4.1)	Settleme-nts Converted to Forest Land - 6.3 Land Converted to Forest Land (CRF Category 4A2)	Difference between estimates	Wetlands Converted to Forest Land - 6.1 Represent -ation of the U.S. Land Base (CRF Category 4.1)	Wetlands Converted to Forest Land - 6.3 Land Converted to Forest Land (CRF Category 4A2)	Difference between estimates	Total
1990	216	318	(103)	805	480	325	79	104	(24)	11	176	(165)	13	36	(23)	10
1995	153	320	(167)	951	503	448	52	110	(58)	19	177	(158)	24	36	(12)	53
2000	169	328	(159)	1,032	516	516	65	113	(48)	18	180	(162)	23	38	(14)	132
2005	154	324	(170)	1,028	508	519	77	113	(36)	18	178	(161)	23	36	(14)	139
2010	136	319	(184)	1,053	530	523	84	117	(33)	18	178	(160)	24	37	(13)	133
2016	118	318	(200)	989	523	466	103	111	(7)	19	179	(159)	20	36	(16)	83
2017	110	315	(205)	959	519	440	108	91	16	19	178	(158)	19	36	(18)	76
2018	101	308	(207)	855	476	379	99	43	56	19	176	(157)	19	36	(18)	53
2019	87	305	(218)	862	473	390	86	43	43	19	177	(158)	16	34	(18)	38
2020	83	310	(227)	867	473	394	89	46	44	19	181	(162)	15	34	(19)	29
2021	82	310	(227)	869	473	396	81	46	36	19	181	(163)	14	34	(20)	22

Uncertainty Analysis

The uncertainty analyses for total net flux of forest C (see Table 6-14 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 C stocks in the United States are based on C 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 C stock estimates. In this section EPA denotes the estimate of C stock at time *t* as Ct and the variances of the estimate of C stock for time *t* as Var(Ct). These calculations follow Bechtold and Patterson (2005). The variance of stock change is then:

Equation A-62: Variance of the C Stock Change

$$Var(Ct2-Ct1)=Var(Ct2)+Var(Ct1)-2\cdot Cov(Ct2,Ct1) \quad (15)$$

The uncertainty of a stock estimate associated with sampling error is U(Ct)s= Var(Ct)0.5. The uncertainty of a stock changes estimate associated with sampling error is U(ΔC)s=Var(Ct2-Ct1)0.5.

Model-based uncertainty is important because the pool-level C models have error. The total modeling mean-squared error (MSEm) is approximately 1,622 $(Mg/ha)^2$. The percent modeling error at time *t* is

Equation A-63: Percent Modeling Error

$$\%U(Ct)m = 100\cdot MSEm/dt \quad (16)$$

Where dt is the total C stock density at time t calculated as Ct/At where At is the forest area at time *t*.

The uncertainty of Ct from modeling error is

Equation A-64: Uncertainty of C Stock Estimate at Time t

$$U(Ct)m=Ct\cdot \%U(Ct)m/100 \quad (17)$$

The model-based uncertainty with respect to stock change is then

Equation A-65: Model-based Uncertainty of C Stock Change

$$U(\Delta C)m=(\ U(Ct1)m + U(Ct2)m - 2\cdot Cov(U(Ct1m,Ct2m)))0.5 \quad (18)$$

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 C Stock Change

$$U(\Delta C)=(\ U(\Delta C)m^2+ U(\Delta C)s^2)0.5 \text{ and the 95 percent confidence bounds was +- } 2\cdot U(\Delta C) \quad (19)$$

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 C 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 C, the census-based estimate of C 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 C in other countries that came from U.S. harvest, compared to storage in the United States.

The uncertainty about HWP and forest ecosystem net C 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 C 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

CO_2 Emissions from Forest Fires

As stated in other sections, the forest inventory approach implicitly accounts for CO_2 emissions due to disturbances. Net C stock change is estimated from successive C stock estimates. A disturbance, such as a forest fire, removes C from the forest. The inventory data, on which net C stock estimates are based, already reflects the C loss from such disturbances because only C remaining in the forest is estimated. Estimating the CO_2 emissions from a disturbance such as fire and adding those emissions to the net CO_2 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 CO_2, CH_4, and N_2O emissions from disturbances such as fire.

Estimates of historic forest fires and associated emissions (i.e., starting from 1990) provided with this report represent a change in methodology from recent years, which is in response to reviewer suggestions. Past reports were modeled after the Tier 1 methodology with country-specific factors replacing the Tier 1 defaults where more specific local data were available. This year's estimates are based on a system of published country-specific models to simulate fire emissions.

Estimated annual emissions (CO_2 and non-CO_2) from forest fires over the interval from 1990 to the current inventory are calculated consistent with IPCC (2006) methodology; 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) or MODIS burned area mapping (MODIS MCD64A1, Giglio et al. 2018). Annual forest fire and emissions estimates were calculated by the Wildland Fire Emissions Inventory System (WFEIS, French et al. 2011, 2014). The WFEIS calculator[180] was used to provide annual emissions estimates by state and year. Note that N_2O emissions are not included in WFEIS calculations; emissions provided here are based on the average N_2O to CO_2 ratio of 0.000166 following Larkin et al. (2014).

Forest areas within the full burn boundaries as defined by either MTBS or MODIS were based on two fuels models 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 of MTBS and MODIS in order to 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 prescribed burn perimeters. 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), and 80 percent of estimated forest area burned was on managed land in 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 records identify fire origin, including many prescribed fires. Based on these 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

[180] See https://wfeis.mtri.org/calculator.

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 Center[181] 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 Councils[182] 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 2022) included fires through 2020. The MODIS-based records include 2001 through 2021. Emissions reported here originate from MTBS burned areas for the 1990 to 2020 interval and include MODIS burned areas for 2001 to 2021. All other parts of calculations – fuels, fire characteristics, and emissions--are via WFEIS and therefore consistent throughout the 1990 to 2021 interval.

Current uncertainty estimates provided with emissions are based on variability among the limited alternate mean estimates per state per year. That is, the two burn sources and the two fuel models produce four annual estimates for 2001 through 2020. Two annual estimates for 1990 through 2000 are MTBS-based while the two for 2021 originate from MODIS-defined burns. 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 calculator[183] 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, but 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. (in preparation).

[181] See https://www.nifc.gov/fire-information/statistics.
[182] See http://www.prescribedfire.net/.
[183] See https://wfeis.mtri.org/calculator.

Table A-204: Areas (Hectares) and Corresponding Emissions (MMT/year) Associated with Past Forest Fires[a]

		1990	1995	2000	2005	2010	2017	2018	2019	2020	2021
Conterminous United States	Forest area burned (1000 ha)	131.0	107.0	793.2	375.1	333.3	1,067.3	926.9	313.0	1,471.7	1,646.4
	C emitted (MMT/yr)	4.3	2.7	24.7	9.6	7.1	36.7	27.0	6.9	55.9	60.9
	CO_2 emitted (MMT/yr)	13.6	8.7	80.2	31.1	23.2	119.0	87.4	22.3	181.2	196.6
Alaska	Forest area burned (1000 ha)	244.9	6.2	123.9	757.0	58.7	27.1	51.0	471.4	9.7	36.5
	C emitted (MMT/yr)	11.9	0.3	7.6	42.4	3.0	1.4	2.3	24.1	0.5	1.8
	CO_2 emitted (MMT/yr)	38.6	1.0	24.5	137.4	9.9	4.5	7.6	77.9	1.6	5.9
Conterminous United States+Alaska	CH_4 emitted (kt/yr)	115.6	21.0	275.8	389.5	69.9	341.5	245.1	228.2	534.2	553.9
	N_2O emitted (kt/yr)	8.7	1.6	17.4	28.0	5.5	20.5	15.8	16.6	30.3	33.6
	CO emitted (kt/yr)	2984.6	504.6	6158.7	10038.7	1810.9	7297.7	5347.0	5885.2	11080.3	11797.5
	NO_x emitted (kt/yr)	47.5	12.1	100.2	144.8	37.5	121.8	99.9	89.3	171.2	201.3

[a] These emissions have already been accounted for in the estimates of net annual changes in C stocks, which accounts for the amount sequestered minus any emissions, including the assumption that combusted wood may continue to decay through time.

Table A-205: Equivalence Ratios, of CH_4 and N_2O to CO_2

Equivalence Ratios[a,b]	
CH_4 to CO_2	28
N_2O to CO_2	265

[a] Source: the IPCC Fifth Assessment Report (2013)

[b] Note that the corresponding values for the equivalence ratios from the IPCC Fourth Assessment Report are 25 and 298 for CH_4 and N_2O, respectively (for example, see IPCC 2007).

Non-CO_2 Emissions from Forest Fires

Emissions of non-CO_2 gases (CH_4, N_2O, CO, and NOx) (Table A-205) are estimated using the same WFEIS calculator approach as described above for estimating CO_2 emissions from forest fires. Values for global warming potential (GWP) to express CH_4 and N_2O as CO_2 equivalents (Table A-218) are based on the IPCC Fifth Assessment Report (IPCC 2013); the corresponding CO_2 equivalents in past reports were based on IPCC (2007). Please see Section 6.2 Non-CO_2 Emissions from Forest Fires for more information on the impact of GWP changes. Estimated uncertainty follows methods described in the previous section.

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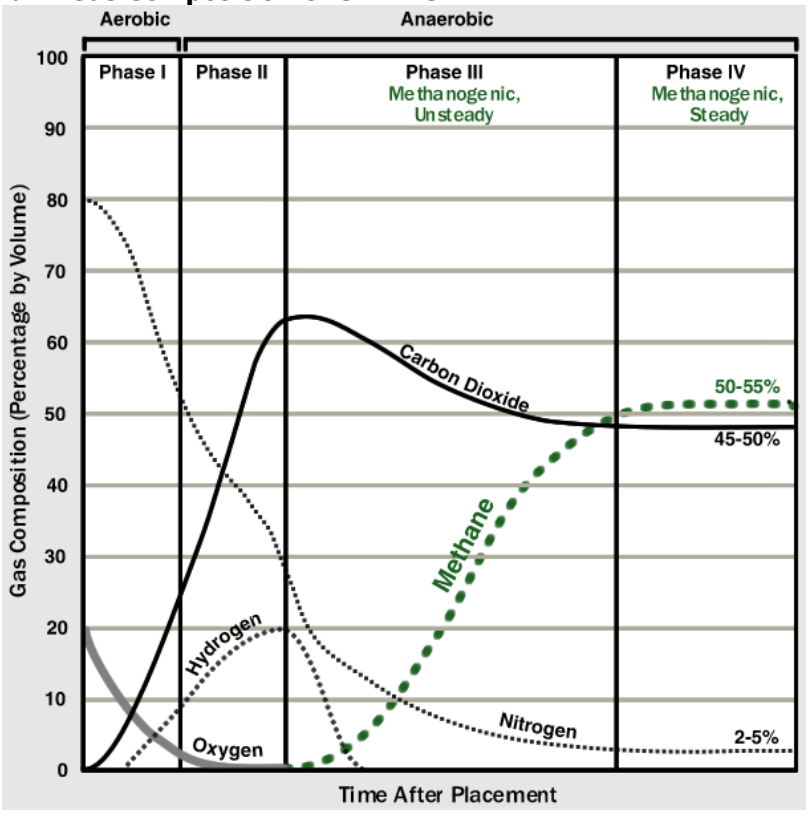
3.14. Methodology for Estimating CH_4 Emissions from Landfills

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 CH_4 and half CO_2.[184] The amount and rate of CH_4 generation depends upon the quantity and composition of the landfilled material, as well as the surrounding landfill environment. Not all CH_4 generated within a landfill is emitted to the atmosphere. The CH_4 can be extracted and either flared or utilized for energy, thus oxidizing the CH_4 to CO_2 during combustion. Of the remaining CH_4, a portion oxidizes to CO_2 as it travels through the top layer of the landfill cover. In general, landfill-related CO_2 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-17 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-17: 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 CH_4 generation. The amount of CH_4 recovered and combusted from MSW landfills is subtracted from the CH_4 generation and is then adjusted with an oxidation factor. The second method used to calculate CH_4 emissions from landfills, also called the back-calculation method, is based off

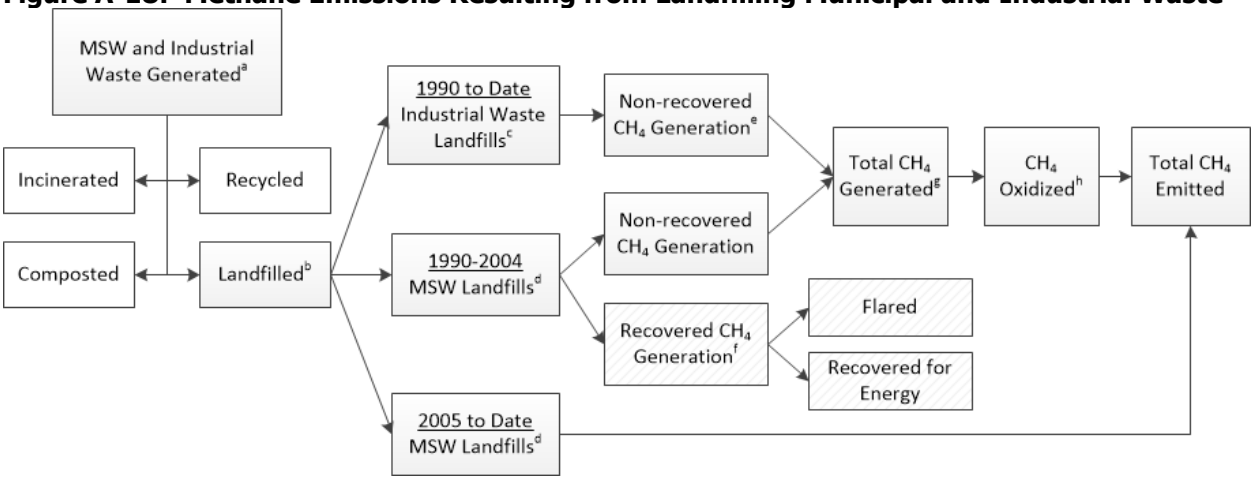
[184] Typically, landfill gas also contains small amounts of nitrogen, oxygen, and hydrogen, less than 1 percent nonmethane volatile organic compounds (NMVOCs), and trace amounts of inorganic compounds.

directly measured amounts of recovered CH_4 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 CH_4 emissions across the time series. The 1990 to 2015 Inventory was the first Inventory to incorporate directly reported GHGRP net CH_4 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 CH_4 generation per year to report a variety of facility-specific information, including historical and current waste disposal quantities by year, CH_4 generation, gas collection system details, CH_4 recovery, and CH_4 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-18 presents the CH_4 emissions process—from waste generation to emissions—in graphical format. A detailed discussion of the steps taken to compile the 1990 to 2021 Inventory are presented in the remainder of this Annex.

Figure A-18: 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 2021 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 2021, directly reported net CH_4 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 2017-2021. 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. CH_4 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 CH_4 generated from MSW landfills and industrial waste landfills are summed. For years 2005 to 2021, MSW landfill CH_4 generated is back-calculated from the annual net CH_4 emissions, recovery, and oxidation; CH_4 generation from industrial waste landfills are summed with the back-calculated MSW landfills CH_4 generation amounts.

[h] An oxidation factor of 10 percent is applied to all CH_4 generated in years 1990 to 2004 (*2006 IPCC Guidelines*; Mancinelli and McKay 1985; Czepiel et al 1996). For years 2005 to 2021, directly reported CH_4 emissions from the GHGRP are used for MSW landfills. Various oxidation factor percentages are included in the GHGRP dataset (0, 10, 25, and 35) with an average percent of 0.14 effectively applied between 2005 to 2009, 0.18 between 2010 to 2016, and 0.21 between 2017 to 2021.

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 CH_4 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 CH_4 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 CH_4 generation between 1990 to 2009, and the methodology used to estimate CH_4 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 CH_4 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 CH_4 generation, estimates for those years were included in the FOD model for completeness in accounting for CH_4 generation rates and are based on the population in those years and the per capita rate for land disposal for the 1960s.

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.[185] 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., 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

[185] 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).

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 and 2022). 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 waste disposal factor has ranged from approximately 77 percent in 1990 to 65.3 percent from 2015 to 2021.

Table A-206 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 CH_4 emissions data, replacing the need for the now discontinued SOG surveys and intermittent EREF estimates.

Table A-206: Solid Waste in MSW and Industrial Waste Landfills Contributing to CH_4 Emissions (MMT unless otherwise noted)

	1990	2005	2017	2018	2019	2020	2021
Total MSW Generated[a]	270	368	327	329	331	334	334
Percent of MSW Landfilled	77%	64%	65%	65%	65%	65%	65%
Total MSW Landfilled	**205**	**234**	**211**	**213**	**214**	**216**	**216**
MSW last 30 years[b]	4,876	5,992	6,501	6,520	6,537	6,548	6,559
MSW since 1940[c]	6,808	9,925	12,509	12,721	12,935	13,150	13,336
Total Industrial Waste Production Data	**196**	**221**	**209**	**212**	**211**	**208**	**206**
Pulp and Paper Sector[d]	129	139	121	124	120	117	114
Food and Beverage Sector[e]	67	82	88	88	91	91	92
Percent Total Industrial Waste Landfilled	**5%**	**5%**	**5%**	**5%**	**5%**	**5%**	**5%**
Total Industrial Waste Landfilled	**9.7**	**10.9**	**11.3**	**11.5**	**11.4**	**11.3**	**11.2**
Pulp and Paper Sector[d]	6.5	6.9	6.1	6.2	6.0	5.9	5.7
Food and Beverage Sector[e]	3.3	4.0	5.3	5.3	5.4	5.5	5.5

[a] This estimate represents the waste that has been in place for 30 years or less, which contributes about 90 percent of the CH_4 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 2021 are based on EREF (2016) and annual population data from the U.S. Census Bureau (2020 and 2022).

[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 and 2022).

[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 and 2022).

[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 2021 are from the FAOStat database.[186]

[e] A disposal factor of 0.046 MT/MT of product is applied to total food 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. Food production values for 1990 to 2020 are from ERG and are projected for 2021 using the 1990 to 2020 ERG estimates (ERG (2022) and FAO (2021)).[187]

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-206 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 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

[186] Available at: http://faostat3.fao.org/home/index.html#DOWNLOAD. Accessed on June 18, 2021.

[187] 2020 USDA-NASS Ag QuickStats. Available at: http://quickstats.nass.usda.gov.

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 CH_4 Generation at MSW Landfills

Step 2a. CH_4 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

$$CH_{4,\text{Solid Waste}} = [G_{CH4,MSW} - R] - Ox$$

where,

$CH_{4,\text{Solid Waste}}$ = Net CH_4 emissions from solid waste

$G_{CH4,MSW}$	=	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 (Lo), and the decay rate constant (k). The equation below provides additional detail on the activity data and emission factors used in the $CH_{4,MSW}$ equation presented above to calculate CH_4 generation.

Equation A-68: Methane Generation from MSW Landfills

$$CH_{4,MSW} = \left[\sum_{x=S}^{T-1}\left\{W_x \times Lo \times \frac{16}{12} \times \left(e^{-k(T-x-1)} - e^{-k(T-x)}\right)\right\}\right]$$

where,

$CH_{4,MSW}$	=	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_o	=	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-207)

The DOC is determined from the CH_4 generation potential (L_0 in m^3 CH_4/Mg waste) as shown in the following equation:

Equation A-69: Degradable Organic Carbon Fraction of Solid Waste

$$DOC = [L_0 \times 6.74 \times 10^{-4}] \div [F \times 16/12 \times DOC_f \times MCF]$$

where,

DOC	=	degradable organic carbon (fraction, kt C/kt waste),
L_0	=	CH_4 generation potential (100 m3 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 CH_4 generation potential[188] of 100 m^3 CH_4/Mg waste (EPA 2008) as described below.

The DOC value used in the CH_4 generation estimates from MSW landfills for 1990 to 2009 is 0.2028, which is based on the CH_4 generation potential of 100 m^3 CH_4/Mg waste (EPA 1998; EPA 2008). After EPA developed the L_o value, RTI analyzed data from a set of 52 representative landfills across the United States in different precipitation ranges to evaluate L_o, and ultimately the national DOC value. The 2004 Chartwell Municipal Solid Waste Facility Directory

[188] Methane generation potential (L_o) varies with the amount of organic content of the waste material. A higher L_o occurs with a higher content of organic waste.

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 L_o were evaluated from landfill gas recovery data for this set of 52 landfills, which resulted in a best fit value for L_o of 99 m^3/Mg of waste (RTI 2004). This value compares favorably with a range of 50 to 162 (midrange of 106) m^3/Mg presented by Peer, Thorneloe, and Epperson (1993); a range of 87 to 91 m^3/Mg from a detailed analysis of 18 landfills sponsored by the Solid Waste Association of North America (SWANA 1998); and a value of 100 m^3/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 m^3/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 L_0 = 100 m^3/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-207 and recommended in EPA's compilation of emission factors (EPA 2008).

Table A-207: 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 CH_4 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-208.

Table A-208: 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

Note: 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. CH_4 Generation at MSW Landfills for 2010 to Present

A different methodology is used to estimate CH_4 generation at MSW landfills between 2010 to 2021. Recent inventories prior to the 1990-2020 Inventory did not separately present CH_4 generation, CH_4 recovery, or CH_4 oxidation from MSW landfills after 2005 because the methodology switched to using the directly reported net CH_4 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 CH_4 generation, CH_4 recovery, and CH_4 oxidation have been added to the 1990 to 2020 Inventory and will be updated annually. The methodology developed to estimate CH_4 generation between 2010 to 2021 is described below.

Step 3: Estimate CH_4 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).[189]

Between 2010 and 2021, the estimated R at MSW landfills is calculated using directly reported annual quantities of R from EPA's GHGRP (EPA 2021a) 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 percent and 11 percent is applied to the total R from EPA's GHGRP from 2010 to 2016 and 2017 to 2021, respectively. In 2021, the Inventory team compared the total R from EPA's GHGRP and EPA's LMOP 2021 database (EPA 2021b); 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 CH_4 Emissions Avoided Through Landfill Gas-to-Energy (LFGE) and Flaring Projects for 1990 to 2009

The quantity of CH_4 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 CH_4 reductions, descriptions of the projects, and information on the methodology used to determine the CH_4 reductions. In general, the CH_4 reductions for each reporting year were based on the measured amount of landfill gas collected and the percent CH_4 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 CH_4 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 CH_4 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 to 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

[189] The 2015 GHGRP dataset is used in the GHGRP MSW landfills dataset described in Step 3a. This database is no longer updated because the methodology has 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.

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 CH_4 recovered to estimate CH_4 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 and in recommendations for closed flares used in the EPA's LMOP.

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

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 CH_4 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 CH_4 recovery in the GHGRP database. For example, if a landfill reporting under EPA's GHGRP was also included in the LFGE database under a project that started in 2002 that is still operational, the CH_4 recovery data in the GHGRP database for that facility was 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 CH_4 recovery was based on the EIA data because landfill owners or operators directly reported the amount of CH_4 recovered using gas flow concentration and measurements, and because the reporting accounted for changes over time. The EIA database only includes facility-reported data through 2006; the amount of CH_4 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 CH_4 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 CH_4 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 CH_4 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 CH_4 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 CH_4 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 CH_4 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 has not been obtained since the 1990 to 2015 Inventory year, when the net CH_4 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 CH_4 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 CH_4 avoided through flaring from the flare vendor database was estimated by summing the estimates of CH_4 recovered by each flare for each year.

Step 3c: Correct Overestimation of CH_4 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, CH_4 avoided would be overestimated, as both the CH_4 avoided from flaring and the LFGE project would be counted. To avoid overestimating emissions avoided from flaring, the CH_4 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 CH_4 avoided due to flaring but was applied to be conservative in the estimates of CH_4 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, potential, 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 CH_4 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 CH_4 recovered from the estimated CH_4 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 to 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 to 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 to 2015 Inventory.

The Inventory methodology now uses directly reported net CH_4 emissions for the 2010 to 2021 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 CH_4 recovered and works back through the system to account for gas not collected by the landfill gas collection and control system (i.e., the collection efficiency).

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 CH_4 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-209: 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 CH_4 emissions data became available for more than 1,200 MSW landfills beginning in 2010. The GHGRP emissions data had to be merged with emissions from the FOD method to avoid a drastic change in emissions in 2010, when the datasets were combined. EPA also had to consider that according to IPCC's good practice, efforts should be made to reduce uncertainty in Inventory calculations and that, when compared to the GHGRP data, the FOD method presents greater uncertainty.

In evaluating the best way to combine the two datasets, EPA considered either using (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 CH_4 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 CH_4 Emissions from MSW Landfills for 2010 to 2016

CH_4 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-210).

Table A-210: 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	CEave1 = (A2*CE2) + A3*CE3 + A4*CE4 + A5*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 CH_4 Emissions from MSW Landfills for 2017 to 2021

The same methodology described in Step 5 is used to estimate CH4 emissions from MSW Landfills for 2017 to 2021, 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 to 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 CH_4 generation; (2) expert knowledge that MSW landfills can generate CH_4 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 2021a) into the Non-Reporting Landfills Database.

    b. Cross-referenced and updated the 2017 LMOP Database (EPA 2017) information with the 2021 LMOP Database (EPA 2021b) 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-211: 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		11 percent
	1.33	(the applied scale-up factor)
GHGRP facilities	11.0	89 percent
Total	12.33	100 percent

An 11 percent scale-up factor is applied annually for 2017 to 2021 because the GHGRP does not capture emissions from all landfills in the United States. In future inventories, the scale-up factor will be reassessed annually 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 CH_4 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 2021. 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-206 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, CH_4 generation at industrial landfills was estimated as seven percent of the total CH_4 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 CH_4 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 through 2021. 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 through 2020 (ERG 2022). An extrapolation based on U.S. population was used for the years 1940 through 1989. The 2021 food and beverage processing sector production data were estimated using the Microsoft Forecast function and the 1990 to 2020 estimates. The 2021 production data will be updated in the next Inventory when data are published by the USDA.

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 CH_4 generation from industrial waste landfills: 1) quantity of waste that is disposed in industrial waste landfills (as a function of production), 2) CH_4 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-206 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_o of 49 m^3/MT); the DOC value for industrial food waste is estimated as 0.26 (L_o of 128 m^3/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_o (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_o range from 50 m^3/Mt to 200 m^3/Mt.[190] 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_o (DOC) from 99 to 49 m^3/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 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 CH_4 generation from industrial waste landfills.

Step 8: Estimate CH_4 Oxidation from MSW and Industrial Waste Landfills

Step 8a: Estimate CH_4 Oxidation from Industrial Waste Landfills for 1990 to Present

A portion of the CH_4 escaping from a landfill oxidizes to CO_2 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 CH_4 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 CH_4 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 2021, the annual weighted average oxidation factor ranges from 21 to 22 percent (EPA 2021a).

The annual amount of CH_4 oxidized is calculated for 1990 to 2004 by applying the 10 percent oxidation factor to the sum of CH_4 generation minus recovery as presented in Equation A-67. The annual amount of CH_4 oxidized is calculated for

[190] 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.

2005 to present by solving for oxidation in Equation A-67 when CH_4 generation, R, and the net CH_4 emission values are known. In other words, when solving Equation A-70 below:

Equation A-70: Back-calculated Methane Oxidation

$$Ox = - (G_{CH4,MSW} + R - CH_{4,Solid\ Waste})$$

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 CH_4 Oxidation from MSW Landfills for 2005 to 2021

For years 2005 to 2021, net CH_4 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 CH_4 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-212: 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/m^2/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,

$$MF = K \times G_{CH4} \ / SArea$$

For Equation HH-6 of this subpart,

$$MF = K \times \left(G_{CH4} - \sum_{n=1}^{N} R_n \right) \Big/ SArea$$

For Equations HH-7 of this subpart,

$$MF = K \times \left(\frac{1}{CE} \sum_{n=1}^{N} \left[\frac{R_n}{f_{Rec,n}} \right] \right) \Big/ SArea$$

For Equation HH-8 of this subpart,

$$MF = K \times \left(\frac{1}{CE} \left\{ \sum_{n=1}^{N} \left[\frac{R_n}{f_{Rec,n}} \right] \right\} - \sum_{n=1}^{N} R_n \right) \Big/ SArea$$

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 2021 ranges from 15 percent to 22 percent.

Table A-213: Applied Oxidation Factors for MSW Landfills

	1990	2005	2017	2018	2019	2020	2021
Applied oxidation factor	0.10	0.15	0.21	0.21	0.21	0.22	0.22

Source: weighted average of reported oxidation factors in net emissions from reporting facilities to GHGRP Subpart HH, EPA 2022.

Step 9: Estimate Total Net CH_4 Emissions for the Inventory

For 1990 to 2004, total net CH_4 emissions were calculated by adding emissions from MSW and industrial landfills, and subtracting CH_4 recovered and oxidized, as shown in Table A-214. A different methodology is applied for 2005 to 2021 where directly reported net CH_4 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 CH_4 reported to the GHGRP for 2005 to 2016, and an 11 percent scale-up factor was applied to the net CH_4 reported to the GHGRP for 2016 to 2021.

Table A-214: CH_4 Emissions from Landfills (kt)

	1990		2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
MSW CH_4 Generation	8,214		10,845	11,037	11,245	11,447	11,642	11,809	11,430	11,742	11,563	11,458	11,213	11,305	11,678	11,880	12,195	12,220	11,944
Industrial CH_4 Generation	484		638	641	645	650	655	658	673	686	699	708	716	723	729	734	739	745	750
MSW CH_4 Recovered	(851)		(5,301)	(5,850)	(6,070)	(6,281)	(6,514)	(6,516)	(6,559)	(6,815)	(6,813)	(6,699)	(6,537)	(6,645)	(6,891)	(6,970)	(7,193)	(7,367)	(7,195)
MSW CH_4 Oxidized	(736)		(843)	(577)	(655)	(736)	(789)	(921)	(848)	(857)	(827)	(852)	(828)	(960)	(1,020)	(1,046)	(1,061)	(1,068)	(1,045)
Industrial CH_4 Oxidized	(48)		(64)	(64)	(64)	(65)	(66)	(66)	(67)	(69)	(69)	(70)	(72)	(72)	(73)	(73)	(74)	(75)	(75)
MSW Net CH_4 Emissions	6,627		4,701	4,610	4,520	4,430	4,339	4,372	4,023	4,070	3,924	3,907	3,848	3,700	3,768	3,864	3,942	3,786	3,704
Industrial Net CH_4 Emissions	436		575	577	580	585	590	592	605	618	629	638	645	651	656	661	665	671	675
Net CH_4 Emissions[a]	**7,063**		**5,275**	**5,188**	**5,100**	**5,015**	**4,929**	**4,964**	**4,629**	**4,687**	**4,553**	**4,544**	**4,493**	**4,350**	**4,424**	**4,525**	**4,607**	**4,456**	**4,379**

Note: Parentheses indicate negative values.

[a] MSW Net CH_4 emissions for years 2010 to 2021 are directly reported CH_4 emissions to the EPA's GHGRP for MSW landfills and are backcasted to estimate emissions for 2005 to 2009. A scale-up factor of 9 percent of each year's emissions from 2005 to 2016, and a scale-up factor of 11 percent of each year's emissions from 2017 to 2021 is applied to account for landfills that do not report annual methane emissions to the GHGRP. Emissions for years 1990 to 2004 are calculated by the FOD methodology.

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ANNEX 4 IPCC Reference Approach for Estimating CO_2 Emissions from Fossil Fuel Combustion

It is possible to estimate carbon dioxide (CO_2) emissions from fossil fuel consumption using alternative methodologies and different data sources than those described in Annex 2.1 Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion. For example, the United Nations Framework Convention on Climate Change (UNFCCC) reporting guidelines request that countries, in addition to their "bottom-up" sectoral methodology, complete a "top-down" Reference Approach for estimating CO_2 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 CO_2 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 CO_2 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-215. Furthermore, waste fuels (e.g., MSW combustion) is not captured as part of the reference approach. Therefore, waste fuels are not used in the comparison between the sectoral and reference approaches in order to improve consistency between the reference and sectoral approaches in terms of estimation coverage.

The C content of fuel varies with the fuel's heat content. Therefore, for an accurate estimation of CO_2 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-215 for 2021), they were converted to units of energy before CO_2 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-216. The resulting fuel type-specific energy data for 2021 are provided in Table A-217.

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:

Apparent Consumption = Production + Imports - Exports - 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:

Secondary Consumption = Imports - Exports - 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-216.

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 CO_2 from Fossil Fuel Combustion). Potential CO_2 emissions were estimated using fuel-specific C coefficients (see Table A-217).[191] 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-218). 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.[192] Finally, to obtain actual CO_2 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 guidance in IPCC (2006) (see Annex 2.1 Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion).

[191] 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-218 for more specific source information.

[192] 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 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.

Step 4: Convert to CO_2 Emissions

Because the *2006 IPCC Guidelines* recommend that countries report greenhouse gas emissions on a full molecular weight basis, the final step in estimating CO_2 emissions from fossil fuel consumption was converting from units of C to units of CO_2. Actual C emissions were multiplied by the molecular-to-atomic weight ratio of CO_2 to C (44/12) to obtain total CO_2 emitted from fossil fuel combustion in million metric tons (MMT). The results are contained in Table A-218.

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 CO_2 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. An examination of past Common Reporting Format (CRF) table submissions during UNFCCC reviews has highlighted the need to further investigate these discrepancies. 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-221 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 2021. The greatest differences lie in lower estimates for petroleum and coal consumption for the Reference Approach (1.2 percent and 2.2 percent, respectively) and higher estimates for natural gas consumption for the Reference Approach (0.7 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, is the most reliable method for the United States to estimate its energy consumption. Additionally, the accounting of pentanes plus as a part of HGL is different between the approaches. The United States reports consumption of all HGL components (i.e., ethane, propane, isobutane, normal butane, ethylene, propylene, isobutylene, butylene, and pentanes plus) for both approaches, but in the Sectoral Approach, pentanes plus is accounted for separately from other HGL components whereas it is included in HGL in the Reference Approach. 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. HGL also includes pentanes plus. 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 CO_2 Emissions

Given these differences in energy consumption data, the next step for each methodology involved estimating emissions of CO_2. Table A-222 summarizes the differences between the two methods in estimated C emissions.

As mentioned above, for 2021, the Reference Approach resulted in a 0.5 percent lower estimate of energy consumption in the United States than the Sectoral Approach. The resulting emissions estimate for the Reference Approach was 1.0 percent higher. Estimates of natural gas and petroleum emissions from the Reference Approach are higher (0.9 percent and 2.7 percent respectively), and coal emission estimates are lower (2.6 percent) than the Sectoral Approach. Fossil emissions from the combustion of municipal solid waste (MSW) including from tires are derived following the same approach for both the reference and sectoral approaches, and thus emissions estimates are equal. Potential reasons for these differences may include:

- *Product Definitions.* Coal data are aggregated differently in each methodology, as noted above. The format used for the Sectoral Approach likely results in more accurate estimates than in the Reference Approach. Also, the Reference Approach relies on a "crude oil" category for determining petroleum-related emissions. Given the many sources of crude oil in the United States, it is not an easy matter to track potential differences in C content between many different sources of crude; particularly since information on the C content of crude oil is not regularly collected.

- *Carbon Coefficients.* The Reference Approach relies on several default C coefficients by rank provided by IPCC (2006), while the Sectoral Approach uses annually updated category-specific coefficients by sector that are likely to be more accurate. Also, as noted above, the C coefficient for crude oil is more uncertain than that for specific secondary petroleum products, given the many sources and grades of crude oil consumed in the United States.

Although the two approaches produce similar results, the United States believes that the "bottom-up" Sectoral Approach provides a more accurate assessment of CO_2 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-215: 2021 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	2,111	[1]	[1]	[1]			
	Bituminous Coal	259,901	[1]	[1]	[1]			
	Sub-bituminous Coal	268,055	[1]	[1]	[1]	367		
	Lignite	47,364	[1]	[1]	[1]	1,221		
	Coke		117	2,083	129			
	Unspecified Coal		5,388	85,115	(41,697)	19,940		1,405
Gaseous Fuels	Natural Gas (Million Cubic Feet)	34,427,185	2,807,961	6,652,609	(82,415)	407,305		71,499
	Still Gas (Thousand Barrels)	0	0	0	0			
Liquid Fuels (Thousand Barrels)	Crude Oil	4,107,585	2,231,550	1,081,390	(108,691)			
	HGL	1,980,085	63,243	842,796	(38,176)			2,644
	Other Liquids	0	474,273	194,678	(2,535)			
	Motor Gasoline	(11,064)	39,387	298,018	(7,583)	228,704		14,671
	Aviation Gasoline		475	0	130			
	Kerosene		293	1,871	(382)			81
	Jet Fuel		57,814	39,200	(2,829)		99,532	6,096
	Distillate Fuel		105,262	390,331	(31,149)	47	17,182	12,285
	Residual Fuel		68,002	35,535	(4,403)	7,000	46,492	7,925
	Naphtha for petrochemical feedstocks		4,868	0	(194)			
	Petroleum Coke		3,766	185,471	(883)	8,836		
	Other Oil for petrochemical feedstocks		1,266	0	(55)	1,240		
	Special Naphthas		4,021	0	(13)			
	Lubricants		16,862	36,387	3,309			172
	Waxes		2,274	1,810	(6)			
	Asphalt/Road Oil		19,609	7,574	1,196			
	Misc. Products		13	503	164			449

[1] Included in Unspecified Coal

Note: Parentheses indicate negative values.

