4. Industrial Processes and Product Use

Industrial Processes and Product Use (IPPU) chapter includes greenhouse gas emissions occurring from industrial processes and from the use of greenhouse gases in products. The industrial processes and product use categories included in this chapter are presented in Figure 4-1 and Figure 4-2. Greenhouse gas emissions from industrial processes can occur in two different ways. First, they may be generated and emitted as the byproducts of various non-energy-related industrial activities. Second, they may be emitted due to their use in manufacturing processes or by end-consumers. Combustion-related energy use emissions from industry are reported in Chapter 3, Energy.

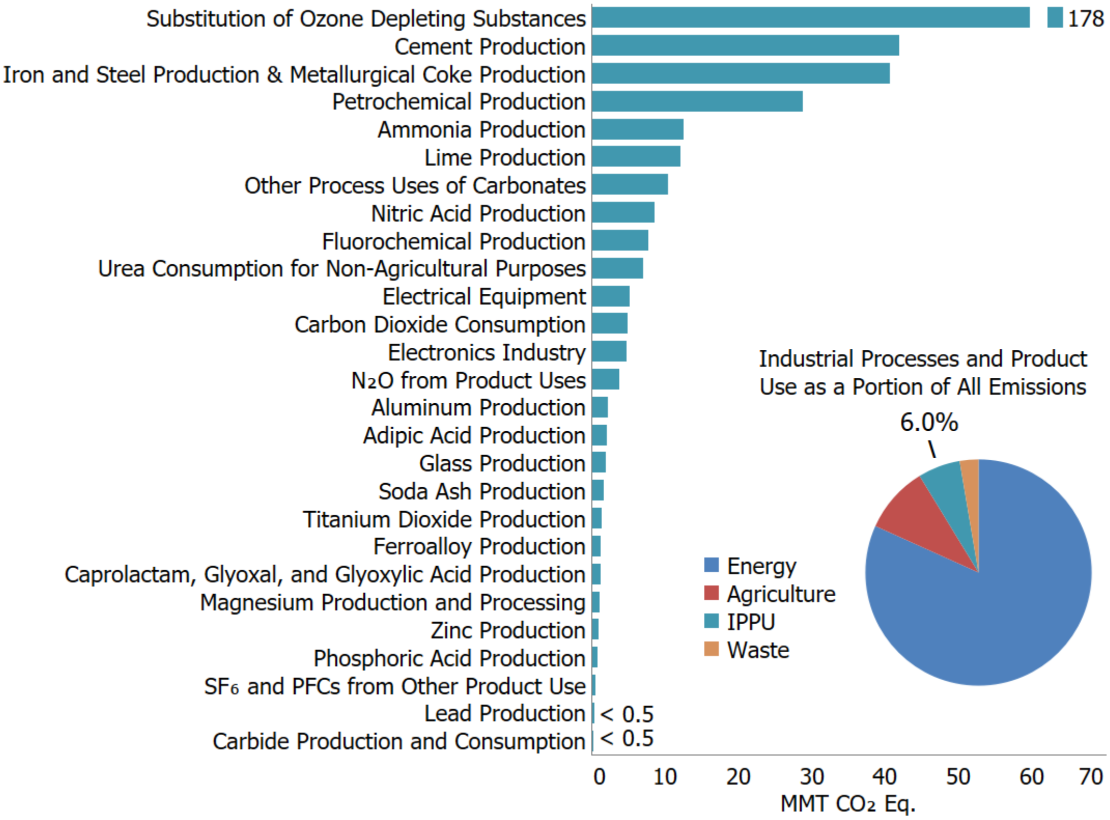
In the case of byproduct emissions, the emissions are generated by an industrial process itself and are not directly a result of energy consumed during the process. For example, raw materials can be chemically or physically transformed from one state to another. This transformation can result in the release of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated greenhouse gases (e.g., HFC-23). The greenhouse gas byproduct generating processes included in this chapter include iron and steel production and metallurgical coke production, cement production, petrochemical production, ammonia production, lime production, other process uses of carbonates (e.g., flux stone, flue gas desulfurization, ceramics production, non-metallurgical magnesia production, and soda ash consumption not associated with glass manufacturing), nitric acid production, adipic acid production, urea consumption for non-agricultural purposes, aluminum production, HCFC-22 production, other fluorochemical production, glass production, soda ash production, ferroalloy production, titanium dioxide production, caprolactam production, zinc production, phosphoric acid production, lead production, and silicon carbide production and consumption.

Greenhouse gases that are used in manufacturing processes or by end-consumers include man-made compounds such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). The present contribution of HFCs, PFCs, SF_6, and NF_3 gases to the radiative forcing effect of all anthropogenic greenhouse gases is small; however, because of their extremely long lifetimes, many of them will continue to persist in the atmosphere long after they were first released. In addition, many of these gases have high global warming potentials; SF_6 is the most potent greenhouse gas the Intergovernmental Panel on Climate Change (IPCC) has evaluated. Use of HFCs continues since they are the primary substitutes for ozone depleting substances (ODS), which are being phased-out under the Montreal Protocol on Substances that Deplete the Ozone Layer; however, production and consumption of HFCs are being phased down under the Kigali Amendment to the Montreal Protocol and in the United States under the American Innovation and Manufacturing Act. Hydrofluorocarbons, PFCs, SF_6, and NF_3 are employed and emitted by a number of other industrial sources in the United States, such as the electronics industry, electric power transmission and distribution, PFCs and SF_6 for other product use, and magnesium metal production and processing. Carbon dioxide is also consumed and emitted through various end-use applications. In addition, nitrous oxide is used in and emitted by the electronics industry and anesthetic and aerosol applications.

In 2022, IPPU generated emissions of 383.2 million metric tons of CO_2 equivalent (MMT CO_2 Eq.), or 6.0 percent of total U.S. greenhouse gas emissions.[1] Carbon dioxide emissions from all industrial processes were 168.9 MMT CO_2 Eq. (168,937 kt CO_2) in 2022, or 3.3 percent of total U.S. CO_2 emissions. Methane emissions from industrial processes resulted in emissions of approximately 0.04 MMT CO_2 Eq. (1 kt CH_4) in 2022, which was 0.01 percent of U.S. CH_4 emissions. Nitrous oxide emissions from IPPU were 16.1 MMT CO_2 Eq. (61 kt N_2O) in 2022, or 4.1 percent of total U.S. N_2O emissions. In 2022 combined emissions of HFCs, PFCs, SF_6, and NF_3 totaled 198.1 MMT CO_2 Eq. Total emissions from IPPU in 2022 were 3.9 percent more than 1990 emissions. Total emissions from IPPU remained relatively constant between 2021 and 2022, increasing by 0.4 percent due to offsetting trends within the sector. More information on emissions of greenhouse gas precursors emissions that also result from IPPU are presented in Section 4.27 of this chapter.

The largest source of IPPU-related emissions is the substitution of ozone depleting substances, which accounted for 46.5 percent of sector emissions in 2022. These emissions have increased by 79.1 percent since 2005, and 3.2 percent between 2021 and 2022. Cement production was the second largest source of IPPU emissions in 2022, accounting for 10.9 percent of IPPU emissions in 2022. Iron and steel production and metallurgical coke production was the third largest source of IPPU emissions, accounting for 10.6 percent of the sector total in 2022.

Figure 4-1: Industrial Processes and Product Use Sector Greenhouse Gas Sources



The increase in overall IPPU emissions since 1990 reflects a range of emission trends among the emission sources, as shown in Figure 4-2. Emissions resulting from most types of metal production have declined significantly since 1990, largely due to production shifting to other countries, but also due to transitions to less-emissive methods of

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[1] Emissions reported in the IPPU chapter include those from all 50 states, including Hawaii and Alaska, as well as from U.S. Territories.

production (in the case of iron and steel) and to improved practices (in the case of PFC emissions from aluminum production). Carbon dioxide and CH_4 emissions from some chemical production sources (e.g., petrochemical production, urea consumption for non-agricultural purposes) have increased since 1990, while emissions from other chemical production sources (e.g., ammonia production, phosphoric acid production) have decreased. Emissions from mineral sources have either increased (e.g., cement production) or not changed significantly (e.g., lime production) since 1990 and largely follow economic cycles. Hydrofluorocarbon emissions from the substitution of ODS have increased drastically since 1990 and are the largest source of IPPU emissions (46.5 percent in 2022), while the emissions of HFCs, PFCs, SF_6, and NF_3 from other sources have generally declined. Nitrous oxide emissions from the production of nitric acid have decreased. Some emission sources (e.g., adipic acid) exhibit varied interannual trends. Trends are explained further within each emission source category throughout the chapter.

Figure 4-2: Trends in Industrial Processes and Product Use Sector Greenhouse Gas Sources

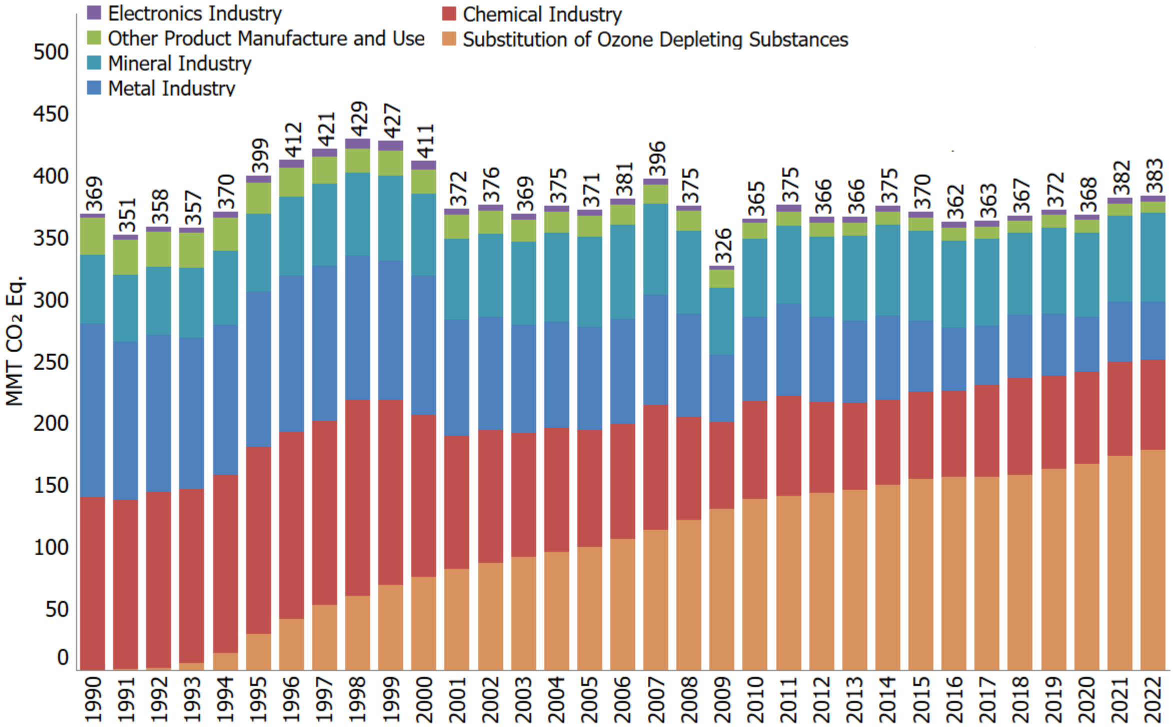

Table 4-1 summarizes emissions for the IPPU chapter in MMT CO_2 Eq. using IPCC *Fifth Assessment Report* (AR5) GWP values, following the requirements of the current United Nations Framework Convention on Climate Change (UNFCCC) reporting guidelines for national inventories (IPCC 2007).[2] Unweighted gas emissions in kt are also provided in Table 4-2. The source descriptions that follow in the chapter are presented in the order as reported to the UNFCCC in the Common Reporting Tables (CRTs), corresponding generally to: mineral industry, chemical industry, metal industry, and emissions from the uses of HFCs, PFCs, SF_6, and NF_3.

Each year, some emission and sink estimates in the IPPU sector of the *Inventory* are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emission estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous *Inventory's* time series (i.e., 1990 to 2021) to

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[2] See http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

ensure that the trend is accurate. Key updates to this year's *Inventory* include the addition of new categories previously not estimated: CO_2 emissions from ceramics production and non-metallurgical magnesia within other process use of carbonates category; fluorinated gases from production of fluorochemicals other than HCFC-22 within the fluorochemical production category; and SF_6 and PFCs from additional product uses within the other product manufacture and use category. In addition, there were changes to the petrochemical production methodology to calculate emissions from methanol production; updates to emission estimates from urea consumption for non-agricultural purposes driven by revisions to quantities of urea applied, urea imports, and urea exports; and revisions to the method for estimating SF_6 emissions from electrical equipment for estimating using CARB data from electrical equipment in California. Together, these methodological and data updates increased IPPU sector greenhouse gas emissions by an average 20.4 MMT CO_2 Eq. (7.2 percent) across the time series. For more information on specific methodological updates, please see the Recalculations Discussion section for each category in this chapter.

Table 4-1: Emissions from Industrial Processes and Product Use (MMT CO_2 Eq.)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**213.7**	**195.9**	**164.4**	**168.2**	**160.7**	**168.8**	**168.9**
Cement Production	33.5	46.2	39.0	40.9	40.7	41.3	41.9
Iron and Steel Production & Metallurgical Coke Production	104.7	70.1	42.9	43.1	37.7	41.9	40.7
Iron and Steel Production	*99.1*	*66.2*	*41.6*	*40.1*	*35.4*	*38.6*	*37.7*
Metallurgical Coke Production	*5.6*	*3.9*	*1.3*	*3.0*	*2.3*	*3.2*	*3.0*
Petrochemical Production	20.1	26.9	27.2	28.5	27.9	30.7	28.8
Ammonia Production	14.4	10.2	12.7	12.4	13.0	12.2	12.6
Lime Production	11.7	14.6	13.1	12.1	11.3	11.9	12.2
Other Process Uses of Carbonates	7.1	8.5	7.9	9.0	9.0	8.6	10.4
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	6.1	6.2	5.8	6.6	7.1
Carbon Dioxide Consumption	1.5	1.4	4.1	4.9	5.0	5.0	5.0
Glass Production	2.3	2.4	2.0	1.9	1.9	2.0	2.0
Soda Ash Production	1.4	1.7	1.7	1.8	1.5	1.7	1.7
Titanium Dioxide Production	1.2	1.8	1.5	1.3	1.3	1.5	1.5
Aluminum Production	6.8	4.1	1.5	1.9	1.7	1.5	1.4
Ferroalloy Production	2.2	1.4	2.1	1.6	1.4	1.6	1.3
Zinc Production	0.6	1.0	1.0	1.0	1.0	1.0	0.9
Phosphoric Acid Production	1.5	1.3	0.9	0.9	0.9	0.9	0.8
Lead Production	0.5	0.6	0.5	0.5	0.5	0.4	0.4
Carbide Production and Consumption	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Substitution of Ozone Depleting Substances	+	+	+	+	+	+	+
Magnesium Production and Processing	0.1	+	+	+	+	+	+
CH_4	**0.1**	**+**	**+**	**+**	**+**	**+**	**+**
Carbide Production and Consumption	+	+	+	+	+	+	+
Ferroalloy Production	+	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	+	+
Petrochemical Production	+	+	+	+	+	+	+
N_2O	**29.6**	**22.2**	**23.1**	**18.7**	**20.8**	**19.7**	**16.1**
Nitric Acid Production	10.8	10.1	8.5	8.9	8.3	7.9	8.6
N_2O from Product Uses	*3.8*	*3.8*	*3.8*	*3.8*	*3.8*	*3.8*	*3.8*

Gas/Source	1990	2005	2018	2019	2020	2021	2022
Adipic Acid Production	13.5	6.3	9.3	4.7	7.4	6.6	2.1
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.5	1.9	1.3	1.2	1.1	1.2	1.3
Electronics Industry	+	0.1	0.2	0.2	0.3	0.3	0.3
HFCs	**47.7**	**121.7**	**163.9**	**168.2**	**170.3**	**177.0**	**182.8**
Substitution of Ozone Depleting Substances[a]	0.3	99.5	157.9	162.1	166.2	172.6	178.1
Fluorochemical Production	47.3	22.1	5.7	5.7	3.8	4.0	4.3
Electronics Industry	0.2	0.2	0.3	0.3	0.3	0.4	0.3
Magnesium Production and Processing	0.0	0.0	0.1	0.1	0.1	+	+
PFCs	**39.5**	**10.2**	**7.4**	**7.3**	**6.6**	**6.3**	**6.7**
Fluorochemical Production	17.5	4.0	2.9	3.0	2.5	2.6	3.0
Electronics Industry	2.5	3.0	2.9	2.6	2.5	2.6	2.7
Aluminum Production	19.3	3.1	1.4	1.4	1.4	0.9	0.8
SF_6 and PFCs from Other Product Use	0.1	0.1	0.2	0.2	0.2	0.1	0.2
Substitution of Ozone Depleting Substances[a]	NO	+	+	+	+	+	+
Electrical Equipment	+	+	0.0	+	+	+	+
SF_6	**37.9**	**20.2**	**7.6**	**8.4**	**8.1**	**8.5**	**7.6**
Electrical Equipment	24.7	11.8	5.0	6.1	5.9	6.0	5.1
Magnesium Production and Processing	5.6	3.0	1.1	0.9	0.9	1.2	1.1
Electronics Industry	0.5	0.8	0.8	0.8	0.8	0.9	0.8
SF_6 and PFCs from Other Product Use	1.3	1.3	0.8	0.6	0.5	0.4	0.6
Fluorochemical Production	5.8	3.3	+	+	+	+	+
NF_3	**0.3**	**1.0**	**0.7**	**1.1**	**1.3**	**1.1**	**1.1**
Electronics Industry	+	0.4	0.5	0.5	0.6	0.6	0.6
Fluorochemical Production	0.3	0.6	0.1	0.6	0.7	0.5	0.5
Total[b]	**368.8**	**371.3**	**367.2**	**371.9**	**367.9**	**381.6**	**383.2**

+ Does not exceed 0.05 MMT CO_2 Eq.

NO (Not Occurring)

[a] Small amounts of PFC emissions from this source are included under HFCs due to confidential business information.

[b] Total does not include other fluorinated gases, such as HFEs and PFPEs, which are reported separately in Section 4.24.

Note: Totals may not sum due to independent rounding. Emissions of F-HTFs that are not HFCs, PFCs or SF_6 are not included in *Inventory* totals and are included for informational purposes only in Section 4.24. Emissions presented for informational purposes include HFEs, PFPMIEs, perfluoroalkylmorpholines, and perfluorotrialkylamines.

Table 4-2: Emissions from Industrial Processes and Product Use (kt)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
CO_2	**213,682**	**195,933**	**164,404**	**168,175**	**160,701**	**168,838**	**168,937**
Cement Production	33,484	46,194	38,971	40,896	40,688	41,312	41,884
Iron and Steel Production & Metallurgical Coke Production	104,740	70,082	42,863	43,095	37,724	41,873	40,672
Iron and Steel Production	*99,132*	*66,161*	*41,581*	*40,089*	*35,398*	*38,648*	*37,718*
Metallurgical Coke Production	*5,608*	*3,921*	*1,282*	*3,006*	*2,325*	*3,224*	*2,954*
Petrochemical Production	20,075	26,882	27,200	28,483	27,926	30,656	28,788
Ammonia Production	14,404	10,234	12,669	12,401	13,006	12,192	12,610
Lime Production	11,700	14,552	13,106	12,112	11,299	11,870	12,208
Other Process Uses of Carbonates	7,103	8,472	7,938	8,973	9,012	8,583	10,384

Gas/Source	1990	2005	2018	2019	2020	2021	2022
Urea Consumption for Non-Agricultural Purposes	3,784	3,653	6,113	6,150	5,805	6,600	7,053
Carbon Dioxide Consumption	1,472	1,375	4,130	4,870	4,970	4,990	5,000
Glass Production	2,263	2,402	1,989	1,940	1,858	1,969	1,956
Soda Ash Production	1,431	1,655	1,714	1,792	1,461	1,714	1,704
Titanium Dioxide Production	1,195	1,755	1,541	1,340	1,340	1,474	1,474
Aluminum Production	6,831	4,142	1,455	1,880	1,748	1,541	1,446
Ferroalloy Production	2,152	1,392	2,063	1,598	1,377	1,567	1,327
Zinc Production	632	1,030	999	1,026	977	1,007	947
Phosphoric Acid Production	1,529	1,342	937	909	901	874	840
Lead Production	516	553	527	531	450	439	428
Carbide Production and Consumption	243	213	184	175	154	172	210
Substitution of Ozone Depleting Substances[a]	+	1	3	3	4	4	4
Magnesium Production and Processing	129	4	2	2	3	3	3
CH_4	**3**	**2**	**2**	**1**	**1**	**1**	**1**
Carbide Production and Consumption	1	+	+	+	+	+	+
Ferroalloy Production	1	+	1	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	1	1	+	+	+	+	+
Petrochemical Production	+	+	+	+	+	+	+
N_2O	**112**	**84**	**87**	**71**	**79**	**74**	**61**
Nitric Acid Production	41	38	32	34	31	30	33
N_2O from Product Uses	*14*	*14*	*14*	*14*	*14*	*14*	*14*
Adipic Acid Production	51	24	35	18	28	25	8
Caprolactam, Glyoxal, and Glyoxylic Acid Production	6	7	5	5	4	5	5
Electronics Industry	+	+	1	1	1	1	1
HFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances[a]	M	M	M	M	M	M	M
Fluorochemical Production	M	M	M	M	M	M	M
Electronics Industry	+	+	+	+	+	+	+
Magnesium Production and Processing	0	0	+	+	+	+	+
PFCs	**101**	**83**	**179**	**173**	**167**	**139**	**172**
Fluorochemical Production	M	M	M	M	M	M	M
Electronics Industry	+	+	+	+	+	+	+
Aluminum Production	M	M	M	M	M	M	M
SF_6 and PFCs from Other Product Use	101	83	178	173	167	138	172
Substitution of Ozone Depleting Substances[a]	NO	+	+	+	+	+	+
Electrical Equipment	+	+	0	+	+	+	+
SF_6	**2**	**1**	**+**	**+**	**+**	**+**	**+**
Electrical Equipment	1	1	*+*	*+*	*+*	*+*	*+*
Magnesium Production and Processing	+	+	+	+	+	+	+
Electronics Industry	+	+	+	+	+	+	+

Gas/Source	1990	2005	2018	2019	2020	2021	2022
SF_6 and PFCs from Other Product Use	0	0	+	+	+	+	+
Fluorochemical Production	0	0	+	+	+	+	+
NF_3	**+**	**0**	**+**	**0**	**0**	**0**	**0**
Electronics Industry	+	+	+	+	+	+	+
Fluorochemical Production	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

M (Mixture of gases)

NO (Not Occurring)

[a] Small amounts of PFC emissions from this source are included under HFCs due to confidential business information.

Note: Totals by gas may not sum due to independent rounding.

This chapter presents emission estimates calculated in accordance with the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (*2006 IPCC Guidelines*) and its refinements. For additional detail on IPPU sources that are not included in this *Inventory* report, please review Annex 5, Assessment of the Sources and Sinks of Greenhouse Gas Emissions Not Included. These sources are not included due to various national circumstances, such as emissions from a source may not currently occur in the United States, data are not currently available for those emission sources (e.g., glyoxal and glyoxylic acid production, CH_4 from direct reduced iron production), emissions are included elsewhere within the *Inventory* report, or data suggest that emissions are not significant (e.g., other various fluorinated gas emissions from other product uses). In terms of geographic scope, emissions reported in the IPPU chapter include those from all 50 states, including Hawaii and Alaska, as well as from 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., cement production, lime production, electrical equipment). EPA will review this on an ongoing basis to ensure emission sources are included across all geographic areas if they occur. Information on planned improvements for specific IPPU source categories can be found in the Planned Improvements section of the individual source category.

In addition, as mentioned in the Energy chapter of this report (Box 3-5), fossil fuels consumed for non-energy uses for primary purposes other than combustion for energy (including lubricants, paraffin waxes, bitumen asphalt, and solvents) are reported in the Energy chapter. According to the *2006 IPCC Guidelines*, these non-energy uses of fossil fuels are to be reported under the IPPU, rather than the Energy sector; however, due to national circumstances regarding the allocation of energy statistics and carbon balance data, the United States reports these non-energy uses in the Energy chapter of this *Inventory*. Although emissions from these non-energy uses are reported in the Energy chapter, the methodologies used to determine emissions are compatible with the *2006 IPCC Guidelines* and are well documented and scientifically based. The methodologies used are described in Section 3.2, Carbon Emitted from Non-Energy Uses of Fossil Fuels and Annex 2.3, Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels. The emissions are reported under the Energy chapter to improve transparency, report a more complete carbon balance, and avoid double counting. For example, only the emissions from the first use of lubricants and waxes are to be reported under the IPPU sector, and emissions from use of lubricants in 2-stroke engines and emissions from secondary use of lubricants and waxes in waste incineration with energy recovery are to be reported under the Energy sector. Reporting non-energy use emissions from only first use of lubricants and waxes under IPPU would involve making artificial adjustments to the non-energy use carbon balance and could potentially result in double counting of emissions. These artificial adjustments would also be required for asphalt and road oil and solvents (which are captured as part of petrochemical feedstock emissions) and could also potentially result in double counting of emissions. For more information, see the Methodology discussion in Section 3.1, CO_2 from Fossil Fuel Combustion, Section 3.2, Carbon Emitted from Non-Energy Uses of Fossil Fuels and Annex 2.3, Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels.

Finally, as stated in the Energy 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—are reallocated to the IPPU chapter, as they are consumed during non-energy related industrial process activity. Emissions from uses of fossil fuels as feedstocks or reducing agents (e.g., petrochemical production, aluminum production, titanium dioxide, zinc production) are reported in the IPPU chapter, unless otherwise noted due to specific national circumstances. This approach is compatible with the *2006 IPCC Guidelines* and is well documented and scientifically based. The emissions from these feedstocks and reducing agents are reported under the IPPU chapter to improve transparency and to avoid double counting of emissions under both the Energy and IPPU sectors. More information on the methodology to adjust for these emissions within the Energy chapter is described in the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion [CRT Source Category 1A]) and Annex 2.1 Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion. Additional information is listed within each IPPU emission source in which this approach applies.

Box 4-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals

Consistent with Article 13.7(a) of the Paris Agreement and Article 4.1(a) of the UNFCCC as well as relevant decisions under those agreements, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally accepted methods provided by the Intergovernmental Panel on Climate Change (IPCC) in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (*2006 IPCC Guidelines*) and its supplements and refinements. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common format in line with the reporting guidelines for the reporting of inventories under the Paris Agreement and the UNFCCC. The Parties' use of consistent methods to calculate emissions and removals for their inventories helps to ensure that these reports are comparable. The presentation of emissions and removals provided in the IPPU chapter do not preclude alternative examinations. Rather, this chapter presents emissions and removals in a common format consistent with how Parties are to report inventories under the Paris Agreement and the UNFCCC. The report itself, and this chapter, follows this common format, and provides an explanation of the application of methods used to calculate emissions and removals from industrial processes and from the use of greenhouse gases in products.

QA/QC and Verification Procedures

The quality of IPPU source categories is assured through application of the U.S. Inventory QA/QC plan outlined in Annex 8. Two types of checks were performed using this plan: (1) general (Tier 1) procedures consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* that focus on annual procedures and checks to be used when gathering, maintaining, handling, documenting, checking, and archiving the data, supporting documents, and files; and (2) source category-specific (Tier 2) procedures that focus on checks and comparisons of the emission factors, activity data, and methodologies used for estimating emissions from the relevant industrial process and product use sources. Examples of these procedures include: checks to ensure that activity data and emission estimates are consistent with historical trends; that consistent, complete and data sources are used and documented; that interpolation or extrapolation techniques are consistent across sources; and that common units, and conversion factors are used where applicable. Consistent with the *2006 IPCC Guidelines*, additional category-specific QC procedures were performed for more significant emission categories or sources where significant methodological and data updates have taken place. Any significant findings and errors identified are documented and corrected. Application of these procedures, specifically category-specific QC procedures and updates/improvements as a result of QA processes (expert, public, and UNFCCC technical expert reviews), are described further within respective source categories, in the Recalculations Discussion and Planned Improvement sections.

For sources that use data from EPA's Greenhouse Gas Reporting Program (GHGRP), EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent.[3] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with the general and category-specific QC procedures including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions. See Box 4-2 below for more information on use of GHGRP data in this chapter.

For most IPPU categories, activity data are obtained via aggregation of facility-level data from EPA's GHGRP (see Box 4-2 below and Annex 9), national commodity surveys conducted by U.S. Geological Survey (USGS) National Minerals Information Center, U.S. Department of Energy (DOE), U.S. Census Bureau, and industry associations such as Air-Conditioning, Heating, and Refrigeration Institute (AHRI), American Chemistry Council (ACC), and American Iron and Steel Institute (AISI) (specified within each source category). The emission factors used include those derived from the EPA's GHGRP and application of IPCC default factors.

Box 4-2: Industrial Process and Product Use Data from EPA's Greenhouse Gas Reporting Program

EPA collects greenhouse gas emissions data from individual facilities and suppliers of certain fossil fuels and industrial gases through its Greenhouse Gas Reporting Program (GHGRP). The GHGRP applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject CO_2 underground for sequestration or other reasons and requires reporting by sources or suppliers in 41 industrial categories. Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases.

In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year, but reporting is required for all facilities in some industries. Calendar year 2010 was the first year for which data were collected for facilities subject to 40 CFR Part 98, though some source categories first collected data for calendar year 2011. For more information, see Annex 9, Use of EPA Greenhouse Gas Reporting Program in Inventory.