Sources: Solid and Gas Fuels: EIA (2022 a and 2022c); Liquid Fuels: EIA (2022b).

Table A-216: 2021 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	23.92						
	Sub-bituminous Coal	17.49				25.83		
	Lignite	13.14				12.87		
	Coke		20.30	24.26	20.30			
	Unspecified		25.00	25.97	20.86	19.77		25.14
Gaseous Fuels	Natural Gas (BTU/Cubic Foot)	1,037	1,025	1,009	1,037	1,037		1,037
	Still Gas (Million Btu/Barrel)		6.00	6.00	6.00		6.00	6.00
Liquid Fuels (Million Btu/Barrel)	Crude Oil	5.69	6.07	5.73	5.73		5.73	5.73
	HGL	4.20	4.20	4.20	4.20		4.20	4.20
	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 (2022a); Unspecified Solid Fuels: EIA (2011).

Table A-217: 2021 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	53.8						-	53.8
	Bituminous Coal	6,217.7						-	6,217.7
	Sub-bituminous Coal	4,688.5				9.5		-	4,679.0
	Lignite	622.5				15.7		-	606.8
	Coke	-	2.4	50.5	2.6			-	(50.8)
	Unspecified	-	134.7	2,210.6	(869.8)	394.3		35.3	(1,565.1)
Gaseous Fuels	Natural Gas	35,701.0	2,878.2	6,712.5	(85.5)	422.4		74.1	31,603.9
	Still Gas	-	-	-	-		-	-	-
Liquid Fuels	Crude Oil	23,372.2	13,538.8	6,191.0	(622.3)		-	-	31,342.3
	HGL	8,313.6	265.5	3,538.6	(160.3)		-	11.1	5,212.0
	Other Liquids	-	2,762.6	1,134.0	(14.8)		-	-	1,643.4
	Motor Gasoline	(55.9)	198.9	1,505.0	(38.3)		-	74.1	(1,249.6)
	Aviation Gasoline	-	2.4	-	0.7		-	-	1.7
	Kerosene	-	1.7	10.6	(2.2)		-	0.5	(6.3)
	Jet Fuel	-	327.8	222.3	(16.0)		565.5	34.6	(409.3)
	Distillate Fuel	-	613.2	2,273.7	(181.4)	0.3	100.1	71.6	(1,507.9)
	Residual Oil	-	427.5	223.4	(27.7)	44.0	292.3	49.8	(54.7)
	Naphtha for petrochemical feedstocks	-	25.5	-	(1.0)		-	-	26.6
	Petroleum Coke	-	22.7	1,117.3	(5.3)	53.2	-	-	(1,142.5)
	Other Oil for petrochemical feedstocks	-	7.4	-	(0.3)	7.2	-	-	0.5
	Special Naphthas	-	21.1	-	(0.1)		-	-	21.2
	Lubricants	-	102.3	220.7	20.1		-	1.0	(137.4)
	Waxes	-	12.6	10.0	(0.0)		-	-	2.6
	Asphalt/Road Oil	-	130.1	50.3	7.9		-	-	71.9
	Misc. Products	-	0.1	2.9	1.0		-	2.6	(1.2)
Total		**78,913.4**	**21,475.4**	**25,473.3**	**(1,992.8)**	**946.6**	**957.9**	**354.7**	**75,358.6**

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

Table A-218: 2021 Potential CO_2 Emissions

Fuel Category	Fuel Type	Apparent Consumption (QBtu)	Carbon Coefficients (MMT Carbon/QBtu)	Potential Emissions (MMT CO_2 Eq.)
Solid Fuels	Anthracite Coal	0.05	28.28	5.6
	Bituminous Coal	6.22	25.43	579.8
	Sub-bituminous Coal	4.68	26.49	454.4
	Lignite	0.61	26.80	59.6
	Coke	(0.05)	31.00	(5.8)
	Unspecified	(1.57)	25.34	(145.4)
Gaseous Fuels	Natural Gas	31.58	14.43	1,670.7
	Still Gas	-	18.20	-
Liquid Fuels	Crude Oil	31.34	20.31	2,333.5
	HGL	5.21	18.54	354.3
	Other Liquids	1.64	20.31	122.4
	Motor Gasoline	(1.25)	19.27	(88.3)
	Aviation Gasoline	0.00	18.86	0.1
	Kerosene	(0.01)	19.96	(0.5)
	Jet Fuel	(0.41)	19.70	(29.6)
	Distillate Fuel	(1.51)	20.22	(111.8)
	Residual Oil	(0.05)	20.48	(4.1)
	Naphtha for petrochemical feedstocks	0.03	18.55	1.8
	Petroleum Coke	(1.14)	27.85	(116.7)
	Other Oil for petrochemical feedstocks	0.00	20.17	0.0
	Special Naphthas	0.02	19.74	1.5
	Lubricants	(0.14)	20.20	(10.2)
	Waxes	0.00	19.80	0.2
	Asphalt/Road Oil	0.07	20.55	5.4
	Misc. Products	(0.00)	-	-
Total				**5,077.3**

+ Does not exceed 0.005 QBtu or 0.05 MMT CO_2 Eq.

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

Sources: C content coefficients by coal rank from USGS (1998), PSU (2010), Gunderson (2019), IGS (2019), ISGS (2019), and EIA (2021); natural gas C content coefficients from EPA (2010) and EIA (2022a); unspecified solid fuel and liquid fuel C content coefficients from EPA (2010) and ICF (2020).

Table A-219: 2021 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	160.3	31.00	4.97	0.10	2.4
Natural Gas	667.3	14.43	9.63	0.59	20.9
Asphalt & Road Oil	898.1	20.55	18.46	1.00	67.4
HGL	2,819.6	16.83	47.44	0.59	102.8
Lubricants	233.6	20.20	4.72	0.09	1.6
Pentanes Plus	202.4	18.24	3.69	0.59	8.0
Petrochemical Feedstocks	[1]	[1]	[1]	[1]	27.7
Petroleum Coke	0.0	27.85	0.00	0.30	0.0
Special Naphtha	76.1	19.74	1.50	0.59	3.3
Waxes/Misc.	[1]	[1]	[1]	[1]	0.7
Misc. U.S. Territories Petroleum	[1]	[1]	[1]	[1]	0.0
Total					**234.7**

[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.

Note: Totals may not sum due to independent rounding.

Table A-220: 2021 Reference Approach CO_2 Emissions from Fossil Fuel Consumption (MMT CO_2 Eq.)

Fuel Category	Potential Emissions	Carbon Sequestered	Net Emissions	Fraction Oxidized	Total Emissions
Coal	948.3	2.4	946.0	100.0%	946.0
Petroleum	2,458.3	211.4	2,246.8	100.0%	2,246.8
Natural Gas	1,670.7	20.9	1,649.9	100.0%	1,649.9
Total	**5,077.3**	**234.7**	**4,842.6**	**-**	**4,842.6**

Note: Totals may not sum due to independent rounding.

Table A-221: Fuel Consumption in the United States by Estimating Approach (TBtu)[a]

Approach	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Sectoral	**69,579**	**74,625**	**82,434**	**83,839**	**78,658**	**77,102**	**76,266**	**75,707**	**79,008**	**78,154**	**71,499**	**75,746**
Coal	18,098	19,210	21,755	22,213	20,305	15,071	13,816	13,404	12,803	10,876	8,805	10,167
Natural Gas	19,147	22,148	23,372	22,267	24,297	27,941	28,154	27,716	30,815	31,913	31,208	31,364
Petroleum	32,334	33,267	37,307	39,359	34,056	34,090	34,296	34,587	35,390	35,364	31,486	34,215
Reference (Apparent)	**68,883**	**74,199**	**82,020**	**83,995**	**78,289**	**76,473**	**75,566**	**75,423**	**78,447**	**77,531**	**70,905**	**75,334**
Coal	17,742	18,764	21,164	22,227	19,883	15,010	13,729	13,305	12,721	10,842	8,743	9,941
Natural Gas	19,255	22,252	23,465	22,334	24,394	28,021	28,237	27,836	30,945	32,081	31,387	31,580
Petroleum	31,887	33,182	37,392	39,434	34,012	33,442	33,599	34,282	34,781	34,608	30,774	33,813
Difference	**-1.0%**	**-0.6%**	**-0.5%**	**0.2%**	**-0.5%**	**-0.8%**	**-0.9%**	**-0.4%**	**-0.7%**	**-0.8%**	**-0.8%**	**-0.5%**
Coal	-2.0%	-2.3%	-2.7%	0.1%	-2.1%	-0.4%	-0.6%	-0.7%	-0.6%	-0.3%	-0.7%	-2.2%
Natural Gas	0.6%	0.5%	0.4%	0.3%	0.4%	0.3%	0.3%	0.4%	0.4%	0.5%	0.6%	0.7%
Petroleum	-1.4%	-0.3%	0.2%	0.2%	-0.1%	-1.9%	-2.0%	-0.9%	-1.7%	-2.1%	-2.3%	-1.2%

[a] Includes U.S. Territories. Does not include international bunker fuels.

Note: Totals may not sum due to independent rounding.

Table A-222: CO_2 Emissions from Fossil Fuel Combustion by Estimating Approach (MMT CO_2 Eq.)[a]

Approach	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Sectoral	**4,853**	**5,154**	**5,743**	**5,889**	**5,454**	**5,130**	**5,024**	**4,978**	**5,132**	**4,994**	**4,477**	**4,806**
Coal	1,720	1,824	2,070	2,121	1,937	1,438	1,319	1,280	1,223	1,038	842	972
Natural Gas	1,005	1,163	1,226	1,172	1,278	1,463	1,470	1,444	1,606	1,663	1,625	1,635
Petroleum	2,115	2,153	2,434	2,583	2,226	2,214	2,221	2,241	2,291	2,280	1,996	2,187
MSW	13	14	13	13	13	14	14	13	13	13	13	12
Reference (Apparent)	**4,830**	**5,172**	**5,741**	**5,952**	**5,471**	**5,151**	**5,043**	**5,024**	**5,171**	**5,037**	**4,511**	**4,855**
Coal	1,669	1,774	2,008	2,110	1,892	1,430	1,305	1,260	1,211	1,034	834	946
Natural Gas	1,012	1,170	1,232	1,176	1,284	1,468	1,476	1,453	1,616	1,675	1,638	1,650
Petroleum	2,135	2,214	2,488	2,654	2,282	2,239	2,248	2,298	2,332	2,315	2,025	2,247
MSW	13	14	13	13	13	14	14	13	13	13	13	12
Difference	**-0.5%**	**0.4%**	**+%**	**1.1%**	**0.3%**	**0.4%**	**0.4%**	**0.9%**	**0.8%**	**0.9%**	**0.8%**	**1.0%**
Coal	-2.9%	-2.7%	-3.0%	-0.5%	-2.3%	-0.6%	-1.1%	-1.6%	-0.9%	-0.4%	-0.9%	-2.6%
Natural Gas	0.7%	0.6%	0.5%	0.3%	0.5%	0.3%	0.4%	0.6%	0.6%	0.7%	0.8%	0.9%
Petroleum	1.0%	2.9%	2.2%	2.7%	2.5%	1.1%	1.2%	2.5%	1.8%	1.5%	1.4%	2.7%
MSW	0.0%	0.0%	0.0%	0.0%	0.0%	0	0	0	0	0	0	0

+ Does not exceed 0.05 percent.

[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

Although this report is intended to be a comprehensive assessment of anthropogenic[139] sources and sinks of greenhouse gas emissions for the United States, 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, in line with guidance from the IPCC in their guidelines for national inventories.

The anthropogenic source and sink category of greenhouse gas emissions described in this annex are not included in the U.S. national inventory estimates. The reasons for not including that source 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 estimating method has been developed, adequate data are not currently available to estimate emissions and/or removals.
- Emissions are determined to be insignificant in terms of overall national emissions, as defined per UNFCCC 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 and are not estimated, 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.

Reporting of inventories to the UNFCCC under Decision 24/CP.19 states that "Where methodological or data gaps in inventories exist, information on these gaps should be presented in a transparent manner." Furthermore, these reporting guidelines allow a country to indicate if a disproportionate amount of effort would be required to collect data for a gas from a specific category that would be insignificant in terms of the overall level and trend in national emissions.[140] Specifically, where the notation key "NE," meaning not estimated, is used in the Common Reporting Format (CRF)[141] tables that accompany this Inventory report submission to the UNFCCC, countries are required to further describe why such emissions or removals have not been estimated (UNFCCC 2013).

Based on the latest UNFCCC reporting guidance, 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 the understanding of such sources or sinks and seeking

[139] The 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*).

[140] Paragraph 37(b) of Decision 24/CP.19 "Revision of the UNFCCC reporting guidelines on annual inventories for Parties included in Annex I to the Convention." See http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

[141] See http://unfccc.int/national_reports/annex_i_ghg_inventories/reporting_requirements/items/2759.php.

to find the data required to estimate related emissions, prioritizing efforts and resources for significant categories. As such improvements are implemented, new emission and removal categories will be quantified and included in the Inventory to enhance 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 CRF submission.

Source and Sink Categories Not Estimated

This section provides additional information on the reasons each category was not estimated, arranged by sector and source or sink category. A summary of these exclusions, including the estimated level of emissions where feasible, is included in Table A-223. Per 37(b) of the UNFCCC Reporting Guidelines Decision 24/CP.19, considering overall level and trend of U.S. emissions, the threshold for significance for estimating emissions from a specific category is 500 kt CO_2 Eq. Collectively, per paragraph 37(b) of the UNFCCC Reporting Guidelines noted above, these exclusions should not exceed 0.1 percent of gross emissions, or 6.35 MMT CO_2 Eq. (6,348 kt CO_2 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 3.6 MMT CO_2 Eq. (3,609 kt CO_2 Eq).

Table A-223: Summary of Sources and Sinks Not Included in the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020

CRF Category Number	Source/Sink Category	Gas(es)	Reason for Exclusion	Estimated 2020 Emissions (kt CO_2 Eq.)
Energy				
1.A Fossil Fuel Combustion *1.A.3 Transport*				
1.A.3.a	Domestic Aviation-Biomass	N_2O	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 2020 under the RFS program. Emissions of N_2O 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.	0.4
1.A.3.b.iv	Motorcycles-Biomass	CH_4 and N_2O	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_2O 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_2O	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_2O 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_2O	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 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_2O factors results in estimated emissions of 39.0 kt CO_2 Eq. per year.	39.0
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	NE

			currently.	
1.A.3.e Other Transportation				
1.A.3.e.i	Pipeline Transport—Liquid Fuels	CO_2, CH_4 and N_2O	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. 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
1.A.3.e.i	Pipeline Transport—Gaseous Fuels	CO_2, CH_4 and N_2O	CO_2 emissions from gaseous fuels used as pipeline transport fuel are estimated in the Inventory, however CH_4 and N_2O emissions from gaseous pipeline fuel use have not been estimated. The CO_2 / non-CO_2 emissions split for other natural gas combustion can be used to estimate emissions. Based on that analysis, non-CO_2 emissions represent approximately 0.43 percent of CO_2 emissions from all natural gas combustion. If that percentage is applied to CO_2 emissions from natural gas use as pipeline fuel, it results in an emissions estimate of 179.6 kt CO_2 Eq. in 2017.	179.6
1.A.3.e.ii	Non-Transportation Mobile-Biomass	CH_4 and N_2O	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_2O factors results in estimated emissions of 256.4 kt CO_2 Eq. per year.	256.4
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	333

			waste incinerator (HMIWI) facilities in the United States[142] 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 CO_2 Eq. per year.	
1.A.5.a	Stationary Fuel Combustion: Biomass in U.S. Territories	CH_4 and N_2O	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-CO_2 emissions from biomass fuels used in Territories can be made based on assuming the same ratio of domestic biomass non-CO_2 emissions to fossil fuel CO_2 emissions. Non-Territories data indicate that biomass non-CO_2 emissions represents 0.2 percent of fossil fuel combustion CO_2 emissions. Applying this same percentage to proxy U.S. Territories fossil fuel combustion CO_2 emissions results in estimated emissions of 74.8 kt CO_2 Eq. from biomass in U.S. Territories.	74.8
1.B Fugitive Emissions from Fuels ***1.B.1 – Solid Fuels***				
1.B.1.a.1.ii, 1.B.1.a.2.ii	Fugitive Emissions from Coal Mining Related to Post-Mining Activities	CO_2	A preliminary analysis by EPA determined that fugitive CO_2 emissions for post-mining activities related to underground coal mining and surface coal mining are negligible. EPA calculated the ratio of underground post-mining CH_4 emissions to net underground CH_4 emissions (0.12). This ratio was then applied to the net underground CO_2 emissions to estimate underground post-mining CO_2 emissions. The underground post-mining CO_2 emissions were estimated to be 236 kt for 2020. Similarly, surface post-mining CO_2 emissions were estimated by multiplying the ratio of surface post-mining CH_4 and surface CH_4 emissions (0.22) with surface CO_2 estimates. The surface post-mining CO_2 emissions were estimated to be 54 kt. Total CO_2 emissions from post-mining activities (underground and surface) were estimated to be 290 kt for 2020. Note, fugitive CO_2 emissions from active underground and surface coal mining are reported based on methods in the *IPCC 2019 Refinement.* Neither the *2006 IPCC Guidelines* nor the *IPCC 2019 Refinement* provide any method for estimating fugitive CO_2 emissions from post-mining activities (see section 3.4 of Chapter 3 of the *Inventory*).	290
1.B.1.a.1.iii	Fugitive Emissions from Abandoned Underground Coal Mines	CO_2	A preliminary analysis by EPA determined that CO_2 emissions for abandoned underground coal mining activities are negligible. EPA notes that neither the *2006 IPCC Guidelines* nor the *IPCC 2019 Refinement* provide any method for estimating fugitive CO_2 emissions from Abandoned Underground Coal Mines. The analysis was based on gas composition data from two abandoned underground mines in two different	93

[142] RTI (2009). Updated Hospital/Medical/Infectious Waste Incinerator (HMIWI) Inventory Database.

			states.[143] An average ratio of CO_2 to CH_4 composition in mine gas was derived for abandoned mines. This ratio was applied as a percentage (1.5 percent) to CH_4 emission estimates to derive an estimate of CO_2 emissions for abandoned mines. Applying a CO_2 emission rate as a percentage of CH_4 emissions for abandoned coal mines results in a national emission estimate below 93 kt CO_2 Eq. per year. Future inventories may quantify these emissions, if it is deemed it will not require a disproportionate amount of effort.	
Industrial Processes and Product Use				
2.A Mineral Industry				
2.A.4.a	Other Process Uses of Carbonates: Ceramics	CO_2	Data are not currently available to estimate emissions from this source. During the expert review process for compilation of the current Inventory, EPA sought expert solicitation on data for carbonate consumption in the ceramics industry but has yet to identify data sources to apply IPCC methods to proxy emissions and assess significance. The *2006 IPCC Guidelines* specify that activity data should consist of national production data for bricks and roof tiles, vitrified clay pipes, and refractory products or the total quantity of carbonates used in ceramics production, which is not currently available. To assess the significance of emissions from ceramics, EPA used data on clay sold or used in the U.S. in lieu of activity data listed above and approximated carbonate use for ceramics production (USGS 2020 Minerals Commodity Summaries for Clay) in 2019 to be 2.86 million metric tons, based on *2006 IPCC Guidelines* defaults of carbonate content for clay (10 percent) and loss factor (1.1). Using a Tier 1 method and default mix of 85 percent limestone and 15 percent dolomite, national emissions from ceramics production were then calculated to be 1.16 million metric tons of CO_2 (or 1,160 kt CO_2 Eq.) for 2019, which exceeds the category-level threshold for significance of 500 kt CO_2 Eq. This estimate does not include emissions from the calcination of other raw materials for ceramics production, including shale, limestone, dolomite, and witherite, and it may include some limestone and dolomite emissions already reported under Other Process Uses of Carbonates. Further research is needed to identify the portion of clay used for ceramics production, as clay has other uses in addition to ceramics (e.g., drilling mud, pet waste absorbents, paper coating and filling, paint, catalysts). EPA plans to include emissions from use of carbonates for ceramic production as a medium-term improvement.	1,160
2.A.4.c	Other Process Uses of Carbonates: Non-metallurgical Magnesium Production	CO_2	Data are not currently available to estimate emissions from this source. During the Expert Review process for compilation of the current Inventory, EPA sought expert solicitation on data for non-metallurgical magnesium production but has yet to	NE

[143] Ibid.

			identify data sources to apply IPCC methods to proxy emissions and assess significance.	
2.B. Chemical Industry				
2.B.4.b	Glyoxal Production	CO_2 and N_2O	Glyoxal production data are not readily available to apply Tier 1 methods and estimate emissions from this source. EPA continues to conduct basic 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, and it is unknown whether production is still occurring in the United States. 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 (Teles et al 2015), and N_2O control equipment have an efficiency of 80 percent, to estimate process emissions of 71,000 mt CO_2 Eq. or 71 kt CO_2 Eq. per year in recent years, which does not exceed the category-level threshold for significance of 500 kt CO_2 Eq. Any further progress on outreach will be included in next (i.e., 1990 through 2021) Inventory report.	71
2.B.4.c	Glyoxylic Acid Production	CO_2 and N_2O	Data on national glyoxylic acid production data are currently not available to estimate emissions from this source using IPCC methods and then assess significance. EPA is conducting basic outreach to relevant trade associations reviewing EPA and other potential databases that may contain the necessary data. Outreach this year did not identify potential data sources. 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 CO_2 Eq. Any further progress on outreach will be included in next (i.e., 1990 through 2021) Inventory report.	NE
2.B.5.b	Calcium Carbide	CH_4	Data are not currently available to estimate CH_4 emissions from this source. It is difficult to obtain production data because there is currently only one U.S. producer of calcium carbide. This information is not collected by USGS, the agency that collects information on silicon carbide. One other facility is believed to have been in operation during portions of the time series and ceased operations in 2014. During the Expert Review process for compilation of the current Inventory, EPA sought expert solicitation on production data for this source but has yet to identify data sources. Using data reported to GHGRP and an estimated amount of calcium carbide produced, CH_4 emissions from calcium carbide production for 2020 are estimated at 1,075 mt CO_2 Eq. (43 mt CH_4) or 1.075 kt CO_2 Eq. which does not exceed the category-level threshold for significance of 500 kt CO_2 Eq.	1.1
2.B.8.d	Petrochemical and Carbon Black Production	CO_2 recovery	EPA's GHGRP has data starting in reporting year 2010 on the amount of CO_2 captured, including at petrochemical facilities and ethylene oxide processes. Due to schedule and resource constraints, data on CO_2 sequestration have not been compiled and need	NE

			to be reviewed to better understand available data to estimate the fate of these captured emissions. Any CO_2 potentially captured from petrochemical facilities is currently assumed to be released.	
2.C. Metal Industry				
2.C.1.c	Iron and Steel Production: Direct Reduced Iron (DRI) Production	CH_4	Data on fuel consumption used in the production of DRI are not readily available to apply the IPCC default Tier 1 CH_4 emission factor; however, 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. The available information on this sector indicates that these emissions are well below the significance threshold.[144] Per this published literature, the United States has never been a significant display manufacturer aside from a small amount of manufacturing in the 1990s, but not mass production.	NE
2.G Other				
2.G.2	Other Product Manufacture and Use: SF_6 and PFCs from Other Product Use	SF_6	Emissions of SF_6 occur from particle accelerators and military applications, and emissions of PFCs and other F-GHGs occur from military applications such as use of fluorinated heat transfer fluids (HTFs). Emissions from some particle accelerators and from military applications are reported by the U.S. government to the Federal Energy Management Program along with emissions of other fluorinated greenhouse gases (e.g., HFCs from mobile and stationary air conditioning) under the categories "Fugitive Fluorinated Gases and Other Fugitive Emissions" and "Industrial Process Emissions." Analysis of the underlying data for 2018 indicated "fugitive" emissions of SF_6 of approximately 600 kt CO_2 Eq. from the U.S. government as a whole, and "process" emissions of SF_6 of approximately 100 kt CO_2 Eq. (Emissions of SF_6 that are known to be accounted for elsewhere, such as under Electrical Transmission and Distribution, have been excluded from these totals.) The sources of the "fugitive" emissions of SF_6 were not identified, but the source of the vast majority of "process" emissions of SF_6 was particle accelerators.	700

[144] 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.

			Note, fugitive emissions of approximately 200 kt CO_2 Eq. of compounds that are commonly used as fluorinated HTFs (HFEs and fully fluorinated compounds, likely perfluoroamines, perfluoromorpholines, and/or PFPMIEs) were also reported. Per paragraph 33 of the UN reporting guidelines, such "additional GHGs" should be reported separately from national totals so are not considered in estimate of 2019 emissions. EPA still plans to contact reporting agencies to better understand the sources of the emissions and the estimation methods used by reporters, which may equate emissions to consumption and therefore over- or underestimate some emissions, depending on the circumstances. This step will help EPA improve its assessment of significance and prioritize incorporating estimates in future Inventory submissions, but has been postponed due to focus on new EPA programs to improve data collection on HFCs (e.g., implementation of regulations phasing down production and consumption of HFCs).	
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).[145] 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 2020. 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_2O	Manure management emissions from camels are not estimated because there is no significant population of camels in the United States.[146] 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).[147] Based on this source, a Tier 1 estimate of manure management CH_4 and N_2O emissions from camels results in a value of approximately 0.14 kt CO_2 Eq. per year from 1990 to 2020. See Chapter 5.2 for more information.	0.1
3.F Field Burning of Agricultural Residues				

[145] *The status of the camel in the United States of America*. Available online at: https://www.soas.ac.uk/camelconference2011/file84331.pdf.
[146] Paragraph 37(b) of Decision 24/CP.19 "Revision of the UNFCCC reporting guidelines on annual inventories for Parties included in Annex I to the Convention." See http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.
[147] *The status of the camel in the United States of America*. Available online at: https://www.soas.ac.uk/camelconference2011/file84331.pdf.

3.F.1.4, 3.F.4	Sugarcane	CH_4 and N_2O	Currently available data did not allow for identification of burning of sugarcane. Based on prior analysis, EPA estimates that sugarcane emissions may range from less than 10.4 to 61.2 kt CO_2 Eq. (0.42 kt CH_4 to 2.45 kt CH_4), and less than 11.4 kt CO_2 Eq. (0.04 kt N_2O), across the 1990 to 2016 time series. The estimate for 2016 (37.8 kt CO_2 Eq.) is the most recent estimate available and can be used as a proxy for 2020. See the Planned Improvements section in Chapter 5.7 Field Burning of Agricultural Residues for more information.	37.8
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 *2006 IPCC Guidelines*. 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.A.1 Forest Land Remaining Forest Land				
4.A.1	N mineralization/ immobilization	N_2O	Direct N_2O 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 Inventory. 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 *2006 IPCC Guidelines*. 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, 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	Carbon stock change in living biomass and dead organic matter are not estimated, other than for forest land converted to cropland, because data are currently not available. The impact of management on perennial biomass C is currently under investigation for agroforestry management and will be included in a future Inventory if stock changes are significant and activity data can be compiled for this source.	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 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_2O emissions are included under 3.F Field	NE

			Burning of Agricultural Residues.	
4.B.1(V)	Biomass Burning—Wildfires	CO_2, CH_4, and N_2O	Emissions from wildfires 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	Carbon stock change in living biomass and dead organic matter are not estimated, other than for forest land converted to cropland, because data are currently not available. The impact of management on perennial biomass C is currently under investigation for agroforestry management and will be included in a future Inventory 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*. 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	Carbon stock change in living biomass and dead organic matter are not estimated, other than for forest land converted to grassland, because data are currently not available. The impact of management on perennial biomass C is currently under investigation for agroforestry management and will be included in a future Inventory 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_2O	Data are currently not available to apply IPCC methods and estimate emissions from rewetting of peat extraction lands and flooded lands.	NE
4.D.1 Wetlands Remaining Wetlands				
4.D.1(V)	Biomass Burning: Controlled Burning, Wildfires	CO_2, CH_4, and N_2O	Data are not currently available to apply IPCC methods to estimate emissions from biomass burning in Wetlands.	NE
4.D.2 Land Converted to Wetlands				
4.D.2(V)	Biomass Burning: Controlled Burning, Wildfires	CO_2, CH_4, and N_2O	Data are not currently available to apply IPCC methods to estimate emissions from	NE

			biomass burning in Wetlands.	
4.E Settlements				
4.E(V)	Biomass Burning in Settlements	CO_2, CH_4, and N_2O	Data are currently not available to apply IPCC methods to estimate emissions from biomass burning in Settlements.	NE
4.E.1 Settlements Remaining Settlements				
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_2O Emissions from N Mineralization/Immobilization (Mineral Soils)	N_2O	Activity data are not available on N_2O emissions from nitrogen mineralization/immobilization in Settlements Remaining Settlements and Land Converted to Settlements as a result of soil organic carbon stock losses from land use conversion and management.	NE
4.E.2 Land Converted to Settlements				
4.E.2	Direct N_2O Emissions from N Mineralization/Immobilization	N_2O	Activity data are not available on N_2O emissions from nitrogen mineralization/immobilization in Settlements Remaining Settlements and Land Converted to Settlements 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_2O	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_2O 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 2020 in the time series. A methodological change was made for 2005 to the current Inventory 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.B Biological Treatment of Solid Waste				
5.B.1.a	Composting – Municipal Solid Waste	Recovered CH_4 and N_2O	CH_4 and N_2O emissions from combustion of the recovered gas at composting sites are very small "so good practice in the Waste Sector does not require their estimation." (IPCC 2006, Volume 5, Chapter 4, pp. 4.5). EPA will periodically assess trends and based on significance consider reflecting as data become available and prioritize with other improvements to make best use of available resources. Estimating emissions at this time, given the likely significance, would require a disproportionate amount of effort, so this will be considered for future Inventories based on trends and available data.	NE
5.C Waste Incineration				

5.C.1	Waste Incineration	CH_4 and N_2O from incineration of sewage sludge	Based on data on the amount of sewage sludge incinerated and assumed emission factors for N_2O and CH_4 from EPA's GHGRP for biomass solids, emissions were estimated to be approximately 9 kt CO_2 Eq. per year. Approximated emissions associated with sewage sludge incineration are considered insignificant for the purposes of inventory reporting under the UNFCCC.	9
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 *IPCC 2019 Refinement* only identifies CH_4 emissions from anaerobic digestion of sludge as a source of emissions to be reported in the Wastewater sector [note that N_2O 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 Inventory 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 CO_2 Eq., which is considered insignificant for the purposes of inventory reporting under the UNFCCC.	5

NE (Not Estimated), indicating also it is not possible 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*.

While summarized below in Table A-224, information on coverage of activities within the United States, the District of Columbia, and U.S. Territories 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.[202] 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-224: Summary of Geographic Completeness

CRF 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 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, 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 and U.S. Territories 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; however, for Hawaii and Alaska some agricultural practices that can increase nitrogen availability in the soil, and thus cause N_2O 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, with the exception of 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, however, for Hawaii and Alaska some emissions and removals from land use and land use change are not included. 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_2O from settlement soils, non-CO_2 emission from grassfires are not estimated. For Hawaii, estimates of CO_2, CH_4, N_2O from peatlands are not estimated. See chapter sections on Uncertainty and Planned Improvements for more details. In addition, U.S. Territories are not included (see Box 6). 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. 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

[202] More information is available at: https://www.usgs.gov/faqs/how-are-us-states-territories-and-commonwealths-designated-geographic-names-information-system.

	expected for outlying Pacific Islands and assumed to be small for other U.S. Territories. Emissions for composting include all 50 states, including Hawaii and Alaska, but not U.S. Territories. Composting emissions from U.S. Territories are assumed to be small and have not yet been approximated. Similarly, EPA is not aware of any anerobic digestion at biogas facilities in U.S. Territories but will review this on an ongoing basis to include these emissions if they are occurring.

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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 (CO_2) 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 CO_2 equivalents (MMT CO_2 Eq.) can be expressed as follows:

Equation A-71: Calculating CO_2 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. In the following decision finalized in November 12, 2022, the countries who are Parties to the United Nations Framework Convention on Climate Change (UNFCCC) have agreed to use consistent GWP values from the *IPCC Fifth Assessment Report* (AR5), based upon a 100-year time horizon, although other time horizon values are available (see Table A-225). While this Inventory uses agreed-upon GWP values according to the specific reporting requirements of the UNFCCC, described below, unweighted gas emissions and sinks in kilotons (kt) are provided in the Trends chapter of this report (Table 2-2) and users of the Inventory can apply different metrics and different time horizons to compare the impacts of different greenhouse gases.

> *…Decides that, until it adopts a further decision on the matter, the global warming potential values used by Parties in their reporting under the Convention to calculate the carbon dioxide equivalence of anthropogenic greenhouse gas emissions by sources and removals by sinks shall be based on the effects of greenhouse gases over a 100-year time horizon as listed in table 8.A.1 in appendix 8.A to the contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,*[203] *excluding the value for fossil methane.*[204]

Greenhouse gases with lifetimes longer than a year or two (e.g., CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, and NF_3) 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

[203] Intergovernmental Panel on Climate Change. 2013. *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. TF Stocker, D Qin, G-K Plattner, et al. (eds.). Cambridge and New York: Cambridge University Press. Available at http://www.ipcc.ch/report/ar5/wg1.
[204] United Nations Framework Convention on Climate Change, see https://unfccc.int/sites/default/files/resource/sbsta2022_L25a01E.pdf.

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., SO_2 products and black carbon) vary spatially, and consequently it is more difficult to quantify their global radiative forcing impacts. 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-225: IPCC AR5 Global Warming Potentials (GWP) and Atmospheric Lifetimes (Years) of Gases Used in this Report

Gas	Atmospheric Lifetime	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_2O)	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_2F_6	10,000	11,100	8,210
C_3F_8	2,600	8,900	6,640
C_4F_6[e]	<1	<1	<1
c-C_5F_8[e]	31 days	2	7
C_4F_{10}	2,600	9,200	6,870
c-C_4F_8	3,200	9,540	7,110
C_5F_{12}	4,100	8,550	6,350
C_6F_{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 CO_2 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 CO_2 is not included.

[d] Methane and N_2O have chemical feedback systems that can alter the length of the atmospheric response, in these cases, global mean atmospheric lifetime (LT) is given first, followed by perturbation time (PT), but only the perturbation time 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). Within this report, the GWP values were revised relative to the IPCC's *Fifth Assessment Report* (AR5) (IPCC 2013) as discussed in Chapter 9, Recalculations and Improvements. Although the AR5 GWP values are used throughout this Inventory report in line with

recent UNFCCC decisions to use AR5 GWPs no later than December 2024, it is informative to review the changes to the 100-year GWP values and the impact they have on the total GWP-weighted emissions of the United States. All GWP values use CO_2 as a reference gas; a change in the radiative efficiency of CO_2 thus impacts the GWP of all other greenhouse gases. Since the *Fourth Assessment Report* (AR4), the IPCC has applied an improved calculation of CO_2 radiative forcing and an improved CO_2 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-226 shows how the GWP values of the other gases relative to CO_2 tend to be larger in AR4, AR5, and AR6 because the revised temporally integrated radiative forcing of CO_2 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 UNFCCC 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 2021). As such, GWP comparisons throughout this chapter are presented relative to AR5 GWPs.