EPA uses annual GHGRP data in a number of categories to improve the national estimates presented in this *Inventory*, consistent with IPCC guidelines (e.g., minerals, chemicals, product uses). Methodologies used in EPA's GHGRP are consistent with IPCC guidelines, including higher tier methods; however, it should be noted that the coverage and definitions for source categories (e.g., allocation of energy and IPPU emissions) in EPA's GHGRP may differ from those used in this *Inventory* in meeting the Paris Agreement and UNFCCC reporting guidelines (IPCC 2011) and is an important consideration when incorporating GHGRP data in the *Inventory*. In line with the Paris Agreement and UNFCCC reporting guidelines, the *Inventory* is a comprehensive accounting of all emissions from source categories identified in the *2006 IPCC Guidelines*. EPA has paid particular attention to ensuring both completeness and time-series consistency for major recalculations that have occurred from the incorporation of GHGRP data into these categories, consistent with *2006 IPCC Guidelines* and the *2019 Refinement*, Volume 1, Chapter 2, Section 2.3, *Use of Facility Data in Inventories.*[4]

For certain source categories in this *Inventory* (e.g., nitric acid production, lime production, cement production, petrochemical production, carbon dioxide consumption, ammonia production, and urea consumption for non-agricultural purposes), EPA has integrated 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

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

[4] See https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch02_DataCollection.pdf.

only publishing data values that meet these aggregation criteria.[5] Specific uses of aggregated facility-level data are described in the respective methodological sections (e.g., including other sources using GHGRP data that is not aggregated CBI, such as aluminum, electronics industry, electrical equipment, HCFC-22 production, and magnesium production and processing). For other source categories in this chapter, as indicated in the respective planned improvements sections,[6] EPA is continuing to analyze how facility-level GHGRP data may be used to improve the national estimates presented in this *Inventory*, giving particular consideration to ensuring time-series consistency and completeness.

Additionally, EPA's GHGRP has and will continue to enhance QA/QC procedures and assessment of uncertainties within the IPPU categories (see those categories for specific QA/QC details regarding the use of GHGRP data).

4.1 Cement Production (CRT Source Category 2A1)

Cement production is an energy- and raw material-intensive process that results in the generation of carbon dioxide (CO_2) both from the energy consumed in making the clinker precursor to cement and from the chemical process to make the clinker. This reporting category (2A1) includes emissions from production of clinker and use of cement kiln dust. Per the IPCC methodological guidance, emissions from fuels consumed for energy purposes during the production of cement are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

During the clinker production process, the key reaction occurs when calcium carbonate ($CaCO_3$), in the form of limestone or similar rocks or in the form of cement kiln dust (CKD), is heated in a cement kiln at a temperature range of about 700 to 1,000 degrees Celsius (1,300 to 1,800 degrees Fahrenheit) to form lime (i.e., calcium oxide, or CaO) and CO_2 in a process known as calcination or calcining. The quantity of CO_2 emitted during clinker production is directly proportional to the lime content of the clinker. During calcination, each mole of $CaCO_3$ heated in the clinker kiln forms one mole of CaO and one mole of CO_2. The CO_2 is vented to the atmosphere as part of the kiln exhaust:

$$CaCO_3 + heat \rightarrow CaO + CO_2$$

Next, over a temperature range of 1000 to 1450 degrees Celsius, the CaO combines with alumina, iron oxide and silica that are also present in the clinker raw material mix to form hydraulically reactive compounds within white-hot semifused (sintered) nodules of clinker. These "sintering" reactions are highly exothermic and produce few CO_2 process emissions. The clinker is then rapidly cooled to maintain quality and then very finely ground with a small amount of gypsum and potentially other materials (e.g., ground granulated blast furnace slag, etc.) to make portland and similar cements.

Masonry cement consists of plasticizers (e.g., ground limestone, lime, etc.) and portland cement, and the amount of portland cement used accounts for approximately 3 percent of total clinker production (USGS 2023b; 2023c). No

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[5] U.S. EPA Greenhouse Gas Reporting Program. Developments on Publication of Aggregated Greenhouse Gas Data, November 25, 2014. See http://www.epa.gov/ghgreporting/confidential-business-information-ghg-reporting.

[6] Ammonia production, glass production, lead production, and other fluorinated gas production.

additional emissions are associated with the production of masonry cement. Carbon dioxide emissions that result from the production of lime used to produce portland and masonry cement are included in Section 4.2.

Carbon dioxide emitted from the chemical process of cement production is the second largest source of industrial CO_2 emissions in the United States. Cement is produced in 34 states and Puerto Rico. Texas, Missouri, California, and Florida were the leading cement-producing states in 2022 and accounted for approximately 43 percent of total U.S. production (USGS 2023b). In 2022, shipments of cement were estimated to have increased by about 3 percent from 2021, and net imports increased by about 17 percent compared to 2021 (USGS 2023b).

In 2022, U.S. clinker production totaled 80,500 kilotons, which was an increase of 1 percent compared to 2021 and an increase of 25 percent compared to 1990 (EPA 2023). The resulting CO_2 emissions were estimated to be 41.9 MMT CO_2 Eq. (41,884 kt) (see Table 4-3 and Table 4-4). The total construction value and cement shipments increased by 11 percent and 4 percent, respectively, during the first nine months of 2022 compared to the same time period in 2021. This increase was attributed to continued economic recovery from the COVID-19 pandemic and the November 2021 passage of the Bipartisan Infrastructure Law. Despite the increases, growth was constrained by increased costs, labor and production shortages, and ongoing supply chain disruptions (USGS 2023b).

Table 4-3: CO_2 Emissions from Cement Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Cement Production	33.5	46.2	39.0	40.9	40.7	41.3	41.9

Table 4-4: CO_2 Emissions from Cement Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Cement Production	33,484	46,194	38,971	40,896	40,688	41,312	41,884

Greenhouse gas emissions from cement production, which are primarily driven by production levels, increased every year from 1991 through 2006 but decreased in the following years until 2009. Emissions from cement production were at their highest levels in 2006 and at their lowest levels in 2009. Emissions in 2009 were approximately 28 percent lower than 2008 emissions and 12 percent lower than 1990 due to the economic recession and the associated decrease in demand for construction materials. Since 2009, emissions have increased by 41 percent due to increasing demand for cement. Cement continues to be a critical component of the construction industry; therefore, the availability of public and private construction funding, as well as overall economic conditions, have considerable impact on the level of cement production.

Methodology and Time-Series Consistency

Carbon dioxide emissions from cement production are estimated using the Tier 2 method from the *2006 IPCC Guidelines* as this is a key category, in accordance with the IPCC methodological decision tree and available data. The Tier 2 methodology was used because detailed and complete data (including weights and composition) for carbonate(s) consumed in clinker production are not available,[7] and thus a rigorous Tier 3 approach is impractical. Tier 2 specifies the use of aggregated plant or national clinker production data and an emission factor, which is the product of the average lime mass fraction for clinker of 65 percent and a constant reflecting the mass of CO_2 released per unit of lime. The U.S. Geological Survey (USGS) mineral commodity expert for cement has confirmed that this is a reasonable assumption for the United States (Van Oss 2013a). This calculation yields an emission factor of 0.510 tons of CO_2 per ton of clinker produced, which was determined as follows:

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[7] As discussed further under "Planned Improvements," most cement-producing facilities that report their emissions to the GHGRP use CEMS to monitor combined process and fuel combustion emissions for kilns, making it difficult to quantify the process emissions on a facility-specific basis. By the end of 2022, the percentage of facilities not using CEMS was 1 percent.

Equation 4-1: *2006 IPCC Guidelines* Tier 1 Emission Factor for Clinker (precursor to Equation 2.4)

$$\mathrm{EF_{clinker}} = 0.650\ \mathrm{CaO} \times \left[\left(44.01\frac{\mathrm{g}}{\mathrm{mole}}\mathrm{CO_2}\right) \div \left(56.08\frac{\mathrm{g}}{\mathrm{mole}}\mathrm{CaO}\right)\right] = 0.510\ \frac{\mathrm{tons\ CO_2}}{\mathrm{ton\ clinker}}$$

During clinker production, some of the raw materials, partially reacted raw materials, and clinker enters the kiln line's exhaust system as non-calcinated, partially calcinated, or fully calcinated cement kiln dust (CKD). To the degree that the CKD contains carbonate raw materials which are then calcined, there are associated CO_2 emissions. At some plants, essentially all CKD is directly returned to the kiln, becoming part of the raw material feed, or is likewise returned to the kiln after first being removed from the exhaust. In either case, the returned CKD becomes a raw material, thus forming clinker, and the associated CO_2 emissions are a component of those calculated for the clinker overall. At some plants, however, the CKD cannot be returned to the kiln because it is chemically unsuitable as a raw material or chemical issues limit the amount of CKD that can be so reused. Any clinker that cannot be returned to the kiln is either used for other (non-clinker) purposes or is landfilled. The CO_2 emissions attributable to the non-returned calcinated portion of the CKD are not accounted for by the clinker emission factor and thus a CKD correction factor should be applied to account for those emissions. The USGS reports the amount of CKD used to produce clinker, but no information is currently available on the total amount of CKD produced annually.[8] Because data are not currently available to derive a country-specific CKD correction factor, a default correction factor of 1.02 (2 percent) was used to account for CKD CO_2 emissions, as recommended by the IPCC (IPCC 2006).[9] Total cement production emissions were calculated by adding the emissions from clinker production and the emissions assigned to CKD.

Small amounts of impurities (i.e., not calcium carbonate) may exist in the raw limestone used to produce clinker. The proportion of these impurities is generally minimal, although a small amount (1 to 2 percent) of magnesium oxide (MgO) may be desirable as a flux. Per the IPCC Tier 2 methodology, a correction for MgO is not used, since the amount of MgO from carbonate is likely very small and the assumption of a 100 percent carbonate source of CaO already yields an overestimation of emissions (IPCC 2006).

The 1990 through 2012 activity data for clinker production were obtained from USGS (Van Oss 2013a; Van Oss 2013b). Clinker production data for 2013 were also obtained from USGS (USGS 2014). USGS compiled the data (to the nearest ton) through questionnaires sent to domestic clinker and cement manufacturing plants, including facilities in Puerto Rico. Clinker production values in the current *Inventory* report utilize GHGRP data for the years 2014 through 2022 (EPA 2023). Clinker production data are summarized in Table 4-5. Details on how this GHGRP data compares to USGS reported data can be found in the section on QA/QC and Verification.

Table 4-5: Clinker Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Clinker Production	64,355	88,783	74,900	78,600	78,200	79,400	80,500

Note: Clinker production from 1990 through 2022 includes Puerto Rico (relevant U.S. Territories).

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2022. The methodology for cement production spliced activity data from two different sources: USGS for

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[8] The USGS *Minerals Yearbook: Cement* notes that CKD values used for clinker production are likely underreported.

[9] As stated on p. 2.12 of the *2006 IPCC Guidelines*, Vol. 3, Chapter 2: "…As data on the amount of CKD produced may be scarce (except possibly for plant-level reporting), estimating emissions from lost CKD based on a default value can be considered good practice. The amount of CO_2 from lost CKD can vary but range typically from about 1.5 percent (additional CO_2 relative to that calculated for clinker) for a modern plant to about 20 percent for a plant losing a lot of highly calcinated CKD (van Oss 2005). In the absence of data, the default CKD correction factor (CF_{ckd}) is 1.02 (i.e., add 2 percent to the CO_2 calculated for clinker). If no calcined CKD is believed to be lost to the system, the CKD correction factor will be 1.00 (van Oss 2005)…"

1990 through 2013 and GHGRP starting in 2014. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the two data sets for years where there was overlap, with findings that the data sets were consistent and adjustments were not needed.

Uncertainty

The uncertainties contained in these estimates are primarily due to uncertainties in the lime content of clinker and in the percentage of CKD recycled inside the cement kiln. Uncertainty is also associated with the assumption that all calcium-containing raw materials are $CaCO_3$, when a small percentage likely consists of other carbonate and non-carbonate raw materials. The lime content of clinker varies from 60 to 67 percent; 65 percent is used as a representative value (Van Oss 2013a). This contributes to the uncertainty surrounding the emission factor for clinker which has an uncertainty range of ±3 percent with uniform densities (Van Oss 2013b). The amount of CO_2 from CKD loss can range from 1.5 to 8 percent depending upon plant specifications, and uncertainty was estimated at ±5 percent with uniform densities (Van Oss 2013b). Additionally, some amount of CO_2 is reabsorbed when the cement is used for construction. As cement reacts with water, alkaline substances such as calcium hydroxide are formed. During this curing process, these compounds may react with CO_2 in the atmosphere to create calcium carbonate. This reaction only occurs in roughly the outer 0.2 inches of the total thickness. Because the amount of CO_2 reabsorbed is thought to be minimal, it was not estimated. EPA assigned uncertainty bounds of ±3 percent and a normal probability density function for clinker production and uncertainty bounds of ±5 percent and a uniform probability density function for the emission factor, based on expert judgment (Van Oss 2013b).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-6. Based on the uncertainties associated with total U.S. clinker production, the CO_2 emission factor for clinker production, and the emission factor for additional CO_2 emissions from CKD, 2022 CO_2 emissions from cement production were estimated to be between 40.1 and 43.8 MMT CO_2 Eq. at the 95 percent confidence level. This confidence level indicates a range of approximately 4 percent below and 5 percent above the emission estimate of 41.9 MMT CO_2 Eq.

Table 4-6: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Cement Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cement Production	CO_2	41.9	40.1	43.8	-4%	+5%

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

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

EPA relied upon the latest guidance from the IPCC on the use of facility-level data in national inventories and applied a category-specific QC process to compare activity data from EPA's GHGRP with existing data from USGS surveys. This was to ensure time-series consistency of the emission estimates presented in the *Inventory*. Total U.S. clinker production is assumed to have low uncertainty because facilities routinely measure this for economic reasons and because both USGS and GHGRP take multiple steps to ensure that reported totals are accurate. EPA verifies annual facility-level GHGRP reports through a multi-step process that is tailored to the reporting industry (e.g., combination of electronic checks including range checks, statistical checks, algorithm checks, year-to-year comparison checks, along with manual reviews involving outside data checks) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015). Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred.[10] Facilities are also required to monitor and maintain records of monthly clinker production per section 98.84 of the GHGRP regulation (40 CFR 98.84).

EPA's GHGRP requires all facilities producing portland cement to report greenhouse gas emissions, including CO_2 process emissions from each kiln, CO_2 combustion emissions from each kiln, CH_4 and N_2O combustion emissions from each kiln, and CO_2, CH_4, and N_2O emissions from each stationary combustion unit other than kilns (40 CFR Part 98 Subpart H). Source-specific quality control measures for the cement production category are included in section 98.84, Monitoring and QA/QC Requirements.

As mentioned above, EPA compares GHGRP clinker production data (EPA 2023) to the USGS clinker production data (USGS 2023a; USGS 2023c). For the year 2014, 2020, and 2022, USGS and GHGRP clinker production data showed a difference of approximately 1 percent. In 2018, the difference between USGS and GHGRP clinker production data was approximately 3 percent, which resulted in a difference in emissions of about 1.2 MMT CO_2 Eq. In 2015, 2016, 2017, 2019, and 2021, that difference was less than 0.5 percent (less than 0.2 MMT CO_2 Eq.) between the two sets of activity data. The information collected by the USGS National Minerals Information Center surveys continue to be an important data source.