Table A-226: Comparison of GWP values and Lifetimes Used in the AR4, AR5, and AR6[c]

	Lifetime (years)			GWP (100 year)				Difference in GWP (Relative to AR5)					
Gas	AR4	AR5	AR6	AR4	AR5[a]	AR5 with feedbacks[b]	AR6[c]	AR4	AR4 (%)	AR5 with feedbacks[b]	AR5 with feedbacks[b] (%)	AR6	AR6 (%)
Carbon dioxide (CO_2)	[d]	[d]	[d]	**1**	**1**	**1**	**1**	**NC**	**NC**	**NC**	**NC**	**NC**	**NC**
Methane (CH_4)[e]	**8.7/12[f]**	**12.4**	**11.8**	**25**	**28**	**34**	**27**	**(3)**	**(11%)**	**6**	**21%**	**(4%)**	**(1)**
Nitrous oxide (N_2O)	**120/114[f]**	**121**	**109**	**298**	**265**	**298**	**273**	**33**	**12%**	**33**	**12%**	**3%**	**8**
Hydrofluorocarbons													
HFC-23	270	222	228	14,800	12,400	13,856	14,600	2,400	19%	1,456	12%	2,200	18%
HFC-32	4.9	5.2	5.4	675	677	817	771	(2)	(0%)	140	21%	94	14%
HFC-41	NA	2.8	2.8	NA	116	141	135	(24)	(21%)	NA	NA	19	16%
HFC-125	29	28.2	30	3,500	3,170	3,691	3,740	330	10%	521	16%	570	18%
HFC-134a	14	13.4	14	1,430	1,300	1,549	1,530	130	10%	249	19%	230	18%
HFC-143a	52	47.1	51	4,470	4,800	5,508	5,810	(330)	(7%)	708	15%	1,010	21%
HFC-152a	1.4	1.5	1.6	124	138	167	164	(14)	(10%)	29	21%	26	19%
HFC-227ea	34.2	38.9	36	3,220	3,350	3,860	3,600	(130)	(4%)	510	15%	250	7%
HFC-236fa	240	242	213	9,810	8,060	8,998	8,690	1,750	22%	938	12%	630	8%
HFC-245fa	7.6	7.7	7.9	1,030	858	1,032	962	172	20%	174	20%	104	12%
HFC-365mfc	8.6	8.7	8.9	794	804	966	914	(10)	(1%)	162	20%	110	14%
HFC-43-10mee	15.9	16.1	17	1,640	1,650	1,952	1,600	(10)	(1%)	302	18%	(50)	(3%)
Fully Fluorinated Species													
SF_6	3,200	3,200	3200	22,800	23,500	26,087	25,200	(700)	(3%)	2,587	11%	1,700	7%
CF_4	50,000	50,000	50,000	7,390	6,630	7,349	7,380	760	11%	750	11%	750	11%
C_2F_6	10,000	10,000	10,000	12,200	11,100	12,340	12,400	1,100	10%	1,240	11%	1,300	12%
C_3F_8	2,600	2,600	2,600	8,830	8,900	9,878	9,290	(70)	(1%)	978	11%	390	4%
C_4F_{10}	2,600	2,600	2,600	8,860	9,200	10,213	10,000	(340)	(4%)	1,013	11%	800	9%
c-C_4F_8	3,200	3,200	3,200	10,300	9,540	10,592	10,200	760	8%	1,052	11%	660	7%
c-C_5F_8	NA	31 days	NA	NA	2.0	NA	NA	NA	NA	NA	NA	NA	NA
C_5F_{12}	4,100	4,100	4,100	9,160	8,550	9,484	9,220	610	7%	934	11%	670	8%
C_6F_{14}	3,200	3,100	3,100	9,300	7,910	8,780	8,620	1,390	18%	870	11%	710	9%
C_4F_6	1.1	NA	NA	0.003	NA	NA	NA	NA	NA	NA	NA	NA	NA
C_4F_8O	NA	NA	3,000	NA	NA	NA	13,900	NA	NA	NA	NA	NA	NA
NF_3	740	500	569	17,200	16,100	17,885	17,400	1,100	7%	1,785	11%	1,300	8%

+ Does not exceed 0.5 percent.

NC (No Change)

NA (Not Applicable)

[a] The GWP values presented here are the ones most consistent with the methodology used in the AR4 report. See footnote e for more information on GWPs for methane of fossil origin.

[b] The GWP values presented here from the AR5 report include climate-carbon feedbacks for the non-CO_2 gases in order to be consistent with the approach used in calculating the CO_2 lifetime.

[c] The 100-year GWPs from AR6 are prepublication values based on the Working Group 1 report published in August 2021. As the report is finalized for full publication, in the final editing process, these values may be updated in corrigenda and EPA will update this analysis to reflect the final value.

[d] For a given amount of CO_2 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 CO_2 (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 biospheric methane in order to account for the CO_2 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 N_2O have chemical feedback systems that can alter the length of the atmospheric response, in these cases, global mean residence time is given first, followed by perturbation time.

Note: Parentheses indicate negative values.

Source: IPCC (2021), IPCC (2013), IPCC (2007).

The choice of 100-year GWP values between the AR4, AR5, and AR6 with or without 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-227 shows the overall trend in U.S. greenhouse gas emissions, by gas, from 1990 through 2021 using the four GWP sets. The table also presents the impact of AR5 GWPs relative to AR4, AR5 values with feedbacks, and AR6 on the total emissions for 1990 and for 2021. Note AR6 GWPs also include climate-carbon feedbacks.

Table A-227: Effects on U.S. Greenhouse Gas Emissions Using AR4, AR5, and AR6[c] GWP values (MMT CO_2 Eq.)

Gas	Difference in Emissions Between 1990 and 2021 (Relative to 1990)			Revisions to Annual Emission Estimates (Relative to AR5)					
				AR4	AR5[b]	AR6	AR4	AR5[b]	AR6
	AR4	AR5[b]	AR6[c]	1990			2021		
CO_2	(73.3)	(73.3)	(73.3)	NC	NC	NC	NC	NC	NC
CH_4	(126.1)	(171.5)	(136.2)	(93.1)	186.2	(31.0)	(77.9)	155.9	(26.0)
N_2O	(13.3)	(13.3)	(12.2)	49.4	NC	12.0	47.9	NC	NC
HFCs, PFCs, SF_6, and NF_3	98.2	117.1	118.5	9.0	10.4	11.1	11.3	31.7	33.7
Total	**(114.5)**	**(141.0)**	**(103.2)**	**(34.7)**	**246.1**	**(8.0)**	**(18.7)**	**235.6**	**19.4**
Percent Change	**-1.8%**	**-2.1%**	**-1.6%**	**-0.5%**	**3.8%**	**-0.1%**	**-0.3%**	**3.7%**	**0.3%**

Table A-228 and Table A-229 show the comparison of emission estimates using AR5 GWP values relative to AR4 GWP values for the non-CO_2 gases (both exclude climate-carbon feedbacks), on an emissions and percent change basis. Table A-230 and Table A-231 show the comparison of emission estimates using AR5 GWP values with climate-carbon feedbacks. The use of AR5 GWP values without climate-carbon feedbacks[205] results in an increase in emissions of CH_4 and SF_6 relative to AR4 GWP values, but a decrease in emissions of other gases. The use of AR5 GWP values with climate-carbon feedbacks does not impact CO_2 and N_2O emissions; however, it results in an increase in emissions of CH_4, SF_6, and NF_3 relative to AR4 GWP values, and has mixed impacts on emissions of other gases. Overall, switching between AR4 and AR5 GWP values does not have a significant effect on total calculated U.S. emissions, resulting in an increase in emissions of less than 1 percent using AR5 GWP values, or approximately 4 percent when using AR5 GWP values with climate-carbon feedbacks. The percent change in emissions is equal to the percent change in the GWP for each gas; however, in cases where multiple gases are emitted in varying amounts the percent change is variable over the years, such as with Substitution of Ozone Depleting Substances.

Table A-232 and Table A-233 show the comparison of emission estimates using AR6 GWP values relative to AR5 GWP values without climate-carbon feedbacks for the non-CO_2 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 2021 increase 0.3 percent relative to emissions estimated using AR5 GWPs). As with the comparison of AR4 and AR5 GWP values presented above, 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).

[205] The IPCC AR5 report provides additional information on emission metrics. See https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter08_FINAL.pdf.

Table A-228: Change in U.S. Greenhouse Gas Emissions Using AR4[a] Relative to AR5[b] GWP Values without Climate Carbon Feedbacks (MMT CO_2 Eq.)

Gas	1990	2005	2017	2018	2019	2020	2021
CO_2	NC	NC	NC	NC	NC	NC	NC
CH_4	(93.1)	(84.8)	(81.7)	(82.9)	(82.3)	(79.5)	(77.9)
N_2O	49.4	50.4	50.2	52.1	49.7	47.0	47.9
HFCs	7.5	10.9	10.2	10.1	10.5	10.6	11.1
PFCs	2.4	0.6	0.4	0.4	0.4	0.4	0.4
SF_6	(0.9)	(0.5)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
NF_3	+	+	+	+	+	+	+
Total	**(34.7)**	**(23.2)**	**(21.1)**	**(20.5)**	**(21.8)**	**(21.7)**	**(18.7)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

NC (No Change)

[a] AR4 values presented here exclude climate carbon feedbacks.

[b] The GWPs values in this column reflect values used in this report from AR5 excluding climate-carbon feedbacks and the value for fossil methane..

Notes: Total emissions presented without LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values.

Table A-229: Change in U.S. Greenhouse Gas Emissions Using AR4[a] Relative to AR5[b] GWP Values without Climate Carbon Feedbacks (Percent)

Gas/Source	1990	2005	2017	2018	2019	2020	2021
CO_2	NC	NC	NC	NC	NC	NC	NC
CH_4	(10.7%)	(10.7%)	(10.7%)	(10.7%)	(10.7%)	(10.7%)	(10.7%)
N_2O	12%	12%	12%	12%	12%	12%	12%
SF_6	(3.0%)	(3.0%)	(3.0%)	(3.0%)	(3.0%)	(3.0%)	(3.0%)
NF_3	6.8%	6.8%	6.8%	6.8%	6.8%	6.8%	6.8%
HFCs	19.2%	9.4%	6.4%	6.3%	6.3%	6.3%	6.4%
PFCs	11.1%	10.7%	10.5%	10.5%	10.7%	10.6%	10.5%
Total	**(0.5%)**	**(0.3%)**	**(0.3%)**	**(0.3%)**	**(0.3%)**	**(0.4%)**	**(0.3%)**

NC (No Change)

[a] AR4 values presented here exclude climate carbon feedbacks.

[b] The GWPs values in this column reflect values used in this report from AR5 excluding climate-carbon feedbacks and the value for fossil methane.

Notes: Total emissions presented without LULUCF. Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table A-230: Change in U.S. Greenhouse Gas Emissions Using AR5 with Climate-Carbon Feedbacks[a] Relative to AR5 without Climate-Carbon Feedbacks[b] (MMT CO_2 Eq.)

Gas	1990	2005	2017	2018	2019	2020	2021
CO_2	NC	NC	NC	NC	NC	NC	NC
CH_4	186.2	169.5	163.5	165.9	164.5	159.1	155.9
N_2O	49.5	50.6	50.3	52.2	49.8	47.1	48.0
HFCs	4.6	20.3	27.9	28.0	28.7	29.3	30.3
PFCs	+	+	+	+	+	+	+
SF_6	3.4	1.7	0.8	0.8	0.9	0.8	0.9
NF_3	+	+	0.1	0.1	0.1	0.1	0.1
Total	**246.1**	**242.8**	**242.9**	**247.5**	**244.4**	**236.7**	**235.6**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

NC (No Change)

[a] The GWP values presented here from the AR5 report include climate-carbon feedbacks for the non-CO_2 gases in order to be consistent with the approach used in calculating the CO_2 lifetime. Additionally, for methane the AR5 reported separate values for fossil versus biogenic methane in order to account for the CO_2 oxidation product and that is not shown on this table. See footnotes to Table A-225.

[b] The GWPs values in this column reflect values used in this report from AR5 excluding climate-carbon feedbacks and the value for fossil methane.

Notes: Total emissions presented without LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values.

Table A-231: 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	2017	2018	2019	2020	2021
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_2O	12.5%	12.5%	12.5%	12.5%	12.5%	12.5%	12.5%
SF_6	11.0%	11.0%	11.0%	11.0%	11.0%	11.0%	11.0%
NF_3	11.1%	11.1%	11.1%	11.1%	11.1%	11.1%	11.1%
HFCs	11.8%	17.4%	17.4%	17.4%	17.4%	17.4%	17.3%
PFCs	11.3%	11.2%	11.2%	11.2%	11.2%	11.1%	11.1%
Total	**3.8%**	**3.3%**	**3.7%**	**3.7%**	**3.7%**	**3.9%**	**3.7%**

NC (No Change)

[a] The GWP values presented here from the AR5 report include climate-carbon feedbacks for the non-CO_2 gases in order to be consistent with the approach used in calculating the CO_2 lifetime. Additionally, for methane the AR5 reported separate values for fossil versus biogenic methane in order to account for the CO_2 oxidation product and that is not shown on this table. See footnotes to Table A-225.

[b] The GWPs values in this column reflect values used in this report from AR5 excluding climate-carbon feedbacks and the value for fossil methane..

Notes: Total emissions presented without LULUCF. Parentheses indicate negative values. Excludes Sinks.

Table A-232: Change in U.S. Greenhouse Gas Emissions Using AR6 Relative to AR5 without Climate-Carbon Feedbacks[a] (MMT CO_2 Eq.)

Gas	1990	2005	2017	2018	2019	2020	2021
CO_2	NC	NC	NC	NC	NC	NC	NC
CH_4	(31.0)	(28.3)	(27.2)	(27.6)	(27.4)	(26.5)	(26.0)
N_2O	12.0	12.2	12.2	12.6	12.0	11.4	11.6
HFCs	6.9	20.3	28.3	28.3	29.0	29.5	30.7
PFCs	1.9	0.5	2.0	2.3	2.2	2.4	2.4
SF_6	2.2	1.1	0.5	0.5	0.6	0.5	0.6
NF_3	+	+	+	+	+	+	0.1
Total	**(8.0)**	**5.9**	**15.7**	**16.1**	**16.5**	**17.4**	**19.4**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

NC (No Change)

[a] The GWPs values in this column reflect values used in this report from AR5 excluding climate-carbon feedbacks and the value for fossil methane.

Notes: Total emissions presented without LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values.

Table A-233: Change in U.S. Greenhouse Gas Emissions Using AR6 Relative to AR5 without Climate-Carbon Feedbacks[a] (Percent)

Gas/Source	1990	2005	2017	2018	2019	2020	2021
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_2O	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%
SF_6	7.2%	7.2%	7.2%	7.2%	7.2%	7.2%	7.2%
NF_3	8.1%	8.1%	8.1%	8.1%	8.1%	8.1%	8.1%
HFCs	17.7%	17.5%	17.6%	17.6%	17.6%	17.6%	17.5%
PFCs	18.8%	17.4%	17.6%	17.6%	17.6%	17.6%	17.5%
Total	**(0.1%)**	**0.1%**	**0.2%**	**0.2%**	**0.2%**	**0.3%**	**0.3%**

NC (No Change)

+ Does not exceed 0.05 percent.

[a] The GWPs values in this column reflect values used in this report from AR5 excluding climate-carbon feedbacks and the value for fossil methane.

Notes: Total emissions presented without LULUCF. Parentheses indicate negative values. Excludes Sinks.

6.2. Ozone Depleting Substance Emissions

Ozone is present in both the stratosphere,[206] where it shields the earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere,[207] 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 1987, nations around the world signed the Montreal Protocol on Substances that Deplete the Ozone Layer. This landmark agreement created an international framework for 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.

In the United States, the Clean Air Act Amendments of 1990 provide the legal instrument for implementation of the Montreal Protocol controls. 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.[208] The production of CFCs, halons, carbon tetrachloride, and methyl chloroform—all Class I substances—has already ended in the United States. However, large amounts of these chemicals remain in existing equipment,[209] 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 are retired from use. Under current Montreal Protocol controls, however, the production for domestic use of all HCFCs as an ODS substitute in the United States must 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-10 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 does provide a range of net GWP values for ozone depleting substances. The *2006 IPCC Guidelines* and the UNFCCC do not include reporting instructions for estimating emissions of ODSs because their use is being phased out under the Montreal Protocol (see note below Table A-10). The effects of these compounds on radiative forcing are not addressed in this report.

[206] 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.

[207] 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.

[208] 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.

[209] Older refrigeration and air-conditioning equipment, fire extinguishing systems, and foam products blown with CFCs/HCFCs may still contain Class I ODS.

Table A-234: 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_3CCl_3	160
CCl_4	1,730
CH_3Br	2
Halon-1211	1,750
Halon-1301	6,290

Note: 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, in 1987 many governments signed the *Montreal Protocol on Substances that Deplete the Ozone Layer* to limit the production and importation of a number of CFCs and other halogenated compounds. The United States furthered its commitment to phase-out ODSs by signing and ratifying the Copenhagen Amendments to the Montreal Protocol in 1992. Under these amendments, the United States committed to ending the production and importation of halons by 1994, and CFCs by 1996, and HCFCs by 2030.
Source: IPCC (2013).

Although the IPCC emission inventory guidelines do not require the reporting of emissions of ozone depleting substances, the United States believes that the inventory presents a more complete picture of climate impacts when EPA includes these compounds. Emission estimates for several ozone depleting substances are provided in Table A-11.

Table A-235: Emissions of Ozone Depleting Substances (kt)

Compound	1990	2005	2017	2018	2019	2020	2021
Class I							
CFC-11	29	12	6	6	6	6	5
CFC-12	136	23	2	1	1	+	+
CFC-113	59	17	0	0	0	0	0
CFC-114	4	1	0	0	0	0	0
CFC-115	8	2	+	+	+	+	0
Carbon Tetrachloride	4	0	0	0	0	0	0
Methyl Chloroform	223	0	0	0	0	0	0
Halon-1211	2	2	1	1	1	1	1
Halon-1301	2	+	+	+	+	+	+
Class II							
HCFC-22	31	74	51	47	43	40	34
HCFC-123	0	1	1	1	1	1	1
HCFC-124	0	2	+	+	+	+	+
HCFC-141b	1	4	7	7	7	7	7
HCFC-142b	1	4	3	4	5	5	5
HCFC-225ca/cb	0	+	+	+	+	+	+

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 3.9, Methodology for Estimating HFC and PFC 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 Cross-Walk of National Emission Inventory (NEI) Categories to the National Inventory Report (NIR) – TO BE UPDATED FOR FINAL INVENTORY REPORT

Emissions of precursor gases (CO, NO_x, NMVOC, and SO_2) occur in all sectors and are summarized in Chapter 2, 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 guidelines. Table A-236 below indicates how NEI Tier 1/Tier 2 categories were recategorized from NEI source categories to those more closely aligned with National Inventory Report (NIR) categories and CRF categories, based on EPA (2022) 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 (2021); see Sections 5.7, 6.2, and 6.6.

Table A-236: Cross-walk of NEI and NIR Categories for Greenhouse Gas Precursors

NEI Category (Tier 1)	NEI Category (Tier 2)	NIR Chapter	NIR Category	CRF Category
Fuel Combustion Electric Utility	Coal	Energy	Fossil Fuel Combustion – Electric Power Sector	1.A.1.a Public Electricity and Heat Production
Fuel Combustion Electric Utility	Gas	Energy	Fossil Fuel Combustion – Electric Power Sector	1.A.1.a Public Electricity and Heat Production
Fuel Combustion Electric Utility	Internal Combustion	Energy	Fossil Fuel Combustion – Electric Power Sector	1.A.1.a Public Electricity and Heat Production
Fuel Combustion Electric Utility	Oil	Energy	Fossil Fuel Combustion – Electric Power Sector	1.A.1.a Public Electricity and Heat Production
Fuel Combustion Electric Utility	Other	Energy	Fossil Fuel Combustion – Electric Power Sector	1.A.1.a Public Electricity and Heat Production
Fuel Combustion Industrial	Coal	Energy	Fossil Fuel Combustion - Industrial	1.A.2.g Other (please specify)
Fuel Combustion Industrial	Gas	Energy	Fossil Fuel Combustion - Industrial	1.A.2.g Other (please specify)
Fuel Combustion Industrial	Internal Combustion	Energy	Fossil Fuel Combustion - Industrial	1.A.2.g Other (please specify)
Fuel Combustion Industrial	Oil	Energy	Fossil Fuel Combustion - Industrial	1.A.2.g Other (please specify)
Fuel Combustion Industrial	Other	Energy	Fossil Fuel Combustion - Industrial	1.A.2.g Other (please specify)
Fuel Combustion Other	Commercial/Institutional Coal	Energy	Fossil Fuel Combustion - Commercial	1.A.4.a Commercial/Institutional
Fuel Combustion Other	Commercial/Institutional Gas	Energy	Fossil Fuel Combustion - Commercial	1.A.4.a Commercial/Institutional
Fuel Combustion Other	Commercial/Institutional Oil	Energy	Fossil Fuel Combustion - Commercial	1.A.4.a Commercial/Institutional
Fuel Combustion Other	Misc. Fuel Combustion (Except Residential)	Energy	Fossil Fuel Combustion - Commercial	1.A.4.a Commercial/Institutional
Fuel Combustion Other	Residential Other	Energy	Fossil Fuel Combustion - Residential	1.A.4.b Residential
Fuel Combustion Other	Residential Wood	Energy	Fossil Fuel Combustion - Residential	1.A.4.b Residential
Petroleum and Related Industries	Asphalt Manufacturing	Energy	Other Energy	1.B.2.d Other
Petroleum and Related Industries	Oil & Gas Production	Energy	Petroleum and Natural Gas Systems	1.B.2.d Other
Petroleum and Related Industries	Petroleum Refineries & Related Industries	Energy	Petroleum and Natural Gas Systems	1.B.2.d Other
Highway Vehicles	Compressed Natural Gas (CNG)	Energy	Fossil Fuel Combustion - Transportation	1.A.3.b Road Transportation
Highway Vehicles	Diesel Fuel	Energy	Fossil Fuel Combustion - Transportation	1.A.3.b Road Transportation
Highway Vehicles	Electricity	Energy	Fossil Fuel Combustion - Transportation	1.A.3.b Road Transportation
Highway Vehicles	Ethanol (E-85)	Energy	Fossil Fuel Combustion - Transportation	1.A.3.b Road Transportation
Highway Vehicles	Gasoline	Energy	Fossil Fuel Combustion - Transportation	1.A.3.b Road Transportation
Off-Highway	Aircraft	Energy	Fossil Fuel Combustion - Transportation	1.A.3.a Domestic Aviation
Off-Highway	Marine Vessels	Energy	Fossil Fuel Combustion - Transportation	1.A.3.d Domestic Navigation
Off-Highway	Non-Road Diesel	Energy	Fossil Fuel Combustion - Transportation	1.A.3.e Other Transportation
Off-Highway	Non-Road Gasoline	Energy	Fossil Fuel Combustion - Transportation	1.A.3.e Other Transportation
Off-Highway	Other	Energy	Fossil Fuel Combustion - Transportation	1.A.3.e Other Transportation
Off-Highway	Railroads	Energy	Fossil Fuel Combustion - Transportation	1.A.3.c Railways

Chemical and Allied Product Manufacturing	Agricultural Chemical Manufacturing	IPPU	Chemical Industry	2.B.10 Other - Other non-specified
Chemical and Allied Product Manufacturing	Inorganic Chemical Manufacturing	IPPU	Chemical Industry	2.B.10 Other - Other non-specified
Chemical and Allied Product Manufacturing	Paint, Varnish, Lacquer, Enamel Manufacturing	IPPU	Chemical Industry	2.B.10 Other - Other non-specified
Chemical and Allied Product Manufacturing	Pharmaceutical Manufacturing	IPPU	Chemical Industry	2.B.10 Other - Other non-specified
Chemical and Allied Product Manufacturing	Organic Chemical Manufacturing	IPPU	Chemical Industry	2.B.10 Other - Other non-specified
Chemical and Allied Product Manufacturing	Other Chemical Manufacturing	IPPU	Chemical Industry	2.B.10 Other - Other non-specified
Chemical and Allied Product Manufacturing	Polymer & Resin Manufacturing	IPPU	Chemical Industry	2.B.10 Other - Other non-specified
Metals Processing	Ferrous Metals Processing	IPPU	Metal Industry	2.C.7 Other - Other non-specified
Metals Processing	Metals Processing NEC	IPPU	Metal Industry	2.C.7 Other - Other non-specified
Metals Processing	Non-Ferrous Metals Processing	IPPU	Metal Industry	2.C.7 Other - Other non-specified
Storage & Transport	Bulk Materials Storage	IPPU	Other Industrial Processes	2.H.3 Other – Storage and Transport
Storage & Transport	Bulk Materials Transport	IPPU	Other Industrial Processes	2.H.3 Other – Storage and Transport
Storage & Transport	Bulk Terminals & Plants	IPPU	Other Industrial Processes	2.H.3 Other – Storage and Transport
Storage & Transport	Inorganic Chemical Storage	IPPU	Other Industrial Processes	2.H.3 Other – Storage and Transport
Storage & Transport	Inorganic Chemical Transport	IPPU	Other Industrial Processes	2.H.3 Other – Storage and Transport
Storage & Transport	Petroleum & Petroleum Product Storage	IPPU	Other Industrial Processes	2.H.3 Other – Storage and Transport
Storage & Transport	Petroleum & Petroleum Product Transport	IPPU	Other Industrial Processes	2.H.3 Other – Storage and Transport
Storage & Transport	Service Stations: Breathing & Emptying	IPPU	Other Industrial Processes	2.H.3 Other – Storage and Transport
Storage & Transport	Service Stations: Stage I	IPPU	Other Industrial Processes	2.H.3 Other – Storage and Transport
Storage & Transport	Service Stations: Stage II	IPPU	Other Industrial Processes	2.H.3 Other – Storage and Transport
Solvent Utilization	Degreasing	IPPU	Other Industrial Processes	2.G.4 Other - Degreasing and Dry Cleaning
Solvent Utilization	Dry Cleaning	IPPU	Other Industrial Processes	2.G.4 Other - Degreasing and Dry Cleaning
Solvent Utilization	Graphic Arts	IPPU	Other Industrial Processes	2.G.4 Other - Graphic Arts
Solvent Utilization	Nonindustrial	IPPU	Other Industrial Processes	2.G.4 Other - Nonindustrial
Solvent Utilization	Solvent Utilization NEC	IPPU	Other Industrial Processes	2.G.4 Other - Other non-specified
Solvent Utilization	Other Industrial	IPPU	Other Industrial Processes	2.G.4 Other - Other non-specified
Solvent Utilization	Surface Coating	IPPU	Other Industrial Processes	2.G.4 Other - Surface Coating
Other Industrial Processes	Agriculture, Food, & Kindred Products	IPPU	Other Industrial Processes	2.H.3 Other - Other Industrial Processes
Other Industrial Processes	Construction	IPPU	Other Industrial Processes	2.H.3 Other - Other Industrial Processes
Other Industrial Processes	Electronic Equipment	IPPU	Other Industrial Processes	2.H.3 Other - Other Industrial Processes
Other Industrial Processes	Machinery Products	IPPU	Other Industrial Processes	2.H.3 Other - Other Industrial Processes

Other Industrial Processes	Mineral Products	IPPU	Mineral Industry	2.H.3 Other - Other Industrial Processes
Other Industrial Processes	Miscellaneous Industrial Processes	IPPU	Other Industrial Processes	2.H.3 Other - Other Industrial Processes
Other Industrial Processes	Rubber & Miscellaneous Plastic Products	IPPU	Other Industrial Processes	2.H.3 Other - Other Industrial Processes
Other Industrial Processes	Textiles, Leather, & Apparel Products	IPPU	Other Industrial Processes	2.H.3 Other - Other Industrial Processes
Other Industrial Processes	Transportation Equipment	IPPU	Other Industrial Processes	2.H.3 Other - Other Industrial Processes
Other Industrial Processes	Wood, Pulp & Paper, & Publishing Products	IPPU	Other Industrial Processes	2.H.3 Other - Other Industrial Processes
Miscellaneous	Agriculture & Forestry	IPPU	NA	NA
Miscellaneous	Health Services	IPPU	Miscellaneous	2.H.3 Other - Other Industrial Processes
Miscellaneous	Catastrophic/Accidental Releases	IPPU	Miscellaneous	2.H.3 Other - Other Industrial Processes
Miscellaneous	Other	IPPU	Miscellaneous	2.H.3 Other - Other Industrial Processes
Miscellaneous	Other Combustion	IPPU	Miscellaneous; NA[a]	2.H.3 Other - Other Industrial Processes
Miscellaneous	Other Fugitive Dust	IPPU	Miscellaneous	2.H.3 Other - Other Industrial Processes
Miscellaneous	Repair Shops	IPPU	Miscellaneous	2.H.3 Other - Other Industrial Processes
Waste Disposal and Recycling	Incineration	Energy	Incineration of Waste	1.A.5.a Stationary
Waste Disposal and Recycling	Open Burning	Energy	Incineration of Waste	1.A.5.a Stationary
Waste Disposal and Recycling	Landfills	Waste	Landfills	5.A.1 Managed Waste Disposal Sites
Waste Disposal and Recycling	POTW	Waste	Wastewater Treatment	5.D.1 Domestic Wastewater
Waste Disposal and Recycling	Industrial Waste Water	Waste	Wastewater Treatment	5.D.2 Industrial Wastewater
Waste Disposal and Recycling	TSDF	Waste	Miscellaneous	5.E Other - Other non-specified
Waste Disposal and Recycling	Other	Waste	Miscellaneous	5.E Other - Other non-specified
Natural Resources	Biogenic	NA	NA	NA
Natural Resources	Geogenic	NA	NA	NA
Natural Resources	Miscellaneous	NA	NA	NA
Wildfires		NA	NA[b]	NA

NA (Not Applicable)

[a] Miscellaneous - Other Combustion emissions from Structural Fires and other sources are allocated to the IPPU miscellaneous NIR category. Miscellaneous – Other Combustion emissions from agricultural fires, forest wildfires, and prescribed burning are not from the NEI and calculated separately in the NIR. Miscellaneous – Other Combustion emissions from Slash Burning (logging) are not included in the NIR.

[b] Wildfire emissions are not from the NEI and 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-237 provides a guide for determining the magnitude of metric units.

Table A-237: 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 Celsius = (Degrees Fahrenheit – 32)*5/9
Degrees Kelvin = Degrees Celsius + 273.15

Density Conversions[210]

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.

1 TJ =	2.388×10^{11} calories
	23.88 metric tons of crude oil equivalent
	947.8 million Btus
	277,800 kilowatt-hours

Converting Various Physical Units to Energy Units

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-238 can be used as default factors, if local data are not available. See Appendix A of EIA's *Monthly Energy Review, November 2021* (EIA 2021) for more detailed information on the energy content of various fuels.

[210] Reference: EIA (2007)

Table A-238: 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)	**1,037**
Liquid Fuels (Million Btu/Barrel)	
Motor gasoline	5.052
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	6.000
Misc. products	5.796

Notes: For petroleum and natural gas, *Monthly Energy Review, November 2022* (EIA 2022). 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-239: Guide to Chemical Formulas

Symbol	Name
Al	Aluminum
Al_2O_3	Aluminum oxide
Br	Bromine
C	Carbon
CH_4	Methane
C_2H_6	Ethane
C_3H_8	Propane
CF_4	Perfluoromethane
C_2F_6	Perfluoroethane, hexafluoroethane
c-C_3F_6	Perfluorocyclopropane
C_3F_8	Perfluoropropane
C_4F_6	Hexafluoro-1,3-butadiene
c-C_4F_8	Perfluorocyclobutane
C_4F_8O	Octafluorotetrahydrofuran
C_4F_{10}	Perfluorobutane
c-C_5F_8	Perfluorocyclopentene
C_5F_{12}	Perfluoropentane
C_6F_{14}	Perfluorohexane
CF_3I	Trifluoroiodomethane
$CFCl_3$	Trichlorofluoromethane (CFC-11)
CF_2Cl_2	Dichlorodifluoromethane (CFC-12)
CF_3Cl	Chlorotrifluoromethane (CFC-13)
$C_2F_3Cl_3$	Trichlorotrifluoroethane (CFC-113)*
CCl_3CF_3	CFC-113a*
$C_2F_4Cl_2$	Dichlorotetrafluoroethane (CFC-114)
C_2F_5Cl	Chloropentafluoroethane (CFC-115)
$CHCl_2F$	HCFC-21
CHF_2Cl	Chlorodifluoromethane (HCFC-22)
$C_2F_3HCl_2$	HCFC-123
C_2F_4HCl	HCFC-124
$C_2FH_3Cl_2$	HCFC-141b
$C_2H_3F_2Cl$	HCFC-142b
$CF_3CF_2CHCl_2$	HCFC-225ca
$CClF_2CF_2CHClF$	HCFC-225cb
CCl_4	Carbon tetrachloride
$CHClCCl_2$	Trichloroethylene
CCl_2CCl_2	Perchloroethylene, tetrachloroethene
CH_3Cl	Methylchloride
CH_3CCl_3	Methylchloroform
CH_2Cl_2	Methylenechloride
$CHCl_3$	Chloroform, trichloromethane
CHF_3	HFC-23
CH_2F_2	HFC-32
CH_3F	HFC-41
C_2HF_5	HFC-125
$C_2H_2F_4$	HFC-134
CH_2FCF_3	HFC-134a
$C_2H_3F_3$	HFC-143*
$C_2H_3F_3$	HFC-143a*
CH_2FCH_2F	HFC-152*
$C_2H_4F_2$	HFC-152a*

CH_3CH_2F	HFC-161
C_3HF_7	HFC-227ea
$CF_3CF_2CH_2F$	HFC-236cb
$CF_3CHFCHF_2$	HFC-236ea
$C_3H_2F_6$	HFC-236fa
$C_3H_3F_5$	HFC-245ca
$CHF_2CH_2CF_3$	HFC-245fa
$CF_3CH_2CF_2CH_3$	HFC-365mfc
$C_5H_2F_{10}$	HFC-43-10mee
CF_3OCHF_2	HFE-125
CF_2HOCF_2H	HFE-134
CH_3OCF_3	HFE-143a
$CF_3CHFOCF_3$	HFE-227ea
$CF_3CHClOCHF_2$	HCFE-235da2
$CF_3CHFOCHF_2$	HFE-236ea2
$CF_3CH_2OCF_3$	HFE-236fa
$CF_3CF_2OCH_3$	HFE-245cb2
$CHF_2CH_2OCF_3$	HFE-245fa1
$CF_3CH_2OCHF_2$	HFE-245fa2
$CHF_2CF_2OCH_3$	HFE-254cb2
$CF_3CH_2OCH_3$	HFE-263fb2
$CF_3CF_2OCF_2CHF_2$	HFE-329mcc2
$CF_3CF_2OCH_2CF_3$	HFE-338mcf2
$CF_3CF_2CF_2OCH_3$	HFE-347mcc3
$CF_3CF_2OCH_2CHF_2$	HFE-347mcf2
$CF_3CHFCF_2OCH_3$	HFE-356mec3
$CHF_2CF_2CF_2OCH_3$	HFE-356pcc3
$CHF_2CF_2OCH_2CHF_2$	HFE-356pcf2
$CHF_2CF_2CH_2OCHF_2$	HFE-356pcf3
$CF_3CF_2CH_2OCH_3$	HFE-365mcf3
$CHF_2CF_2OCH_2CH_3$	HFE-374pcf2
$C_4F_9OCH_3$	HFE-7100
$C_4F_9OC_2H_5$	HFE-7200
CH_2CFCF_3	HFO-1234yf
$CHFCHCF_3$	HFO-1234ze(E)
$CF_3CHCHCF_3$	HFO-1336mzz(Z)
$C_3H_2ClF_3$	HCFO-1233zd(E)
$CHF_2OCF_2OC_2F_4OCHF_2$	H-Galden 1040x
$CHF_2OCF_2OCHF_2$	HG-10
$CHF_2OCF_2CF_2OCHF_2$	HG-01
CH_3OCH_3	Dimethyl ether
CH_2Br_2	Dibromomethane
CH_2BrCl	Dibromochloromethane
$CHBr_3$	Tribromomethane
$CHBrF_2$	Bromodifluoromethane
CH_3Br	Methylbromide
CF_2BrCl	Bromodichloromethane (Halon 1211)
$CF_3Br(CBrF_3)$	Bromotrifluoromethane (Halon 1301)
CF_3I	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_2O_3	Ferric oxide
FeSi	Ferrosilicon
GaAs	Gallium arsenide
H, H_2	atomic Hydrogen, molecular Hydrogen
H_2O	Water
H_2O_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_2O	Nitrous oxide
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_3	Nitrate radical
NO_x	Nitrogen oxides
Na	Sodium
Na_2CO_3	Sodium carbonate, soda ash
Na_3AlF_6	Synthetic cryolite
O, O_2	atomic Oxygen, molecular Oxygen
O_3	Ozone
S	atomic Sulfur
H_2SO_4	Sulfuric acid
SF_6	Sulfur hexafluoride
SF_5CF_3	Trifluoromethylsulphur pentafluoride
SO_2	Sulfur dioxide
Si	Silicon
SiC	Silicon carbide
SiO_2	Quartz

1 * Distinct isomers.

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ANNEX 7 Uncertainty – TO BE UPDATED FOR FINAL INVENTORY REPORT

The annual U.S. Inventory presents the best effort to produce emission estimates for greenhouse gas source and sink categories in the United States. These estimates were generated according to the UNFCCC reporting guidelines, 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 U.S. Inventory, including the sources of uncertainty characterized throughout the Inventory associated with various source categories (including emissions and sinks), and the methods used to collect, quantify, and present this uncertainty information. An Addendum to Annex 7 is provided separately which includes additional information related to the uncertainty characteristics of input variables used in the development of the overall uncertainty estimates reported in Section 1.7 of the Inventory report.