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

EPA is continuing to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates for the Cement Production source category. Most cement production facilities reporting under EPA's GHGRP use Continuous Emission Monitoring Systems (CEMS) to monitor and report CO_2 emissions, thus reporting combined process and combustion emissions from kilns. In implementing further improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon, in addition to category-specific QC methods recommended by the *2006 IPCC Guidelines*.[11] EPA's long-term improvement plan includes continued assessment of the feasibility of using additional GHGRP information beyond aggregation of reported facility-level clinker data, in particular disaggregating the combined process and combustion emissions reported using CEMS, to separately present national process and combustion emissions streams consistent with IPCC and UNFCCC guidelines. This long-term planned analysis is still in development and has not been applied for this current *Inventory*.

EPA continues to review methods and data used to estimate CO_2 emissions from cement production in order to account for organic material in the raw material and to discuss the carbonation that occurs across the duration of the cement product. Work includes identifying data and studies on the average carbon content for organic materials in kiln feed in the United States and on CO_2 reabsorption rates via carbonation for various cement products. This information is not reported by facilities subject to GHGRP reporting. This is a long-term improvement.

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[10] See GHGRP Verification Fact Sheet https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

[11] See IPCC Technical Bulletin on Use of Facility-Specific Data in National Greenhouse Gas Inventories http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf and the *2019 Refinement*, Volume 1, Chapter 2, Section 2.3, *Use of Facility Data in Inventories* at https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch02_DataCollection.pdf.

4.2 Lime Production (CRT Source Category 2A2)

Lime is a manufactured product with many industrial, chemical, and environmental applications. This reporting category (2A2) includes process emissions from the production of lime. Per the IPCC methodological guidance, emissions from fuels consumed for energy purposes during the production of lime are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Lime production involves three main processes: stone preparation, calcination, and hydration. Carbon dioxide (CO_2) is generated during the calcination stage, when limestone—consisting of calcium carbonate ($CaCO_3$) and/or magnesium carbonate ($MgCO_3$)—is roasted at high temperatures in a kiln to produce calcium oxide (CaO) and CO_2. The CO_2 is given off as a gas and is normally emitted to the atmosphere.

$$CaCO_3 \rightarrow CaO + CO_2$$

Some facilities, however, recover CO_2 generated during the production process for use in sugar refining and precipitated calcium carbonate (PCC) production.[12] PCC is used as a filler or coating in the paper, food, and plastic industries and is derived from reacting hydrated high-calcium quicklime with CO_2, a production process that does not result in net emissions of CO_2 to the atmosphere.

For U.S. operations, the term “lime” refers to a variety of chemical compounds. These include CaO, or high-calcium quicklime; calcium hydroxide ($Ca(OH)_2$), or hydrated lime; dolomitic quicklime ([$CaO \bullet MgO$]); and dolomitic hydrate ([$Ca(OH)_2 \bullet MgO$] or [$Ca(OH)_2 \bullet Mg(OH)_2$]).

The current lime market is approximately distributed across six end-use categories, as follows: metallurgical uses, 35 percent; environmental uses, 29 percent; chemical and industrial uses, 21 percent; construction uses, 10 percent; miscellaneous uses, 3 percent; and refractory dolomite, 1 percent (USGS 2021). The major uses are in steel making, chemical and industrial applications (such as the manufacture of fertilizer, glass, paper and pulp, and precipitated calcium carbonate, and in sugar refining), flue gas desulfurization (FGD) systems at coal-fired electric power plants, construction, and water treatment, as well as uses in mining, pulp and paper and precipitated calcium carbonate manufacturing (USGS 2023a). Lime is also used as a CO_2 scrubber, and there has been experimentation on the use of lime to capture CO_2 from electric power plants. Both lime (CaO) and limestone ($CaCO_3$) can be used as a sorbent for FGD systems. Emissions from limestone consumption for FGD systems are reported under Section 4.4 Other Process Uses of Carbonate Production (CRT Source Category 2A4).

Emissions from lime production have fluctuated over the time series depending on lime end-use markets – primarily the steel making industry and FGD systems for utility and industrial plants – and also energy costs. One significant change to lime end-use since 1990 has been the increase in demand for lime for FGD at coal-fired electric power plants, which can be attributed to compliance with sulfur dioxide (SO_2) emission regulations of the Clean Air Act Amendments of 1990. Phase I went into effect on January 1, 1995, followed by Phase II on January 1, 2000. To supply lime for the FGD market, the lime industry installed more than 1.8 million tons per year of new capacity by the end of 1995 (USGS 2023a). The need for air pollution controls continued to drive the FGD lime market, which had doubled between 1990 and 2019 (2021, 2023a, 2023b).

The U.S. lime industry temporarily shut down some individual gas-fired kilns and, in some case, entire lime plants during 2000 and 2001, due to significant increases in the price of natural gas. Lime production continued to

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[12] The amount of CO_2 captured from lime production for sugar refining and PCC production is reported under CRT Source Category 2H3 “Other”, but within this report, they are included in this chapter.

decrease in 2001 and 2002, a result of lower demand from the steel making industry, lime's largest end-use market, when domestic steel producers were affected by low priced imports and slowing demand (USGS 2023a).

Emissions from lime production peaked in 2006 at approximately 30.3 percent above 1990 levels, due to strong demand from the steel and construction markets (road and highway construction projects), before dropping to its second lowest level in 2009 at approximately 2.5 percent below 1990 emissions, driven by the economic recession and downturn in major markets including construction, mining, and steel (USGS 2023a). In 2010, the lime industry began to recover as the steel, FGD, and construction markets also recovered (USGS 2023a). Fluctuation in lime production since 2015 has been driven largely by demand from the steel making industry (USGS 2021). In 2020, a significant decline in lime production occurred due to plants temporarily closing as a result of the global COVID-19 pandemic (USGS 2023a). This resulted in the lowest level of emissions in 2020 at approximately 3.4 percent below 1990 emissions. Emissions increased annually since then, with 2022 levels similar to emissions in 2019.

Lime production in the United States—including Puerto Rico—was reported to be 16,994 kilotons in 2022, an increase of about 1.3 percent compared to 2021 levels (USGS 2023a). Compared to 1990, lime production increased by about 7.3 percent. At year-end 2022, 73 primary lime plants were operating in the United States, including Puerto Rico (USGS 2023a).[13] Principal lime producing states were, in alphabetical order, Kentucky, Missouri, Ohio, and Texas (USGS 2023a).

U.S. lime production resulted in estimated net CO_2 emissions of 12.2 MMT CO_2 Eq. (12,208 kt) (see Table 4-7 and Table 4-8). Carbon dioxide emissions from lime production increased by about 2.8 percent compared to 2021 levels. Compared to 1990, CO_2 emissions have increased by about 4.3 percent. The trends in CO_2 emissions from lime production are directly proportional to trends in production, which are described above.

Table 4-7: CO_2 Emissions from Lime Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Lime Production	11.7	14.6	13.1	12.1	11.3	11.9	12.2

Table 4-8: Gross, Recovered, and Net CO_2 Emissions from Lime Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Gross	11,959	15,074	13,609	12,676	11,875	12,586	12,750
Recovered[a]	259	522	503	564	576	716	542
Net Emissions	**11,700**	**14,552**	**13,106**	**12,112**	**11,299**	**11,870**	**12,208**

Note: Totals may not sum due to independent rounding.

[a] For sugar refining and PCC production.

Methodology and Time-Series Consistency

To calculate emissions, the amounts of high-calcium and dolomitic lime produced were multiplied by their respective emission factors, consistent with Tier 2 methodology from the *2006 IPCC Guidelines* and in accordance with the IPCC methodological decision tree and available data. The emission factor is the product of the stoichiometric ratio between CO_2 and CaO, and the average CaO and MgO content for lime. The CaO and MgO content for lime is assumed to be 95 percent for both high-calcium and dolomitic lime (IPCC 2006). The emission factors were calculated as follows:

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[13] In 2022, 68 operating primary lime facilities in the United States reported to the EPA Greenhouse Gas Reporting Program.

Equation 4-2: *2006 IPCC Guidelines* Tier 2 Emission Factor for Lime Production, High-Calcium Lime (Equation 2.9)

$$\mathrm{EF}_{\text{High-Calcium Lime}} = \left[\left(44.01\,\frac{\mathrm{g}}{\mathrm{mole}}\,\mathrm{CO_2}\right) \div \left(56.08\,\frac{\mathrm{g}}{\mathrm{mole}}\,\mathrm{CaO}\right)\right] \times \left(0.9500\,\frac{\mathrm{CaO}}{\mathrm{lime}}\right) = 0.7455\ \frac{\mathrm{g\ CO_2}}{\mathrm{g\ lime}}$$

Equation 4-3: *2006 IPCC Guidelines* Tier 2 Emission Factor for Lime Production, Dolomitic Lime (Equation 2.9)

$$\mathrm{EF}_{\text{Dolomitic Lime}} = \left[\left(88.02\,\frac{\mathrm{g}}{\mathrm{mole}}\,\mathrm{CO_2}\right) \div \left(96.39\,\frac{\mathrm{g}}{\mathrm{mole}}\,\mathrm{CaO \bullet MgO}\right)\right] \times \left(0.9500\ \frac{\mathrm{CaO \bullet MgO}}{\mathrm{lime}}\right) = 0.8675\ \frac{\mathrm{g\ CO_2}}{\mathrm{g\ lime}}$$

Production was adjusted to remove the mass of chemically combined water found in hydrated lime, determined according to the molecular weight ratios of H_2O to ($Ca(OH)_2$ and [$Ca(OH)_2 \bullet Mg(OH)_2$]) (IPCC 2006). These factors set the chemically combined water content to 27 percent for high-calcium hydrated lime, and 30 percent for dolomitic hydrated lime.

The *2006 IPCC Guidelines* (Tier 2 method) also recommends accounting for emissions from lime kiln dust (LKD) through application of a correction factor. LKD is a byproduct of the lime manufacturing process typically not recycled back to kilns. LKD is a very fine-grained material and is especially useful for applications requiring very small particle size. Most common LKD applications include soil reclamation and agriculture. Emissions from the application of lime for agricultural purposes are reported in the Agriculture chapter under 5.5 Liming (CRT Source Category 3G). Currently, data on annual LKD production is not readily available to develop a country-specific correction factor. Lime emission estimates were multiplied by a factor of 1.02 to account for emissions from LKD (IPCC 2006). See the Planned Improvements section associated with efforts to improve uncertainty analysis and emission estimates associated with LKD.

Lime emission estimates were further adjusted to account for the amount of CO_2 captured for use in on-site processes. All the domestic lime facilities are required to report these data to EPA under its GHGRP. The total national-level annual amount of CO_2 captured for on-site process use was obtained from EPA's GHGRP (EPA 2023) based on reported facility-level data for years 2010 through 2022. The amount of CO_2 captured/recovered for non-marketed on-site process use is deducted from the total gross emissions (i.e., from lime production and LKD). The net lime emissions are presented in Table 4-7 and Table 4-8. GHGRP data on CO_2 removals (i.e., CO_2 captured/recovered) was available only for 2010 through 2022. Since GHGRP data are not available for 1990 through 2009, IPCC "splicing" techniques were used as per the *2006 IPCC Guidelines* on time-series consistency (IPCC 2006, Volume 1, Chapter 5).

Lime production data (i.e., lime sold and non-marketed lime used by the producer) by type (i.e., high-calcium and dolomitic quicklime, high-calcium and dolomitic hydrated lime, and dead-burned dolomite) for 1990 through 2022 (see Table 4-9) were obtained from U.S. Geological Survey (USGS) *Minerals Yearbook* (USGS 2023a) and are compiled by USGS to the nearest ton. Dead-burned dolomite data are additionally rounded by USGS to no more than one significant digit to avoid disclosing company proprietary data. Production data for the individual quicklime (i.e., high-calcium and dolomitic) and hydrated lime (i.e., high-calcium and dolomitic) types were not provided prior to 1997. These were calculated based on total quicklime and hydrated lime production data from 1990 through 1996 and the three-year average ratio of the individual lime types from 1997 to 1999. Natural hydraulic lime, which is produced from CaO and hydraulic calcium silicates, is not manufactured in the United States (USGS 2023a). Total lime production was adjusted to account for the water content of hydrated lime by converting hydrate to oxide equivalent based on recommendations from the IPCC and using the water content values for high-calcium hydrated lime and dolomitic hydrated lime mentioned above, and is presented in Table 4-10 (IPCC 2006). The CaO and $CaO \bullet MgO$ contents of lime, both 95 percent, were obtained from the IPCC (IPCC 2006).

Table 4-9: High-Calcium- and Dolomitic-Quicklime, High-Calcium- and Dolomitic-Hydrated, and Dead-Burned-Dolomite Lime Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
High-Calcium Quicklime	11,166	14,100	12,400	11,300	10,700	11,200	11,500
Dolomitic Quicklime	2,234	2,990	2,810	2,700	2,390	2,700	2,640
High-Calcium Hydrated	1,781	2,220	2,430	2,430	2,320	2,430	2,410
Dolomitic Hydrated	319	474	265	267	252	244	244
Dead-Burned Dolomite	342	200	200	200	200	200	200

Table 4-10: Adjusted Lime Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
High-Calcium	12,466	15,721	14,174	13,074	12,394	12,974	13,259
Dolomitic	2,800	3,522	3,196	3,087	2,766	3,071	3,011

Note: Minus water content of hydrated lime.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

The uncertainties contained in these estimates can be attributed to slight differences in the chemical composition of lime products and CO_2 recovery rates for on-site process use over the time series. Although the methodology accounts for various formulations of lime, it does not account for the trace impurities found in lime, such as iron oxide, alumina, and silica. Due to differences in the limestone used as a raw material, a rigid specification of lime material is impossible. As a result, few plants produce lime with exactly the same properties.

In addition, a portion of the CO_2 emitted during lime production will actually be reabsorbed when the lime is consumed, especially at captive lime production facilities. As noted above, lime has many different chemical, industrial, environmental, and construction applications. In many processes, CO_2 reacts with the lime to create calcium carbonate (e.g., water softening). Carbon dioxide reabsorption rates vary, however, depending on the application. For example, 100 percent of the lime used to produce precipitated calcium carbonate reacts with CO_2, whereas most of the lime used in steel making reacts with impurities such as silica, sulfur, and aluminum compounds. Quantifying the amount of CO_2 that is reabsorbed would require a detailed accounting of lime use in the United States and additional information about the associated processes where both the lime and byproduct CO_2 are "reused." Research conducted thus far has not yielded the necessary information to quantify CO_2 reabsorption rates.[14] Some additional information on the amount of CO_2 consumed on site at lime facilities, however, has been obtained from EPA's GHGRP.

In some cases, lime is generated from calcium carbonate byproducts at pulp mills and water treatment plants.[15] The lime generated by these processes is included in the USGS data for commercial lime consumption. In the pulping industry, mostly using the Kraft (sulfate) pulping process, lime is consumed in order to causticize a process liquor (green liquor) composed of sodium carbonate and sodium sulfide. The green liquor results from the dilution of the smelt created by combustion of the black liquor where biogenic carbon (C) is present from the wood. Kraft

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[14] Representatives of the National Lime Association estimate that CO_2 reabsorption that occurs from the use of lime may offset as much as a quarter of the CO_2 emissions from calcination (Males 2003).