7.1. Overview

The uncertainty analysis conducted in support of the Inventory (1) determines the quantitative uncertainty associated with the emission source and sink estimates presented in the main body of this report, (2) evaluates the relative contribution of the input parameters to the uncertainty associated with each source or sink category estimate and in the overall inventory and (3) estimates the uncertainty in the overall emissions 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 U.S. 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, such as CO_2 emissions from energy-related combustion activities, the impact of uncertainties on overall emission estimates is relatively small. For some other limited categories of emissions, uncertainties could have a larger impact on the estimates presented (i.e., storage factors of non-energy uses of fossil fuels). In all source and sink category chapters, the inventory emission estimates include "Uncertainty and Time-Series Consistency" 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. Given the very low emissions for these source categories, uncertainty estimates were not derived.

7.2. Methodology and Results

The United States has developed both a quality assurance and quality control (QA/QC) and uncertainty management plan (EPA 2002). 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 U.S. plan includes procedures and guidelines, and forms and templates, for developing quantitative assessments of uncertainty in the national Inventory estimates (EPA 2002). For the 1990 through 2020 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 United States is continuing efforts to develop quantitative estimates of uncertainty for all source categories using Approach 2. In following the UNFCCC requirement under Article 4.1, 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 U.S. Inventory; therefore, no quantitative uncertainty estimates have been developed for these categories.[157] CO_2 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 CO_2 emissions from Biomass and Biofuel Consumption as a memo item for informational purposes, consistent with the UNFCCC reporting requirements.

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., non-gaussian), (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 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.

[157] 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.

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 than 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 body of this report provides an overview of the input parameters and sources of uncertainty for each source and sink category. Table A-240 summarizes results based on assessments of source and sink category-level uncertainty. The table presents base year (1990) and current year (2020) 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 2020 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-240: Summary Results of Source and Sink Category Uncertainty Analyses

Source or Sink Category	Base Year Emissions[a]	2020 Emissions[b]	2020 Uncertainty[b]	
	MMT CO_2 Eq.	MMT CO_2 Eq.	Lower Bound	Upper Bound
CO_2	**5,122.5**	**4,715.7**	**-3%**	**3%**
Fossil Fuel Combustion	4,731.2	4,342.7	-2%	4%
Non-Energy Use of Fuels	112.2	121.0	-37%	49%
Cement Production	33.5	40.7	-6%	6%
Iron and Steel Production & Metallurgical Coke	*104.7*	*37.7*	*-17%*	17%
Natural Gas Systems	*31.9*	*35.4*	-16%	19%
Petroleum Systems	9.6	30.2	*-22%*	26%
Petrochemical Production	21.6	30.0	-5%	6%
Incineration of Waste	12.9	13.1	-17%	17%
Ammonia Production	13.0	12.7	-10%	11%
Lime Production	11.7	11.3	-2%	2%
Other Process Uses of Carbonates	6.2	9.8	-19%	29%
Urea Consumption for Non-Agricultural Purposes	3.8	6.0	-14%	14%
Urea Fertilization	2.4	5.3	-43%	3%
Carbon Dioxide Consumption	1.5	5.0	-5%	5%
Liming	4.7	2.4	-111%	98%
Coal Mining	4.6	2.2	-68%	76%
Glass Production	2.3	1.9	-2%	2%
Aluminum Production	6.8	1.7	-2%	2%
Soda Ash Production	1.4	1.5	-9%	8%
Ferroalloy Production	2.2	1.4	-13%	13%
Titanium Dioxide Production	1.2	1.3	-13%	13%
Zinc Production	0.6	1.0	-19%	20%
Phosphoric Acid Production	1.5	0.9	-18%	20%
Lead Production	0.5	0.5	-15%	16%
Carbide Production and Consumption	0.2	0.2	-9%	9%
Abandoned Oil and Gas Wells	+	+	-83%	197%
Magnesium Production and Processing	0.1	+	-4%	4%
Wood Biomass, Ethanol, and Biodiesel Consumption[c]	*219.4*	*291.6*	*NE*	*NE*
International Bunker Fuels[d]	*103.6*	*69.6*	*NE*	*NE*
CH_4	**780.8**	**650.4**	**-10%**	**10%**
Enteric Fermentation	163.5	175.2	-11%	18%
Natural Gas Systems	195.5	164.9	-18%	18%
Landfills	176.6	109.3	-23%	22%

Manure Management	34.8	59.6	-18%	20%
Coal Mining	96.5	41.2	-9%	17%
Petroleum Systems	47.8	40.2	-28%	32%
Wastewater Treatment	20.3	18.3	-35%	23%
Rice Cultivation	16.0	15.7	-75%	75%
Stationary Combustion	8.6	7.9	-34%	125%
Abandoned Oil and Gas Wells	6.5	6.9	-83%	197%
Abandoned Underground Coal Mines	7.2	5.8	-22%	20%
Composting	0.4	2.3	-58%	58%
Mobile Combustion	6.5	2.2	-8%	24%
Field Burning of Agricultural Residues	0.4	0.4	-18%	18%
Petrochemical Production	0.2	0.3	-57%	46%
Anaerobic Digestion at Biogas Facilities	+	0.2	-54%	54%
Carbide Production and Consumption	+	+	-9%	9%
Ferroalloy Production	+	+	-12%	13%
Iron and Steel Production & Metallurgical Coke	+	+	-21%	23%
Anaerobic Digestion at Biogas Facilities	+	+	NE	NE
International Bunker Fuels[d]	*0.2*	*0.1*	*NE*	*NE*
N_2O	**450.5**	**426.1**	**-21%**	**27%**
Agricultural Soil Management	316.0	316.2	-27%	26%
Stationary Combustion	25.1	23.2	-24%	51%
Manure Management	13.9	19.7	-16%	24%
Mobile Combustion	44.6	17.4	-8%	19%
Wastewater Treatment	16.6	23.5	-35%	194%
Nitric Acid Production	12.1	9.3	-5%	5%
Adipic Acid Production	15.2	8.3	-5%	5%
N_2O from Product Uses	4.2	4.2	-24%	24%
Composting	0.3	2.0	-58%	58%
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.7	1.2	-31%	32%
Incineration of Waste	0.5	0.4	-53%	162%
Electronics Industry	+	0.3	-10%	11%
Field Burning of Agricultural Residues	0.2	0.2	-17%	17%
Petroleum Systems	+	+	-22%	26%
Natural Gas Systems	+	+	-16%	19%
International Bunker Fuels[d]	*0.9*	*0.6*	*NE*	*NE*
HFCs, PFCs, SF_6 and NF_3	**99.7**	**189.2**	**-8%**	**8%**
Substitution of Ozone Depleting Substances	0.2	176.3	-3%	14%
Electronics Industry	3.6	4.4	-6%	7%
Electrical Transmission and Distribution	23.2	3.8	-16%	18%
HCFC-22 Production	46.1	2.1	-7%	10%
Aluminum Production	21.5	1.7	-6%	7%
Magnesium Production and Processing	5.2	0.9	-9%	9%
Total Gross Emissions[e]	**6,453.5**	**5,981.4**	**-3%**	**3%**
LULUCF Emissions[f]	31.4	53.2	-17%	18%
LULUCF Carbon Stock Change Flux[g]	(892.0)	(812.2)	25%	-25%
LULUCF Sector Net Total[h]	**(860.6)**	**(758.9)**	**27%**	**-26%**
Net Emissions (Sources and Sinks)[e]	**5,592.8**	**5,222.4**	**-6%**	**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.

\+ Does not exceed 0.05 MMT CO_2 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.

[d] Emissions from International Bunker Fuels are not included in the totals.

[e] Totals exclude emissions for which uncertainty was not quantified.

[f] LULUCF emissions include the CH_4 and N_2O emissions reported for Peatlands Remaining Peatlands, forest fires, drained organic soils, grassland fires, and Coastal Wetlands Remaining Coastal Wetlands; CH_4 emissions from Land Converted to Coastal Wetlands, Land Converted to Flooded Land, and Flooded Land Remaining Flooded Land; and N_2O emissions from forest soils and settlement soils.

[g] 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.

[h] The LULUCF Sector Net Total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Overall (Aggregate) Inventory Level Uncertainty Estimates

The overall level uncertainty estimate for the U.S. Inventory was developed using the IPCC Approach 2 uncertainty estimation methodology for 1990 and 2020. 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) across all sources and categories as a function of gas. 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 6,330.2 to 6,761.5 MMT CO_2 Eq., reflecting a relative 95 percent confidence interval uncertainty range of -2 percent to 5 percent with respect to the total U.S. greenhouse gas emission estimate of approximately 6,453.5 MMT CO_2 Eq. The uncertainty interval associated with total CO_2 emissions, ranges from -2 percent to 5 percent of total CO_2 emissions estimated. The results indicate that the uncertainty associated with the inventory estimate of the total CH_4 emissions ranges from -8 percent to 12 percent, uncertainty associated with the total inventory N_2O emission estimate ranges from -19 percent to 28 percent, and uncertainty associated with fluorinated greenhouse gas (F-GHG) emissions ranges from -9 percent to 13 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 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-241: Quantitative Uncertainty Assessment of Overall National Inventory Emissions for 1990 (MMT CO_2 Eq. and Percent)

Gas	1990 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to GHG Estimate[a]				Mean[b]	Standard Deviation[b]
		(MMT CO_2 Eq.)		(%)		(MMT CO_2 Eq.)	
		Lower Bound[c]	Upper Bound[c]	Lower Bound	Upper Bound		
CO_2	5,122.5	5,017.3	5,357.6	-2%	5%	5,186.5	88.0
CH_4[d]	780.8	720.1	871.5	-8%	12%	794.9	38.8
N_2O[d]	450.5	365.6	574.9	-19%	28%	457.8	54.1
PFCs, HFCs, SF_6, and NF_3[d]	99.7	90.2	112.5	-9%	13%	100.4	5.6
Total Gross Emissions	**6,453.5**	**6,330.2**	**6,761.5**	**-2%**	**5%**	**6,539.5**	**110.6**
LULUCF Emissions[e]	31.4	29.3	33.8	-7%	8%	31.5	1.1
LULUCF Carbon Stock Change Flux[f]	(892.0)	(1,183.9)	(709.3)	33%	-20%	(944.1)	119.3
LULUCF Sector Net Total[g]	**(860.6)**	**(1,152.7)**	**(677.7)**	**34%**	**-21%**	**(912.6)**	**119.3**
Net Emissions (Sources and Sinks)	**5,592.8**	**5,306.8**	**5,953.6**	**-5%**	**6%**	**5,626.9**	**163.9**

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.

[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 CH_4, N_2O, and high GWP gases used in the inventory emission calculations for 1990.

[e] LULUCF emissions include the CH_4 and N_2O emissions reported for Peatlands Remaining Peatlands, forest fires, drained organic soils, grassland fires, and Coastal Wetlands Remaining Coastal Wetlands; CH_4 emissions from Land Converted to Coastal Wetlands, Land Converted to Flooded Land, and Flooded Land Remaining Flooded Land; and N_2O 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 CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

The overall uncertainty model results indicate that the 2020 U.S. greenhouse gas emissions are estimated to be within the range of approximately 5,863.8 to 6,253.0 MMT CO_2 Eq., reflecting a relative 95 percent confidence interval uncertainty range of -3 percent to 3 percent with respect to the total gross U.S. greenhouse gas emission estimate of approximately 5,981.4 MMT CO_2 Eq. The uncertainty interval associated with total CO_2 emissions, which constitute about 79 percent of the total U.S. greenhouse gas emissions in 2020, ranges from -3 percent to 3 percent of total CO_2 emissions estimated. The results indicate that the uncertainty associated with the inventory estimate of the total CH_4 emissions ranges from -10 percent to 10 percent, uncertainty associated with the total inventory N_2O emission estimate ranges from -21 percent to 27 percent, and uncertainty associated with fluorinated greenhouse gas (F-GHG) emissions ranges from -8 percent to 8 percent. When the LULUCF sector is included in the analysis, the uncertainty is estimated to be -6 to 6 percent of Net Emissions (sources and sinks) in 2020.

A summary of the overall quantitative uncertainty estimates is shown below.

Table A-242: Quantitative Uncertainty Assessment of Overall National Inventory Emissions for 2020 (MMT CO_2 Eq. and Percent)

Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to GHG Estimate[a]				Mean[b]	Standard Deviation[b]
		(MMT CO_2 Eq.)		(%)		(MMT CO_2 Eq.)	
		Lower Bound[c]	Upper Bound[c]	Lower Bound	Upper Bound		
CO_2	4,715.7	4,610.6	4,908.0	-3%	3%	4,759.8	76.4
CH_4[d]	650.4	595.9	723.6	-10%	10%	659.7	32.6
N_2O[d]	426.1	342.4	551.1	-21%	27%	436.1	53.3
PFC, HFC, SF_6, and NF_3[d]	189.2	182.6	213.7	-8%	8%	198.2	7.9
Total Gross Emissions	**5,981.4**	**5,863.8**	**6,253.0**	**-3%**	**3%**	**6,053.7**	**98.2**
LULUCF Emissions[e]	53.2	44.4	62.9	-17%	18%	53.5	4.9
LULUCF Carbon Stock Change Flux[f]	(812.2)	(1,075.7)	(647.8)	25%	-25%	(860.2)	109.4
LULUCF Sector Net Total[g]	**(758.9)**	**(1,023.2)**	**(594.5)**	**27%**	**-26%**	**(806.7)**	**109.6**
Net Emissions (Sources and Sinks)	**5,222.4**	**4,956.9**	**5,540.9**	**-6%**	**6%**	**5,247.0**	**148.1**

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.

[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 CH_4, N_2O, and high GWP gases used in the inventory emission calculations for 2020.

[e] LULUCF emissions include the CH_4 and N_2O emissions reported for Peatlands Remaining Peatlands, forest fires, drained organic soils, grassland fires, and Coastal Wetlands Remaining Coastal Wetlands; CH_4 emissions from Land Converted to Coastal Wetlands, Land Converted to Flooded Land, and Flooded Land Remaining Flooded Land; and N_2O 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 CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

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., 2020) 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 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., 2020), 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 submission, 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., 2020) 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 2020 and are shown in Table A-243.

Table A-243: Quantitative Assessment of Trend Uncertainty (MMT CO_2 Eq. and Percent)

Gas/Source	Base Year Emissions[a]	2020 Emissions	Emissions Trend	Trend Range[b]	
	(MMT CO_2 Eq).)		(%)	(%)	
				Lower Bound	Upper Bound
CO_2	**5,122.5**	**4,715.7**	**-8%**	**-12%**	**-4%**
Fossil Fuel Combustion	4,731.2	4,342.7	-8%	-13%	-4%
Non-Energy Use of Fuels	112.2	121.0	8%	-39%	80%
Cement Production	33.5	40.7	22%	7%	40%
Iron and Steel Production & Metallurgical Coke Production	104.7	37.7	-64%	-72%	-55%
Natural Gas Systems	31.9	35.4	11%	-14%	42%
Petroleum Systems	9.6	30.2	214%	115%	357%
Petrochemical Production	21.6	30.0	39%	28%	51%
Incineration of Waste	12.9	13.1	2%	-20%	30%
Ammonia Production	13.0	12.7	-3%	-18%	19%
Lime Production	11.7	11.3	-3%	-6%	-1%
Other Process Uses of Carbonates	6.2	9.8	57%	24%	113%
Urea Consumption for Non-Agricultural Purposes	3.8	6.0	58%	27%	97%
Urea Fertilization	2.4	5.3	118%	23%	281%
Carbon Dioxide Consumption	1.5	5.0	238%	196%	288%
Liming	4.7	2.4	-49%	-601%	523%
Coal Mining	4.6	2.2	-53%	-87%	68%
Glass Production	2.3	1.9	-19%	-22%	-16%
Aluminum Production	6.8	1.7	-74%	-75%	-73%
Soda Ash Production	1.4	1.5	2%	-10%	16%
Ferroalloy Production	2.2	1.4	-36%	-46%	-24%
Titanium Dioxide Production	1.2	1.3	12%	-7%	34%
Zinc Production	0.6	1.0	60%	22%	109%
Phosphoric Acid Production	1.5	0.9	-39%	-55%	-17%
Lead Production	0.5	0.5	-4%	-22%	18%
Carbide Production and Consumption	0.2	0.2	-37%	-48%	-21%
Abandoned Oil and Gas Wells	0.0	+	9%	-1494%	1331%
Magnesium Production and Processing	0.1	+	-99%	-99%	-99%
Wood Biomass and Biofuel Consumption[c]	*219.4*	*291.6*	*33%*	*NE*	*NE*
International Bunker Fuels[d]	*103.6*	*69.6*	*-33%*	*NE*	*NE*
CH_4	**780.8**	**650.4**	**-17%**	**-28%**	**-5%**
Enteric Fermentation	163.5	175.2	7%	-21%	45%
Natural Gas Systems	195.5	164.9	-16%	-35%	9%
Landfills	176.6	109.3	-38%	-56%	-12%
Manure Management	34.8	59.6	71%	9%	168%
Coal Mining	96.5	41.2	-57%	-64%	-49%
Petroleum Systems	47.8	40.2	-16%	-46%	33%
Wastewater Treatment	20.3	18.3	-10%	-46%	30%
Rice Cultivation	16.0	15.7	-2%	-528%	905%
Stationary Combustion	8.6	7.9	-8%	-66%	156%
Abandoned Oil and Gas Wells	6.5	6.9	6%	-87%	752%
Abandoned Underground Coal Mines	7.2	5.8	-20%	-43%	13%
Composting	0.4	2.3	498%	161%	1255%
Mobile Combustion	6.5	2.2	-66%	-70%	-58%
Field Burning of Agricultural Residues	0.4	0.4	14%	-22%	66%
Petrochemical Production	0.2	0.3	43%	-43%	251%
Anaerobic Digestion at Biogas Facilities	+	0.2	952%	349%	2386%
Carbide Production and Consumption	+	+	-46%	-57%	-30%

Ferroalloy Production	+	+	-43%	-52%	-33%
Iron and Steel Production & Metallurgical Coke Production	+	+	-69%	-77%	-59%
Incineration of Waste	+	+	-13%	*NE*	*NE*
International Bunker Fuels[d]	*0.2*	*0.1*	*-54%*	*NE*	*NE*
N_2O	**450.5**	**426.1**	**-5%**	**-31%**	**32%**
Agricultural Soil Management	316.0	316.2	0%	-36%	58%
Stationary Combustion	25.1	23.2	-7%	-48%	71%
Manure Management	13.9	19.7	41%	-7%	115%
Mobile Combustion	44.6	17.4	-61%	-70%	-43%
Wastewater Treatment	16.6	23.5	42%	-55%	268%
Nitric Acid Production	12.1	9.3	-23%	-29%	-18%
Adipic Acid Production	15.2	8.3	-45%	-48%	-42%
N_2O from Product Uses	4.2	4.2	0%	-25%	28%
Composting	0.3	2.0	498%	167%	1249%
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.7	1.2	-28%	-54%	15%
Incineration of Waste	0.5	0.4	-13%	-76%	203%
Electronics Industry	+	0.3	730%	454%	1518%
Field Burning of Agricultural Residues	0.2	0.2	15%	-20%	65%
Petroleum Systems	+	+	153%	50%	329%
Natural Gas Systems	+	+	105%	40%	197%
International Bunker Fuels[d]	*0.9*	*0.6*	*-30%*	*NE*	*NE*
HFCs, PFCs, SF_6, and NF_3	**99.7**	**189.2**	**90%**	**73%**	**125%**
Substitution of Ozone Depleting Substances	0.2	176.3	77486%	29230%	797019%
Electronics Industry	3.6	4.4	25%	10%	42%
Electrical Transmission and Distribution	23.2	3.8	-84%	-89%	-75%
HCFC-22 Production	46.1	2.1	-95%	-96%	-95%
Aluminum Production	21.5	1.7	-92%	-93%	-92%
Magnesium Production and Processing	5.2	0.9	-82%	-85%	-78%
Total Gross Emissions[e]	**6,453.5**	**5,981.4**	**-7%**	**-12%**	**-3%**
LULUCF Emissions[f]	31.4	53.2	70%	39%	103%
LULUCF Carbon Stock Change Flux[g]	(892.0)	(812.2)	-9%	-37%	30%
LULUCF Sector Net Total[h]	**(860.6)**	**(758.9)**	**-12%**	**-40%**	**28%**
Net Emissions (Sources and Sinks)[e]	**5,592.8**	**5,222.4**	**-7%**	**-14%**	**1%**

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.

\+ Does not exceed 0.05 MMT CO_2 Eq. or 0.5 percent.

NE (Not Estimated)

[a] Base Year is 1990 for all sources.

[b] The 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.

[c] Emissions from Wood Biomass and Biofuel Consumption are not included specifically in the energy sector totals.

[d] Emissions from International Bunker Fuels are not included in the totals.

[e] Totals exclude emissions for which uncertainty was not quantified.

[f] LULUCF emissions include the CH_4 and N_2O emissions reported for Peatlands Remaining Peatlands, forest fires, drained organic soils, grassland fires, and Coastal Wetlands Remaining Coastal Wetlands; CH_4 emissions from Land Converted to Coastal Wetlands, Land Converted to Flooded Land, and Flooded Land Remaining Flooded Land; and N_2O emissions from forest soils and settlement soils.

[g] 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.

[i] The LULUCF Sector Net Total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

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 and Time-Series Consistency 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 (e.g., the 2023 or 2024 Inventory 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 U.S. 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 methodological 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 reducing 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 CO_2 equivalent each year. The reported GHGRP data undergo a multi-step verification process, including automated data checks to ensure consistency, comparison against expected ranged for similar facilities and industries, and statistical analysis. See Annex 9 for more information on use of GHGRP data in the Inventory.

In addition to improving Inventory input data and methodologies, the use of EPA's GHGRP data also reduces uncertainty in select Inventory emission categories. For example, replacing highly uncertain emission factor estimates with GHGRP data for the Coal Mining category reduced the 95 percent uncertainty bounds for methane emissions from this category from -15 percent to 18 percent in the 1990 to 2011 inventory down to -9 percent to 17 percent in the current (1990 to 2020) Inventory. Methane emission estimates from MSW landfills were also revised with GHGRP data, which resulted in methodological and data quality improvements that also reduced the 95 percent uncertainty bounds for this category compared to the prior use of default emission factors with larger assumed uncertainties.

Additional ongoing improvements to the U.S. Inventory uncertainty analyses for select categories will help to *eliminate 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. 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 (1990 to 2020) 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. 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, etc.), updating methods for select sources (e.g., Offshore Production, unassigned high-emitters), or including new sources (e.g., anomalous leak events)

within the Petroleum and Natural Gas System categories. 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 include the incorporation of new, more accurate and representative data, updates to emission models and conceptualization (including moving to Tier 2 methods for all sources), as well as revised uncertainty estimates to the account for recent updates. 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, including efforts to improve the accuracy of emission factors, collect more detailed and representative activity data, as well as provide better estimates of input parameter uncertainty. For example, further research is needed in some cases to improve the accuracy of emission factors, including those currently applied to CH_4 and N_2O 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.

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 assumptions described above due to limited data availability in the base year.

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ANNEX 8 QA/QC Procedures – TO BE UPDATED FOR FINAL INVENTORY REPORT

8.1. Background

The purpose of this annex is to describe 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; proper management, incorporation, and aggregation of data; and review of the numbers and estimates to ensure that they are as accurate and transparent as possible. Quality control—in the form of both good practices (such as documentation procedures) and checks on whether good practices and procedures are being followed—is applied at every stage of inventory development and document preparation. In addition, quality assurance occurs at two stages—an expert review and a public review. While both phases can significantly contribute to 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 the inventory data and methods. As described in respective source 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 Management Plan) guides the process of ensuring the quality of the Inventory. The QA/QC Management 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 Management Plan procedures also stress continual improvement, providing for corrective actions that are designed to improve the inventory estimates over time.

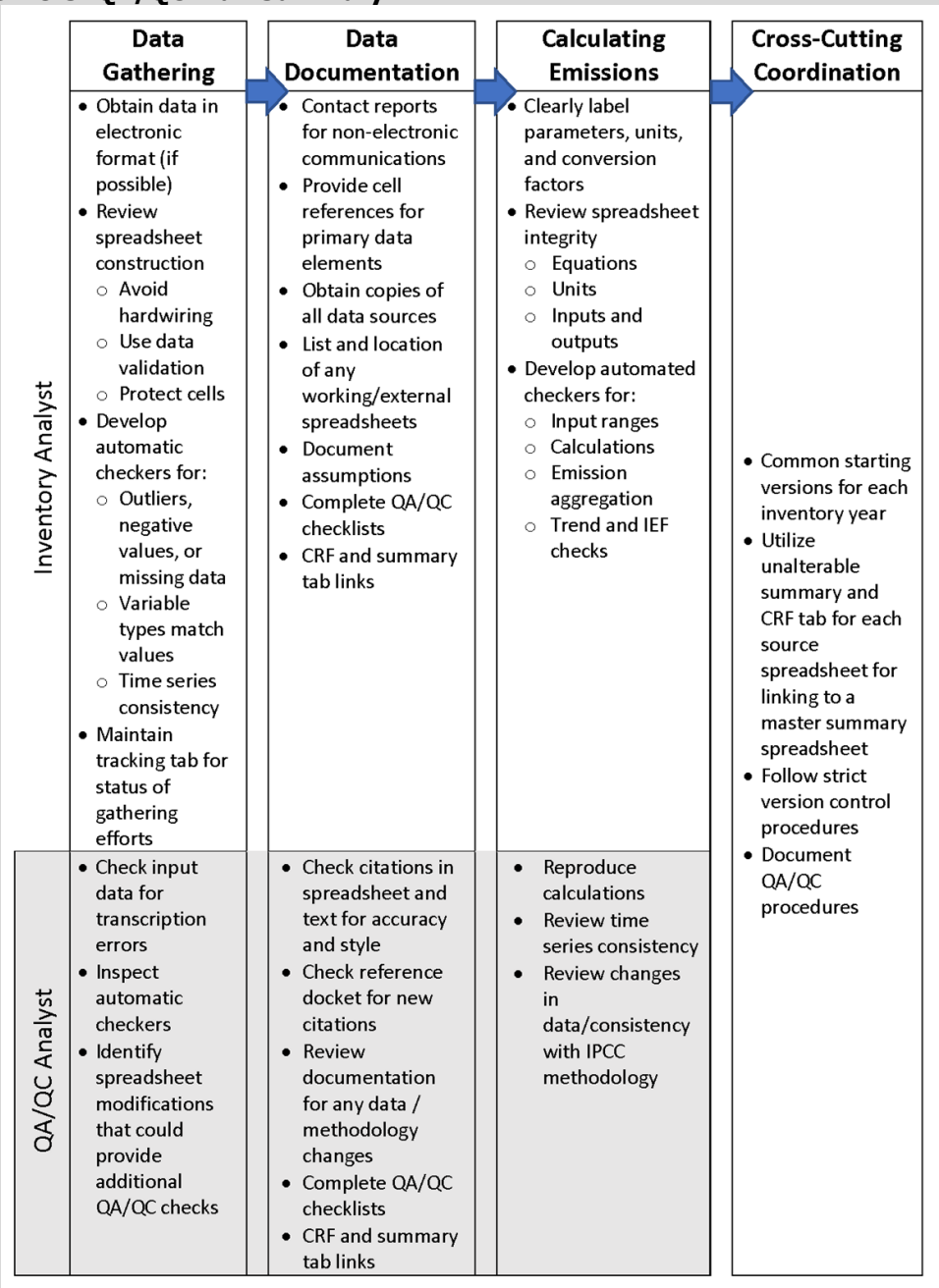
Key attributes of the QA/QC Management Plan are summarized in Figure A-19. These attributes include:

- *Procedures and Forms:* detailed and specific systems that serve to standardize the process of documenting and archiving information, as well as to guide the implementation of QA/QC and the analysis of uncertainty.
- *Implementation of Procedures:* application of QA/QC procedures throughout the whole Inventory development process from initial data collection, through preparation of the emission estimates, to publication of the Inventory.
- *Quality Assurance:* expert and public reviews for both the Inventory estimates and the report (which is the primary vehicle for disseminating the results of the Inventory development process). The expert technical review conducted by the UNFCCC supplements these QA processes, consistent with the QA good practice recommended in the *2006 IPCC Guidelines* (IPCC 2006).
- *Quality Control*: application of *General (Tier 1) and Category-specific (Tier 2)* quality controls and checks, as recommended by *2006 IPCC Guidelines* (IPCC 2006), along with consideration of secondary data and category-specific checks (additional Tier 2 QC) in parallel, and coordination with the uncertainty assessment; the development of protocols and templates, which provide for more structured communication and integration with the suppliers of secondary information.
- *Record Keeping:* provisions to track which procedures have been followed, the results of the QA/QC process, uncertainty analysis, and feedback mechanisms for corrective action based on the results of the investigations, which provide for continual data quality improvement and guided research efforts.
- *Multi-Year Implementation*: a schedule for coordinating the application of QA/QC procedures across multiple years, especially for category-specific QC, focusing on key categories.
- *Interaction and Coordination:* promoting communication within the EPA, across Federal agencies and departments, state government programs, and research institutions and consulting firms involved in supplying

data or preparing estimates for the Inventory. The QA/QC Management Plan itself is intended to be revised to reflect new information that becomes available as the program develops, methods are improved, or additional supporting documents become necessary. Further information on verification will be included in future submissions.

In addition, based on the national QA/QC Management Plan for the Inventory, source and sink-specific QA/QC plans have been developed for a number of sources and sinks. These plans follow the procedures outlined in the national QA/QC plan, but tailor the procedures to the specific text and spreadsheets of the individual sources. 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, public and the international technical expert reviews (e.g., UNFCCC) 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.

Figure A-19: U.S. QA/QC Plan Summary



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 Agency*[158] and *A Summary of General Assessment Factors for Evaluating the Quality of Scientific*

[158] 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.

and Technical Information.[159] 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-244 defines each factor and explains how it was considered during the process of creating the current Inventory.

Table A-244: 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 *Inventory of U.S. Greenhouse Gas Emissions and Sinks* 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, as required per UNFCCC Annex I country reporting requirements. The U.S. emissions calculations follow the *2006 IPCC Guidelines* developed specifically for UNFCCC inventory reporting. 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 *2006 IPCC Guidelines* 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 *2006 IPCC Guidelines* developed specifically for UNFCCC reporting purposes of international greenhouse gas inventories.
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 *Inventory of U.S. Greenhouse Gas Emissions and Sinks* are extensively documented in the *2006 IPCC Guidelines*. The Inventory report describes its adherence to the *2006 IPCC Guidelines*, and the U.S. Government agencies provide data to implement the *2006 IPCC Guidelines* approaches. Any changes made to calculations, due to updated data and methods, are explained and documented in the report consistent with UNFCCC reporting guidelines.
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 *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. In accordance with the *2006 IPCC Guidelines*, 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

[159] 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.

		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 *Inventory of U.S. Greenhouse Gas Emissions and Sinks* have been independently verified and peer reviewed as part of their publication in the *2006 IPCC Guidelines* and the *2019 Refinement*. In cases where the methodology differs slightly from the *2006 IPCC Guidelines*, 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 estimates in the Inventory in response to the feedback received during the Expert, Public, and UNFCCC Review periods, 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 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.[160]

As noted above in section 8.2, the expert technical review conducted by the UNFCCC supplements these QA processes. This review by an international expert review team (ERT) occurs after submission of the final report to the UNFCCC and assesses consistency with UNFCCC reporting guidelines. More information on the UNFCCC reporting guidelines and the review process can be found here:

[160] See https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

- UNFCCC Reporting Guidelines for annual national greenhouse gas inventories[161]
- UNFCCC Review Process and Guidelines for annual national greenhouse gas inventories[162]
- Inventory Review reports of annual submissions (latest reviews).[163]

Table A-245 includes responses to findings from the latest UNFCCC expert review to facilitate future reviews. The most recent review was conducted the week of November 2-7, 2020 and focused on the annual Inventory submitted in April 2020.

[161] Available online at: https://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2.
[162] Available online at: https://unfccc.int/resource/docs/2014/cop20/eng/10a03.pdf#page=3.
[163] Available online at: https://unfccc.int/process/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/inventory-review-reports-2019.