[15] Some carbide producers may also regenerate lime from their calcium hydroxide byproducts, which does not result in emissions of CO_2. In making calcium carbide, quicklime is mixed with coke and heated in electric furnaces. The regeneration of lime in this process is done using a waste calcium hydroxide (hydrated lime) [$CaC_2 + 2H_2O \rightarrow C_2H_2 + Ca(OH)_2$], not calcium carbonate [$CaCO_3$]. Thus, the calcium hydroxide is heated in the kiln to simply expel the water [$Ca(OH)_2$ + heat $\rightarrow CaO + H_2O$], and no CO_2 is released.

mills recover the calcium carbonate “mud” after the causticizing operation and calcine it back into lime—thereby generating CO_2—for reuse in the pulping process. Although this re-generation of lime could be considered a lime manufacturing process, the CO_2 emitted during this process is mostly biogenic in origin and therefore is not included in the industrial processes totals (Miner and Upton 2002). In accordance with IPCC methodological guidelines, any such emissions are calculated by accounting for net carbon fluxes from changes in biogenic carbon reservoirs in wooded or crop lands (see the Land Use, Land-Use Change, and Forestry chapter).

In the case of water treatment plants, lime is used in the softening process. Some large water treatment plants may recover their waste calcium carbonate and calcine it into quicklime for reuse in the softening process. Further research is necessary to determine the degree to which lime recycling is practiced by water treatment plants in the United States.

Another uncertainty is the assumption that calcination emissions for LKD are around 2 percent. EPA assigned uncertainty ranges of ±2 percent and a triangular probability density function for the LKD correction factor based on expert judgment (RTI 2023). The National Lime Association (NLA) has commented that the estimates of emissions from LKD in the United States could be closer to 6 percent. They also note that additional emissions (approximately 2 percent) may also be generated through production of other byproducts/wastes (off-spec lime that is not recycled, scrubber sludge) at lime plants (Seeger 2013). Publicly available data on LKD generation rates, total quantities not used in cement production, and types of other byproducts/wastes produced at lime facilities are limited. NLA compiled and shared historical emissions information and quantities for some waste products reported by member facilities associated with generation of total calcined byproducts and LKD, as well as methodology and calculation worksheets that member facilities complete when reporting. There is uncertainty regarding the availability of data across the time series needed to generate a representative country-specific LKD factor. Uncertainty of the activity data is also a function of the reliability and completeness of voluntarily reported plant-level production data. EPA assigned uncertainty ranges of ±1 percent for lime production and a normal probability density function, based on expert judgment (USGS 2012). Further research, including discussion with NLA, and data is needed to improve understanding of additional calcination emissions to consider revising the current assumptions that are based on the *2006 IPCC Guidelines*. More information can be found in the Planned Improvements section below.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-11. Lime CO_2 emissions for 2022 were estimated to be between 12.1 and 12.3 MMT CO_2 Eq. at the 95 percent confidence level. This confidence level indicates a range of approximately 1 percent below and 1 percent above the emission estimate of 12.2 MMT CO_2 Eq.

Table 4-11: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Lime Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Lime Production	CO_2	12.2	12.1	12.3	-1%	+1%

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

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as noted in the introduction of the IPPU chapter (see Annex 8 for more details).

More details on the greenhouse gas calculation, monitoring and QA/QC methods associated with reporting on CO_2 captured for onsite use applicable to lime manufacturing facilities can be found under Subpart S (lime manufacturing) of the GHGRP regulation (40 CFR Part 98).[16] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2023).[17] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

EPA plans to review GHGRP emissions and activity data reported to EPA under Subpart S of the GHGRP regulation (40 CFR Part 98), and aggregated activity data on lime production by type in particular. In addition, initial review of data has identified that several facilities use CEMS to report emissions. Under Subpart S, if a facility is using a CEMS, they are required to report combined combustion emissions and process emissions. EPA continues to review how best to incorporate GHGRP and notes that particular attention will be made to also ensuring time-series consistency of the emissions estimates presented in future *Inventory* reports, consistent with IPCC and UNFCCC guidelines. This is required because the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this *Inventory*. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[18]

Future improvements involve improving and/or confirming the representativeness of current assumptions associated with emissions from production of LKD and other byproducts/wastes as discussed in the Uncertainty section, per comments from the NLA provided during a prior Public Review comment period for a previous (1990 through 2018) *Inventory.* EPA met with NLA in summer of 2020 for clarification on data needs and available data and to discuss planned research into GHGRP data. Previously, EPA met with NLA in spring of 2015 to outline specific information required to apply IPCC methods to develop a country-specific correction factor to more accurately estimate emissions from production of LKD. In 2016, NLA compiled and shared historical emissions information reported by member facilities on an annual basis under voluntary reporting initiatives from 2002 through 2011 associated with generation of total calcined byproducts and LKD. Reporting of LKD was only differentiated for the years 2010 and 2011. This emissions information was reported on a voluntary basis consistent with NLA's facility-level reporting protocol, which was also provided to EPA. To reflect information provided by NLA, EPA updated the qualitative description of uncertainty. At the time of this *Inventory*, this planned improvement is in process and has not been incorporated into this current *Inventory* report.

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[16] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

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

[18] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf and the *2019 Refinement*, Volume 1, Chapter 2, Section 2.3, *Use of Facility Data in Inventories* at https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch02_DataCollection.pdf.

4.3 Glass Production (CRT Source Category 2A3)

Glass production is an energy and raw-material intensive process that results in the generation of carbon dioxide (CO_2) from both the energy consumed in making glass and the glass production process itself. This reporting category (2A3) includes emissions from the production of glass. Emissions from fuels consumed for energy purposes during the production of glass are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Glass production employs a variety of raw materials in a glass-batch. These include formers, fluxes, stabilizers, and sometimes colorants. The major raw materials (i.e., fluxes and stabilizers) that emit process-related CO_2 emissions during the glass melting process are limestone, dolomite, and soda ash. The main former in all types of glass is silica (SiO_2). Other major formers in glass include feldspar and boric acid (i.e., borax). Fluxes are added to lower the temperature at which the batch melts. Most commonly used flux materials are soda ash (sodium carbonate, Na_2CO_3) and potash (potassium carbonate, K_2O). Stabilizers make glass more chemically stable and keep the finished glass from dissolving and/or falling apart. Commonly used stabilizing agents in glass production are limestone ($CaCO_3$), dolomite ($CaCO_3MgCO_3$), alumina (Al_2O_3), magnesia (MgO), barium carbonate ($BaCO_3$), strontium carbonate ($SrCO_3$), lithium carbonate (Li_2CO_3), and zirconia (ZrO_2) (DOE 2002). Glass makers also use a certain amount of recycled scrap glass (cullet), which comes from in-house return of glassware broken in the production process or other glass spillage or retention, such as recycling or from cullet broker services.

The raw materials (primarily soda ash, limestone, and dolomite) release CO_2 emissions in a complex high-temperature chemical reaction during the glass melting process. This process is not directly comparable to the calcination process used in lime manufacturing, cement manufacturing, and process uses of carbonates (i.e., limestone/dolomite use) but has the same net effect in terms of generating process CO_2 emissions (IPCC 2006).

The U.S. glass industry can be divided into four main categories: containers, flat (window) glass, fiber glass, and specialty glass. The majority of commercial glass produced is container and flat glass (EPA 2009). The United States is one of the major global exporters of glass. Domestically, demand comes mainly from the construction, auto, bottling, and container industries. There are more than 1,700 facilities that manufacture glass in the United States, with the largest companies being Corning, Guardian Industries, Owens-Illinois, and PPG Industries.[19]

The glass container sector is one of the leading soda ash consuming sectors in the United States. In 2022, glass production accounted for 49 percent of total domestic soda ash consumption (USGS 2023). Emissions from soda ash production are reported in Section 4.12.

In 2022, 2,250 kilotons of soda ash, 1,370 kilotons of limestone, 925 kilotons of dolomite, and 1.9 kilotons of other carbonates were consumed for glass production (USGS 2023; EPA 2023). Use of soda ash, limestone, dolomite, and other carbonates in glass production resulted in aggregate CO_2 emissions of 2.0 MMT CO_2 Eq. (1,956 kt), which are summarized in Table 4-12 and Table 4-13. Overall, emissions have decreased by 14 percent compared to 1990. Emissions decreased by 1 percent compared to 2021 levels.

Emissions from glass production have remained relatively consistent over the time series with some fluctuations since 1990. In general, these fluctuations were related to the behavior of the export market and the U.S. economy. Specifically, the extended downturn in residential and commercial construction and automotive industries between 2008 and 2010 resulted in reduced consumption of glass products, causing a drop in global demand for limestone, dolomite, and soda ash and resulting in lower emissions. Some commercial food and beverage package

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[19] Excerpt from Glass & Glass Product Manufacturing Industry Profile, First Research. Available online at: http://www.firstresearch.com/Industry-Research/Glass-and-Glass-Product-Manufacturing.html.

manufacturers are shifting from glass containers towards lighter and more cost-effective polyethylene terephthalate (PET) based containers, putting downward pressure on domestic consumption of soda ash (USGS 1995 through 2015b). Glass production in 2022 was steady, changing by no more than 2 percent over the course of the year (Federal Reserve 2023).

Table 4-12: CO_2 Emissions from Glass Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Glass Production	2.3	2.4	2.0	1.9	1.9	2.0	2.0

Table 4-13: CO_2 Emissions from Glass Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Glass Production	2,263	2,402	1,989	1,940	1,858	1,969	1,956

Methodology and Time-Series Consistency

Carbon dioxide emissions were calculated based on Tier 3 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data, by multiplying the quantity of input carbonates (i.e., limestone, dolomite, soda ash, and other carbonates) by the carbonate-based emission factor (in metric tons CO_2/metric ton carbonate) and the average carbonate-based mineral mass fraction.

2010 through 2022

The methodology for estimating CO_2 emissions from glass production for years 2010 through 2022 used the quantities of limestone, dolomite, and a group of other carbonates (i.e., barium carbonate, potassium carbonate, lithium carbonate, and strontium carbonate) used for glass production, obtained from GHGRP (EPA 2023). USGS data on the quantity of soda ash used for glass production was used because it was obtained directly from the soda ash producers and includes use by smaller artisanal glass operations, which are excluded in the GHGRP data.

GHGRP collects data from glass production facilities with greenhouse gas emissions greater than 25,000 metric tons CO_2 Eq. The reporting threshold is used to exclude artisanal glass operations that are expected to have much lower greenhouse gas emissions than the threshold. These smaller facilities have not been accounted for yet for this portion of the time series for limestone, dolomite, or other carbonates due to limited data. Facilities report the total quantity of each type of carbonate used in glass production each year to GHGRP, with data collection starting in 2010 (EPA 2023).

Using the total quantities of each carbonate, EPA calculated the metric tons of emissions resulting from glass production by multiplying the quantity of input carbonates (i.e., limestone, dolomite, soda ash, and other carbonates) by carbonate-based emission factors in metric tons CO_2/metric ton carbonate (limestone, 0.43971; dolomite, 0.47732; soda ash, 0.41492; and other carbonates, 0.262), and by the average carbonate-based mineral mass fraction for each year. IPCC default emission factors were used for limestone, dolomite, and soda ash, and the emission factor for other carbonates is based on expert judgment (RTI 2022).

1990 through 2009

Data from GHGRP on the quantity of limestone, dolomite, and other carbonates used in glass production are not available for 1990 through 2009. Additionally, USGS does not collect data on the quantity of other carbonates used for glass production.

To address time-series consistency, total emissions from 1990 to 2009 were calculated using the Federal Reserve Industrial Production Index for glass production in the United States as a surrogate for the total quantity of carbonates used in glass production. The production index measures real output expressed as a percentage of real output in a base year, which is currently 2017 (Federal Reserve 2023). Since January 1971, the Federal Reserve has released the monthly glass production index for NAICS code 3272 (Glass and Glass Product Manufacturing) as part of release G.17, “Industrial Production and Capacity Utilization” (Federal Reserve 2023). The monthly index values for each year were averaged to calculate an average annual glass production index value. Total annual process emissions were calculated by taking a ratio of the average annual glass production index for each year to the average annual glass production index for base year 2017, and multiplying by the calculated 2017 emissions (process-related) based on GHGRP data.

Emissions from limestone, dolomite, and other carbonate consumption were disaggregated from total annual emissions, using the average percent contribution of each to annual emissions from these three carbonates for 2010 through 2014 based on GHGRP data: 64.5 percent limestone, 35.5 percent dolomite, and 0.1 percent other carbonates.

The methodology for estimating CO_2 emissions from the use of soda ash for glass production and data sources for the amount of soda ash used in glass production are consistent with the methodology used for 2010 through 2022. The average mineral mass fractions for soda ash are only available starting in 2010. The average carbonate-based mineral mass fractions from the GHGRP, averaged across 2010 through 2014, indicate that soda ash contained 98.7 percent sodium carbonate (Na_2CO_3). This averaged value is used to estimate emissions for 1990 through 2009. The years 2010 to 2014 were used to determine the average carbonate-based mineral mass fractions because those years were deemed to better represent historic glass production from 1990 to 2009.

Data on soda ash used for glass production for 1990 through 2022 were obtained from the U.S. Bureau of Mines (1991 and 1993a), the USGS *Minerals Yearbook: Soda Ash* (USGS 1995 through 2015b), and USGS *Mineral Industry Surveys for Soda Ash* (USGS 2017 through 2023). Data on limestone, dolomite, and other carbonates used for glass production and on average carbonate-based mineral mass fraction for 2010 through 2022 were obtained from GHGRP (EPA 2023). The quantities of limestone, dolomite, and other carbonates were calculated for 1990 through 2009 using the Federal Reserve Industrial Production Index (Federal Reserve 2023).

The amount of limestone, dolomite, soda ash, and other carbonates used in glass production each year and the annual average Federal Reserve production indices for glass production are shown in Table 4-14.

Table 4-14: Limestone, Dolomite, Soda Ash, and Other Carbonates Used in Glass Production (kt) and Average Annual Production Index for Glass and Glass Product Manufacturing

Activity	1990	2005	2018	2019	2020	2021	2022
Limestone	1,409	1,690	1,442	1,370	1,334	1,397	1,370
Dolomite	714	857	871	883	824	893	925
Soda Ash	3,177	3,050	2,280	2,220	2,130	2,280	2,250
Other Carbonates	2	3	2	2	2	2	1.9
Total	**5,302**	**5,599**	**4,596**	**4,475**	**4,289**	**4,572**	**4,547**
Production Index[a]	94.3	113.1	102.5	99.8	92.4	88.3	86.8

[a] Average Annual Production Index uses 2017 as the base year.

Note: Totals may not sum due to independent rounding.

As discussed above, methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare USGS and GHGRP data sets for 2010 through 2022. To address the inconsistencies, adjustments were made as described above.

Uncertainty

The methodology in this *Inventory* report uses GHGRP data for the average mass fraction of each mineral used in glass production. These minerals are limestone, dolomite, soda ash, and other carbonates (barium carbonate ($BaCO_3$), potassium carbonate (K_2CO_3), lithium carbonate (Li_2CO_3), and strontium carbonate ($SrCO_3$)). The mass fractions are reported directly by the glass manufacturers, for each year from 2010 to 2022.