Table A-245: Response to UN Review of the 2020 Inventory Submission

ID#	*Issue Classification*	*Recommendation Made in Previous Review Report Including ERT Assessment and Rationale*	*Response on Status of Issue*
General			
G.1	Annual submission (G.1, 2019) G.1, 2018) (G.1, 2016) (G.1, 2015) (9, 2013) (8, 2012) Completeness	Improve the completeness of the inventory, in particular for those categories for which there are methodologies in the 2006 IPCC Guidelines. Addressing. The United States improved the completeness of the inventory. The Party still reports "NE" for a number of categories (see annex II for a list of the completeness issues identified by the ERT). The ERT noted that the Party's planned improvements include incorporating some of these categories into future submissions and/or providing additional information on the likely level of emissions and removals in annex 5 to the NIR (see also ID# G.2 below).	The United States is still addressing this issue and notes planned improvements include incorporating these categories into future submissions and/or providing additional information on the likely level of emissions and removals in Annex 5 to the National Inventory Report (NIR). EPA has approximated significance of additional categories for some categories, per ongoing research into available data and also included some categories previously not estimated (e.g., Flooded Lands Remaining Flooded Lands and Lands Converted to Flooded Lands). Remaining improvements will be made over time as data becomes available and prioritized with other improvements to make best use of available resources.
G.2	Annual submission (G.2, 2019) Completeness	The United States reported in the NIR (annex 5, table A-247, p.A-416) a summary of sources and sinks not included in the inventory. This table covers both sources and sinks for which methodologies are provided in the 2006 IPCC Guidelines and those without methodologies. The ERT commends the Party for the transparency provided by the table but notes that a numerical value was not provided in the "Estimated 2017 emissions" column for all sources and sinks that occur in the United States and for which there are methodologies in the 2006 IPCC Guidelines. During the review, the Party stated that, in some cases, approximated AD are currently unavailable to derive a likely level of emissions or removals. Further, the effort to develop a proxy estimate is better invested in developing estimates to include in the inventory itself as part of ongoing planned improvements. The ERT acknowledges the point made by the Party but notes that in accordance with paragraph 37(b) of the UNFCCC Annex I inventory reporting guidelines, Parties should provide justifications for exclusions in terms of the likely level of emissions for all mandatory sources and sinks considered insignificant and the total national aggregate of estimated emissions for all gases and categories considered insignificant shall remain below 0.1 per cent of national total GHG emissions. The ERT recommends that the United States provide a justification in the NIR, based on the likely level of emissions as per paragraph 37(b) of the UNFCCC Annex I inventory reporting guidelines, for all sources and sinks that occur but are considered insignificant and excluded from the inventory and for which there are methodologies provided in the *2006 IPCC Guidelines*. The ERT	The United States is still addressing this issue and notes that planned improvements include incorporating these categories into future submissions and/or providing additional information on the likely level of emissions and removals in Annex 5 to the NIR. These improvements will be made over time as data becomes available and prioritized with other improvements to make best use of available resources. Annex 5 of the current (i.e., 2022) submission does include updates to both quantitative and qualitative assessments of significance for some categories.

		recommends that the Party provide in its next NIR evidence that the total national aggregate of estimated emissions for all mandatory gases and categories considered insignificant remains below 0.1 per cent of national total GHG emissions.	
Energy			
E.1	1. General (energy sector) – gaseous fuels– CO_2 and CH_4 (E.2, 2019) (E.18, 2018) Convention reporting adherence	Addressing. Examine if the uncertainty analysis needs to be updated to reflect the findings of the research on the natural gas combustion and document the findings in future submissions. The uncertainty analysis is provided in the NIR (pp.3-35–3-37) for CO_2 from fossil fuel combustion, with supporting information given in annexes 2.2 and 7. The Party explains in the NIR that the uncertainty estimates are not affected by the updates to the carbon content of natural gas in the 2019 submission, and that the general findings regarding the carbon content of fuels given in NIR annex 2.2 (pp.A-103–A-106) still apply for natural gas without updating. The uncertainty range reported in the 2020 submission for CO_2 emissions from natural gas combustion was in the 2019 inventory submission with the exception of United States territories, where the lower bound differs by 1 percentage point (from –13 per cent in the 2019 submission to –12 per cent in the 2020 submission). During the review, the Party clarified that this was attributable to statistical variations in the approach used (Monte Carlo analysis). The ERT considers that this issue has not been fully addressed because no specific information has been documented to demonstrate that the impact of updates to the carbon content of natural gas on the uncertainty analysis is negligible.	This issue was addressed in the previous (i.e., 2021) submission. The 2021 NIR and current submission include specific information to demonstrate that the impact of updates to the carbon content of natural gas on the uncertainty analysis is negligible. See the 2021 NIR Section 3.1 pp. 3-36: "For the United States, however, the impact of these uncertainties on overall CO_2 emission estimates is believed to be relatively small. See, for example, Marland and Pippin (1990). See also Annex 2.2 for a discussion of uncertainties associated with fuel carbon contents. Recent updates to carbon factors for natural gas and coal utilized the same approach as previous Inventories with updated recent data, therefore, the uncertainty estimates around carbon contents of the different fuels as outlined in Annex 2.2 were not impacted and the historic uncertainty ranges still apply."
E.2	1. General (energy sector) – gaseous fuels– CO_2 and CH_4 (E.2, 2020) (E.3, 2019) (E.18, 2018) Transparency	Addressing. Research CO_2 EF data for fuel gas used by upstream oil and gas producers, and natural gas that has been processed and injected into downstream distribution networks, in order to determine whether a different CO_2 EF for fuel gas used in offshore oil and gas production than the CO_2 EF for the processed gas that enters the transmission, storage and distribution networks used in power and industrial plants and by other users is warranted and whether it can be determined; and document the findings of the research on the CO_2 EFs in the NIR. During the review, the Party noted that, as reported in the NIR (section 3, p.3-36 and annex 2.2), the annual natural gas carbon content was updated across the time series to reflect annual heat content data for natural gas obtained from EIA. The CO_2 EF was based on the heat content of natural gas. EIA also reports the heat content of natural gas produced as the same value as natural gas consumed, meaning that the same EF would be used in both upstream and downstream operations. However, the Party did not document the findings of this research on CO_2 EFs in the NIR.	This issue was addressed in the previous (i.e., 2021) submission. The 2021 NIR documents research on why a separate CO_2 emission factor (EF) for fuel gas used by upstream oil and gas producers is not needed. See the 2021 NIR Annex Section 2.2 pp. A-96: "Furthermore, research was done on CO_2 emission factors for fuel gas used by upstream oil and gas producers in order to determine whether a different CO_2 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. It was determined that a different factor was not warranted as natural gas carbon content is based on the heating value of the gas and EIA reports that the heat content of dry natural gas produced (which is used in upstream oil and gas production) is the same value as natural gas consumed in downstream operations (EIA 2020a). Therefore, the same carbon factor is used for all natural gas consumption including upstream operations. This language was retained

			in the 2022 NIR submission."
E.3	Fuel combustion – reference approach – all fuels – CO_2 (E.3, 2020) (E.3, 2019) (E.3, 2018) (E.5, 2016) (E.5, 2015) (32, 2013) (41, 2012) Transparency	Addressing. Provide a more transparent clarification of how the difference in emissions between the reference and the sectoral approach is determined and which fuels are subtracted as NEU and feedstocks. For the reference approach, the values reported in CRF table 1.A(c) for apparent energy consumption and apparent energy consumption excluding NEU were the same for the entire time series. The Party explained in the NIR (p.3-38) that emissions from carbon that was not stored during NEU of fuels are subtracted under the sectoral approach and reported separately but are not subtracted under the reference approach. Thus, emission estimates under the reference approach are comparable to those under the sectoral approach, except that the emissions from NEU of fuels are included in the reference approach. The ERT noted that a similar explanation was included in annex 4 to the NIR (p.A-482). During the review, the Party confirmed that (1) the emission scope of the reference and the sectoral approaches is the same since carbon emissions from NEU (i.e. carbon not excluded) are included in both approaches, except for other fossil fuels (see ID# E.25 in table 5); (2) the energy consumption covered by the sectoral approach includes both fuel 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; and (3) where 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. The ERT considers that it would be useful to include this explanation in the NIR of future inventory submissions.	This issue was addressed in the previous (i.e., 2021) submission. The United States refers the ERT to the 2021 NIR (annex 4, starting on pp. A-470) describing the different treatments of NEU under the reference and sectoral approaches. Further clarification is in the 2021 NIR Chapter 3 (pp. 3-39) and additional language is included in the 2021 submission to address this issue; see Annex 4 pp. A-471 under Step 3 of the Reference Approach description: "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." Also, footnote 139 (pp. A-471): "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 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."
E.4	Feedstocks, reductants and other NEU of fuels – all fuels – CO_2 (E.5, 2019) (E.4, 2018) (E.7, 2016) (E.7, 2015) (38, 2013) (47, 2012) Comparability	Not resolved. Report only emissions from fuels combusted for the use of energy under fuel combustion, and reallocate the relevant emissions currently reported under the subcategory NEU (other) and part of the fuel used under the subcategory United States territories (other). Emissions from NEU of lubricants and waxes and other (e.g., asphalt and road oil), which should be reported under CRF category 2.D, were still reported under fuel combustion under category 1.A.5 and combined with emissions from NEU of other fuels (see ID# E.3 above), and as "IE" under the IPPU sector. Like in the 2019 submission, the Party indicated in the NIR (p.3-54, box 3-5) that these emissions cannot be reallocated to IPPU owing to national circumstances, in particular where a carbon balance calculation was performed on the basis of the aggregated amount of fossil fuels used for NEU, and that artificial adjustments to reallocate emissions could lead to transparency issues. The ERT noted that a similar	The United States reiterates that it uses a country-specific methodology for non-energy use of fuels in line with para. 10, Decision 24/CP.19 to most accurately portray U.S. emissions from NEU. The United States has improved the explanation of its country-specific approach to the allocation of NEU of fuels in the introduction of the IPPU Chapter 4 and Annex 2 of the 2021 NIR. The United States continues to evaluate ways to update this approach, including reallocation of lubricant non-combustion emissions and will provide more clarification as applicable in the future NIRs (i.e., 2023 submission).

		explanation was provided in the IPPU section of the NIR (p.4-6), where it is stated that artificial adjustments would result in the carbon emissions for lubricants, waxes, asphalt and road oil being reported under the IPPU sector, while carbon storage for those subcategories would be reported under the energy sector. The ERT noted that the carbon balance approaches for most petrochemical products were provided in NIR annex 2.3 (pp.A-141–A-157). Taking lubricants as an example, the ERT remarked that, according to the information provided in the NIR (pp.A-152–A-154), 92 per cent of lubricants are categorized as lubricant oils and the remaining 8 per cent as lubricant greases. Annex 2.3 to the NIR also provides information on the commercial and environmental fate of oil lubricant (table A-85) and grease lubricant (table A-86), with information on the percentage combusted during use and not combusted during use. The ERT is of the view that emissions relevant to lubricant use could be allocated consistently with the 2006 IPCC Guidelines by using the existing statistical information and assumptions mentioned above without raising transparency concerns. While reallocating the small portion of emissions associated with non-combustion use to the IPPU sector may not improve the overall accuracy of the inventory, it would improve its comparability with the inventories of other Annex I Parties (see ID# I.18 below).	
E.5	Feedstocks, reductants and other NEU of fuels – CO_2 (E.6, 2019) (E.19, 2018) Accuracy	Addressing. Continue to research the data for the emissions from NEU of fuels reported under the energy and IPPU sectors mass-balance method used across petrochemical production to estimate CO_2 emissions from NEU of fuels and the method based on process emissions reported under facility- level reporting used to estimate emissions from feedstock consumption under IPPU, and further clarify the country-specific approach used in the NIR consistently with paragraph 10 of the UNFCCC Annex I inventory reporting guidelines. The Party reported in its NIR (p.4-58) that some degree of double counting may occur between CO_2 emissions from NEU of fuels in the energy sector and CO_2 process emissions from petrochemical production in the IPPU sector, but that data integration is not feasible as feedstock data from EIA used to estimate NEU of fuels were aggregated by fuel type, rather than disaggregated by both fuel type and individual IPPU industries. The Party noted in the NIR (footnote 65 on p.3-48) and further clarified during the review that this is not considered to be a significant issue since NEU industrial release data (e.g., the Toxics Release Inventory) include different categories of sources to those included under the IPPU sector, and the NEU estimates account for roughly 20 per cent of the emissions captured in the IPPU sector. During the review, the Party further clarified that, for 2018, carbon emissions from industrial releases from NEU of	This issue was addressed in the current (i.e., 2022) submission. See, for example, the 2022 NIR Section 3.2 for the following discussion: "It is important to ensure no double counting of emissions between fuel combustion, non-energy use of fuels and industrial process emissions. For petrochemical feedstock production, our review of the categories suggests this is not a significant issue since the non-energy use industrial release data includes different categories of sources and sectors than those included in the Industrial Processes and Product Use (IPPU) emissions category for petrochemicals. Further data integration is not available at his time because feedstock data from the EIA used to estimate non-energy uses of fuels are aggregated by fuel type, rather than disaggregated by both fuel type and particular industries. Also, GHGRP-reported data on quantities of fuel consumed as feedstocks by petrochemical producers is unable to be used due to the data failing GHGRP CBI aggregation criteria. "

		fuels, reported as 6,500 kt CO_2 in table A-67 of annex 2.3 to the NIR (p.A-136), represent 21.8 per cent of the emissions from petrochemical production (29,700 kt CO_2 eq) reported under the IPPU sector, as shown in NIR table 4-46 (p.4-59) and CRF table 2(I).A-H (sheet 1) for category 2.B.8. However, the ERT considers that the Party has not yet fully addressed the recommendation, in particular the potential issue related to possible double counting, which the Party considers not to be significant, by describing how the country-specific approach is better able to reflect the Party's national situation and how these methodologies are compatible with the 2006 IPCC Guidelines (see ID#s E.4 above and I.12 below).	
E.6	International aviation – liquid fuels – CO_2, CH_4 and N_2O (E.6, 2019) (E.5, 2018) (E.6, 2016) (E.6, 2015) (35, 2013) Transparency	Addressing. Harmonize and reconcile the data between the reference and the sectoral approach for the reporting of jet kerosene consumption between CRF tables 1.A(b) and 1.D or furnish an adequate explanation of inconsistencies, where appropriate. There are still inconsistencies in the reporting of jet kerosene consumption as international bunker fuel between CRF tables 1.A(b) and 1.D (e.g., 198.85 Mbbl (approx. 1,207,361.48 TJ) and 1,209,889.16 TJ for 2018, respectively). An explanation was provided in footnote 6 to table A-244 of NIR annex 4 (p.4-487), indicating that jet kerosene used in international aviation has a different NCV based on data specific to that source. The Party clarified during the review that physical values of jet kerosene consumption are converted on the basis of a combined calorific value across all sources of jet fuel (export, import and stock change, as shown in CRF table 1.A(b)), which may result in inconsistency with jet fuel data for international aviation (as shown in CRF table 1.D). The Party further clarified that the value in CRF table 1.D is based on bunkers only (198.85 Mbbl and heating content of 6,084.42 TJ/Mbbl) while the values in table 1.A(b) are based on apparent consumption, including imports, exports and so on, and average heating value (–227.08 Mbbl and 6071.71 TJ/Mbbl). The ERT is of the view that the amount of jet fuel used as international bunker fuel should be reported as a single value that is consistent across the approaches used in the inventory reporting. In this regard, the ERT considers that the footnote and the additional information provided do not fully explain the inconsistencies between CRF tables 1.A(b) and 1.D. The ERT believes it is necessary to provide in the NIR the reason why different heating values are applied to jet kerosene in CRF tables 1.A(b) and 1.D to resolve this issue.	This issue was addressed in the current (i.e., 2022) submission. See the 2022 NIR Annex 4, Footnote 6 to Table A-229 for the following discussion: "Jet fuel used in bunkers has a different heating value based on data specific to that source." Values in CRF Table 1.A(b) and 1.D match for residual and distillate fuels for international bunker consumption. For jet fuel, there is a small discrepancy because of the difference in granularity of data. In the Sectoral Approach, jet fuels are broken out by different types with varying densities used to calculate consumption. In the Reference Approach, only one heat content is used to calculate consumption for all jet fuel from bunker fuels.

E.7	1.A Fuel combustion – sectoral approach – biomass – CH_4 and N_2O (E.9, 2019) (E.20, 2018) Completeness	Not resolved. Advance the research on CH_4 and N_2O emissions from the combustion of landfill gas, sewage gas and other biogas in order to review data sources for biogas, review the reporting of non-CO_2 emissions in the waste sector and assess the need to add new estimates. The NIR did not contain information on any such research. In addition, in the 2020 inventory submission, the amount of CH4 recovered for energy use for subcategory 5.A.1.a anaerobic (managed waste disposal sites) was reported in CRF table 5.A as numerical values for 1990–2004 and as "NE" for 2005–2018, and in the 2018 inventory submission as "IE" for 2005–2016. During the review, the Party clarified that it is conducting research on the sources of data on biogas use and biogas combustion for energy purposes to confirm whether or not these emissions are reported elsewhere, and that updates to CH_4 and N_2O emissions from the combustion of landfill gas, sewage gas and other biogas will be made, as needed, and described in future inventory submissions (see ID# W.9 below).	The United States is still investigating sources of data on biogas use and combustion for energy and confirming whether these emissions are not reported elsewhere. Updates will be implemented as needed and described in future submissions.
E.8	1.A.2.g Other (manufacturing industries and construction) – liquid fuels – CO_2, CH_4 and N_2O (E.12, 2019) (E.22, 2018) Transparency	Addressing. Document the impacts of the new model and the validity of the outputs and transparently document the recalculations in the NIR when the latest version of the model (MOVES2014b) is incorporated in the inventory. The MOVES2014b model has been incorporated in inventory development since the 2019 inventory submission, in which the impact of the recalculation on CH4 and N_2O emissions was explained without any reference to CO_2 emissions. According to the information provided in the 2020 NIR (p.3-36), no particular recalculation was performed for non-road mobile machinery. In addition, no documentation on the validity of the outputs of the model was included in the NIR. During the review, the Party emphasized that (1) the use of the MOVES2014b model was limited primarily to the estimation of CH4 and N_2O emissions from non-transportation mobile sources; (2) the model was also used to generate vehicle age distributions that were used to estimate CH4 and N_2O emissions from transportation sources; (3) it plans to incrementally improve the discussion of the validity of the MOVES2014b model in future inventory submissions; and (4) the model was not used to derive CO_2 emissions from non-road mobile machinery, which were calculated using fuel consumption data from EIA and were included under the industrial and commercial categories of the inventory, so any recalculations performed using the MOVES2014b model will not impact the estimated CO_2 emissions from non-transportation mobile sources. The ERT considers that this issue has not yet been fully resolved as the NIR does not indicate that the recalculation using the MOVES2014b model had no impact on CO_2 emissions from non-road	See explanation included in the current (i.e., 2022) submission in Section 3.1 (CH_4 and N_2O from Mobile Combustion) of Chapter 3 and Annex 3.2. The use of the MOVES model in the development of the Inventory is limited primarily to the estimation of CH_4 and N_2O emissions from non-transportation mobile sources. The model is also used to generate vehicle age distributions and mileage accumulations that are used to estimate CH_4 and N_2O emissions from Transportation sources. The United States plans to incrementally improve the discussion of the validity of the MOVES model in future submissions.

		mobile machinery, and the NIR could provide more information on specific assumptions that were made and modifications to the MOVES2014b model (see ID# E.14 below).	
E.9	1.A.2.g Other (manufacturing industries and construction) – liquid fuels – CO_2, CH_4 and N_2O (E.12,2019) (E.23, 2018) Comparability	Not resolved. Research whether data are available to accurately reallocate emissions from fuel use by agricultural mobile machinery from subcategory 1.A.2.g to 1.A.4.c.ii and fuel use for fishing vessels to 1.A.4.c.iii in order to improve the comparability of the submission and ensure that emissions of all gases from a given source are reported under the same IPCC category. If data are not available to accurately reallocate emissions to the different categories, clarify, in the NIR, the country-specific approach taken consistently with paragraph 10 of the UNFCCC Annex I inventory reporting guidelines. The NIR did not state that such data are not available or clarify the use of the country-specific approach. The Party stated during the review that it is researching and comparing various AD sources, in addition to updating the MOVES model inputs (see ID# E.12 above). This will include researching the availability of data for addressing the allocation of emissions from fuel use by agricultural mobile machinery from subcategory 1.A.2.g (other) to 1.A.4.c.ii (off-road vehicles and other machinery) and fuel use for fishing vessels to 1.A.4.c.iii (fishing).	The United States is researching the availability of data for addressing the allocation of emissions from fuel use by agricultural mobile machinery from subcategory 1.A.2.g (other) to 1.A.4.c.ii (off-road vehicles and other machinery). The United States has researched data on allocating emissions and fuel use for fishing vessels to category 1.A.4.c.iii (fishing) and determined that the information is not available. The activity data (AD) on marine fuel use is not specified in terms of type of vessel and includes recreational vehicles as well as cargo and passenger carrying, military (i.e., U.S. Navy), fishing, and miscellaneous support ships (e.g., tugboats). More information stating the data is not available is found in the latest submission. See Annex 3.2 of the 2022 NIR.
E.10	1.A.2.g Other (manufacturing industries and construction) – liquid fuels – CO_2, CH_4 and N_2O (E.14, 2019) (E.24, 2018) Accuracy	Addressing. Research data by non-road mobile machinery vehicle type across the different data sets, including the Federal Highway Administration and MOVES model outputs, to determine the optimum AD estimate for each subsource under non-road mobile machinery, and improve inventory accuracy, as necessary, including for CO_2, CH_4 and N_2O emissions from industrial, commercial, agricultural machinery and fishing vessels. According to the NIR (p.3-40), EPA tested an alternative approach for disaggregating gasoline between road and non-road use. It used on-road fuel consumption output from the MOVES2014b model to determine the percentage of the Federal Highway Administration consumption data totals that are attributable to highway transportation sources, and then applied this to the EIA total data to determine gasoline consumption from highway transportation sources, such that the remainder could be defined as industrial and commercial consumption and allocated to non-road mobile machinery. However, as the results of the test revealed differences between fuel consumption data from the MOVES2014b model and those from the Federal Highway Administration, no changes were made to the methodology for estimating motor gasoline consumption for non-road mobile sources. The ERT considers that this issue has not been fully addressed as the optimum AD were not determined for each subsource under non-road	The United States notes that information on AD used to calculate non-road mobile source emissions is discussed in the NIR Section 3.1 and Annex 3.2. The language from the 2020 NIR specified in the issue rationale in terms of testing an alternative approach was in reference to a specific backcasting methodology used to address a time series inconsistency. As noted, that test determined that no changes were needed to the current approach and the AD being used were appropriate. The United Stated is therefore unsure of the basis of this issue in the UNFCCC reporting guidelines and *2006 IPCC Guidelines* and requests clarification on how optimum AD has not been determined.

		mobile machinery.	
E.11	1.A.3 Transport – liquid fuels – CO_2, CH_4 and N_2O (E.15, 2019) (E.25, 2018) Accuracy	Addressing. Advance the research in order to implement as soon as practicable the following improvements indicated during the review: Updating on-road diesel CH_4 and N_2O EFs; Developing improved methodology and data sources to estimate emissions from class II and III (short-line and regional) rail locomotives; Applying a consistent methodology over time to estimate vehicle miles travelled for on-road vehicles by vehicle type, defined by wheel base; Including ongoing research and documentation of minor emissions sources currently not included in the inventory, such as urea use in trucks, bio jet fuel, and compressed natural gas or liquefied petroleum gas use in shipping. (a) Resolved. For the 2020 inventory submission, the Party updated the CH_4 and N_2O EFs for diesel oil for subcategory 1.A.3.b road transportation for years after 2006. For example, the CH_4 EF for diesel oil for 2017 was updated from 0.24 kg/TJ in the 2019 inventory submission to 0.53 kg/TJ in the 2020 inventory submission. The Party explained in the NIR (p.3-46) that CH_4 and N_2O EFs for on-road gasoline and diesel oil vehicles were developed on the basis of annual certification data compiled by EPA instead of regression analyses (for N_2O) or the ratio of non-methane organic gas emission standards (for CH_4). It remarked during the review that certification data containing CH_4 and N_2O emission information for the period preceding 2006 were not available; (b) Resolved. It also explained in the NIR (p.3-46) that the methodology for estimating fuel consumption and emissions from class II and III rail locomotives was updated to use surrogate carload data reported by the company Railinc for 2014 onward, as 2014 is the last year for which the Party was able to receive class II and III fuel consumption data from the American Short Line and Regional Railroad Association; (c) Not resolved. During the review, the Party confirmed that it will apply a more consistent methodology over time to estimate vehicle miles travelled for on-road vehicles by vehicle type; (d) Not resolved. The ERT noted that the emissions from urea use for non-agricultural purposes presented on page 4-32 of the NIR did not contain any specific information on trucks. It also noted that, according to annex 5 to the NIR (p.A-493), N_2O emissions from biomass fuel use in	Items (a) and (b) were addressed in the 2020 submission as noted by the ERT. For item (d), the United States notes that urea use in trucks is captured under Urea Consumption for Non-Agricultural Purposes. For example, see pg. 4-32 of the 2020 NIR that indicates "In addition, urea is used for abating nitrogen oxide (NO_x) emissions from coal-fired power plants and diesel transportation motors." Emissions from urea use in trucks is specifically captured under this source. Furthermore, in the current (i.e., 2022) NIR the United States has updated the estimate for non-CO_2 emissions from bio-jet fuel and found them to be insignificant. See Annex 5 of the 2022 NIR. Additional research (i.e., on issue c) and improvements will be undertaken in stages over future submissions, pending data availability.

		domestic aviation were not estimated as they are considered insignificant. During the review, the Party confirmed that it will include research results and document minor emissions sources not currently included in the inventory in stages over the 2021 and 2022 inventory submissions, pending data availability.	
E.12	1.A.3.b Road transportation – liquid fuels – CO_2 (E.16, 2019) (E.26, 2018) Accuracy	Not resolved. Review and update the time series of diesel and gasoline CO_2 EFs, including, where necessary, the data on fuel densities and carbon share by fuel grade, and report on progress, or document in the NIR that the EFs applied are accurate and representative of emissions across the time series, and update the uncertainty analysis as needed to reflect the findings of the research. The ERT noted that the Party did not revise the CO_2 EFs for diesel oil and gasoline for subcategory 1.A.3.b road transportation in the 2020 inventory submission and continued to use constant values for the EFs for gasoline (67.62 t CO_2/TJ) for 2008–2017 (the EFs vary between 70.68 and 71.55 t CO_2/TJ for other years) and for diesel (70.10 t CO_2/TJ) for the entire time series, without justifying the accuracy of the EFs. During the review, the Party clarified that it is in the process of updating the time series of diesel oil and gasoline CO_2 EFs, and that additional considerations identified by expert input during the 2020 inventory compilation cycle had the update. The Party expected to address this issue in the 2021 inventory submission.	This issue was addressed in the current submission (i.e., 2022 submission). The update of the time series of diesel and gasoline was implemented in the previous (i.e., April 2021) NIR submission. See the Recalculations discussion in the Energy Chapter on page 3-40 in the submission available online on UNFCCC website https://unfccc.int/documents/272415 or on EPA's website at https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2019.
E.13	1.A.3.b Road transportation – liquid fuels – CO_2 (E.17, 2019) (E.27, 2018) Completeness	Addressing. Either present information in the NIR to justify the omission of any fossil carbon component in the CO_2 EF for biofuel use (e.g. fatty acid methyl ester use) or update the inventory estimates to account for emissions from the fossil carbon component of biofuels and explain the estimations in the NIR. The inventory was not updated to account for possible emissions from the fossil carbon component of biofuels. The Party explained in footnote 97 to page 3-114 of the NIR that CO_2 emissions from biodiesel do not include emissions associated with the carbon contained in methanol used in the process of combustion, as emissions from methanol use in combustion are assumed to be accounted for under NEU. It also explained in a footnote to page A-134 of NIR annex 2.3 that natural gas used as a petrochemical feedstock includes use in production of methanol and that, as a result, the carbon storage factor developed for natural gas as petrochemical feedstocks (65 per cent stored and 35 per cent emitted for 2018) takes into consideration the emissions from the use of the resulting products, including methanol. However, the ERT noted that table A-67 of NIR annex 2.3 (p.A-136) shows the carbon stored and emitted by products obtained from petrochemical feedstock for 2018 but provides no specific information on methanol, which is one of the products obtained from	In addition to the existing documentation described in the NIR (footnote 91 and footnote 85 in Annex 2.3), the United States will continue to examine ways to incorporate information into Table A-67 of NIR Annex 2.3 to further clarify uses of methanol as part of petrochemical feedstocks.

		natural gas. During the review, the Party clarified that it will examine ways to incorporate more information into table A-67 of NIR annex 2.3 to further clarify uses of petrochemical feedstocks. The ERT considers that the issue of possible underestimation has not been fully addressed, since emissions from methanol combustion, which is assumed to be included under NEU (CRF category 1.A.5 other), are not transparently estimated and reported.	
E.14	1.A.3.b Road transportation –liquid fuels – CH_4 and N_2O (E.18, 2019) (E.28, 2018) Convention reporting adherence	Addressing. Include descriptions of the MOVES model used to estimate CH_4 and N_2O emissions from road transportation and the 2016 GREET model used to generate EF inputs for alternative fuel vehicles, and information to verify that the models have been tested and calibrated to be representative of the United States fleet, fuels, driving conditions, road types and vehicle types. The Party reported in the NIR (p.3-44) that CH_4 and N_2O EFs for alternatively fuelled vehicles were developed on the basis of the 2018 GREET model and provided a related reference in annex 3.2 (p.A-219) (Argonne National Laboratory, 2018). It also provided a reference for the MOVES model in annex 3.2 (p.A-220). During the review, the Party reiterated its plans to incrementally improve discussion of the validity of the MOVES and GREET models in future inventory submissions. In relation to the list of provisional main findings, the Party provided an additional document (EPA, 2020) showing that the CH4 and N_2O EFs for on-highway gasoline and diesel vehicles generated by MOVES2014b were reviewed by experts in October 2019. The ERT considers that this issue has not been fully addressed as no reference to the expert review of EFs was included in NIR.	The United States plans to incrementally improve the discussion of the validity of the MOVES model in future submissions.
E.15	1.A.5.b Mobile – solid and gaseous fuels, and biomass use – CO_2, CH_4 and N_2O (E.21, 2019) (E.31, 2018) Transparency	Addressing. The Party reported CO_2, CH_4 and N_2O emissions from solid and gaseous fuel and biomass use in 1.A.5.b (other mobile (military)) as "NA". The Party reported in CRF table 1.A(a) (sheet 4) "NO" for consumption of solid and gaseous fuels and biomass for CO_2, CH_4 and N_2O emissions for subcategory 1.A.5.b other – mobile (military) for the whole time series, but "NA" for other fossil fuels.	This issue was addressed in the current submission, see CRF Table1.A(a)s4 in the 2022 Inventory Submission, the CO_2, CH_4 and N_2O emissions from solid, gaseous, biomass and other fossil fuels use in 1.A.5.b (other mobile (military)) are all reported as NO.
E.17	1.B.2.c Venting and flaring – CO_2 and CH_4 (E.23, 2019) (E.16, 2018) (E.20, 2016) (E.20, 2015)	Addressing. Enhance transparency in reporting CH4 emissions from petroleum systems from venting and flaring, in accordance with the UNFCCC Annex I inventory reporting guidelines. The Party still reported "IE" for CO_2 and CH4 emissions from venting and flaring in CRF table 1.B.2 and did not provide any specific information on venting and flaring in the NIR. During the review, the Party reiterated the clarification and response provided during previous reviews, namely that providing an	The United States reiterates its previous clarification and response provided during previous reviews. Language was added to the NIR, noting "The United States reports data to the UNFCCC using this Inventory report along with Common Reporting Format (CRF) tables. This note is provided for those reviewing the CRF tables: The notation key "IE" is used for CO_2 and CH_4 emissions from venting and flaring in CRF table 1.B.2. Disaggregating flaring and venting estimates across the

	Transparency	estimate of disaggregated flaring and venting emissions would involve the application of many assumptions, which would result in inconsistent reporting and, potentially, decreased transparency. The Party also clarified during the review that there were inconsistencies in data availability across segments (such as gathering) within oil and gas activities systems and noted that EF data available for activities that cover flaring (such as heavy fuel oil well completions with flaring) include emissions from multiple sources (flaring, venting and leaks).	Inventory would involve the application of assumptions and could result in inconsistent reporting and, potentially, decreased transparency. Data availability varies across segments within oil and gas activities systems, and emission factor data available for activities that include flaring can include emissions from multiple sources (flaring, venting and leaks)." This language can be found on page 3-76 and 3-94 and 3-95 of the 2021 NIR and the same language is also included in in Chapter 3, Sections 3.6 and 3.7 of the current submission (2022 NIR).
E.18	1.C CO_2 transport and storage – CO_2 (E.25, 2019) Transparency	Not Resolved. Report on the progress on the research to enable estimation of emissions for category 1.C.2, and provide a description of emission pathways associated with EOR and CCS processes for all relevant categories, including how leakage from CO_2 geological storage formations is assessed for both EOR and CCS projects. No progress was reported in the NIR, and CO_2 emissions for subcategories 1.C.2.a injection and 1.C.2.b storage were reported as "IE" for all years of the time series in the 2019 and 2020 inventory submissions. During the review, the Party clarified that it will continue to review new data available from the GHGRP and other sources of information for consideration in updating emission estimates and allocations from category 1.C.1 transport of CO_2 and subcategories 1.C.2.a injection and 1.C.2.b storage. The Party indicated that it will provide an update, as appropriate, in future inventory submissions on recalculations and planned improvements, where feasible.	The United States continues to review new data from its GHGRP and other sources for consideration in updating emissions estimates from transport of CO_2 (category 1.C.1), injection (category 1.C.2.a), and storage (category 1.C.2.b). The Party will provide an update as appropriate in future submissions in recalculations and, where feasible in planned improvements. This improvement will be made over time as data becomes available and prioritized with other improvements to make best use of available resources.
E.19	1.C CO_2 transport and storage – CO_2 (E.26, 2019) Comparability	Not resolved. Report on the progress on the research to enable estimation of emissions for category 1.C.2, and provide a description of emission pathways associated with EOR and CCS processes for all relevant categories, including how leakage from CO_2 geological storage formations is assessed for both EOR and CCS projects. The total amount of CO_2 captured for storage was reported as "NA" for all years of the time series in the 2019 and 2020 inventory submissions. During the review, the Party clarified that it will review and correct notation key use as appropriate in a future inventory submission.	This issue has been addressed in the latest submission. The United States reviewed and corrected the notation keys reported under 1.C.2 as appropriate.
E.20	1.C CO_2 transport and storage – CO_2 Comparability (E.26, 2019)	Not resolved. Report the total amounts of CO_2 injected at storage sites and the total leakage from transport, injection and storage as "IE". CO_2 emissions for the total amounts of CO_2 injected at storage sites and total leakage from transport, injection and storage were reported as "NA" for all years of the time series in the 2019 and 2020 inventory submissions. During the review, the Party clarified that it will review and correct notation key use as appropriate in a future inventory submission.	This issue has been addressed in the current (i.e., 2022) submission. The United States reported the total amounts of CO_2 injected at storage sites and the total leakage from transport, injection and storage as "IE".

E.21	Fuel combustion – reference approach – gaseous and liquid fuels – CO_2 Convention Reporting Adherence	The Party provided an explanation in annex 4 to the NIR of the comparison between the reference approach and the sectoral approach. The energy data presented in NIR table A-249 (pp.A-490–A-491) for fuel consumption under the reference approach match the data presented in CRF table 1.A(c); however, the energy data reported under the sectoral approach do not match those presented in CRF table 1.A(c) for natural gas, petroleum and total values (excluding other fossil fuels). For example, NIR table A-249 shows natural gas consumption of 30,788 TBtu for 2018 under the sectoral approach, equal to 34,483.2 PJ, whereas a value of 32,630.1 PJ is given in CRF table 1.A(c). During the review, the Party clarified that the natural gas data presented in NIR table A-249 include natural gas for combustion and NEU, and that the gaseous fuels data in CRF table 1.A(c) are derived from CRF table 1.A(a) and include natural gas for combustion and NEU as well as still gas for NEU, which is included as a gaseous fuel as opposed to a liquid fuel. The ERT recommends that the Party consistently treat still gas as liquid fuel under the sectoral and reference approaches to improve consistency between CRF tables 1.A(a), 1.A(b), 1.A(c) and the NIR table that compares fuel consumption under the two approaches (see also ID# E.22 below).	The United States reports Still Gas under petroleum in the NIR because it is a petroleum product. However, still gas is physically a gas, consisting primary of methane and ethane, and some hydrogen and other trace gases. Therefore, the United States will continue to report still gas as a gaseous fuel in CRF. The most recent submission also lists still gas as a gaseous fuel in the NIR. See Tables A-228 through A-231 in the current 2022 NIR.
E.22	Fuel combustion – reference approach – all fuels – CO_2 Comparability	The Party reported the quantity of carbon stored (carbon excluded) in CRF table 1.A(b) and the quantity of carbon excluded from the reference approach in CRF table 1.A(d). The ERT notes that the total carbon stored in liquid, solid and gaseous fuels for 2018 (60,469.88 kt C) is exactly the same in both tables, but that the disaggregated values are drastically different. For example, carbon stored in liquid, solid and gaseous fuels are reported as 57,034.45, 562.68 and 2,872.72 kt C, respectively, in CRF table 1.A(b) but as 38,903.00, 16,784.93 and 4,781.96 kt C, respectively, in CRF table 1.A(d). During the review, the Party clarified that the data in CRF table 1.A(d) were taken from the reference approach but recharacterized to reflect the Party's fuel categories, as explained in NIR annex 4 (p.A-483). It also clarified that asphalt and road oil are treated as a solid fuel, and still gas is treated as a gaseous fuel (see ID# E.21 above, under both the reference and the sectoral approach. The ERT is of the view that treating asphalt and road oil as a solid fuel is not in accordance with the 2006 IPCC Guidelines (vol. 2, table 1.1). To improve consistency between CRF tables 1.A(b) and 1.A(d) and compliance with the 2006 IPCC Guidelines, the ERT recommends that the Party consistently categorize asphalt and road oil as liquid fuels under both the reference and sectoral approaches.	The United States has updated the CRF in the current (i.e., 2022) submission so that Asphalt and Road Oil are reported as a liquid fuel in Tables 1.A9(b) and 1.A(d) for consistency with how it is reported in the NIR.

E.23	Feedstocks, reductants and other NEU of fuels – all fuels – CO_2 Convention Reporting Adherence	The ERT noted that the Party reported CO_2 emissions from NEU of fuels under category 1.A.5.a in CRF table 1.A(a)s4 and only reported them for certain years (1990, 2005 and 2014–2018) in NIR table 3-20 (p.3-48). The data from the two sources are different; for example, the NIR and CRF table 1.A(a)s4 report 129.5 and 136.4 Mt CO_2, respectively, for 2018. During the review, the Party clarified that, in CRF table 1.A(a)s4, category 1.A.5.a covers incineration of waste, United States territories and NEU. Emissions from NEU listed in CRF table 1.A(a)s4 do not include NEU of lubricants and other petroleum in United States territories (i.e. American Samoa, Guam, Puerto Rico, the United States Virgin Islands, Wake Island and other United States Pacific islands); these emissions are allocated to territories together with other emissions in United States territories. For example, for 2018, the total emissions from NEU of lubricants and other petroleum in United States territories stood at 136.4 Mt CO_2 (i.e., 5.1 Mt CO_2 (NIR table 3-22, p.3-20) plus 129.5 Mt CO_2 (CRF table 1.A(a)s4)), as reported in NIR table 3-20. The ERT concluded that the NIR and CRF tables do not transparently explain what is included under category 1.A.5.a. The ERT recommends that the Party reconcile the emission data on NEU of fuel reported in the NIR and CRF table 1.A(a)s4 by either reallocating NEU of lubricants and other petroleum in United States territories to NEU in CRF table 1.A(a)s4 or adding a footnote to NIR table 3-20 to explain how the data reported in that table differ from those presented in CRF table1.A(a)s4.	This issue has been addressed in the current (i.e., 2022) submission. A footnote was added to Table 3-20 in the NIR explaining the differences.
E.24	Feedstocks, reductants and other NEU of fuels – solid fuels – CO_2 Transparency	Whereas the Party reports in the NIR (p.3-50; annex 2.3, pp.A-133 and A-156) that storage factors, including those for industrial coking coal and distillate fuel oil (0.1 and 0.5, respectively), were taken from the 2006 IPCC Guidelines, which in turn draw on data from Marland and Rotty (1984), the ERT understands that the 2006 IPCC Guidelines do not provide storage factors for NEU of fuels. During the review, the Party clarified that the storage factors for industrial coking coal and distillate fuel oil were taken from the Revised 1996 IPCC Guidelines but primarily from Marland and Rotty (1984). The ERT recommends that in future submissions the Party include the correct reference, that is to the Revised 1996 IPCC Guidelines rather than the 2006 IPCC Guidelines, for storage factors for industrial coking coal and distillate fuel oil, together with a justification of their applicability	This issue has been addressed in the current 2022 NIR submission. The reference has been changed to the original source of the data Marland and Rotty (1984). Annex 2.3 provides the justification for use of these factors.