The methodology uses the quantities of limestone, dolomite, and other carbonates used in glass manufacturing which is reported directly by the glass manufacturers for years 2010 through 2022 and the amount of soda ash used in glass manufacturing which is reported by soda ash producers for the full time series. EPA assigned an uncertainty range of ±5 percent and a normal probability density function for all carbonate quantities and the Federal Reserve Industrial Production Index for glass production, and using this suggested uncertainty provided in Section 2.4.2.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). EPA assigned an uncertainty range of ±2 percent for the carbonate emission factors, ±2 percent for the mineral mass fractions, and ±1 percent for the calcination fraction, and using this suggested uncertainty provided in Section 2.4.2.1 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a triangular probability density function was assigned for emission factors, mineral mass fractions, and calcination fraction.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-15. In 2022, glass production CO_2 emissions were estimated to be between 1.9 and 2.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 2 percent below and 2 percent above the emission estimate of 2.0 MMT CO_2 Eq.

Table 4-15: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Glass Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Glass Production	CO_2	2.0	1.9	2.0	-2%	+2%

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

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[20] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

Recalculations Discussion

During annual QC, a transcription error for the 1990 value of CO_2 emissions from glass production was identified and corrected in Table 4-12 and Table 4-13. No recalculations were needed or performed due to this transcription error, and no other recalculations were performed for the 1990 through 2021 portion of the time series.

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[20] GHGRP Report Verification Factsheet. See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

Planned Improvements

EPA plans to evaluate updates to uncertainty levels for the activity data and mineral mass fraction values from EPA's GHGRP. This is a near-term planned improvement that is anticipated for inclusion in 2025 report.

Some glass producing facilities in the United States do not report to EPA's GHGRP because they fall below the reporting threshold for this industry. EPA will continue ongoing research on the availability of data to better assess the completeness of emission estimates from glass production and how to refine the methodology to ensure complete national coverage of this category. When reporting began in 2010, EPA received data from more facilities that were above the reporting threshold than expected, and total emissions for these reporting facilities were higher than expected for all glass production facilities in the United States (EPA 2009). Research will include reassessing previous assessments of GHGRP industry coverage using the reporting threshold of 25,000 metric tons CO_2 Eq. This is a medium-term planned improvement.

4.4 Other Process Uses of Carbonates (CRT Source Category 2A4)

Limestone ($CaCO_3$), dolomite ($CaCO_3MgCO_3$),[21] and other carbonates such as soda ash, magnesite, and siderite are basic materials used by a wide variety of industries, including construction, agriculture, chemical, metallurgy (i.e., iron and steel production, ferroalloy production, and magnesium production), glass production, environmental pollution control, ceramics production, and non-metallurgical magnesia production. This reporting category (2A4) includes emissions from other uses of limestone, dolomite, and other carbonates not included in other categories; the production of ceramics; other uses of soda ash not included elsewhere; and the production of non-metallurgical magnesia. This section addresses mineral industry use of these carbonates: limestone, dolomite, soda ash, and magnesite. Emissions from the use of these carbonates are organized into four subcategories: other process uses of carbonates (i.e., limestone and dolomite consumption), ceramics production, other uses of soda ash, and non-metallurgical magnesia production.

For industrial applications, carbonates are heated sufficiently enough to calcine the material and generate CO_2 as a byproduct.

$$CaCO_3 \rightarrow CaO + CO_2$$

$$MgCO_3 \rightarrow MgO + CO_2$$

Examples of such applications include limestone used as a flux or purifier in metallurgical furnaces, as a sorbent in flue gas desulfurization (FGD) systems for utility and industrial plants, and as a raw material for the production of glass, lime, and cement.

Emissions from limestone and dolomite used in the production of cement, lime, glass, and iron and steel are excluded from the other process uses of carbonates category and reported under their respective source categories (e.g., Section 4.3, Glass Production). Emissions from soda ash production are reported under Section 4.12, Soda Ash Production (CRT Source Category 2B7). Emissions from soda ash consumption associated with glass manufacturing are reported under Section 4.3, Glass Production (CRT Source Category 2A3). Emissions from the use of limestone and dolomite in liming of agricultural soils are included in the Agriculture chapter under Section 5.5, Liming (CRT Source Category 3G). Emissions from limestone and dolomite used in the production of iron and steel and magnesium production are reported under Section 4.18, Iron and Steel Production (CRT Source Category 2C1).

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[21] Limestone and dolomite are collectively referred to as limestone by the industry, and intermediate varieties are seldom distinguished.

Emissions from dolomite used in the production of magnesium are reported under Section 4.21, Magnesium Production and Processing (CRT Source Category 2C4). As noted in Section 4.19, Ferroalloy Production (CRT Source Category 2C2), emissions from the production of ferromanganese are not included in this *Inventory* because of the small number of manufacturers of these materials in the United States. Government information disclosure rules prevent the publication of production data for these production facilities. Emissions from fuels consumed for energy purposes during these processes are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter in Section 3.1, Fossil Fuel Combustion (CRT Source Category 1A). Both lime (CaO) and limestone ($CaCO_3$) can be used as a sorbent for FGD systems. Emissions from lime consumption for FGD systems and from sugar refining are reported under Section 4.3, Lime Production (CRT Source Category 2A2). Emissions from the use of dolomite in primary magnesium metal production are reported under Section 4.21, Magnesium Production and Processing (CRT Source Category 2C4).

Limestone and dolomite are widely distributed throughout the world in deposits of varying sizes and degrees of purity. Large deposits of limestone occur in nearly every state in the United States, and significant quantities are extracted for industrial applications. In 2018, the leading limestone producing states were Texas, Florida, Ohio, Missouri, and Pennsylvania, which contributed 46 percent of the total U.S. output (USGS 2022a). Dolomite deposits are found in the United States, Canada, Mexico, Europe, Africa, and Brazil. In the United States, the leading dolomite producing states are Pennsylvania, New York, and Utah which currently contribute more than a third of the total U.S. output (USGS 2022a).

Ceramics include the production of bricks and roof tiles, vitrified clay pipes, refractory products, expanded clay products, wall and floor tiles, table and ornamental ware (i.e., household ceramics), sanitary ware, technical ceramics (e.g., aerospace, automotive, electronic, or biomedical applications), and inorganic bonded abrasives. Most ceramic products are made from one or more different types of clay (e.g., shales, fire clay, and ball clay) with varying carbonate contents. The process of manufacturing ceramic products, regardless of the product type or scale, is essentially the same. This process consists of raw material processing (grinding, calcining, and drying), forming (wet or dry process), firing (single or multiple stage firing process), and final processing. Process CO_2 emissions are produced during the calcination process in the kiln or dryer, where carbonates are heated to high temperatures which results in metal oxides and CO_2. In 2018, the leading clay producing states were Georgia, Wyoming, Texas, Alabama, and North Carolina, which contributed 60 percent of the total U.S. output (USGS 2022f).

Other uses of soda ash include the consumption of soda ash for non-glass purposes. Excluding glass production, soda ash consumption by end use in 2022 included chemicals, 54 percent, soap and detergent manufacturing, 9 percent; distributers, 10 percent; flue gas desulfurization, 7 percent; other uses, 17 percent; pulp and paper production, 1 percent; and water treatment, 2 percent (USGS 2023a). Chemicals produced using soda ash include sodium-based inorganic chemicals such as sodium bicarbonate, sodium chromates, sodium phosphates, and sodium silicates. (USGS 2022g). Internationally, two types of soda ash are produced: natural and synthetic. In 2019, 93 percent of the global soda ash production came from China, the United States, Russia, Germany, India, Turkey, Poland, and France. The United States only produces natural soda ash and only in two states: Wyoming and California (USGS 2021a).

Non-metallurgical magnesia production comprises of three categories of magnesia products: calcined magnesia, deadburned magnesia, and fused magnesia. Magnesia is produced by calcining magnesite ($MgCO_3$) which results in the release of CO_2. Non-metallurgical magnesia is used in agricultural, industrial, refractory, and electrical insulating applications. Specific applications include fertilizers, construction materials, plastics, and flue gas desulphurization. China, Russia, and Turkey account for 83 percent of global production capacity of magnesia from magnesite (USGS 2022e). In the United States, only one facility located in Nevada produces non-metallurgical magnesia using magnesite as the raw material.

In 2022, 18,671 kilotons (kt) of limestone, 2,052 kt of dolomite, 2,391 kt of soda ash, and 388 kt of magnesite were consumed for these emissive applications, which excludes consumption for the production of cement, lime, glass, and iron and steel (Willett 2023; USGS 2022b). Usage of limestone, dolomite, soda ash, and magnesite resulted in aggregate CO_2 emissions of 10.4 MMT CO_2 Eq. (10,384 kt) (see Table 4-16 and Table 4-17). The 2022 emissions increased 21 percent compared to 2021, primarily as a result of increased limestone consumption attributed to sulfur oxide removal. Growth in the public and private construction markets contributed to an increase in consumption of crushed stone in 2022. Overall emissions have increased 46 percent from 1990 through 2022.

Table 4-16: CO_2 Emissions from Other Process Uses of Carbonates (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Other Uses of Carbonates	4.8	6.2	6.3	7.4	7.4	7.0	8.8
Ceramics Production	0.8	0.8	0.4	0.4	0.4	0.4	0.4
Other Uses of Soda Ash[a]	1.4	1.3	1.1	1.0	1.0	1.0	1.0
Non-Metallurgical Magnesia Production	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Total	**7.1**	**8.5**	**7.9**	**9.0**	**9.0**	**8.6**	**10.4**

[a] Soda ash consumption not associated with glass manufacturing.
Note: Totals may not sum due to independent rounding.

Table 4-17: CO_2 Emissions from Other Process Uses of Carbonates (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Other Uses of Carbonates	4,843	6,155	6,283	7,386	7,441	6,972	8,781
Ceramics Production	757	822	418	399	397	400	407
Other Uses of Soda Ash[a]	1,390	1,305	1,069	1,036	958	979	992
Non-Metallurgical Magnesia Production	113	191	169	152	216	231	204
Total	**7,103**	**8,472**	**7,938**	**8,973**	**9,012**	**8,583**	**10,384**

[a] Soda ash consumption not associated with glass manufacturing.
Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Other Uses of Carbonates (Limestone and Dolomite Consumption)

Carbon dioxide emissions from other uses of carbonates, specifically limestone and dolomite consumption, were calculated using a Tier 2 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data, by multiplying the quantity of limestone or dolomite consumed by the emission factor for limestone or dolomite calcination, respectively: 0.43971 metric ton CO_2/metric ton carbonate for limestone and 0.47732 metric ton CO_2/metric ton carbonate for dolomite.[22] This methodology was used for limestone and dolomite used for flux stone, flue gas desulfurization systems, chemical stone, mine dusting or acid water treatment, and acid neutralization. Flux stone used during the production of iron and steel was deducted from the other uses of carbonates source category estimate and attributed to the iron and steel production source category estimate. Similarly, limestone and dolomite consumption for glass manufacturing, cement, and lime manufacturing are excluded from this category and attributed to their respective categories.

Consumption data for 1990 through 2022 of limestone and dolomite used for flux stone, flue gas desulfurization systems, chemical stone, mine dusting or acid water treatment, and acid neutralization (see Table 4-18) were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook: Crushed Stone Annual Report* (1995a through 2023b), preliminary data for 2022 from USGS Crushed Stone Commodity Expert (Willett 2023), American Iron and Steel Institute limestone and dolomite consumption data (AISI 2018 through 2021), and the U.S. Bureau of Mines (1991 and 1993a), which are reported to the nearest ton. In addition, the estimated values for limestone and dolomite consumption for flux stone used during the production of iron and steel were adjusted using emissions data from the EPA's Greenhouse Gas Reporting Program (GHGRP) Subpart Q for the iron and steel sector to account for the impacts of the COVID-19 pandemic in 2020 and 2021. Iron and steel GHGRP process emissions data

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[22] *2006 IPCC Guidelines*, Volume 3: Chapter 2, Table 2.1.

decreased by approximately 8 percent from 2021 to 2022 (EPA 2023). This adjustment method is consistent with the method used in Section 4.18, Iron and Steel Production (CRT Source Category 2C1).

During 1990 and 1992, the USGS did not conduct a detailed survey of limestone and dolomite consumption by end-use; therefore, data on consumption by end use for 1990 was estimated by applying the 1991 ratios of total limestone and dolomite consumption by end use to total 1990 limestone and dolomite consumption values. Similarly, the 1992 consumption figures were approximated by applying an average of the 1991 and 1993 ratios of total limestone and dolomite use by end uses to the 1992 total values.

In 1991, the U.S. Bureau of Mines, now known as the USGS, began compiling production and end use information through surveys of crushed stone manufacturers. Manufacturers provided different levels of detail in survey responses, so information was divided into three categories: (1) production by end-use, as reported by manufacturers (i.e., “specified” production); (2) production reported by manufacturers without end-uses specified (i.e., “unspecified-reported” production); and (3) estimated additional production by manufacturers who did not respond to the survey (i.e., “unspecified-estimated” production). Additionally, each year the USGS withholds data on certain limestone and dolomite end-uses due to confidentiality agreements regarding company proprietary data. For the purposes of this analysis, emissive end-uses that contained withheld data were estimated using one of the following techniques: (1) the value for all the withheld data points for limestone or dolomite use was distributed evenly to all withheld end-uses; (2) the average percent of total limestone or dolomite for the withheld end-use in the preceding and succeeding years; or (3) the average fraction of total limestone or dolomite for the end-use over the entire time period.

A large quantity of crushed stone was reported to the USGS under the category “unspecified uses.” A portion of this consumption is believed to be limestone or dolomite used for emissive end uses. The quantity listed for “unspecified uses” was, therefore, allocated to all other reported end-uses according to each end-use’s fraction of total consumption in that year.[23]

Table 4-18: Limestone and Dolomite Consumption from Other Uses of Carbonates (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Limestone	10,016	10,465	12,816	15,146	13,707	12,788	17,891
Dolomite	919	3,254	1,356	1,520	2,962	2,826	1,915
Total	**10,935**	**13,719**	**14,172**	**16,667**	**16,669**	**15,614**	**19,806**

Note: Totals may not sum due to independent rounding.

Ceramics Production

Carbon dioxide emissions from ceramics production were calculated using a Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data, by multiplying the quantity of clay consumed for emissive purposes by a carbonate content value of clay of 10 percent, limestone fraction of 85 percent and dolomite fraction of 15 percent, respectively, and by the emission factor for limestone or dolomite calcination, respectively: 0.43971 metric ton CO_2/metric ton of limestone and 0.47732 metric ton CO_2/metric ton of dolomite.[24] To estimate annual process CO_2 emissions, EPA evaluated the end-uses of each type of clay published by USGS to identify the emissive end-uses that fall into the ceramics production subcategory. The emissive end-uses were organized into three groups: ceramics, glass, and floor & tile; refractories; and heavy clay products. The total limestone and dolomite consumption from the three emissive groupings for ceramics production for 1990 through 2022 (see Table 4-19) were obtained from USGS (Simmons 2024).

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[23] This approach was recommended by USGS, the data collection agency.