E.25	Fuel combustion – reference approach – other fossil fuels – CO_2, CH_4 and N_2O Consistency	Data on the non-biomass portion of waste, reported to IEA for all years, are missing from CRF table 1.A(b). In the 2020 submission, the ERT notes that the AD and emissions for other fossil fuels are reported under CRF categories 1.A.1.a (public electricity and heat production) and 1.A.5.a (incineration of waste) under the sectoral approach, but as "NA" in CRF tables 1A(b) and 1A(c) under the reference approach, for the whole time series. During the review, the Party clarified that comparisons of energy use and CO_2 values between the sectoral and reference approaches concern only fossil fuel sources (coal, natural gas and petroleum) and exclude waste fuels for reasons of consistency, as shown in table A-250 (NIR annex 4, p.A-491). The ERT recommends that the Party either take into account other fossil fuels under the reference approach when completing CRF table 1.A(b) or document that waste fuels are not used in the comparison between the sectoral and reference approaches in order to improve consistency between the reference and sectoral approaches in terms of estimation coverage, and amend the reference approach column in CRF table 1.A(c) as needed.	This issue has been addressed in the current 2022 NIR submission. Language was added to Annex 4 of the NIR to indicate that waste fuels are not used in the comparison between the sectoral and reference approaches in order to improve consistency between the reference and sectoral approaches in terms of estimation coverage.
E.26	Fuel combustion – reference approach – LPG – CO_2 Comparability	The ERT noted that data on LPG production, trade and stock changes reported under NGL in CRF table 1.A(b) seem to be different to those reported to IEA. For example, apparent consumption of NGL for 2017 is reported in the CRF table as 3,634,913 TJ (gross calorific value), equivalent to 3,453,168 TJ (NCV), but to IEA as 4,669,988 TJ (NCV), while LPG is reported as "NA" in the CRF table and as –1,238,360 TJ (NCV) to IEA. All headings for LPG are reported as "NA" except for "C stored" for the whole time series in CRF table 1.A(b). During the review, the Party clarified that LPG is a fuel category under the sectoral approach while NGL is not. LPG statistics reported under the sectoral approach consist of both NGL and LPG (as explained briefly in NIR annex 4, p.A-483), while under the reference approach, LPG falls under NGL and liquefied refinery gases, whose carbon content is based on the EF for LPG reported under the sectoral approach. The Party believes that this is the most accurate approach for calculating emissions under both the sectoral and reference approaches. The ERT recommends that the Party either estimate NGL and LPG consistently between the reference and sectoral approaches or explain in the NIR why covering different fuels under the reference approach applying a different list of fuels than that used for the sectoral approach is the most accurate way to estimate emissions under both approaches, and change the notation key reported for LPG in CRF table 1.A(b) from "NA" to "IE".	The discussion in Annex 4 of the NIR has been updated to further clarify differences in the fuel definitions in the reference and sectoral approach. LPG as a category is no longer used; it was replaced with Hydrocarbon Gas Liquids (HGL). The following language was included "Additionally, the accounting of pentanes plus as a part of HGL is different between the approaches. The United States reports consumption of all HGL components (i.e., ethane, propane, isobutane, normal butane, ethylene, propylene, isobutylene, butylene, and pentanes plus) for both approaches, but in the Sectoral Approach, pentanes plus is accounted for separately from other HGL components whereas it is included in HGL in the Reference Approach." Furthermore, the notation key reported for LPG in CRF table 1.A(b) has been changed from "NA" to "IE".

E.27	1.A.2.g Other (manufacturing industries and construction) – all fuels – CO_2, CH_4 and N_2O Transparency	The ERT noted that, in the recalculation performed for subcategory 1.A.2.g (other) in the 2020 submission, the values reported for fuel consumption and CO_2 emissions were reduced by more than 20 per cent for the whole time series, whereas those reported for CH_4 and N_2O emissions were reduced by only 5–6 and 2–3 per cent, respectively. It also noted that fuel distribution among categories changed significantly in the 2020 submission compared with the 2019 submission. For example, for 2017, fuel consumption increased by 2,838,783.55 TJ under category 1.A.1 and decreased by 2,930,213.62 TJ under category 1.A.2 and by 293,474,205 TJ under subcategory 1.A.2.g. According to the explanation provided in the NIR (pp.3-38–3-39), EIA updated the data for LPG consumption in economic sectors and revised sector allocations for propane and total LPG for 2010–2017, and for natural gas, distillate fuel oil and kerosene for 2017, without providing any explanation for the significant changes noted by the ERT. The discussion in the NIR (pp.3-38–3-39) of the impact of the recalculation on overall emissions similarly fails to broach these changes. During the review, the Party noted that, in addition to the reallocation of liquid fuels, as reported in the NIR (box 3-4, p.3-34), the values reported in the CRF tables for petroleum refining (subcategory 1.A.1.b) and manufacture of solid fuels (subcategory 1.A.1.c) were corrected to include part of the total fuel consumption when calculating energy use under subcategory 1.A.2.g. That correction accounted for most of the revisions in energy use between categories 1.A.1 and 1.A.2 for 2017. The Party explained that biomass energy use under category 1.A.2 and related non-CO_2 emissions are not disaggregated to subcategories (i.e., 1.A.2.a–f) and are reported only under subcategory 1.A.2.g, whereas biomass consumption remains unchanged in the 2020 submission. It noted that since the majority of non- CO_2 emissions are driven by biomass combustion, the adjustment made to fossil energy use and CO_2 emissions did not have as significant an impact on non-CO_2 emissions. The ERT recommends that the Party provide information in the NIR on the recalculation of emission estimates and clearly indicate the reason for any changes and corrections compared with previous submissions.	The United States has provided information in the NIR on the recalculation of emission estimates and clearly indicated the reason for any changes and corrections compared with previous submissions. See, for example, the recalculation discussions in Section 3.1 of the Energy chapter of the NIR.
E.29	1.A.3 Transport– all fuels – CO_2, CH_4 and N_2O Transparency	In CRF summary table 3, the United States reported on its use of a combination of default and higher-tier methods and a mix of default and country-specific EFs for estimating GHG emissions for subcategory 1.A.3, which was identified as a key category in NIR annex 1 (p.A-3). However, the NIR did not contain an explanation for every instance of the default method and parameters being used to estimate emissions for key	This issue was addressed in the previous (i.e., 2021) submission. See Section 3.1, pp. 3-46 of the 2021 NIR which states that "The non-road mobile category for CH_4 and N_2O includes ships and boats, aircraft, locomotives and off-road sources (e.g., construction or agricultural equipment). For non-road sources, fuel-based emission factors are applied to data on fuel consumption, following the IPCC Tier 1 approach,

		categories. The ERT noted that this is not in accordance with paragraphs 11 and 50(c) of the UNFCCC Annex I inventory reporting guidelines, which state that the Party should make every effort to use a method recommended in the 2006 IPCC Guidelines or otherwise shall explain in its annual GHG inventory submission why it was unable to implement a recommended method in accordance with the decision trees in the 2006 IPCC Guidelines. During the review, the Party clarified that the use of default methods for gases for subcategories within the key categories (1.A.3) estimating CH4 and N_2O emissions from off-road transport (category 1.A.3) could be enhanced. The ERT noted that the reasons for the Party's inability to implement higher-tier methods for this category were not transparently described in the NIR. In response, the Party explained why it had been unable to implement higher-tier methods for estimating CH_4 and N_2O emissions from off-road transport (category 1.A.3). The ERT recommends that the United States include the explanation shared with the ERT during the review in its NIR describing why it was unable to implement a recommended method in accordance with the decision trees in the 2006 IPCC Guidelines, as outlined in paragraphs 11 and 50(c) of the UNFCCC Annex I inventory reporting guidelines, where default methods and emission parameters were used for estimating GHG emissions and removals for categories identified as key, particularly for category 1.A.3 (CH_4 and N_2O for off-road sources), which includes ships and boats, aircraft, locomotives and off-road sources (i.e. construction or agricultural equipment).	for locomotives, aircraft, ships and boats. The Tier 2 approach would require separate fuel-based emissions factors by technology for which data are not available. For some of the non-road categories, 2-stroke and 4-stroke technologies are broken out and have separate emission factors; those cases could be considered a Tier 2 approach."
E.30	1.A.5.a Stationary – other fossil fuels – CO_2, CH_4 and N_2O Accuracy	According to the NIR (p.3-56; table 3-27, p.3-57), the amount of waste incinerated for 2012–2018 is assumed to be equal to the amount for 2011, and waste discarded for 2014–2018 is constant. This results in a constant ratio of incinerated waste to total waste for 2014–2018 (7.6 per cent). The ERT notes that according to historical data on MSW generation in the United States for 2000–2018 published on the OECD website (https://data.oecd.org/waste/municipal-waste.htm), 265.2 Mt waste was generated in 2018, whereas according to the NIR (table 3-27) this figure is 273.1 Mt. It also notes that the OECD data are comparable to those used for estimating emissions from waste incineration, as reported in the NIR, and do not show how much of the waste is incinerated. During the review, the Party acknowledged that the reporting of constant values for waste incineration for years after 2011 is an issue and stated that it has drawn up an improvement plan to investigate additional sources of MSW data (NIR p.3-58), including data on how much waste is incinerated, and will include the results in a future submission. The ERT recommends that the	This issue has been addressed in the current (i.e., 2022) submission. The methodology for waste incineration was updated for the 2022 submission. See the NIR Energy chapter Section 3.3 for a discussion of the updated methodology.

		Party use updated data to estimate GHG emissions from waste incineration, including by updating the amount of waste generated and the ratio of incineration for the latest year of the time series, and examine the applicability of data from the OECD website and other sources.	
IPPU			
I.3	2.A.4 Other process uses of carbonates – CO_2 (1.3, 2019) (I.5, 2018) (I.17, 2016) (I.17, 2015) Completeness	Addressing. Conduct further research and consultation with industry, state- level regulators and/or statistical agencies to access additional AD and EFs and/or to seek verification of the current method and assumptions for estimating emissions from ceramics, non-metallurgical magnesium production and from other limestone and dolomite use; and report on progress in the NIR. The Party reported CO_2 emissions from other limestone and dolomite use under category 2.A.4.d (other) in NIR section 4.4 and CRF table2(I).A-Hs1, but "NE" for categories 2.A.4.a (ceramics) and 2.A.4.c (non-metallurgical magnesium production) in CRF table 2(I).A-Hs1. The Party reported its progress and the status of this issue in the NIR (p.4-27). During the review, the Party clarified that there is no reportable progress in identifying data for the estimation of emissions based on further outreach and that efforts continue under the current cycle (see NIR annex 5, p.A-495).	See Annex 5 of the current (i.e., 2022) NIR. Using recently identified surrogate data in place of activity data as identified in the *2006 IPCC Guidelines*, the United States assessed that national emissions from ceramics production will exceed the category-level threshold for significance of 500 kt. EPA is still assessing if emissions are already reflected in other process uses of carbonates. The United States has made no reportable progress in identifying data to estimate emissions for non-metallurgical magnesium production based on further outreach. Efforts will continue with next Inventory cycle.
I.4	2.B.1 Ammonia production – CO_2 (I.4, 2019) (I.7, 2018) (I.19, 2016) (I.19, 2015) Comparability	Not resolved. Allocate emissions from all fossil fuel uses (i.e. fuel and feedstock use) for ammonia production under subcategory 2.B.1 of the IPPU sector in accordance with the 2006 IPCC Guidelines. The Party reported CO_2 emissions from fossil fuel use as fuel for energy use for ammonia production under the energy sector (NIR p.4-27). During the review, the Party clarified that its planned improvements (NIR p.4-31) include assessing anticipated new data for updating EFs to include both fuel and feedstock CO_2 emissions and to improve consistency with the 2006 IPCC Guidelines (vol. 3, chap. 3.2). The Party indicated that this is a long-term improvement to be included in the 2024 or 2025 submission at the earliest. Until these additional data are available and have been assessed as indicated in the NIR, consistently with the UNFCCC Annex I inventory reporting guidelines, the United States has provided an explanation on the use of a country-specific or national method as noted in the NIR (p.4-29).	The United States reiterates that it currently uses a country-specific methodology for ammonia production emissions consistent with para. 10, Decision 24/CP.19 to most accurately portray U.S. emissions from ammonia production. See the NIR IPPU chapter Section 4.5 for the discussion of the country-specific methodology. CO_2 emissions from production of synthetic ammonia from natural gas feedstock are estimated using a country-specific approach modified from the *2006 IPCC Guidelines* (IPCC 2006) Tier 1 and 2 methods. In the country-specific approach, to avoid double counting, emissions are not based on total fuel requirement per the *2006 IPCC Guidelines* due to data disaggregation limitations of energy statistics provided by the EIA. A country-specific emission factor is developed and applied to national ammonia production to estimate emissions from feedstock consumption, excluding consumption of fuel for energy purposes to avoid double counting and compatibility with methods in *2006 IPCC Guidelines*. The United States will continue to review the use of GHGRP data to better understand energy use for ammonia production and any information will be included as appropriate in future submissions.

I.6	2.B.2 Nitric Acid production – N_2O (I.25, 2019) Transparency	Not resolved. Include in the NIR an explanation of the trends observed for N_2O emissions and AD for nitric acid production. The observed trends in N_2O emissions and AD for nitric acid production for 2014–2016 were not explained in the NIR. During the review, the Party clarified that work is ongoing to update trend explanations in the 2021 submission.	This issue has been addressed in the current April 2022 submission. See the NIR IPPU chapter Section 4.7 for an expanded discussion on observed trends in emissions and nitric acid production.
I.8	2.B.4 Caprolactam, glyoxal and glyoxylic acid production – N_2O (I.7, 2019) (I.31, 2018) Completeness	Not resolved. Gather the necessary data and report N_2O emissions from glyoxal and glyoxylic acid production. The Party reported AD and N_2O emissions from glyoxal and glyoxylic acid production as "NE" in CRF table 2(I).A-Hs1. During the review, the Party clarified that potential data sources for glyoxal and glyoxylic acid were being investigated on the basis of ongoing research. It stated that progress on AD gathering and N_2O estimates will be included in the 2022 or 2023 submission. If production of glyoxal and/or glyoxylic acid is found to not occur in the United States, then the notation key will be revised from "NE" to "NO".	See Annex 5 of the current (2022) NIR. EPA has identified potential data sources for glyoxal, and glyoxylic acid based on ongoing research efforts. Using limited data on the range of domestic production and import of glyoxal, EPA estimates that emissions from glyoxal production do not exceed the category-level threshold for significance of 500 kt in recent years. Research suggests that glyoxylic acid may not be produced in the United States at levels that would exceed the category-level threshold for significance of 500 kt. EPA hopes to report more progress in the next (i.e., April 2023) submission, but anticipates the earliest reflection of this data, if useful, would be the April 2024 submission as additional historical data to develop the time series has not been identified.
I.9	2.B.5 Carbide production – CO_2 (I.8, 2019) (I.32, 2018) Comparability	Addressing. Allocate CO_2 emissions from production of calcium carbide to the IPPU sector in line with the 2006 IPCC Guidelines or provide clarity in the NIR as to the country-specific approach taken. The Party reported CO_2 emissions from coke use for calcium carbide production under the energy sector, with an appropriate explanation in the NIR and the correct notation key ("IE") in CRF table (I).A-H. During the review, the Party clarified that there are no AD for calculating CO_2 emissions from calcium carbide production under the IPPU sector. The ERT noted that, according to annex 5 to the NIR (pp.A-495–A-496), EPA has initiated research to obtain data from the limited production facilities in the United States (fewer than five). During the expert review of the inventory compilation, EPA sought input on production data for CO_2 emissions from calcium carbide production but was unable to identify data sources for applying tier 1 methods.	The United States reiterates that a country-specific approach was taken for CO_2 emissions from production of calcium carbide. Footnote 15 in the 2022 NIR (pp. 4-19) indicates calcium carbide is produced from quicklime and petroleum coke. Any emissions from quicklime production are included in lime production emissions (Section 4.2). Furthermore, Section 4.10 (pp. 4-48) in the 2020 NIR indicates that CO_2 (from petroleum coke used in calcium carbide production) is implicitly accounted for in the storage factor calculation for the non-energy use of petroleum coke in the Energy chapter. Table A-65 on pp. A-133 of the 2020 NIR Annexes indicates a storage factor of 30 percent for petroleum coke used in non-energy uses. This indicates effectively that 70 percent of any CO_2 emissions associated with petroleum coke used in calcium carbide production is released and accounted for under NEU emissions in the Inventory. There is no way to disaggregate and report emissions specifically associated with petroleum coke used in calcium carbide production (as is done for silicon carbide) since production data are not available for calcium carbide to estimate emissions directly.

I.11	2.B.8 Petrochemical and carbon black production –CH_4 and N_2O (I.9, 2019) (I.10, 2018) (I.22, 2016) (I.22, 2015) Completeness	Not resolved. Progress with plans to analyse new data reported by facilities (i.e. GHGRP data) and include emissions from combustion and flaring from installations not currently included in the inventory. The Party stated in the NIR (p.4-63) that CH_4 emissions from ethylene production reported under the GHGRP have not been included as this would result in double counting of carbon (i.e. all carbon in the CH_4 emissions would also be included in the CO_2 emissions from ethylene processing units, which are subset of facilities reporting under the GHGRP use alternative methods to the carbon balance approach). During the review, the Party clarified that EPA continues to assess the GHGRP data to determine how best to disaggregate and incorporate them into the inventory.	The United States also points to Section 4.13 of the 2022 NIR in the QA/QC and Verification discussion, that "The CH_4 emissions from ethylene production under the GHGRP have not been included in this chapter because this approach double counts carbon (i.e., all of the carbon in the CH_4 emissions is also included in the CO_2 emissions from the ethylene process units)." So, it is not just an issue that the flaring emissions are small but that the carbon at least is already included in CO_2 emission estimates. The United States continues to assess its GHGRP data for ways to better disaggregate the data and incorporate it into the Inventory and any information will be included as appropriate in future submissions.
I.12	2.B.8 Petrochemical and carbon black production –CO_2 and CH_4 (I.10 2019) (I.12, 2018) (I.25, 2016) (I.25, 2015) Comparability	Addressing. Develop a methodology that is consistent with the 2006 IPCC Guidelines as soon as is practicable, allocating relevant fuel and feedstock emissions within the IPPU sector. The ERT considers that the recommendation has not been addressed because the CO_2 emissions for category 2.B.8 were not fully allocated to the IPPU sector. As with ID# E.5 above, the Party will resolve this issue by describing how the country-specific approach is better able to reflect its national situation and providing a description of how these methodologies are compatible with the 2006 IPCC Guidelines.	The United States reiterates that it uses an approach for calculating emissions associated with petrochemical and carbon black production that is consistent with the *2006 IPCC Guidelines*. Per question E.5, the issue of potential double counting is discussed in the current 2022 submission. See Section 4.13 of the 2022 NIR for the following discussion: "It is important to ensure no double counting of emissions between fuel combustion, non-energy use of fuels and industrial process emissions. For petrochemical feedstock production, our review of the categories suggests this is not a significant issue since the non-energy use industrial release data includes different categories of sources and sectors than those included in the IPPU emissions category for petrochemicals. As noted previously in the methodology section, data integration is not available at his time because feedstock data from the EIA used to estimate non-energy uses of fuels are aggregated by fuel type, rather than disaggregated by both fuel type and particular industries. Also, GHGRP-reported data on quantities of fuel consumed as feedstocks by petrochemical producers is unable to be used due to the data failing GHGRP CBI aggregation criteria."

I.16	2.C.1 Iron and steel production – CO_2 (I.14, 2019) (I.17, 2018) (I.28, 2016) (I.28, 2015) Transparency	Addressing. Explain the allocation of the emissions from coke production and iron and steel production across both the energy and IPPU sectors, including the amount of carbon stored in the products of iron and steel production (this could be done, for example, through the provision of a quantitative summary of the carbon balance that the Party uses to compile and quality check the inventory estimates). The Party explained in NIR section 4.16 and annex 2 the allocation of the CO_2 emissions from iron and steel production across both the IPPU and energy sectors. In its clarifications on the list of provisional main findings, the Party indicated that factors are reported transparently in the NIR (p.4-80), including the material carbon contents for metallurgical coke production (NIR table 4-66) and the production and consumption data for the calculation of CO_2 emissions from metallurgical coke production (NIR tables 4-67 and 4-68). However, the ERT noted that the United States did not confirm its allocation of CO_2 emissions from coke production through a fully transparent tracking of carbon flows as per the previous recommendation. The ERT considers that the recommendation has not yet been fully addressed because the Party did not confirm the allocation of CO_2 emissions from coke production by providing a fully transparent tracking of carbon flows.	The United States reiterates that the Party has transparently reported in its NIR. See the 2022 NIR Annex 2.1 for how emissions and carbon stored from iron and steel production have been allocated between the energy and IPPU sectors. The Party has also documented emission factors used in the iron and steel and coke production emissions estimates. See for example Table 4-66 on pp. 4-80, Table 4-69 on pp. 4-81 and Tables 4-70 and 4-71 on pp. 4-82 of the 2020 NIR. The United States will continue to review ways to improve the presentation of data and any updates will be included as appropriate in future submissions.
I.17	2.C.4 Magnesium production – SF_6 (I.15, 2019) (I.35, 2018) Consistency	Addressing. Investigate the reasons for the SF_6 IEF increase between 2009 and 2011 and report in the NIR on the outcome of the investigation and on any recalculations of AD, IEF or emissions resulting from those investigations. The Party did not report in the NIR the outcomes of any such investigation or the reasons for the increase in the SF_6 IEF between 2009 and 2011. During the review, the Party clarified that the increase in SF_6 emissions between 2010 and 2011 was attributable partially to one facility anomalously reporting high emissions for 2011 and partially to increased production. It also stated that the 2021 NIR will include a discussion on the trends in the SF_6 IEF. The ERT noted that the SF_6 emissions for 2009–2011 were revised in the previous submission and approved by the ERT, and that there have been no new recalculations since the previous submission. The ERT considers that the recommendation has not yet been fully addressed because the Party did not include in the NIR an explanation of the outstanding trends on the IEF for magnesium production.	Adjustments to the activity data are discussed in the recalculation sections of Section 4.20 in the 2019 and 2020 NIRs. The 2021 NIR included a discussion on the trends in the SF_6 IEF. The revised activity data more accurately reflects the change in production that occurred during the recession. The large increase in SF_6 emissions from 2010 to 2011 is due in part to 1 facility reporting anomalously high emissions in 2011 and also partially due to increased production.

I.18	2.D Non-energy products from fuels and solvent use – CO_2 (I.16, 2019) (I.36, 2018) Comparability	Not resolved. Estimate separately CO_2 emissions from lubricants and paraffin wax use and report them under category 2.D. The Party reported CO_2 emissions from paraffin wax as "IE" under category 2.D (non-energy products from fuels and solvent use). The ERT noted that AD on the use of waxes are available for the Party, for example, in NIR table 3-22 (pp.3-49 and 3-50). The ERT is of the view that emissions from wax use could be determined on the basis of the statistical information and assumptions provided in the NIR and reported under category 2.D.	As per ID # above E.4, the United States reiterates that it uses a country-specific methodology for non-energy use of fuels in line with para. 10, Decision 24/CP.19 to most accurately portray U.S. emissions from NEU. The United States has improved the explanation of its country-specific approach to the allocation of NEU of fuels in the introduction of the IPPU chapter 4 and Annex 2 of the 2021 NIR. The United States continues to evaluate ways to update this approach, including reallocation of lubricant non-combustion emissions and will provides more clarification as applicable in future Inventory NIRs (i.e., 2023 submission).
I.23	2.G.2 SF_6 and PFCs from other product use – SF_6 (I.22, 2019) (I.37, 2018) Completeness	Addressing. Investigate possible SF_6 emissions from airborne warning and control systems, particle accelerators and radars and include them in the next submission, providing a description of the identified sources, the SF_6 emissions from them for the entire time series, a methodology description and an uncertainty analysis, in accordance with the 2006 IPCC Guidelines (vol. 2, chap. 8, pp.8.23–8.25 and 8.26–8.30). The Party reported SF_6 emissions for category 2.G.2 as "NE" and PFC emissions as "NA" in CRF table 2(II). It clarified in NIR annex 5 (p.A-496) that emissions from some particle accelerators and from military applications are reported by the Government to the Federal Energy Management Program. The updated analysis of the underlying data for 2018 identified fugitive SF_6 emissions of pproximately 600 kt CO_2 eq. The Party noted that the sources of the identified emissions are probably particle accelerators and compounds commonly used as fluorinated heat transfer fluid (NIR p.A-496). According to NIR annex 5 (p. A-496), EPA plans to contact reporting agencies to better understand the sources of the emissions and the estimation methods used by reporters. The ERT considers that the recommendation has not yet been resolved because the identified emissions of SF_6 and PFCs for category 2.G.2 were not reported in the CRF tables.	See Annex 5 of the NIR. EPA's analysis of reported data is ongoing, and EPA is continuing to review the available reported data and the methods used to estimate emissions.
I.26	2.A.1 Cement production – CO_2 Accuracy	The United States reported in the NIR (p.4-10) that it used the tier 2 method from the 2006 IPCC Guidelines for estimating CO_2 emissions for the key category 2.A.1 cement production. The ERT noted that non-carbonate sources of CaO in clinker production were not taken into consideration, as stated in the NIR (p.4-11), whereas it is good practice under the chosen tier 2 method to identify non-carbonate sources, for example slag, fly ash and so on, and exclude them from CaO content in clinker (2006 IPCC Guidelines, vol. 3, chap. 2, pp.2.12 and 2.14). During the review, the Party confirmed that non-carbonate sources of CaO were not included in the estimates and informed the ERT about a planned	The United States continues to review data from GHGRP and other sources on CaO content of clinker and inputs of non-carbonate CaO for consideration in order to estimate a country-specific CO_2 emission factor for clinker. An update will be provided, as appropriate, in future submissions.

		improvement involving the identification of non-carbonate raw materials used in clinker production. The ERT noted that the estimates of CO_2 emissions for category 2.A.1 cement production may be not accurate because non-carbonate sources of CaO were not included in the estimates, which is not in compliance with the Party's chosen tier 2 method from the 2006 IPCC Guidelines. The ERT recommends that the Party identify the amount of non-carbonate sources of CaO used in cement production (category 2.A.1) by fully implementing the planned improvement related to the use of non-carbonate raw materials in clinker production, and revise estimates of CO_2 emissions in accordance with the tier 2 method from the 2006 IPCC Guidelines by correcting the amount of CaO from non-carbonate sources if data of noncarbonate CaO sources are available.	
I.27	2.A.3 Glass production – CO_2 Transparency	The Party used the tier 3 method from the 2006 IPCC Guidelines (vol. 2, chap. 2.4, p.2.28) for estimating CO_2 emissions from glass production on the basis of carbonates used, including limestone, dolomite and soda ash (NIR p.4-20). According to the NIR (section 4.3), AD on carbonate use can be obtained directly from national statistics and are not consistent across the time series. For example, dolomite consumption is reported as 541 kt for 2005 but as 0 kt for 2014–2018 (NIR table 4-12, pp.4-20–4-21). During the review, the Party clarified that updating the AD for glass production is a priority among its planned improvements. In its clarifications to the ERT, the Party reiterated information in the NIR that may impact data consistency, such as withheld data. The ERT recommends that the Party explain transparently in the NIR the reasons for the dramatic reduction in reported dolomite use for glass production, from 541 kt for 2005 to 0 kt for 2014–2018, and ensure that all major carbonates (limestone, dolomite and soda ash) are estimated for the whole inventory period.	This issue has been addressed in the latest submission. New AD on dolomite is consistent across the time series. See the current 2022 NIR IPPU chapter Section 4.3 for a discussion on new AD from GHGRP used for 2010-2020 and a revised methodology for 1990-2009 to address time-series consistency.
I.28	2.B.7 Soda ash production – CO_2 Transparency	The Party reported in NIR table 4-44 (p.4-56) the soda ash production AD used for estimating CO_2 emissions. However, the ERT noted that according to the NIR (p.4-55), the EF for CO_2 emissions was applied for trona consumption (0.0974 t CO_2/t trona) but not for soda ash production. During the review, the Party clarified that the data provided in NIR table 4-44 correspond not to soda ash production but to trona consumption. The ERT also noted that the AD description provided in CRF table 2(I).A-Hs1 was also not clearly related to trona consumption and still described AD as "soda ash production". The ERT recommends that the Party correct the table heading for the AD from "soda ash production" to "trona consumption" in the NIR and clarify the AD description in CRF table 2(I).A-Hs1.	This issue was addressed in the April 2021 submission. See the previous 2021 NIR IPPU chapter Section 4.12 p. 4-58, table 4-44 for the revised title: Trona Ore Use (kt) and the footnote clarifying that trona ore use is assumed to be equal to trona ore production.

I.29	2.B.10 Other (chemical industry) – N_2O Comparability	The Party reported CO_2 emissions from SiC consumption under category 2.B.10 in CRF table 2(I).A-Hs1 (e.g. some 97.41 kt CO_2 in 2018). During the review, the Party clarified that these emissions stem from the use of SiC in non-abrasive applications, which include steel smelting and other end-uses, where SiC is heated to a sufficiently high temperature that carbon is oxidized and released as CO_2. The ERT agreed with the provided explanation but noted that emissive sources of SiC are not transparently described in the NIR. It also noted that emissions from SiC use were reported in the NIR (section 4.10) as a sum total that also included emissions from SiC production. The ERT recommends that the Party clarify the emissive non-abrasive applications of SiC, document why these emissions are not reported elsewhere (e.g. category 2.C.1) and separately report in the NIR CO_2 emissions from SiC production and SiC use.	See the 2022 NIR IPPU chapter Section 4.10 for clarification on why emissive non-abrasive applications of SiC are reported here and not elsewhere. See also Tables 4-36 and 4-37 which show emissions by SiC production and consumption.
I.30	2.C.1 Iron and steel production – CO_2 Accuracy	The Party included coke breeze production in the estimates of CO_2 emissions from coke production (NIR pp.4-79–4-80). The amount of coke breeze produced was approximated using a production factor of 0.075 t coke breeze/t coking coal consumed (NIR p.4-79) because actual data were not available. However, the ERT noted that actual data on coke breeze production in the United States can be obtained from EIA quarterly coal reports. The ERT compared the estimated data on coke breeze production used in the GHG inventory (1,248 kt coke breeze for 2018) with the EIA statistics (636 kt coke breeze for 2018) and concluded that coke breeze production was potentially overestimated in the inventory. The overestimation of coke breeze production could lead to an underestimation of emissions because the emissions are estimated using the carbon balance method, where the carbon content of products (coke and coke breeze) is subtracted from the carbon inputs (coking coal). During the review, the Party acknowledged the difference between the EIA statistics and the data used for estimating CO_2emissions. In its clarifications on the list of provisional main findings, the Party indicated that: (a) Industry data more accurately represent coke output data in relation to the other industry data used (data on coke production output are linked to other sources of iron and steel production emissions, including sinter production, where coke breeze is often used, and non-energy use of energy where coal tar is utilized); (b) Use of industry data allows for a consistent approach across the different emission categories; (c) Overall, there is no underestimation or overestimation of CO_2 emissions because all carbon associated with the coal used to make the coke is eventually accounted for, either in the coke production process or where the coke is eventually used, and a consistent approach is used to	The United States notes that the methodology used to calculate coke production emissions is described in Section 4.17 of the 2022 NIR. See for example Tables 4-67 and 4-68 on pp. 4-88. The Party continues to assess EIA data on coke breeze production and the impact of this change on emission estimates. The Party will provide an update as appropriate in future submissions.

		track the carbon throughout (see ID# I.31 below). The ERT recommends that the Party revise estimates of CO_2 emissions from coke production taking into account national statistics on coke breeze production, for example from EIA quarterly coal reports, or demonstrate in the NIR that CO_2 emissions from coke production were not underestimated by using industry data on coke breeze production instead of EIA statistics, and explain how there is a consistent approach used to track carbon throughout the calculations.	
I.31	2.C.1 Iron and steel production – CO_2 Accuracy	The Party reported coke consumption for pig iron production in NIR table 4-72 (p.4-83) (e.g. 7,618 kt for 2018) and carbon content in the coke used in estimates in NIR table 4-69 (p.4-81) (0.83 t C/t coke). During the review, the Party clarified that data on coke consumption are reported in t dry coke according to the data source (American Iron and Steel Institute annual statistical report). The ERT noted that the chosen carbon content of coke does not correspond to the coke consumption units because the expected value of carbon content for dry coke is significantly higher (e.g. according to the CO_2 Emissions Data Collection User Guide (version 7) of the World Steel Association, the carbon content of dry coke is approximately 0.89 t C/t dry coke or 3.257 t CO_2/t dry coke). The ERT concluded that CO_2 emissions for category 2.C.1 iron production were probably underestimated because the carbon content of coke chosen for estimates was incorrect. In the estimation of the ERT, the missing emissions might account for 1,675.96 kt CO_2 for 2018 for iron production, but emissions would be overestimated by the same amount for coke production. During the review, the Party explained that underestimated emissions from coke consumption were included in other parts of the inventory. However, the ERT was unable to confirm this because the Party did not provide the initial sources of data used in estimates. The ERT recommends that the Party specify in the NIR the units of coke consumption and coke production (t coke or t dry coke) and provide supporting data sources, and revise estimates of CO_2 emissions as needed from pig iron production and coke production by applying a carbon content value for coke that corresponds to the AD for coke production or consumption.	The United States uses the carbon content for coke as provided in the *2006 IPCC Guidelines*, Volume 3, Table 4.3 on p. 4-27 for a Tier 2 methodology. EPA asked the data provider of coke consumption for pig iron production for information on carbon content for this AD and will continue to assess available resources. As noted in the NIR, the United States utilizes a country-specific approach based on Tier 2 methodologies. See the 2022 NIR submission, IPPU chapter Section 4.17 for additional clarification that the units for coke consumed for pig iron production are consistent with the units for the carbon content of coke.
I.32	2.C.1 Iron and steel production – CO_2 Accuracy	The Party estimated that the carbon content of pellets, sinter and natural ore used in pig iron production is equal to the carbon content of direct reduced iron (2 per cent) (NIR p.4-84). During the review, the Party did not provide any relevant sources to justify the chosen carbon content value for pellets, sinter and natural ore. In its clarifications on the list of provisional main findings, the Party indicated that, given the lack of default carbon content values for pellets, sinter and natural ore, it	The United States reiterates the previous clarification and response provided during the previous review. In the absence of a default carbon content value from the *2006 IPCC Guidelines* and the *2019 Refinement* for pellet, sinter, or natural ore consumed for pig iron production, the United States uses a country-specific approach based on Tier 2 methodologies. EPA assumes that pellets, sinter, and natural ore used as an input for pig iron production have the same carbon content as

		adopted a country-specific approach to determine these values, as documented in the NIR (table 4-69, p.4-81). It added that, although iron and steel is a key category, any updates to estimates for subcategories resulting from updates to the carbon content of pellets, sinter and natural ore are unlikely to lead to a significant recalculation of total emissions for iron and steel. Noting that the carbon content of pellets, sinter and natural ore is likely to be significantly lower than 2 per cent, the ERT concluded that the related CO_2 emissions might not be accurate. Moreover, the failure of the Party to provide any justification for its chosen carbon content value for pellets, sinter and natural ore is not in compliance with paragraph 50(a) of the UNFCCC Annex I inventory reporting guidelines. The ERT recommends that the Party justify its chosen carbon content value of 2 per cent for pellets, sinter and natural ore by indicating that it used a country-specific approach of assuming the same carbon content as direct reduced iron (2 per cent), with confirmation by the references to the relevant data sources in the NIR, or otherwise revise the emission estimates for iron and steel production (category 2.C.1) by updating the carbon content value for pellets, sinter and natural ore used in pig iron production on the basis of relevant data sources.	direct reduced iron (2 percent). See the 2022 NIR submission, IPPU chapter Section 4.17 for this clarification on this country-specific approach. Current QC and outreach do not indicate that this approach needs to be changed.
I.33	2.C.1 Iron and steel production – CO_2 Accuracy	The Party included in its estimates of CO_2 emissions from iron and steel production (category 2.C.1) flux consumption for electric arc furnace steel and basic oxygen furnace steel production (NIR table 4-72, p.483). According to the NIR (p.4-81), the amount of flux used in pig iron production was deducted from other process uses of carbonates (CRF source category 2.A.4) to avoid double counting. During the review, the Party explained that data for flux consumption in both basic oxygen furnace and electric arc furnace steel production were obtained from American Iron and Steel Institute annual statistical reports. In its clarifications on the list of provisional main findings, the Party indicated that the flux consumption data provided by the American Iron and Steel Institute include all flux types, including limestone, lime and fluorspar, and that it only accounts for the use of fluxes containing carbon (limestone and dolomite) in iron and steel sector emissions, since the emissions associated with other fluxes are reported for their individual sectors (e.g. lime production). The ERT recommends that the Party transparently describe in the NIR the type of fluxes used in iron and steel production and ensure that only CO_2 emissions from the emissive source of fluxes are reported under category 2.C.1 and consumption of carbonates under category 2.A.4 is adjusted to subtract emissive sources accounted for elsewhere but not by subtracting non-carbonate fluxes.	The United States reiterates the previous clarification and response provided during the previous review. The current 2022 NIR submission clarifies in the IPPU chapter Section 4.17 that the United States includes only carbon-containing fluxes (I.e., limestone and dolomite) in emissions calculations from electric arc furnace and basic oxygen furnace steel production.

Agriculture			
A.1	3. General (agriculture) – CH_4 and N_2O (A.25, 2019) Completeness	Not resolved. Include in the NIR (e.g. in annex 5) an indication of the sources and categories not estimated for Hawaii and Alaska. If the emissions are insignificant, the ERT recommends that the Party justify their exclusion on the basis of the likely level of emissions in accordance with paragraph 37(b) of the UNFCCC Annex I inventory reporting guidelines. The Party reported in its NIR (pp.5-44 and 5-54) that the current inventory includes N_2O emissions from mineral fertilizer and Nex on pasture, range and paddock in Alaska and Hawaii and drained organic soils in Hawaii, but excludes CH_4 and N_2O emissions from field burning of agricultural residues in those States. During the review, the Party clarified that work is under way to assemble these data for Alaska and Hawaii for inclusion in either the 2021 or 2022 NIR.	Work is ongoing to assemble this data for Alaska and Hawaii for inclusion in the NIR. This will be provided at the earliest in the 2024 submission.
A.2	3. General (agriculture) – CH_4 and N_2O (A.26, 2019) Consistency	Not resolved. Explore the use of alternative data sources to derive AD for the years of the time series where no DAYCENT data are available (2013–2017), and if alternative data sets are not available, the ERT recommends that the Party use proxy data or extrapolation methods to derive AD. The Party reported in its NIR that surrogate data, trend analysis and statistical approaches were used to estimate CH_4 emissions from rice cultivation for 2016–2018 (p.5-24), N_2O emissions from managed soils for 2016–2018 (p.5-36) and CO_2 emissions from field biomass burning for 2015–2018 (p.5-36). However, the ERT noted that the AD reported in CRF tables 3.C for 2015–2018 and 3.F for 2014–2018 are simply the same figures. During the review, the Party clarified that it will continue to seek out alternative data sources to derive the inventory estimates for the portion of the time series not covered by the National Resources Inventory. It noted that this is a medium- to long-term update.	The United States will continue to seek out alternative data sources to drive the Inventory estimates for the portion of the time series not covered by the NRI. This is a medium- to long-term update.
A.3	3.A Enteric fermentation – CH_4 (A.2, 2019) (A.16, 2018) Convention reporting adherence	Not resolved. Undertake a quantitative uncertainty assessment in conjunction with future planned methodological updates. The Party reported the same uncertainty range in its NIR (p.5-8) as in previous submissions (i.e. a range of 11 per cent below to 18 per cent above the 2018 emission estimates). The ERT noted that the last quantitative uncertainty analysis for CH_4 emissions from enteric fermentation was undertaken for the 2003 GHG inventory submission. During the review, the Party reiterated its previous response, namely that updates will be accounted for in methodological refinements planned for future submissions.	The United States reiterates its previous response that updates will be considered with methodological refinements planned and underway in future submissions.

A.4	3.A.1 Cattle – CH_4 (A.6, 2019) (A.20, 2018) Accuracy	Not resolved. Update regional diet characterization data used in the estimation of CH_4 emissions from cattle in order to more accurately reflect the differences in diets across farms and states. The Party reported regional digestible energy intake, which is expressed in percentage of GE, and average CH_4 conversion rate data in NIR tables A-172 and A-173 and GE by animal type and state in table A-174 of NIR annex 3.10. These data are the same as those reported in the previous submission. In the footnotes to these tables it is indicated that they will be updated for the entire time series in the next inventory submission. During the review, the Party informed the ERT that work is under way to address this issue by the 2022 submission at the earliest and that, since the 2021 NIR will focus on the improvement, rather than the running, of the Cattle Enteric Fermentation Model, updated values will not be available until the 2022 NIR, when the model is next run.	Work is underway to address this in future submissions; the earliest will be the next (i.e., 2023) submission.
A.7	3.A.1 Cattle –CH_4 (A.4, 2019) (A.18, 2018) Accuracy	Not resolved. Improve the accuracy of the milk fat percentage, for example by investigating the possibility of using additional data sources for information on milk fat percentage values, such as creameries and agricultural extension services. The Party reported in its NIR (p.5-9) that, according to information obtained through recent improvements, the 4 per cent value is still representative of milk fat for 2018. During the review, the Party informed the ERT that it had obtained a source for milk fat percentages and expected to include these new values in the 2022 submission. The ERT commends the efforts made by the Party but considers that the issue remains unresolved as the milk fat value has not been updated as recommended.	The United States considers this issue resolved. Updated milk fat percentages are included in the current submission. These values ranged from 3.7 percent to 4.1 percent across the time series and are more representative of U.S. livestock industry.
A.8	3.A.1 Cattle –CH_4 (A.5, 2019) (A.19, 2018) Accuracy	Addressing. Investigate the possibility of using additional data sources (e.g. farm extension services) to derive country-specific information on calf births from dairy cows throughout the year and report on the results of this investigation in the NIR. The Party reported in NIR annex 3.10 (p.A-301) that the number of births is assumed to be distributed equally throughout the year for calf births from dairy cows but noted in the planned improvements section (p.5-9) that it is seeking data for births by month. During the review, the Party informed the ERT that work is under way to identify sources of data. It noted that this is a long-term improvement and will be included in the 2023 submission at the earliest.	To date, the primary data source identified did not provide monthly data on calf births. This is a longer-term improvement and the earliest this could be incorporated would be the 2024 submission.
A.9	3.A.2 Sheep – CH_4 (A.7, 2019) (A.21, 2018) Accuracy	Not resolved. Update the sheep population distribution as data availability allows, focusing resources as appropriate, in line with the 2006 IPCC Guidelines. The Party reported in NIR annex 3.11 (p.A-326) that population distribution data for lamb and sheep on feed are not available for after 1993. During the review, the Party informed the ERT	It should be noted that the animal population distribution data used to calculate Enteric Fermentation emissions (A.21, 2018 ERT issue) for sheep were taken from the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) agricultural statistics database (USDA 2021a) or the Census of Agriculture (USDA 2019) and

		that it expects to include updated sheep EFs and populations in the 2021 and 2022 submissions, respectively.	updated on an annual basis. For sheep and goats, default national emission factors were updated in the 2021 submission to reflect revisions made in the *2019 IPCC Refinement to the 2006 IPCC Guidelines* and improve the accuracy of emissions. EPA understands from exchange with ERT that the issue is manure management waste management distribution systems for sheep. The last year of available waste management distribution data for sheep is 2001. As described in the Annex 3.11, due to lack of additional data, data for years 2002 and beyond are assumed to be the same as 2001. Based on expert opinion cited, it was assumed that all sheep manure not deposited in feedlots was deposited on pasture, range, or paddock lands.
A.10	3.B Manure management – CH_4 (A.11, 2019) (A.25, 2018) Convention reporting adherence	Not resolved. Update the quantitative uncertainty assessment. The Party reported in its NIR (p.5-16) that the quantitative uncertainty analysis for CH_4 and N_2O emissions from manure management was performed in 2002 using approach 2 from the 2006 IPCC Guidelines, and that the uncertainty estimates were applied directly to the values for 2018. During the review, the Party reiterated its previous response, namely that the updates will be accounted for in the methodological refinements planned for future submissions.	The United States reiterates its previous response that updates will be considered with methodological refinements planned and underway in future submissions.
A.11	3.B Manure management – CH_4 and N_2O (A.12, 2019) (A.5, 2018) (A.14, 2016) (A.14, 2015) Accuracy	Addressing. Obtain updated MMS data and estimate emissions using the updated MMS usage data; if this is not possible, report on progress in the effort to update the MMS data. The Party reported in NIR annex 3.11 updated MMS data for dairy cows (p.A-330), swine (p.A-331) and poultry (p.A-332); however, data for other livestock types, such as sheep, have not been updated since 2001. During the review, the Party informed the ERT that it will report on further progress in the 2021 submission.	The United States considers this issue to be resolved as the 2020 and 2021 NIR submissions have reported on progress to update MMS data. Efforts are underway with support from the USDA to update waste management system data in the Inventory.
A.12	3.B Manure management – N_2O (A.14, 2019) (A.26, 2018) Accuracy	Addressing. Investigate other potential data sources of animal MMS data, such as extension services (i.e. agricultural advisory services). The Party reported in its NIR (p.5-18) that waste management system distribution data for dairy cows were updated using data from the 2016 Agricultural Resource Management Survey of dairy producers, and anaerobic digestion data were updated for swine, dairy cows and poultry using data from the EPA AgSTAR Program. The Party also reported that it is continuing to investigate new sources of MMS data. During the review, the Party informed the ERT that further progress on animal MMS data will be reported in the 2021 submission. The ERT commends the Party's progress but considers that the recommendation has not yet been fully addressed; for example, the MMS distribution data for sheep have not	Please see response to A.11; work is ongoing to obtain and incorporate updated data.

		been updated since 2001 (NIR annex 3.11, p.A-332) (see ID# A.11 above).	
A.13	3.B.1 Cattle – CH_4 (A.16, 2019) (A.7, 2018) (A.15, 2016) (A.15, 2015) Transparency	Addressing. If not using a more disaggregated livestock categorization in estimating emissions, use option A in reporting data and emissions for cattle in the CRF tables; if applying option C, report the values for population size, allocation by climate region to cool and temperate regions, typical animal mass, volatile solid daily excretion and CH_4 producing potential for all other cattle subcategories of option C in CRF tables 3.B(a)s1 and 3.B(a)s2. The Party applied option C and disaggregated data on cattle characterization reported in CRF table 3.B(a)s1, such as livestock population, typical animal mass, volatile solid daily excretion and CH_4 producing potential. Data on population size in CRF table 3.B(a)s1 and MMS in CRF table 3.B(a)s2 are still reported according to dairy and non-dairy cattle, rather than according to disaggregated information on population allocations to climate regions and usage of MMS. During the review, the Party reiterated its previous response, namely that updates will be accounted for in methodological refinements planned for future submissions. The Party is still investigating the possibility of reporting disaggregated climate parameters in the CRF tables.	The United States reiterates its previous response that updates will be considered with methodological refinements planned and underway in future submissions. The United States is still investigating the possibility of reporting disaggregated climate parameters in the CRF Reporter.
A.15	3.B.1 Cattle – N_2O (A.29, 2019) Transparency	Not resolved. Report the correct Nex values for beef calves, dairy calves and beef replacements in CRF table 3.B(b) so that they reflect the true average Nex rate. Discrepancies persist in the reported total N excreted and the results calculated by multiplying population by Nex rate for dairy cows, beef calves and dairy calves in CRF table 3.B(b). During the review, the Party indicated that it is currently investigating the possibility of providing disaggregated Nex rates for these cattle types in its 2022 submission.	CRF reported Nex rates are <u>average</u> N excretion rates for all U.S. states. For cattle, the United States calculates the N excreted for each state using a state-specific N excretion rate factor and then combines all states to calculate and report the total national N excreted value shown in the CRF table. The total reported N excreted by MMS type and total N excreted reported in the CRF tables reflect the actual totals calculated. Reporting a different value for Nex rates other than the weighted values currently reported would not accurately reflect the information used in calculating emissions. Therefore, the United States does not believe it is appropriate to report a different, average value just to ensure values N excretion values align.
A.16	3.B.1 Cattle – N_2O (A.30, 2019) Transparency	Not resolved. Replace the Nex rates for dairy cattle and non-dairy cattle with "IE" and explain in the documentation box of CRF table 3.B(b) that the Nex rates are reported against individual livestock classes. The Party continued to report "IE" for the Nex rate for heifer stockers and beef replacements in CRF table 3.B(b) in its 2020 submission. During the review, the Party indicated that it is currently investigating the possibility of updating disaggregated Nex rates for these cattle types in its 2022 submission. The ERT considers that the recommendation has not yet	The United States is currently investigating the possibility of providing the Nex values for these disaggregated cattle types in a future Inventory. The earliest we could disaggregate Nex rates by cattle type is the 2024 submission.

		been addressed.	
A.17	3.B.1 Sheep–CH_4 and N_2O (A.31, 2019) Transparency	Not resolved. Include information on MMS distribution for sheep in NIR table A-189. The Party did not report MMS distribution for sheep in NIR table A-189 (annex 3.11, pp.A-346–A-347). During the review, the Party informed the ERT that it is currently working on including these values in the 2022 submission.	This issue has been resolved in the current (i.e., 2022) submission).
A.18	3.D Direct and indirect N_2O emissions from agricultural soils – N_2O (A.19, 2019) (A.30, 2018) Completeness	Not resolved. Include all N_2O emissions from the States of Alaska and Hawaii in the emissions reported under this category or clearly outline in the improvement plan steps for including those emissions in the inventory. The Party reported that N_2O emissions from the States of Alaska and Hawaii are not included in the current inventory for agricultural soil management, with the exception of N_2O emissions from drained organic soils in cropland and grassland for Hawaii and synthetic fertilizer and pasture, range and paddock N amendments for grassland in Alaska and Hawaii. This issue is identified in the Party's planned improvements in its NIR (p.5-45). During the review, the Party informed the ERT that work is under way to assemble these data for inclusion in the agricultural soil N_2O estimates by either the 2021 or 2022 submission.	Work is underway to assemble this data for inclusion in the Agricultural Soils N_2O estimates. This will be provided in the 2024 submission at earliest.
A.19	3.D Direct and indirect N_2O emissions from agricultural soils – N_2O (A.20, 2019) (A.32, 2018) Transparency	Not resolved. Provide additional information in the NIR on the quantities and N content of commercial organic amendments (e.g. biosolids, dried blood and compost) applied to agricultural soils. The Party did not report additional information on the N content of commercial organic amendments included in the NIR (section 5.4). During the review, the Party informed the ERT that it will include this information in a future inventory if the unique N content of each of the non-commercial organic amendments can be found.	This has been resolved with the previous 2021 submission; see page 5-40.
A.20	3.D Direct and indirect N_2O emissions from agricultural soils – N_2O (A.32, 2019) Convention reporting adherence	Not resolved. Correct the text in its NIR to reflect the actual method applied, namely that N_2O emissions from tobacco crops are estimated using the DAYCENT model (tier 3 method). The Party reported in its NIR (p.5-36) both that DAYCENT is used and that it is not used to estimate N_2O emissions from tobacco. During the review, the Party indicated that this issue will be addressed in the 2021 submission.	This has been resolved with the previous 2021 submission.

A.23	3.D.a.3 Urine and dung deposited by grazing animals – N_2O (A.41, 2019) Transparency	Not resolved. Include in the NIR the information provided to the ERT explaining the approach used to allocate N deposited in urine and dung to each county and how the DAYCENT model uses these data in the estimation of N_2O emissions. The Party did not include in its NIR information on the approach used to allocate N deposited in urine and dung to each county and how the DAYCENT model uses these data in the estimation of N_2O emissions. During the review, the Party informed the ERT that it planned to include an additional explanation on the approach used to allocate N deposited in the 2021 submission.	This has been resolved with the previous 2021 submission; see page A-366.
A.24	3.D.b Indirect N_2O emissions from managed soils – N_2O (A.24, 2019) (A.12, 2018) (A.18, 2016) (A.18, 2015) Transparency	Addressing. Provide an explanation of how the methodology and the DAYCENT model used to estimate N volatilized and N loss are both compatible with the 2006 IPCC Guidelines and based on science. The ERT was unable to identify any additional explanation in the NIR on how the methodology and the DAYCENT model used to estimate N volatilized and N loss are both compatible with the 2006 IPCC Guidelines and based on science in its NIR. During the review, the Party informed the ERT that additional information will be added to the NIR for either the 2021 or 2022 submission.	Information has been updated in the recent submission and is transparently reported in Chapter 5 and Annex 3.12 of the NIR, which provides detailed information on how DayCent is used to generate the amount of N volatilized and how this is used in combination with IPCC defaults to estimate emissions of indirect N_2O. This information is consistent with the *2006 IPCC Guidelines*. In addition, following peer-reviewed publications are provided in the NIR on the use of DayCent for estimating soil N_2O emissions that speak to scientific basis of the model. These papers are referenced in Chapter 10 and Annex 3.12. Del Grosso, S.J., A.R. Mosier, W.J. Parton, and D.S. Ojima (2005) "DAYCENT Model Analysis of Past and Contemporary Soil N_2O and Net Greenhouse Gas Flux for Major Crops in the USA." *Soil Tillage and Research*, 83: 9-24. doi: 10.1016/j.still.2005.02.007. Del Grosso, S.J., S.M. Ogle, W.J. Parton, and F.J. Breidt (2010) "Estimating Uncertainty in N_2O Emissions from U.S. Cropland Soils." *Global Biogeochemical Cycles*, 24, GB1009, doi:10.1029/2009GB003544. Del Grosso, S.J., W.J. Parton, C.A. Keough, and M. Reyes-Fox. (2011) Special features of the DAYCENT modeling package and additional procedures for parameterization, calibration, validation, and applications, in Methods of Introducing System Models into Agricultural Research, L.R. Ahuja and Liwang Ma, editors, p. 155-176, American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, WI. USA. Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel (2001) "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In Schaffer, M., L. Ma, S. Hansen, (eds.). Modeling Carbon and Nitrogen Dynamics for Soil Management. CRC Press. Boca Raton, Florida. 303-332. Del Grosso, S.J., T. Wirth, S.M. Ogle, W.J. Parton (2008) Estimating

			agricultural nitrous oxide emissions. EOS 89, 529-530. Delgado, J.A., S.J. Del Grosso, and S.M. Ogle (2009) "15N isotopic crop residue cycling studies and modeling suggest that IPCC methodologies to assess residue contributions to N_2O-N emissions should be reevaluated." *Nutrient Cycling in Agroecosystems*, DOI 10.1007/s10705-009-9300-9. Scheer, C., S.J. Del Grosso, W.J. Parton, D.W. Rowlings, P.R. Grace (2013) Modeling Nitrous Oxide Emissions from Irrigated Agriculture: Testing DAYCENT with High Frequency Measurements, Ecological Applications, in press. Available online at: http://dx.doi.org/10.1890/13-0570.1.
A.25	3. General (agriculture) – CH_4 and N_2O Transparency	The GE values reported in NIR table A-174 (pp.A-313–A-314) for each subcategory differ significantly among States. For example, the annual GE for dairy cows is reported as 29 MJ/1,000 head in Alaska and 262,323 MJ/1,000 head in California. During the review, the Party clarified that the values reported in NIR table A-174 represent total GE for each animal type in each State rather than on a per-head basis. The ERT recommends that the Party correct the unit in the title of NIR table A-174 from "MJ/1,000 head" to "MJ/head".	This has been resolved with the previous 2021 submission.
A.26	3. General (agriculture) – N_2O Convention Reporting Adherence	The ERT noted that Nex on pasture, range and paddock for 2018 was reported in CRF table 3.D as 3,569,237,661.43 kg N/year, while total Nex on pasture, range and paddock for cattle, sheep, swine and other livestock for 2018 was reported in CRF table 3.B(b) as 4,036,707,495.09 kg N/year. It also noted that N data reported by the Party for pasture, range and paddock manure used in agricultural soil management and manure management are inconsistent between these CRF tables for 1997–2018. The ERT acknowledges that the Party noted this discrepancy in the NIR (annex 3.11, p.A-326, footnote 93). The ERT recommends that the Party report the same values for Nex on pasture, range and paddock in CRF tables 3.B(b) and 3.D.	The United States does not consider this to be an issue. This was clearly described in footnote 93 (page A-326) in Annex 3.11 of the 2020 submission and resolved with the 2021 submission.
A.27	3.D.a.2 Organic N fertilizers – N_2O Convention Reporting Adherence	The ERT considers that the average N content of biosolids of 69 per cent reported by the Party in the NIR (annex 3.12, p.A-377) is too high according to common scientific knowledge on the N content ratio of organic material. During the review, the Party clarified that the reported percentage was a typographical error and that the N content of biosolids used in estimating the total applied N from biosolids is assumed to be 3.9 per cent. The error has no impact on the estimated emissions. The ERT recommends that the Party correct the reported percentage for the average N content	This issue has been addressed in the current (i.e., 2022) submission.

		of biosolids.	
A.29	3.F Field burning of agricultural residues – CH_4 and N_2O Transparency	The ERT noted that the equation in the NIR (p.5-53) applied to calculate carbon or N released from biomass burning is incorrect. During the review, the Party stated that this typographical error in the equation would be corrected in the next inventory report and noted that carbon or N released from biomass burning was calculated using a country-specific approach based on the equation from the Revised 1996 IPCC Guidelines (vol. 3, p.4.82), as the Party clearly described in box 5-6 of the NIR. The Party noted that the calculation was performed according to the correct equation so will not require any recalculations. The ERT recommends that the Party correctly report the equation used to calculate carbon or N released from biomass burning.	The United States considers this issue as resolved. The equation for biomass burning was updated in the previous 2021 submission.
A.30	3.H Urea application – CO_2 Accuracy	The Party reported in its NIR (chap. 4.6, pp.4-32–4-35) that CO_2 emissions from the application of urea to agricultural soils were estimated using the Monte Carlo analysis, with an EF uncertainty range of 50 to 100 per cent of emissions and a triangular distribution. During the review, the Party explained that it applied a probabilistic Monte Carlo analysis based on the methods described in the 2006 IPCC Guidelines (vol. 1, chap. 3). It added that the result was based on the posterior distribution of the analysis, with the mode as the estimated highest probability value, and the confidence interval provided by distribution percentiles of 2.5 and 97.5. The ERT noted that the 2006 IPCC Guidelines (vol. 1, chap. 3) provide guidance on how to use the Monte Carlo analysis for combining uncertainties, not for reporting emission estimates. Moreover, the country-specific EFs were not justified in the light of specific national circumstances or well documented in the NIR. The ERT recommends that the Party demonstrate that the country specific EFs are appropriate for its specific national circumstances and are more accurate than the default data provided in the 2006 IPCC Guidelines, or otherwise apply the IPCC default value (0.2 t CO_2-C/t urea) for this category.	The United States considers this issue as resolved. Please see the updated description for Urea Fertilization included in the previous 2021 submission (see page 5-50, QA/QC and Verification, and Recalculations Discussion).
LULUCF			
L.1	4. General (LULUCF) – CO_2, CH_4 and N_2O (L.1, 2019) (L.2, 2018) (L.2, 2016) (L.2, 2015)	Addressing. Conclude the technical work under way to be able to provide estimates for the carbon stock changes in the living biomass and DOM pools for each conversion category from forest land to any other land use for each year based on a reliable land-use change matrix, and report on the achievements made. The United States reported carbon losses in the living biomass and DOM pools for categories 4.B.2.1 (forest land converted to cropland), 4.C.2.1 (forest land converted to grassland) and	The United States does not currently include estimates for the categories of Forest Land Converted to Other Land. These categories will be included in a future Inventory submission and will contain the estimates of carbon stock loss as a result of converting forest to these lands. The United States does not currently include estimates for the

	(81, 2013) Completeness	4.E.2.1 (forest land converted to settlements) and in the living biomass pool only for category 4.D.2.3.1 (forest land converted to other wetlands) for the first time for 2018. Categories 4.D.2.2.1 (forest land converted to flooded land) and 4.F.2.1 (forest land converted to other land) are still reported as "NE" or "NA" in its CRF table 4.F. During the review, the Party clarified that it does not currently include estimates for the categories forest land converted to other land or flooded land, or land converted to flooded land. These categories will be included in a future inventory submission and will contain the estimates of carbon stock loss as a result of converting forest land to these lands mentioned above. With respect to flooded lands, the United States plans to include the flooded land categories when it applies the updated guidance on flooded lands from the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The ERT considers that the recommendation has not yet been fully addressed because the Party did not include carbon stock change estimates for living biomass and DOM for all managed lands in the inventory.	categories of Flooded Land/Land Converted to Flooded Land or Other Land/Land Converted to Other Land. With respect to flooded lands, the United States is planning to include these when it applies the updated guidance on flooded lands from the *2019 Refinement to the 2006 IPCC Guidelines*. However, it will take several years to disaggregate the carbon stock changes from lands converted to flooded lands by the individual land use categories. Overall, this should be a very minor category as most flooded lands in the United States were created well before 1990.
L.2	4. General (LULUCF) – CO_2, CH_4 and N_2O (L.2, 2019) (L.3, 2018) (L.3, 2016) (L.3, 2015) (82, 2013) (97, 2012) Completeness	Addressing. Include all managed United States lands in the inventory; improve the consistency of the time series of national areas; and report on the achievements made. The land-use matrix of CRF table 4.1 and the land representation tables in the NIR (tables 6-6 and 6-7, pp.6-10–6-11) include all areas of managed and unmanaged land in the United States except for United States territories. During previous reviews, the Party clarified that it plans to include these territories in future submissions, including preliminary land-use information for the United States territories in NIR table 6-9. In addition, the "total area" columns of CRF background tables 4.A, 4.B, 4.C, 4.D, 4.E and 4.F do not include managed land areas where emissions or removals do not occur. Instead, the different coverage of the reported area is highlighted in a documentation box for some of the CRF background tables. During the review, the Party explained that it has included further information in the NIR to explain the deviations. NIR tables 6-33 and 6-37 demonstrate that the area of managed land left out for categories 4.B.1 and 4.B.2 is greater than 1 kha, while NIR tables 6-41 and 6-49 show the deviations for categories 4.C.1 and 4.C.2, respectively, resulting from not including managed grassland in Alaska. Similarly, deviations between the areas given in CRF tables 4.1 and 4.A are documented in NIR annex 3.13 tables A-231 and A-233. The ERT considers that the recommendation has not yet been fully addressed because the Party did not include all managed lands in the inventory.	See the following tables included in 2022 NIR: Table 6-31: Area of Managed Land in Cropland Remaining Cropland that is not included in the current Inventory (Thousand Hectares) Table 6-35: Area of Managed Land in Land Converted to Cropland that is not included in the current Inventory (Thousand Hectares) Table 6-39: Area of Managed Land in Grassland Remaining Grassland in Alaska that is not included in the current Inventory (Thousand Hectares) Table 6-47: Area of Managed Land in Land Converted to Grassland in Alaska that is not included in the current Inventory (Thousand Hectares) Annex Table A-213: Forest Land Area Estimates and Differences Between Estimates in 6.1 Representation of the U.S. Land Base (CRF Category 4.1) and 6.2 Forest Land Remaining Forest Land (CRF Category 4A1) (kha) Annex Table A-217: Land Converted to Forest Land area estimates and differences between estimates in the Representation of the U.S. Land Base (CRF Category 4.1) and Land Converted to Forest Land (CRF Category 4A1) (kha)

L.3	4. General (LULUCF) – CO_2, CH_4 and N_2O (L.3, 2019) (L.36, 2018) Convention reporting adherence	Not resolved. Until the Party is able to report anthropogenic emissions and removals from the entire national managed land area, report non-estimated managed land as a subdivision in the relevant CRF tables (i.e. tables 4.A, 4.B, 4.C, 4.D and 4.E), so that the managed land area for each land category reported in CRF table 4.1 corresponds with that reported for the same category in CRF tables 4.A, 4.B, 4.C, 4.D and 4.E. In CRF table 4.1 the United States reported for the first time areas for forest land (unmanaged), grassland (unmanaged) and wetlands (unmanaged) for the whole time series. The Party did not report non-estimated managed land as a subdivision in CRF tables 4.A, 4.B, 4.C, 4.D and 4.E (see ID# L.2 above). During the review, the Party clarified that it is considering reporting insignificant emissions as "NE" and justifying their exclusion in accordance with paragraph 37(b) of the UNFCCC Annex I inventory reporting guidelines. In its clarifications on the list of provisional main findings, the Party indicated that it reports areas for managed lands that are not included in the estimates of: (a) CRF table 4.A in NIR annex 3.13, page 442, table A-231; and NIR table A-233, page 447; (b) CRF table 4.B in NIR chapter 6.4, page 65, table 6-33; and NIR chapter 6.5, page 71, table 6-37; (c) CRF table 4.C in NIR chapter 6.6, page 79, table 6-41; and NIR chapter 6.7, page 90, table 6-49; (d) CRF table 4.D – work is under way to include information on additional wetlands such as flooded lands. The coastal wetlands estimates are assumed to include all managed coastal wetlands, but the area data are not linked to the land representation (see pp.6-98–6-99 of the NIR for more information); (e) CRF table 4.E for drained organic soils in NIR chapter 6.10, page 118, table 6-78; and NIR chapter 6.11, page 142, table 6-93. Explanations were also included in the documentation boxes of the CRF tables. The ERT considers that the recommendation has not yet been fully addressed because the Party did not report managed lands that have not been estimated as a subdivision in CRF tables 4.A, 4.B, 4.C, 4.D and 4.E.	The United States will consider this suggestion for the 2023 or 2024 NIR and CRF submission (i.e., use of notation key NE).
L.4	4. General (LULUCF) – CO_2, CH_4 and N_2O (L.41, 2019) Transparency	Report in the NIR preliminary emission or removal estimates for the land areas of the United States territories reported as a preliminary result of the planned improvement carried out in the Party's inventory. The Party reported preliminary land-use data for United States territories but did not report any preliminary emission or removal estimates for these land areas. During the review, the Party clarified that work to improve the land representation and tracking of managed and unmanaged land will be initiated in 2021 with a view to updating NIR chapter 6 for the 2022 or 2023 submission. The improvement is expected to have been fully implemented by the 2024 submission.	Work is still underway to develop the activity data needed to estimate emissions and removals from U.S. Territories.

L.5	Land representation – CO_2, CH_4 and N_2O (L.4, 2019) (L.7, 2018) (L.21, 2016) Consistency	Not resolved. Resolve the inconsistencies in land-use areas in the time series reported in the CRF tables. The discrepancy between land-use areas in the time series reported in CRF table 4.1, where the final area at the end of a given year is not the same as the initial area of the subsequent year, remains unresolved. For example, the final area reported for category 4.1.1 forest land remaining forest land (unmanaged) for 2017 is 281,651.72 kha, while the total initial area reported for 2018 is 281,563.37 kha. During previous reviews, the Party explained that the land-use areas in CRF table 4.1 were entered in accordance with the IPCC definitions of remaining land (land that remains subject to the same use for 20 years) and converted land (cumulative area of conversion over the past 20 years) and also stated that the heading of CRF table 4.1 can be understood to allow it to be compiled in accordance with the IPCC definition (namely, using the 20-year conversion). The ERT considers that the Party should bear in mind that the CRF tables are designed to be presented as an inventory of emissions for individual years, with a separate set of tables for each year. The land transition matrix in CRF table 4.1, once published, is designed to show the changes that have occurred that year between land uses, not between land conversion categories. This approach helps to ensure transparency, as it prevents the duplication of information on land areas within an accounting category provided in CRF tables 4.A–4.F. For example, where a Party converts 100 kha from grassland to settlements each year under a default IPCC method, CRF table 4.1 would show for any given year the movement of 100 kha from grassland under initial use and to settlements under final use. By contrast, CRF table 4.E would show 2,000 kha under land converted to settlements to represent 20 years of cumulative conversions for which emissions are calculated in relation to land-use changes over time. CRF tables 4.1 and 4.E would be deemed consistent where the total area of settlements is the same. This is in accordance with the 2006 IPCC Guidelines (vol. 4), which state that Parties should retain land in a conversion category for the conversion period (CRF tables 4.A–F) while transparently reporting on the new transitions for each year (CRF table 4.1). Further information on the compilation of land transition matrices can be found in the 2006 IPCC Guidelines (vol. 4, chap. 3.3), along with examples of final matrices (vol. 4, chap. 3.3, tables 3.5 and 3.6).	See explanation included in NIR Chapter 6 Section 6.1 and documentation box in CRF Table 4.A.
L.6	Land representation – CO_2, CH_4 and N_2O (L.42, 2019)	Not resolved. Include the land-use changes that occurred during the periods 1971–1978 for land converted to cropland, grassland and settlements, and 1971– 1981 for land converted to forest land, in order to ensure that the areas of land converted categories for all inventory	Work is still underway with the goal of reporting in the 2023 or 2024 submission.

	Accuracy	years since 1990 contain the accumulated total of the land-use changes over the past 20 years. The Party did not report the complete time series for the land-use transition categories mentioned in the recommendation. During the review, the Party explained that it will improve the transparency of the reporting in the 2021 submission and that it plans to report in the 2023 and 2024 submissions improvements to land representation that will allow for tracking additional land-use conversions.	
L.7	Land representation – CO_2, CH_4 and N_2O (L.43, 2019) Accuracy	Addressing. Revise the area of unmanaged grassland for Alaska and report on the changes in the NIR. During the previous review, the United States informed the ERT that the area of unmanaged grassland in Alaska had been overestimated and would be revised. The current ERT noted that no land-use transitions were reported between managed and unmanaged grassland (CRF table 4.1). During the review, the Party clarified that areas of managed and unmanaged grassland were recalculated on the basis of updated underlying data sources and that the recalculation resulted in decreased areas of unmanaged grassland. However, the Party reported in NIR table 6-41 that 50,040 kha of managed grassland in Alaska is not yet included in the inventory. As a result, the ERT considers that the recommendation has not yet been fully addressed.	Work is still underway to reconcile the area of managed grassland in Alaska and the area estimated in the Inventory. This will be updated for the 2023 or 2024 submission.
L.8	Land representation – CO_2, CH_4 and N_2O (L.43, 2019) Transparency	Not resolved. Increase the transparency regarding the approach to classifying managed and unmanaged land and include a specific example of the change from managed land to unmanaged land in the NIR because this type of land-use change is not common in the inventory reporting of other Parties. The NIR does not include an explanation of the Party's approach to classifying managed and unmanaged land or include an example of the change from managed to unmanaged land.	The Land Representation chapter of the NIR provides detailed information on the definition of managed and unmanaged land, the sources of land-use data, the criteria used to designate managed lands (with lands not designated as managed being unmanaged lands) and the approach for combining the land-use data sets. We are unaware of a reporting specific example of the change from managed to unmanaged land and appreciate clarity on the basis for this reporting. A multi-year effort to improve on the land representation, including the use of additional datasets, is underway and will improve on the transparency of the methods. While this effort will be ongoing for years to come, the initial updates should be completed by the 2023 or 2024 submissions.
L.9	Land representation – CO_2, CH_4 and N_2O (L.6, 2019) (L.9, 2018) (L.23,2016) (L.22, 2015) Transparency	Addressing. When providing detailed information in the NIR on how the different data sources were harmonized, provide explicit information on how the model ensures consistent integration of the three data sources, for example by including a visual flow chart of data processing during the harmonization process. Three sets of land-use data are used: NRI, Forestry Inventory and Analysis and NLCD (see also ID# L.10 below). The Party explains in the NIR (pp.6-20–6-24) how different land data sources are used and harmonized to classify national land data into IPCC land-use	See section "Approach for Combining Data Sources" in Chapter 6 of the current (2022) NIR submission. In addition, the United States will be modifying its approach for developing the land representation over the next several years and will update the NIR throughout this process.

		categories. During the review, it also explained that it will modify its approach to developing land representation over the next few years and will update its NIR accordingly. The ERT considers that the recommendation has not yet been fully addressed because explicit information on how the three data sources are consistently integrated was not provided.	
L.11	4.A Forest land – CO_2 (L.10, 2019) (L.39, 2018) Convention reporting adherence	Addressing. Report up-to-date information on the verification of the outputs of the model used to estimate SOC changes in mineral soils, for example, at the level of annual fluxes in single specific sites representative of the variability of the population or, as done for the DAYCENT model for agricultural soils (NIR figure A-12), at the level of the total cumulated (across the time series and the entire territory modelled) net flux. No information is provided in the NIR on verification of forest soil estimation by model, despite a background research paper on the soil estimation approach being cited in annex 3 to the NIR (p.A-361). During the review, the Party explained that it expects to report this information in the 2022 or 2023 submission.	Additional detail will be included in Annex 3.13 in a future submission—e.g., tables by broad forest types and average C stock per unit area, and stock changes. The discussion on uncertainty will also be expanded to discuss issue of consistency in soil depth across land use categories. We will also provide data on plot level soil carbon. We anticipate reporting this information in the next (2023) submission at the earliest.
L.13	4.A Forest land – CO_2 and N_2O (L.13, 2019) (L.42, 2018) Transparency	Addressing. Calculate the carbon stock change in each carbon pool at the level of each single plot and then aggregate the results at the state and national level, and explain any recalculations in the NIR. During the previous review, the Party provided additional information on the methodology in response to a question raised by the ERT about double counting of carbon. The previous ERT considered that the methodology for calculating carbon stock change on forest land was appropriately applied taking into account the information provided by the Party. However, it noted that the information provided in the NIR did not demonstrate that the stock-difference method for forest land was applied at each land-use category level. During the most recent review, the Party explained that it will provide the requisite information in the NIR of its next submission. The ERT considers that the recommendation has not yet been fully addressed because the Party did not update the NIR information demonstrating that the stock-difference method for forest land was applied at each land-use category level.	The United States provided this supplemental information in the Annex 3.13 to the 2021 NIR.
L.14	4.A.1 Forest land remaining forest land – CO_2 (L.14, 2019) (L.13, 2018) (L.26, 2016)	Not resolved. Provide in an annex to the NIR detailed tables on average carbon fluxes by region and type (e.g., the region and forest type classifications described in Smith et al. (2006) and used for estimating downed deadwood and understory, which might better reflect the diversity of forest types and age classes). The United States did not provide tables with average carbon fluxes disaggregated by region, state or forest type. During the review, the Party explained that this	We are still unsure on the reporting requirement and basis in methodological guidance that requires providing detailed tables on average carbon fluxes by region.