[24] *2006 IPCC Guidelines*, Volume 3: Chapter 2, Table 2.1.

Table 4-19: Limestone and Dolomite Consumption from Ceramics Production (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Limestone	1,444	1,569	797	762	758	764	776
Dolomite	255	277	141	135	134	135	137
Total	**1,699**	**1,846**	**938**	**897**	**892**	**899**	**913**

Note: Totals may not sum due to independent rounding.

Other Uses of Soda Ash

Carbon dioxide emissions from soda ash consumption were calculated using a Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. Excluding glass manufacturing which is reported under Section 4.3 Glass Production (CRT Source Category 2A3), most soda ash is consumed in chemical production, with smaller amounts used in soap production, pulp and paper, flue gas desulfurization, and water treatment. In these applications, it is assumed that one mole of carbon is released for every mole of soda ash used. Thus, approximately 0.113 metric tons of carbon (or 0.415 metric tons of CO_2) are released for every metric ton of soda ash consumed. The activity data for soda ash consumption for 1990 to 2022 (see Table 4-20) were obtained from the *U.S. Geological Survey (USGS) Minerals Yearbook for Soda Ash* (1994 through 2015b) and *USGS Mineral Industry Surveys for Soda Ash* (USGS 2017a, 2018, 2019, 2020b, 2021b, 2022a, 2023a). Soda ash consumption data were collected by the USGS from voluntary surveys of the U.S. soda ash industry.

Table 4-20: Other Uses of Soda Ash Consumption Not Associated with Glass Manufacturing (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Soda Ash[a]	3,351	3,144	2,576	2,497	2,310	2,360	2,391

[a] Soda ash consumption is sales reported by producers which exclude imports. Historically, imported soda ash is less than 1 percent of the total U.S. consumption (Kostick 2012).

Non-Metallurgical Magnesia Production

Carbon dioxide emissions from non-metallurgical magnesia production were calculated using a Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data, by multiplying the quantity of magnesium ore extracted from the mine and processed at the facility by the carbonate content for magnesite or limestone, respectively, and by the emission factor for magnesite or limestone calcination, respectively: 0.52197 metric ton CO_2/metric ton carbonate for magnesite and 0.43971 metric ton CO_2/metric ton carbonate for limestone.[25] A USGS report on magnesite deposits at Gabbs, Nevada lists the carbonate content of magnesite as 98 percent magnesite and 1 percent limestone (USGS 1948). In the absence of other data, all magnesium ore extracted from the mine is assumed to be used for non-metallurgical magnesium production. Magnesium ore extracted from the mine and processed at the facility for non-metallurgical magnesia production for 2002 through 2022 (see Table 4-21) was obtained from the Nevada Department of Environmental Quality (McNeece 2023). This data was not available for 1990 through 2001. To address this gap in data availability and time-series consistency, carbonate consumption for 1990 through 2001 were estimated by multiplying the average ratio of magnesium ore consumption to production capacity for 2002 to 2004 by the production capacity of the facility in Nevada. Production capacity for 1990 through 2001 was obtained from the *USGS Minerals Yearbook for Magnesium Compounds* (USGS 1990 through 2002).

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[25] *2006 IPCC Guidelines*, Volume 3: Chapter 2, Table 2.1.

Table 4-21: Magnesite and Limestone Consumption from Non-Metallurgical Magnesia Production (kt)

Activity	1990	2005	2018	2019	2020	2021	2022
Magnesite	214	363	321	289	410	439	388
Limestone	2	4	3	3	4	4	4
Total	**216**	**367**	**325**	**292**	**414**	**443**	**392**

Note: Totals may not sum due to independent rounding.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied for non-metallurgical magnesia production to compare the magnesium ore consumption data to production capacity data for years where there was overlap. To address inconsistencies, adjustments were made, as described above.

Uncertainty

The uncertainty levels presented in this section account for uncertainty associated with activity data. Data on limestone and dolomite consumption are collected by USGS through voluntary national surveys. USGS contacts the mines (i.e., producers of various types of crushed stone) for annual sales data. Data on other carbonate consumption are not readily available. The producers report the annual quantity sold to various end-users and industry types. USGS estimates the historical response rate for the crushed stone survey to be approximately 70 percent, and the rest is estimated by USGS. Large fluctuations in reported consumption exist, reflecting year-to-year changes in the number of survey responders. The uncertainty resulting from a shifting survey population is exacerbated by the gaps in the time series of reports. The accuracy of distribution by end use is also uncertain because this value is reported by the producer/mines and not the end user. Additionally, there is significant inherent uncertainty associated with estimating withheld data points for specific end uses of limestone and dolomite. Lastly, much of the limestone consumed in the United States is reported as “other unspecified uses;” therefore, it is difficult to accurately allocate this unspecified quantity to the correct end-uses. EPA contacted the USGS National Minerals Information Center Crushed Stone commodity expert to assess the current uncertainty ranges associated with the limestone and dolomite consumption data compiled and published by USGS. During this discussion, the expert confirmed that EPA’s range of uncertainty was still reasonable (Willett 2017). EPA assigned an uncertainty range of ±10 percent for limestone and dolomite consumption, based on expert judgement (Willett 2017). EPA assigned an uncertainty range of ±5 percent for soda ash consumption, and using this suggested uncertainty provided in Volume 3, Chapter 2, Section 2.4.2.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023).

Uncertainty in the estimates also arises in part due to variations in the chemical composition of limestone. In addition to calcium carbonate, limestone may contain smaller amounts of magnesia, silica, and sulfur, among other minerals. The exact specifications for limestone or dolomite used as flux stone vary with the pyrometallurgical process and the kind of ore processed. EPA assigned an uncertainty range of ±3 percent for the CO_2 emission factors for limestone and dolomite consumption, and using this suggested uncertainty provided in Volume 3, Chapter 2, Section 2.5.2.1 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023).

For emissions from ceramics production, data on clay consumption are collected by USGS through voluntary national surveys. Large fluctuations in reported consumption exist, reflecting year-to-year changes in the number of survey responders. The accuracy of distribution by end use is also uncertain because this value is reported by the producer and not the end user. Uncertainty in the estimates also arises in part due to the variations in the carbonate content of the various clays used for the various types of ceramics. As discussed above, as no information is available on the carbonate content for each clay, fractions of limestone and dolomite consumed and a carbonate content for clay from the *2006 IPCC Guidelines* are used. EPA assigned an uncertainty range of ±10 percent for the activity data and ±3 percent for the emission factors, consistent with uncertainty ranges for limestone and dolomite activity data and emission factors for other process uses of carbonates, respectively.

For emissions from soda ash consumption, the primary source of uncertainty results from the fact that these emissions are dependent upon the type of processing employed by each end-use. Specific emission factors for each end-use are not available, so a Tier 1 default emission factor is used for all end-uses. Therefore, there is uncertainty surrounding the emission factors from the consumption of soda ash. Additional uncertainty comes from the reported consumption and allocation of consumption within sectors that is collected on a quarterly basis by the USGS. Efforts have been made to categorize company sales within the correct end-use sector. EPA assigned an uncertainty range of ±2 percent for the CO_2 emission factor for soda ash consumption. The uncertainty range is derived from the default ranges for soda ash consumption for glass production in Volume 3, Chapter 2, Section 2.4.2.1 of the *2006 IPCC Guidelines* which is representative of soda ash consumption not associated with glass production, based on expert judgment (RTI 2023).

For non-metallurgical magnesia production, uncertainties arise due to variations in the chemical composition of the carbonates used in production of caustic-calcined magnesia production. As noted, minor quantities of other carbonates beyond limestone and magnesite are also used but unknown. These other carbonates are likely small and have a minimal impact on the derived emission factor. EPA assigned an uncertainty range of ±10 percent for the activity data and ±3 percent for the emission factors, consistent with uncertainty ranges for limestone and dolomite activity data and emission factors for other process uses of carbonates, respectively. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-22.

A normal probability density function was assigned for all activity data, and a triangular probability density function was assigned for all emission factors (RTI 2023). Carbon dioxide emissions from other process uses of carbonates in 2022 were estimated to be between 9.2 and 12.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below and 15 percent above the emission estimate of 10.4 MMT CO_2 Eq.

Table 4-22: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Other Process Uses of Carbonates (MMT CO_2 Eq. and Percent)

Source	**Gas**	**2022 Emission Estimate (MMT CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)**		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Other Process Uses of Carbonates	CO_2	10.4	9.2	12.0	-12%	+15%

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

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

For the current *Inventory*, emission estimates for new subcategories ceramics production and non-metallurgical magnesia production were incorporated across the entire time series. No other recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

EPA plans to review the uncertainty ranges assigned to activity data. This planned improvement is currently planned as a medium-term improvement.

4.5 Ammonia Production (CRT Source Category 2B1)

Emissions of carbon dioxide (CO_2) occur during the production of synthetic ammonia (NH_3), primarily through the use of natural gas, petroleum coke, or naphtha as a feedstock. The natural gas-, naphtha-, and petroleum coke-based processes produce CO_2 and hydrogen (H_2), the latter of which is used in the production of ammonia. The brine electrolysis process for production of ammonia does not lead to process-based CO_2 emissions. This reporting category (2B1) includes emissions from the production of ammonia. Due to national circumstances, emissions from fuels consumed for energy purposes during the production of ammonia are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter. More information on this approach can be found in the Methodology section below.

Ammonia production requires a source of nitrogen (N) and hydrogen (H). Nitrogen is obtained from air through liquid air distillation or an oxidative process where air is burnt and the residual nitrogen is recovered. In the United States, the majority of ammonia is produced using a natural gas feedstock as the hydrogen source. One synthetic ammonia production plant located in Kansas is producing ammonia from petroleum coke feedstock. In some U.S. plants, some of the CO_2 produced by the process is captured and used to produce urea rather than being emitted to the atmosphere. In 2022, 16 companies operated 35 ammonia producing facilities in 16 states. Approximately 60 percent of domestic ammonia production capacity is concentrated in Louisiana, Oklahoma, and Texas (USGS 2023).

Synthetic ammonia production from natural gas feedstock consists of five principal process steps. The primary reforming step converts methane (CH_4) to CO_2, carbon monoxide (CO), and hydrogen (H_2) in the presence of a catalyst. Only 30 to 40 percent of the CH_4 feedstock to the primary reformer is converted to CO and CO_2 in this step of the process. The secondary reforming step converts the remaining CH_4 feedstock to CO and CO_2. In the shift conversion step, the CO in the process gas from the secondary reforming step (representing approximately 15 percent of the process gas) is converted to CO_2 in the presence of a catalyst, water, and air. Carbon dioxide is removed from the process gas by the shift conversion process, and the H_2 is combined with the nitrogen (N_2) gas in the process gas during the ammonia synthesis step to produce ammonia. The CO_2 is included in a waste gas stream with other process impurities and is absorbed by a scrubber solution. In regenerating the scrubber solution, CO_2 is released from the solution.

The conversion process for conventional steam reforming of CH_4, including the primary and secondary reforming and the shift conversion processes, is approximately as follows:

$$0.88CH_4 + 1.26Air + 1.24H_2O \rightarrow 0.88CO_2 + N_2 + 3H_2$$

$$N_2 + 3H_2 \rightarrow 2NH_3$$

To produce synthetic ammonia from petroleum coke, the petroleum coke is gasified and converted to CO_2 and H_2. These gases are separated, and the H_2 is used as a feedstock to the ammonia production process, where it is reacted with N_2 to form ammonia.

Not all of the CO_2 produced during the production of ammonia is emitted directly to the atmosphere. Some of the ammonia and some of the CO_2 produced by the synthetic ammonia process are used as raw materials in the production of urea [$CO(NH_2)_2$], which has a variety of agricultural and industrial applications.

The chemical reaction that produces urea is:

$$2NH_3 + CO_2 \rightarrow NH_2COONH_4 \rightarrow CO(NH_2)_2 + H_2O$$

Only the CO_2 emitted directly to the atmosphere from the synthetic ammonia production process is accounted for in determining emissions from ammonia production. The CO_2 that is captured during the ammonia production process and used to produce urea does not contribute to the CO_2 emission estimates for ammonia production presented in this section. Instead, CO_2 emissions resulting from the consumption of urea are attributed to the urea consumption or urea application source category (under the assumption that the carbon stored in the urea during its manufacture is released into the environment during its consumption or application). Emissions of CO_2 resulting from agricultural applications of urea are accounted for in Section 5.6. Emissions of CO_2 resulting from non-agricultural applications of urea (e.g., use as a feedstock in chemical production processes) are accounted for in Section 4.6.

Emissions from fuel used for energy at ammonia plants are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter. The consumption of natural gas and petroleum coke as fossil fuel feedstocks for NH_3 production are adjusted for within the Energy chapter as these fuels were consumed during non-energy related activities. More information on this methodology is described in Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Total emissions of CO_2 from ammonia production in 2022 were 12.6 MMT CO_2 Eq. (12,610 kt) and are summarized in Table 4-23 and Table 4-24. Ammonia production relies on natural gas as both a feedstock and a fuel, and as such, market fluctuations and volatility in natural gas prices affect the production of ammonia. Since 1990, emissions from ammonia production have decreased by 12 percent. Emissions in 2022 increased by about 3 percent from the 2021 levels. One facility in Kansas produces ammonia from petroleum coke and began operations in 2000. All other facilities use natural gas as feedstock.

Emissions from ammonia production increased steadily from 2015 to 2018, due to the addition of new ammonia production facilities and new production units at existing facilities in 2016, 2017, and 2018. Agriculture continues to drive demand for nitrogen fertilizers, accounting for approximately 88 percent of domestic ammonia consumption (USGS 2023).

Table 4-23: CO_2 Emissions from Ammonia Production (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Ammonia Production	14.4	10.2	12.7	12.4	13.0	12.2	12.6

Table 4-24: CO_2 Emissions from Ammonia Production (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Ammonia Production	14,404	10,234	12,669	12,401	13,006	12,192	12,610

Methodology and Time-Series Consistency

Estimates of CO_2 emissions from the production of synthetic ammonia for 2010 through 2022 are estimated using a country-specific approach consistent with Tier 3 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data (IPCC 2006). The methodology for 2010 to 2022 directly uses the process CO_2 emissions reported to subpart G of the U.S. EPA Greenhouse Gas Reporting Program (GHGRP) (EPA 2018, EPA 2023). Estimates for 1990 to 2009 emissions are based on reported and calculated data on natural gas and petroleum coke feedstock used for ammonia production, consistent with IPCC Tier 2 methods and in accordance with the IPCC methodological decision tree and available data.

Emissions from fuel used for energy at ammonia plants are accounted for in the Energy chapter. This approach differs slightly from the *2006 IPCC Guidelines* which indicates that “in the case of ammonia production no distinction is made between fuel and feedstock emissions with all emissions accounted for in the IPPU Sector.” Disaggregated data on fuel used for ammonia feedstock and fuel used for energy for ammonia production are not available in the United States. The Energy Information Administration (EIA), where energy use data are obtained for the *Inventory* (see the Energy chapter), does not provide data broken out by industrial category. EIA data are only available at the broad industry sector level. Furthermore, the GHGRP data used to estimate emissions are based on feedstock use and not fuel use. The method uses the same science informing the 2006 IPCC guidelines and is consistent with avoiding double counting in the reporting of fuel use emissions under Energy and IPPU reporting. See more information in introduction to this Chapter.