	Transparency	information will be included in the 2021 or 2022 submission.	
L.15	4.B Cropland – CO_2 (L.16, 2019) (L.18, 2018) (L.14, 2016) (L.14, 2015) (93, 2013) (107, 2012) Completeness	Not resolved. Estimate the carbon stock changes in living biomass in perennial crops for all years in the time series. The United States did not report biomass stock changes in perennial cropland (for either cropland remaining cropland or land converted to cropland). The ERT considers that, if no information is available other than the time series of areas covered by perennial crops reported in the national statistics on agriculture, the Party should consider using this information and the tier 1 methodology from the 2006 IPCC Guidelines (vol. 4, chap. 5) to prepare a time series of estimates of biomass changes in perennial crops. The carbon stock dynamic of the perennial cropland area in 1989 can be assumed to be at equilibrium and can be modelled for 1990 onward on the basis of the ageing of trees and changes in the area planted. The issue applies to both cropland remaining cropland and land converted to cropland. During the review, the Party explained that this information will be included in the 2022 submission.	This work is underway and will be included in the next (2023) submission at the earliest.
L.17	4.B.2.2 Grassland converted to cropland – CO_2 (L.46, 2018) Completeness	Not resolved. Estimate biomass carbon stock changes using the IPCC default method and factors or, where available, country-specific methods and factors, and report the estimations in the NIR. The Party did not provide estimates and "NE" was reported for carbon stock changes in biomass in grassland converted to cropland in CRF table 4.B. During the review, the Party explained that it is working to address completeness over time as improved data become available and to prioritize the work in line with other improvements to make best use of available resources.	This work is underway and will be included in the next (2023) submission at the earliest.
L.18	4.B Cropland 4.C Grassland – CO_2 and N_2O (L.19, 2019) (L.47, 2018) Convention reporting adherence	Not resolved. Verify the model's output for the entire time series from 1990 onward and for all applicable land categories (e.g. by verifying the model's output for each land-use category, or for the total of the land-use categories, or for any subaggregation, as long as the total estimate of all land-use categories modelled is verified) and report on the verification and the results in the NIR. The Party reported the same verification in the NIR as in the previous submission; that is, comparing SOC changes with lower tiers (figure A-13). Therefore, the concern of previous ERTs regarding coverage of land categories (i.e. that the output of the DAYCENT model was verified for carbon stock change in cropland remaining cropland, but not for other land-use categories and gases) has not been addressed. During the review, the Party explained that it still plans to improve the documentation on the model and refine the calibration used for the model, and to implement an additional verification, alongside ongoing methodological refinements for	As noted to the prior ERT, efforts to improve the documentation and calibration are ongoing as well as implementation of additional verification, in step with ongoing methodological refinements for estimating soil carbon, soil N_2O and soil CH_4. This will be addressed in the next (2023) submission at the earliest.

		estimating soil carbon, soil N_2O and soil CH_4. It noted that this issue will be addressed in the 2021 and 2022 submissions. In its clarifications on the list of provisional main findings, the Party indicated that it has provided documentation on the model's prediction capability for SOC on grassland and cropland (see NIR annex 3.12, p.A-405, figure A-12); the output of the model is also shown for N_2O and CH_4 (figures A-14–A-15); and these comparisons lend credibility to the ability of DAYCENT to predict emissions and removals for these gases. The Party indicated that it has allocated available resources to other improvements instead of conducting a tier 1 analysis, which would effectively entail compiling the inventory twice, and that it will work towards making this addition to the 1990–2020 inventory for reporting in 2022. The ERT considers that the recommendation has not yet been addressed because the Party has not verified the model's output for the entire time series from 1990 onward.	
L.20	4.C Grassland – CO_2 (L.21, 2019) (L.49, 2018) Transparency	Not resolved. Report woody grassland as a subdivision of the grassland category, estimate accordingly the area and carbon stock change for all carbon pools of woody grassland within the category grassland remaining grassland and within all land-use categories of conversion from and to grassland, and report the estimations in the NIR. The Party did not estimate carbon stock changes on woody grassland. Further, the Party has removed from the NIR (box 6-6, p.6-71, of the 2019 NIR) an explanation on grassland woody biomass analysis and a reference to its plans to include the woody grassland subcategory in its reporting. The Party explained during the review that while it intends to include this subcategory in the 2021 submission, owing to administrative delays it may have to include it in the 2022 submission instead. In its clarifications on the list of provisional main findings, the Party indicated that it reports all carbon stock pools for woodland that occur on grassland (i.e. land that does not meet the definition of forest land). It acknowledges that there may be some woody grassland which is not included and is reviewing the data with a view to making the relevant refinements in the future. The ERT considers that the recommendation has not yet been addressed because the Party did not report emissions and uptake under the woody grassland subcategory in CRF table 4.C.	The United States reports carbon stock changes for all pools for a subcomponent of grasslands referred to as woodlands. Woodlands are former forest lands that no longer meet the definition of forest lands and are now classified in the grassland category. Because these woodlands were formerly part of the forest land category, data are collected on woody/perennial biomass and these data are used to report on the carbon stock changes. For other grasslands not part of the woodlands, we do not have woody/perennial biomass data and are not able to report at this time. The United States is assessing how to assemble perennial biomass data for these other grasslands for future reporting. The earliest this would occur is the next (2023) submission.
L.22	4.C.2.2 Cropland converted to grassland–CO_2 (L.24, 2019) (L.51, 2018)	Not resolved. Estimate biomass carbon stock change using the IPCC default method and factors or, where available, country-specific methods or factors, and explain the estimations in the NIR. The Party did not provide estimates and reported "NE" for carbon stock changes in biomass on cropland converted to grassland. The Party explained during the review that while it intends to include carbon stock changes in biomass on cropland converted to grassland in the 2021 submission,	This work is underway and will be included in the next (2023) submission at the earliest.

	Completeness	owing to administrative delays it may have to include it in the 2022 submission instead.	
L.23	4.D.1 Wetlands remaining wetlands – CO_2, CH_4, and N_2O (L.25, 2019) (L.25, 2018) (L.34, 2016) (L.27, 2015) Transparency	Addressing. Noting the need to determine the quantity of peat harvested per ha and the total area undergoing peat extraction, provide the respective AD and IEFs for the on-site CH_4 and N_2O emission estimates in CRF table 4(II) for organic soils under peat extraction. The Party explained in the NIR (p.6-91) that it used the total peat extraction area as AD for on-site CH_4 emissions and the nutrient-rich peat production area as AD for on-site N_2O emissions. However, these AD were not included in CRF table 4(II). In a documentation box to CRF table 4(II), the Party explains that, since different areas are used to estimate CH_4 and N_2O emissions, it is not possible to provide the AD and IEF for both gases on the same row. The ERT suggests that the Party report the area for CH_4 emissions and the values for CH_4 and N_2O emissions and explain the resulting N_2O IEF value.	Documentation on our approach was provided in the documentation box in CRF Table 4(II) of the previous (2021) and current (2022) submission.
L.24	4.D.2.2 Land converted to flooded land – CO_2 (L.26, 2019) (L.53, 2018) Completeness	Not resolved. Estimate carbon stock change in flooded land using the 2006 IPCC Guidelines (vol. 4, chap. 7) default method and factors or, where available, country-specific methods or factors, and explain the estimations in the NIR. Carbon stock changes in all carbon pools for land Carbon stock changes in all carbon pools for land converted to flooded land are reported as "NE" for the whole time series. During the review, the Party explained that improvements in this regard are planned for the 2022 submission. (See also ID# L.1 above for the case of forest land converted to flooded land.)	This is addressed in the current submission for 2022.
L.25	4.D.2.3 Land converted to wetlands – CO_2 (L.27, 2019) (L.54, 2018) Completeness	Not resolved. Estimate biomass and DOM carbon stock changes for forest land converted to other wetlands as planned for the 2020 submission, and explain the estimations in the NIR. The Party has reported carbon stock changes in living biomass for land converted to other wetlands (category 4.D.2.3) as numerical values since the 2019 submission, as opposed to "NE" in the 2018 submission. However, it reported carbon stock changes in DOM for category 4.D.2.3 as "NE" in the 2018, 2019 and 2020 submissions. During the review, the Party explained that it plans to make improvements in this regard for future inventory submissions.	Work is planned to report on this information in a future submission.

L.27	4.E Settlements – CO_2 (L.29, 2019) (L.27, 2018) (L.15, 2016) (L.15, 2015) (94, 2013) Accuracy	Addressing. Eliminate the overlap between the urban forest inventory and the forest inventory. The Party updated the tree cover area in settlements (urban forest area) in the 2020 submission and indicated in the NIR that it plans to address the overlap between the forest and urban forest inventories (under planned improvements in settlements, p.6-126). The Party explained in the NIR that there may be a minor overlap between the forest and urban forest inventories and that this will be addressed when new NLCD data become available. It added during the review that it plans to take steps over the next few years to develop spatially explicit and spatially continuous representations of land to eliminate such overlaps and to enable the production of better settlement area estimates.	This overlap is still being investigated with new NLCD data. EPA anticipates reporting an updated status of this consideration in the next (i.e., 2023) submission.
L.28	4.E.1 Settlements remaining settlements– CO_2 (L.30, 2019) (L.55, 2018) Comparability	Not resolved. Remove the reporting of the carbon stock change associated with yard trimmings and food scraps from under the settlements category and allocate it to the category other under the relevant sector. The Party continues to report carbon stock changes associated with yard trimmings and food scraps under the settlements category instead of category 4.H (other). During the review, the Party indicated that this reallocation will be addressed in the 2022 submission. The Party could see the issue will be resolved by reporting emissions from landfilled yard trimmings and food scraps under category 4.H (other), applying a country-specific method or under category 4.G (HWP) as an additional “other” HWP pool in solid waste disposal sites while continuing to ensure that the methods used are consistent with the waste sector reporting as per the 2006 IPCC Guidelines (vol. 4, chap. 12.2.1, and vol. 5, chap. 3.4).	Carbon stock estimates are reported as negative "Emissions" under 4.H. The estimates for landfilled yard trimmings and food scraps are estimates of changes in carbon stock, rather than emissions. Carbon stock change is not included as a measure for 4.H Other category. Carbon storage estimates within the Inventory are associated with particular land uses. For example, harvested wood products are reported under Forest Land Remaining Forest Land because these wood products originated from the forest ecosystem. Similarly, C stock changes in yard trimmings and food scraps are reported under Settlements Remaining Settlements because the bulk of the C, which comes from yard trimmings, originates from settlement areas. While the majority of food scraps originate from cropland and grassland, in this Inventory they are reported with the yard trimmings in the Settlements Remaining Settlements section. Additionally, landfills are considered part of the managed land base under settlements (see Section 6.1 Representation of the U.S. Land Base), and reporting these C stock changes that occur entirely within landfills fits most appropriately within the Settlements Remaining Settlements section given these U.S.-specific circumstances and country approach, and therefore reported under 4.E.1.
L.29	4.E.1 Settlements remaining settlements – CO_2 (L.31, 2019) (L.55, 2018) Comparability	Not resolved. Report information on the long- term stored carbon stock of yard trimmings and food scraps, as well as on its annual changes, in the memo item in CRF table 5. The Party did not report in the memo item in CRF table 5 on the long-term storage of carbon in waste disposal sites or on the annual change in total long-term carbon storage. During the review, the Party indicated that this will be addressed in the 2021 or 2022 submission. The ERT considers that the recommendation has not yet been addressed because the Party did not report on the long-term storage of carbon in waste disposal sites in the memo item in CRF table 5.	This has been updated in the current CRF submission; see Table 5 of the 2022 CRF submission.

L.30	Cropland converted to settlements Grassland converted to settlements– CO_2 (L.32, 2019) (L.56, 2018) Completeness	Not resolved. Estimate biomass carbon stock change for cropland converted to settlements (category 4.E.2.2) and grassland converted to settlements (category 4.E.2.3) using the IPCC default method and factors (2006 IPCC Guidelines, vol. 4, chap. 8) or, where available, country-specific methods or factors, and explain the estimations in the NIR. The Party did not estimate carbon stock changes in biomass for cropland converted to settlements and grassland converted to settlements. During the review, the Party explained that it plans to report this information in the 2022 submission.	Work is planned to report on this information in a future submission.
L.31	4.F.2 Land converted to other land – CO_2 (L.33, 2019) (L.57, 2018) Completeness	Not resolved. Report estimates of carbon stock change for land converted to other land using the IPCC default method and factors (2006 IPCC Guidelines, vol. 4, chap. 9) or, where available, country-specific methods or factors, and explain the estimations in the NIR. The Party reported all carbon stock changes in all carbon pools under category 4.F.2 as "NA" (previously "NE"). During the review, the Party explained that it was unable to report the required information under this category but plans to do so in a future submission. It also explained that the notation key was mistakenly changed to "NA" and will be changed back to "NE" in the next submission. (See also ID# L.1 above for the issue of forest land converted to other land.)	Work is planned to report on this information in a future submission.
L.32	4.G HWP – CO_2 (L.34, 2019) (L.58, 2018) Transparency	Not resolved. Complete CRF table 4.Gs2 with aggregated values in t carbon for each of the three HWP subcategories (solid wood, paper and paperboard, and other) and report in the NIR a table with all subcategories used by the model to calculate the HWP contribution as well as the conversion factors to carbon weight applied for each subcategory. The United States did not complete CRF table 4.Gs2 and reported only the values of paper and paperboard for 1990–2018. It reported "IE" for sawnwood and wood panels. During the review, the Party explained that it is working towards improving the reporting of HWP in its 2021 submission.	Work is planned to improve reporting of HWP in the CRF Reporter for the 2023 or 2024 submission.
L.34	4.H Other (LULUCF) – CH_4 (L.36, 2019) (L.60, 2018) Transparency	Not resolved. Report the complete calculation of the decay rates applied to yard trimmings and food scraps as well as information on the impact that the calculation has on the CH_4 emission rates applied to other MSW. While the decay rates are properly explained (see ID# L.33 above), there is still a transparency issue between the LULUCF and waste sectors. The CH_4 emissions from yard trimmings and food scraps are reported in the waste sector as part of total CH_4 emissions from MSW. As disaggregated CH_4 emissions from yard trimmings and food scraps are not reported in the waste sector (NIR p.6-135), it is not possible to check the relationship or consistency between carbon storage and the CH_4 emissions from yard	This issue was resolved with 2020 submission. Discussion of decay rates begins at the end of page 6-131 in the NIR (2020 submission).

		trimmings and food scraps. In the NIR, the Party explains that there are no plans to disaggregate these waste components in the data in the waste sector, which will hamper the separate reporting of CH_4 emission from yard trimmings and food scraps. During the review, the Party stated that it considers this issue to have been resolved. However, the ERT is of the opinion that, while it may be difficult to provide evidence of consistency between sectoral methods, the Party should at least demonstrate that the methods used are not inconsistent. This could be done by showing that carbon losses resulting from the decay of yard trimmings and food scraps as calculated under LULUCF are in keeping with the waste sector estimates of CH_4 emitted from landfills. Alternatively, the Party could perform a model calculation of CH_4 emissions from the yard trimming and food scraps carbon pool in landfills (see also ID# L.29 above) and compare the results with the waste sector CH_4 estimates. The ERT considers that the recommendation has not yet been fully addressed because the Party did not explain in the NIR how the decay of yard trimmings and food scraps reported in CRF table 4.E (recommended to be moved to category 4.H, see ID# L.28 above) is consistent with the emissions of CH_4 from landfills reported in the waste sector.	
L.35	4.A Forest land 4(II) Emissions and removals from drainage and rewetting and other management of organic/mineral soils – CO_2, CH_4 and N_2O (L.44, 2019) Transparency	Not resolved. Provide information regarding which emissions or removals are estimated under carbon stock change in forest organic soils (category 4.A) and drained forest organic soils (category 4(II)) and how it avoids double counting of emissions between the two sources in the NIR and in the relevant documentation boxes of CRF tables 4.A and 4(II). No information is provided either in the NIR or in the documentation boxes of CRF tables 4.A or 4(II) on the avoidance of double counting. During the review, the Party clarified that it plans to report this information in a future submission.	Carbon stock change from drained organic soils are reported under the Forest Ecosystem stock changes. See footnote "a" in Table 6-11: "These estimates include carbon stock changes from drained organic soils from both Forest Land Remaining Forest Land and Land Converted to Forest Land. See the section below on CO_2, CH_4, and N_2O Emissions from Drained Organic Soils for the methodology used to estimate the C flux from drained organic soils. Also, see Table 6-22 and Table 6-23 for greenhouse gas emissions from non-CO_2 gas changes from drainage of organic soils from Forest Land Remaining Forest Land and Land Converted to Forest Land."
L.37	4(III) Direct N_2O emissions from N mineralization/ immobilization – N_2O (L.37, 2019) (L.61, 2018) Completeness	Not resolved. Estimate N_2O emissions associated with the mineralization of the N content of SOC losses in mineral soils for forest land, wetlands, settlements and other land, as well as for their conversion to and from cropland and grassland, using the IPCC default method and factors (2006 IPCC Guidelines, vol. 4, chap. 11) or, where available, country-specific methods or factors, and report the estimations in CRF table 4(III) and the NIR. Direct N_2O emissions associated with the mineralization of the N content of SOC losses in mineral soils are not estimated. During the review, the Party informed the ERT that work is under way to enable all land categories to be reported in future submissions. The ERT considers that the recommendation has not yet been addressed because the Party	Work is underway to report these emissions for all land categories in future submissions.

		did not provide data on N_2O emissions associated with mineralization of N as a result of SOC losses in mineral soils.	
L.38	4(IV) Indirect N_2O emissions from managed soils – N_2O (L.38, 2019) (L.62, 2018) Completeness	Not resolved. Estimate indirect N_2O emissions associated with the mineralization of the N content of SOC losses in mineral soils for forest land, wetlands, settlements and other land and report them in CRF table 4(IV), and explain the estimations in the NIR. No indirect N_2O emissions associated with organic matter are reported. During the review, the Party clarified that work is under way to report these emissions for all land categories in future submissions.	Work is underway to report these emissions for all land categories in future submissions.
L.39	4(V) Biomass burning – CO_2, CH_4 and N_2O (L.39, 2019) (L.35, 2018) (L.42, 2016) (L.33, 2015) Completeness	Not resolved. Noting that CH_4 and N_2O emissions from forest fires are key categories, estimate CH_4 and N_2O emissions from biomass burning for land converted to forest land, land converted to wetlands, cropland, grassland and settlements; and populate CRF table 4(V). While CH_4 and N_2O emissions from biomass burning for forest land and grassland are estimated, all burning is reported under forest land remaining forest land and grassland remaining grassland. The Party explained that it is currently unable to separately report the emissions from land converted to forest land and land converted to grassland but will continue to explore ways of doing so. Biomass burning from wildfires on cropland and biomass burning on wetlands and settlements were not estimated owing to a lack of data.	As noted in our original response, we are unable to report on these emissions at the level of land use conversion, but will continue to explore approaches for doing this in future Inventories.
L.40	4.F Other land – CO_2, CH_4 and N_2O Comparability	The Party reported "NA" for all entries in CRF table 4.F (other land) owing to a lack of data. It explained in the NIR (chaps. 6.12–6.13, pp.6-142–6-143) that, while it is conducting research to track carbon pools for other land, it is unable to estimate CO_2, CH_4 and N_2O emissions for other land or land converted to other land. The ERT notes that, according to the UNFCCC Annex I inventory reporting guidelines, categories that are not estimated should be reported as "NE" where emissions or uptake can be expected. During the review, the Party stated that it will report the correct notation key in its next submission. It added that, while it is not currently developing estimates for other lands, it will aim to complete CRF table 4.F with the information available. The ERT recommends that the Party report numerical values in CRF table 4.F for managed areas of other land and "NE" for carbon pools for which numerical values cannot be reported, or otherwise develop an assumption for carbon pools being in equilibrium.	The notation keys for Table 4.F have been changed to NE for the current submission. Area estimates will be provided in future submissions.
L.41	4.G HWP – CO_2 Transparency	According to the NIR (p.6-35), the Party reports HWP using the production approach. Data for HWP are reported in CRF table 4.G (a separate issue regarding this reporting is detailed under ID# L.32 in table	The United States is unsure of the basis of this recommendation in the UNFCCC reporting guidelines and *2006 IPCC Guidelines* as they do not specify where HWP should be presented in the report; therefore, HWP is

		3). The ERT noted that the value for carbon stock change in forest land remaining forest land presented in NIR tables 6-1, 6-3, 6-4 and 6-5 (–663.2 Mt CO_2 eq) differs from the value reported in CRF table 4.1 (–565.2 Mt CO_2 eq). In a footnote to NIR tables 6-1 and 6-3 (but not to NIR tables 6-4 and 6-5), the Party explains that this figure also includes the uptake of carbon in HWP. This is contrary to reporting conventions, according to which HWP should be reported under category 4.G (including HWP in solid waste disposal sites) and not under forest land remaining forest land (category 4.A.1). The ERT considers that reporting HWP as a separate concept rather than as a subcategory of forest land is important, as HWP can sometimes fall under other land uses, such as forest converted to grassland, or former perennial horticulture on cropland. The same rationale is behind the recommendation to report the carbon balance of yard trimmings and food scraps under other (category 4.H) rather than as a sub-component of settlements (category 4.E) (see ID# L.28 in table 3). The ERT recommends that the Party clearly differentiate between HWP and forest carbon stock changes in the NIR and ensure consistent reporting between the CRF and NIR tables.	included within the forest chapter of the NIR because that is the source of wood that goes into the HWP estimates, but HWP estimates and methods are presented and documented separately. See the section on Harvest Wood Carbon (pp. 6-35 of the NIR). In the CRF submission, all HWP emissions are reported under 4.G.
Waste			
W.1	5. General (waste) – CO_2, CH_4 and N_2O (W.1, 2019) (W.1, 2018) (W.9, 2016) (W.9, 2015) Transparency	Not resolved. Provide background information that is consistent with the data actually used for the emission estimates, including the waste management practices. The United States reported in the NIR (annex 3.14, table A-236) the total amount of MSW generated and landfilled based on research by EPA, BioCycle and the Environmental Research and Education Foundation. However, the trend in the amount of MSW landfilled differs with the decreasing trend of CH_4 emissions from landfilled MSW for 1990–2018 (NIR tables 7-3–7-4). In addition, the ratio of landfilled MSW to total MSW generated for 2017 is reported as 65 per cent in NIR table A-236 but as 52.1 per cent in NIR box 7-4 (p.7-16). In its clarifications on the list of provisional main findings, the Party indicated that an explanation for these differences is provided in the NIR (annex 3.14, page A-463). However, the ERT considers that this explanation is narrative rather than quantitative, and that the Party should provide an analysis of the discrepancies and the data used for the emission estimates, such as waste composition data, DOC in MSW and background information on MSW streams, like the waste stream analysis by waste type provided in the 2006 IPCC Guidelines (vol. 5, chap. 2, box 2.1) (see also ID# W.3 below).	Additional information and an explanation of differences has been added in recent NIRs to explain different data sources and also estimation methods over the time series. In the current (i.e., April 2022) submission, the trends in amount of MSW waste generated, waste landfilled, and resulting CH_4 emissions are explained in Section 7.1, pp. 7-6. The differences noted in the two ratios of MSW landfilled to MSW generated are due to the two data sources and methods used by these reports. As explained in Box 7-3, the SOG and EREF data are used in the MSW methodology, while data from *EPA Facts and Figures* is presented in Box 7-4 to show trends of waste management in the United States for illustrative purposes. The discussion on the quantitative differences between these two data sources was added to Annex 3.14, Box A-3 (on p. A-451) of the April 2021 NIR submission and is retained in the current submission; see Annex 3.14. It is unclear that information outlined in Chapter 2 is required for reporting, as it is an example and as noted in the example itself depends on available data and national circumstances. The example in Chapter 2 is not consistent with our available data. Noting Section 3.8 of Volume 5 of the *2006 IPCC Guidelines* does not suggest including such an analysis. We are unsure of how this issue can be resolved in light of data sources and methodological refinements in recent years to incorporate facility-level

			GHGRP data.
W.8	5.A.1 Managed waste disposal sites – CH_4 (W.15, 2019) Transparency	Addressing. Include information to justify the oxidation factor used, including references and supporting data relevant to national circumstances as well as an uncertainty analysis for the oxidation factor applied in the estimation. The United States provided information in the NIR (pp.A-473–474) to justify the use of a country-specific oxidation factor greater than the default value of 0.1. During the review, the Party explained that it is planning to include additional detail in the discussion of the uncertainty analysis. This reporting is planned for the 2021 submission.	Addressed in current NIR submission Section 7.1 Uncertainty and Annex 3.14, Figure A-19.
W.9	5.A.1.a Anaerobic – CH_4 (W.7, 2019) (W.16, 2018) Comparability	Addressing. Estimate and report the amounts of CH_4 flared and CH_4 for energy recovery for anaerobic waste disposal sites, but, until that is possible, report them as "NE" instead of "IE" in CRF table 5.A. The United States reported the amount of CH_4 flared and used for energy recovery as "NE" in CRF table 5.A. During the previous review, the Party explained its use of directly reported GHGRP net emissions and noted that facilities were not required to report separately the total amounts of CH_4 recovered for energy and CH_4 flared. However, the ERT notes that the EPA Landfill Methane Outreach Program provides information on the amount of landfill gas collected and flared. It also notes that the 2006 IPCC Guidelines (vol. 5, chap. 3, p.3.18) state that if recovered gas is used for energy, then the resulting GHG emissions should be reported under the energy sector. Therefore, the Party should report the amount of CH_4 for energy recovery in CRF table 5.A and include a corresponding explanation in the NIR, taking into account the good practice outlines in the 2006 IPCC Guidelines.	This issue was addressed in the 2020 submission. See CRF Tables 5.A and Table 9 of the 2020 submission and NIR Annex 5. CH_4 has been reported as NE. Per engagement with the reporting community, future technical corrections to EPA's GHGRP may allow for reporters to indicate volumes of gas sent to flaring and to energy projects. Reporting of this information by facilities would allow EPA to report separate amounts for CH_4 flared and CH_4 for energy recovery. The timing for such updates has not been proposed and the initial data reported will only reflect information for the latest year of time series and will require some effort to develop time series information to include in the national Inventory submission.
W.10	5.A.1.a Anaerobic – CH_4 (W.8, 2019) (W.7, 2018) (W.12, 2016) (W.11, 2015) Accuracy	Addressing. Obtain up-to-date data on the type and fractions of organic waste placed in industrial waste landfills; and revise the CH_4 estimates for all major industrial waste landfills. The United States provided information in the NIR (p.7-10) on an EPA analysis to validate the assumption that most of the organic waste which would result in CH4 emissions is disposed of at pulp-, paper- and food-processing facilities (54 per cent) and food manufacturing facilities (7 per cent). However, the ERT believes that the Party should consider including other industries (e.g. metal foundries, petroleum refineries and chemical manufacturing facilities) as recommended in the 2016 review report (FCCC/ARR/2016/USA, ID# W.12). According to the NIR (p.7-15), EPA plans to investigate the prevalence of food-related waste deposited in industrial waste landfills and will record the findings from this exercise in	Progress was included in 2021 submission NIR Section 7.1. Work is still in progress to finalize a memorandum summarizing literature search and data availability.

		a memorandum and implement during the following inventory cycle any warranted changes to the methodology or assumptions for industrial waste landfills. The ERT welcomes the Party's provision of this information on the estimation of CH_4 emissions from industrial waste landfill.	
W.11	5.B.2 Anaerobic digestion at biogas facilities – CH_4 (W.19, 2019) (W.8, 2018) (W.14, 2016) (W.13, 2015) Transparency	Not resolved. Estimate and report CH_4 emissions from unintentional leakages using the default value of 5 per cent provided in the 2006 IPCC Guidelines. During the review, the Party explained that unintentional leakages of CH_4 emissions from anaerobic digestion of organic waste, as described in the 2006 IPCC Guidelines (vol. 5, chap. 4.1), will be reported in the 2021 submission, as indicated in the NIR (p.7-39).	The United State has included estimates from anaerobic digestion at biogas facilities in the April 2021 submission. See Section 7.4 of the Waste Chapter of the current NIR submission.
W.13	5.C.1 Waste incineration – CO_2, CH_4 and N_2O (W.13, 2019) (W.10, 2018) (W.15, 2016) (W.14, 2015) Transparency	Not resolved. Provide in the NIR consistent information on the data that are used for the estimation of emissions from waste incineration (e.g. on the percentage of waste incinerated in 2013 reported in figure 7-2 and tables 3-26 and A- 272 of the 2016 NIR). Inconsistencies still exist in the combustion ratio of MSW between NIR figure 7-3 (12.7 per cent) and NIR table 3-27 (7.6 per cent). During the review, the United States explained that the percentage of waste incineration shown in figure 7-3 comes from a different source than that used for table 3-27 and does not represent the data used in the analysis for estimating emissions from waste incineration. However, the ERT considers that this inconsistency should be clearly explained in the NIR or NIR figure 7-3 should be removed.	For the current April 2022 submission the United States has updated the approach to calculating emissions from waste incineration. See Sections 3.3 and Annex 3.7 of the 2022 NIR. The updated approach does not rely on the combustion ratio of MSW but rather the tons of MSW combusted and emission factors. The tons of MSW combusted comes from multiple sources including the data discusses in Section 7.1 but also other sources including EPA's GHGRP. The data used for MSW incineration emissions is not inconsistent with the data used to develop landfill emissions.
W.15	5.D.2 Industrial wastewater – CH_4 (W.13, 2019) (W.14, 2018) (W.5, 2016) (W.5, 2015) (105, 2013) Completeness	Not resolved. Include information on the non-estimation of CH_4 emissions from sludge under industrial wastewater. The Party did not include information on emissions from sludge in the NIR. During the review, the Party explained that sludge removed from industrial wastewater is not estimated owing to insufficient data and that an explanation will be added in annex 5 to the next submission in line with paragraph 37(b) of the UNFCCC Annex I inventory reporting guidelines.	The United States has included an explanation in Annex 5 of the previous and current submissions, including a quantified estimate of methane emissions from sludge from industrial wastewater treatment demonstrating insignificance of these emissions.

W.16	5.C.1 Waste incineration – CO_2 Accuracy	The Party reported in the CRF tables CO_2 emissions from waste incineration (category 5.C) as "IE" and stated in the NIR (pp.3-55 and 7-39) that CO_2 emissions from incineration of plastics, synthetic rubber, synthetic fibres and carbon black in scrap tyres are accounted for under category 1.A.5 (fuel combustion – other) instead of category 5.C (waste incineration). During the review, the Party explained that CO_2 emissions from waste nappies and waste fossil oil are included under the NEU emission estimates. The Party also explained that CO_2 emissions from paper and cardboard waste are not estimated because paper waste was assumed to have 0 per cent fossil carbon content. The default range of fossil carbon fraction in the 2006 IPCC Guidelines is 0–5 per cent, and the default value is 1 per cent (vol. 5, chap. 2, table 2.4, p.2.14). The Party informed the ERT that it applies a country-specific parameter of 0 per cent fossil carbon content in paper waste based on the approach from the EPA Reduction Model (WARM). The Party noted that it could refer to the Waste Reduction Model in a future submission. The ERT recommends that the United States provide an explanation for reporting 0 per cent fossil carbon content in paper waste as a country-specific parameter as well as the reference on which the parameter is based.	For the April 2022 submission the United States has updated the approach to calculating emissions from waste incineration. See Sections 3.3 and Annex 3.7 of the 2022 NIR. The updated approach uses a country-specific emission factor for CO_2 emissions from MSW combustion. The CO_2 factor is based on measured CO_2 emissions divided by the amount of MSW combusted. Therefore, the factor would take into account any C in the MSW including from waste nappies, fossil oil, paper, etc.
W.17	5.C.1 Waste incineration – CH_4 and N_2O Completeness	The ERT noted there were approximately 170 sewage sludge incineration plants in operation in the United States in the early 1990s according to the EPA website (https://www.epa.gov/sites/production/files/2020-10/documents/c02s02.pdf) and that CH_4 and N_2O emissions from incineration of sewage sludge may not be reported in the national inventory, as the emissions reported under category 5.C.1 (waste incineration – biogenic – MSW) are reported as "IE". During the review, the Party explained that CH_4 and N_2O emissions from incineration of wastewater treatment plant sludge are likely estimated as emissions from MSW even though wastewater treatment plant sludge is not officially categorized as MSW, or that emissions could be considered insignificant given the increasing regulatory pressure on sludge incineration. However, the ERT cannot be assured that CH_4 and N_2O emissions are accurately estimated in line with the *2006 IPCC Guidelines* because AD or emission estimates are not clearly shown in the NIR. It notes that the *2006 IPCC Guidelines* (vol. 5, chap. 5, table 5.6) provide a default N_2O EF for sewage sludge of 900 g N_2O/t waste (wet weight) and the default N_2O EF for MSW of 50–60 g N2O/t waste (wet weight), but could not assess whether these emissions are included in the inventory on the basis of the information provided in the NIR and during the review week. The ERT recommends that the United States estimate CH_4 and N_2O emissions from incineration of sewage sludge at wastewater treatment	The United States considered the potential emissions associated with sewage sludge incineration and concluded they are insignificant. Based on data on the amount of sewage sludge incinerated and assumed emission factors for N_2O and CH_4 from our GHGRP for biomass solids, emissions were estimated to be approximately 9 kt CO_2 Eq. per year.

		plants in the country and either include estimates or otherwise provide an explanation in the NIR demonstrating that these emissions are already included in the inventory estimation.	

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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 identified in the *2006 IPCC Guidelines* needed to understand the United States' total net greenhouse gas emissions in line with the UNFCCC reporting guidelines, 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 facilities[218] 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 41 industrial categories ("Subparts"[219]), including direct greenhouse gas emitters,[220] fossil fuel suppliers, industrial gas suppliers, and facilities that inject carbon dioxide (CO_2) underground for sequestration or other reasons.[221] In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year.[222]

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.[223]

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 individual facilities or groups of facilities.[224] More information on EPA's GHGRP can be found at https://www.epa.gov/ghgreporting.

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[218] 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).

[219] See https://www.epa.gov/ghgreporting/resources-subpart-ghg-reporting.

[220] Data reporting by affected facilities includes the reporting of emissions from fuel combustion at that affected facility.

[221] See https://www.epa.gov/ghgreporting/resources-subpart-ghg-reporting and http://ghgdata.epa.gov/ghgp/main.do.

[222] 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 CO_2 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 CO_2 Eq. for five years or below 15,000 metric tons CO_2 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.

[223] See GHGRP Verification Fact Sheet https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

[224] See http://ghgdata.epa.gov.

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-246 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 *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),[225] 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.[226] 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.[227] 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).

[225] 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.
[226] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.
[227] 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-246: Summary of EPA GHGRP Data Use in U.S. Inventory

Inventory Category	GHGRP Industry Subpart	Initial Calendar Year of Reporting under GHGRP	Reporting Threshold[228]	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 [229]	
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	•	•	•	•	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
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

[228] Y=25,000 $MTCO_2$ Eq., or industry-specific threshold other than 25,000 $MTCO_2$ 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.

[229] 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 Category	GHGRP Industry Subpart	Initial Calendar Year of Reporting under GHGRP	Reporting Threshold[228]	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 [229]	
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
Carbon Dioxide Consumption	PP – Suppliers of Carbon Dioxide	2010	Y	•				4.15
Iron and Steel Production and Metallurgical Coke Production	Q – Iron and Steel Production	2010	Y	•				4.17
Aluminum Production	F – Aluminum Production	2010	N	•				4.19
Magnesium Production and Processing	T – Magnesium Production	2011	Y	•				4.20
Lead Production	R – Lead Production	2010	Y				•	4.21
Electronics Industry	I – Electronics Manufacturing	2011	Y	•				4.23

Inventory Category	GHGRP Industry Subpart	Initial Calendar Year of Reporting under GHGRP	Reporting Threshold[228]	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 [229]	
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)				•	4.24
Electrical Transmission and Distribution	DD – Use of Electric Transmission and Distribution Equipment; SS – Manufacture of Electric Transmission and Distribution Equipment	2011	Y	•	•	•		4.25
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