Petroleum Coke Feedstock

Since 2000, one facility in the United States has produced ammonia using petroleum coke as a feedstock. For 2010 to 2022, CO_2 emissions from the production of synthetic ammonia from petroleum coke feedstock were estimated using CO_2 emissions reported by the facility to GHGRP (EPA 2018; EPA 2023).

For 2006 to 2009, CO_2 emissions from the production of synthetic ammonia from petroleum coke feedstock were estimated by multiplying the following: quantity of petroleum coke feedstock reported by the facility (CVR 2008 through 2022); the *Inventory* heating content value for petroleum coke (consistent with values used in the Energy chapter); the petroleum coke carbon content; and a stoichiometric CO_2/C factor of 44/12.

For 2000 to 2005, the quantity of petroleum coke feedstock was not available and was estimated by multiplying the average ratio of petroleum coke feedstock quantity to ammonia production quantity produced from petroleum coke from 2006 through 2010 by total ammonia production for 2000 to 2005 (ACC 2023). The years 2006 to 2010 were used to determine the average ratio of petroleum coke feedstock quantity to the ammonia quantity produced from petroleum coke because that period was deemed to better represent historic ammonia production from petroleum coke for the period from 2000 to 2005.

For 2000 to 2005, CO_2 emissions from the production of synthetic ammonia from petroleum coke feedstock were estimated by multiplying the following: the average ratio of petroleum coke feedstock quantity to ammonia production quantity; total ammonia production quantity (ACC 2023); the *Inventory* heating content value for petroleum coke (consistent with values used in the Energy chapter); the petroleum coke carbon content; and the stoichiometric ratio of CO_2 to C (44/12).

Natural Gas Feedstock

For 2017 through 2022, facilities directly reported to GHGRP the quantity of natural gas feedstock used for ammonia production along with the carbon content of the natural gas feedstock (EPA 2018; EPA 2023).

For 2010 through 2016, the quantity of natural gas feedstock was calculated using GHGRP process CO_2 emissions for 2010 through 2016, average molecular weight of the feedstock from 2017 through 2021, and average carbon content from 2017 through 2021. Data from years 2017 to 2021 were used to determine the average molecular weight and the average carbon content because that period better represents historic ammonia production from 2010 to 2016. Using all available data from 2017 to 2021 allowed for the maximum number of data points available at the time of adopting this methodology to ensure that the average was representative. The averages were not updated using later data to exclude any new facilities that might not be representative of facilities that were operating during the earlier years of the GHGRP.

For 2010 to 2022, CO_2 emissions from the production of synthetic ammonia from natural gas feedstock were estimated using the CO_2 emissions reported to the GHGRP (EPA 2018; EPA 2023) and subtracting the CO_2 emissions from the production of synthetic ammonia from petroleum coke feedstock as determined in the Petroleum Coke Feedstock section above.

For 1990 to 2009, the quantity of natural gas feedstock was not available and was estimated by multiplying the average ratio of natural gas feedstock quantity to ammonia production quantity from 2010 through 2014 by total ammonia production for each year for 1990 to 2009 (ACC 2023). The years 2010 to 2014 were used to determine the average ratio of natural gas feedstock quantity to ammonia production because that period better represents historic ammonia production from 1990 to 2009.[26] For 1990 to 2009, CO_2 emissions from the production of synthetic ammonia from natural gas feedstock were estimated using the natural gas feedstock quantity as determined above and the *Inventory* CO_2 emissions factor and heating content value for natural gas (consistent with values used in the Energy chapter).

Urea Production Adjustments

Emissions of CO_2 from ammonia production from both feedstocks and for all years from 1990 to 2022 were adjusted to account for the use of some CO_2 emissions resulting from ammonia production as a raw material in the production of urea. The CO_2 emissions reported for ammonia production are reduced by a factor of 0.733, which corresponds to a stoichiometric CO_2/urea factor of 44/60, assuming complete conversion of ammonia (NH_3) and CO_2 to urea (IPCC 2006; EFMA 2000), and multiplied by total annual domestic urea production.

All synthetic ammonia production and subsequent urea production are assumed to be from the same process—conventional catalytic reforming of natural gas feedstock, with the exception of ammonia production from petroleum coke feedstock at the one facility located in Kansas.

Table 4-25: Total Ammonia Production, Total Urea Production, and Recovered CO_2 Consumed for Urea Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Total Ammonia Production	15,425	10,143	16,010	16,410	17,020	15,420	16,800
Total Urea Production	7,450	5,270	10,700	11,400	11,500	10,521	11,272
Recovered CO_2 Consumed for Urea Production	5,463	3,865	7,847	8,360	8,433	7,715	8,266

Total ammonia production, total urea production, and recovered CO_2 consumed for urea production are shown in Table 4-25. Total ammonia production data for 2011 through 2022 were obtained from American Chemistry Council (ACC 2023). For years 1990 through 2011, ammonia production data were obtained from the Census Bureau of the U.S. Department of Commerce (U.S. Census Bureau 1991 through 1994, 1998 through 2011) as reported in *Current Industrial Reports Fertilizer Materials and Related Products* annual and quarterly reports. Data on facility-level process emissions for 2010 through 2022 and data on natural gas feedstock used and carbon content of the natural gas feedstock starting in 2017 were obtained from GHGRP (EPA 2018; EPA 2023). Natural gas and petroleum coke heating values come from national-level data (EIA 2023), and natural gas and petroleum coke carbon contents are the same as used in the Energy chapter calculations.

Data on urea production for 2010 through 2022 were obtained from GHGRP (EPA 2018, EPA 2023). Urea production data for 2009 through 2010 were obtained from the U.S. Census Bureau (U.S. Census Bureau 2010 and 2011). Urea production data for 1990 through 2008 were obtained from the USGS *Minerals Yearbook: Nitrogen* (USGS 1994-2009). The U.S. Census Bureau ceased collection of urea production statistics in 2011.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. The methodology for ammonia production spliced activity data from different sources: U. S. Census Bureau data for 1990 through 2010, ACC data beginning in 2011, and GHGRP data beginning in 2010 and 2017. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the two data sets for years where there was overlap, with findings that the data sets were consistent and adjustments were not needed.

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[26] The number of facilities reporting to GHGRP has increased since 2010: 22 facilities reported from 2010 to 2012; 23 from 2013 to 2015; 26 in 2016; 28 in 2017 and 29 from 2018 to 2022. Using data from 2010 to 2014 excludes the newer facilities that might not be representative of facilities in earlier years.

Uncertainty

The uncertainties presented in this section are primarily due to how accurately the emission factor used represents an average across all ammonia plants using natural gas feedstock. Uncertainty in the back calculation of natural gas feedstock used for 1990 through 2009 also exists. Using the average ratio of natural gas feedstock quantity to ammonia production, determined using GHGRP data from 2010 to 2014, does not account for efficiency gains in ammonia production since 1990 (e.g., potential decreases in gas usage per ton of ammonia, manufacturing shift from steam-driven turbines to electrical-drive turbines). Uncertainties are also associated with ammonia production estimates and the assumption that all ammonia production and subsequent urea production was from the same process—conventional catalytic reforming of natural gas feedstock, with the exception of one ammonia production plant located in Kansas that is manufacturing ammonia from petroleum coke feedstock. Uncertainty is also associated with the representativeness of the emission factor used for the petroleum coke-based ammonia process. It is also assumed that ammonia and urea are produced at co-located plants from the same natural gas raw material. The uncertainty of the total urea production activity data, based on USGS *Minerals Yearbook: Nitrogen* data, is a function of the reliability of reported production data and is influenced by the completeness of the survey responses. EPA assigned an uncertainty range of ±5 percent for ammonia production and a range of ±2 percent for urea production, natural gas feedstock quantity, petroleum coke feedstock quantity, and carbon content of natural gas feedstock, and using the suggested uncertainty provided in Section 3.2.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Per this expert judgement, a normal probability density function was assigned for all variables.

Recovery of CO_2 from ammonia production plants for purposes other than urea production (e.g., commercial sale, etc.) has not been considered in estimating the CO_2 emissions from ammonia production, as data concerning the disposition of recovered CO_2 are not available. Such recovery may or may not affect the overall estimate of CO_2 emissions depending upon the end use to which the recovered CO_2 is applied. Further research is required to determine whether byproduct CO_2 is being recovered from other ammonia production plants for application to end uses that are not accounted for elsewhere; however, for reporting purposes, CO_2 consumption for urea production is provided in this chapter.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-26. Carbon dioxide emissions from ammonia production in 2022 were estimated to be between 12.2 and 13.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 4 percent below and 4 percent above the emission estimate of 12.6 MMT CO_2 Eq.

Table 4-26: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Ammonia Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Ammonia Production	CO_2	12.6	12.2	13.1	-4%	+4%

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

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied to ammonia production emission estimates consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to ammonia facilities can be found under Subpart G (Ammonia Production) of the regulation (40 CFR Part 98).[27] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent.[28] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

More details on the greenhouse gas calculation, monitoring, and QA/QC methods applicable to reporting of urea produced at ammonia production facilities can be found under Section 4.6 Urea Consumption for Non-Agricultural Purposes.

Recalculations

For 2021, the urea consumption value was changed from a rounded value to a more precise unrounded value. As a result, recalculations were performed for emissions from ammonia for 2021. Compared to the previous *Inventory*, total CO_2 emissions from the production of ammonia production (from natural gas and petroleum coke feedstocks) decreased by less than 1 percent (15 kt) in 2021.

Planned Improvements

Currently the *Inventory* does not separately track fuel energy use for ammonia production. To be more consistent with *2006 IPCC Guidelines*, EPA is considering whether to include natural gas fuel use as part of ammonia production emissions as a future improvement. The data are still being evaluated as part of EPA's efforts to disaggregate other industrial sector categories' energy use in the Energy chapter of the *Inventory*. If possible, this will be incorporated in future *Inventory* reports. If incorporated, the fuel energy use and emissions will be removed from current reporting under Energy to avoid double counting.

4.6 Urea Consumption for Non-Agricultural Purposes (CRT Source Category 2B10)

Urea is produced using ammonia (NH_3) and carbon dioxide (CO_2) as raw materials. All urea produced in the United States is assumed to be produced at ammonia production facilities where both ammonia and CO_2 are generated. There were 35 plants producing ammonia in the United States in 2022, with two additional plants sitting idle for the entire year (USGS 2023b).

The chemical reaction that produces urea is:

$$2NH_3 + CO_2 \rightarrow NH_2COONH_4 \rightarrow CO(NH_2)_2 + H_2O$$

This section accounts for CO_2 emissions associated with urea consumed exclusively for non-agricultural purposes. This reporting category (2B10) includes emissions from IPCC assessment reports that do not fall within any other CRT source category, which includes emissions from urea consumption for non-agricultural purposes. Emissions of CO_2 resulting from agricultural applications of urea are accounted for in Section 5.6 of the Agriculture chapter.

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[27] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

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

The industrial applications of urea include its use in adhesives, binders, sealants, resins, fillers, analytical reagents, catalysts, intermediates, solvents, dyestuffs, fragrances, deodorizers, flavoring agents, humectants and dehydrating agents, formulation components, monomers, paint and coating additives, photosensitive agents, and surface treatments agents. In addition, urea is used for abating nitrogen oxide (NO_x) emissions from coal-fired power plants and diesel transportation motors.

Emissions of CO_2 from urea consumed for non-agricultural purposes in 2022 were estimated to be 7.1 MMT CO_2 Eq. (7,053 kt) and are summarized in Table 4-27 and Table 4-28. Net CO_2 emissions from urea consumption for non-agricultural purposes have increased by approximately 86 percent from 1990 to 2022 and increased by approximately 7 percent from 2021 to 2022.

Table 4-27: CO_2 Emissions from Urea Consumption for Non-Agricultural Purposes (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Urea Consumption	3.8	3.7	6.1	6.2	5.8	6.6	7.1

Table 4-28: CO_2 Emissions from Urea Consumption for Non-Agricultural Purposes (kt CO_2)

Source	1990	2005	2018	2019	2020	2021	2022
Urea Consumption	3,784	3,653	6,113	6,150	5,805	6,600	7,053

Methodology and Time-Series Consistency

Emissions of CO_2 resulting from urea consumption for non-agricultural purposes are estimated using a country-specific method consistent with the Tier 1 method used to estimate emissions from ammonia production in the *2006 IPCC Guidelines* which states that the "CO_2 recovered [from ammonia production] for downstream use can be estimated from the quantity of urea produced where CO_2 is estimated by multiplying urea production by 44/60, the stoichiometric ratio of CO_2 to urea" (IPCC 2006). The amount of urea consumed in the United States for non-agricultural purposes is multiplied by a factor representing the amount of CO_2 used as a raw material to produce the urea. This method is based on the assumption that all of the carbon in urea is released into the environment as CO_2 during use.

The amount of urea consumed for non-agricultural purposes in the United States is estimated by deducting the quantity of urea fertilizer applied to agricultural lands, which is obtained directly from the Agriculture chapter (see Table 5-25), from the total domestic supply of urea as reported in Table 4-29. The domestic supply of urea is estimated based on the amount of urea produced plus urea imports and minus urea exports. A factor of 0.733 tons of CO_2 per ton of urea consumed is then applied to the resulting supply of urea for non-agricultural purposes to estimate CO_2 emissions from the amount of urea consumed for non-agricultural purposes. The 0.733 tons of CO_2 per ton of urea emission factor is based on the stoichiometry of carbon in urea. This corresponds to a stoichiometric ratio of CO_2 to urea of 44/60, assuming complete conversion of carbon in urea to CO_2 (IPCC 2006; EFMA 2000).

Urea production data for 1990 through 2008 were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook: Nitrogen* (USGS 1994 through 2009a). Urea production data for 2009 through 2010 were obtained from the U.S. Census Bureau (2011). The U.S. Census Bureau ceased collection of urea production statistics in 2011. Urea production data for 2011 through 2022 were obtained from GHGRP (EPA 2018; EPA 2023a; EPA 2023b).

Urea import data for 2022 were not available at the time of publication and were estimated using 2021 values. Urea import data for 2013 to 2021 were obtained from the USGS *Minerals Yearbook: Nitrogen* (USGS 2023a). Urea import data for 2011 and 2012 were taken from U.S. Fertilizer Import/Exports from the United States Department of Agriculture (USDA) Economic Research Service Data Sets (U.S. Department of Agriculture 2012). USDA suspended updates to this data after 2012. Urea import data for the previous years were obtained from the U.S. Census Bureau *Current Industrial Reports Fertilizer Materials and Related Products* annual and quarterly reports for

1997 through 2010 (U.S. Census Bureau 2001 through 2011), The Fertilizer Institute (TFI 2002) for 1993 through 1996, and the United States International Trade Commission Interactive Tariff and Trade DataWeb (U.S. ITC 2002) for 1990 through 1992 (see Table 4-29).

Urea export data for 2022 were not available at the time of publication and were estimated using 2021 values. Urea export data for 2013 to 2021 were obtained from the USGS *Minerals Yearbook: Nitrogen* (USGS 2023a). Urea export data for 1990 through 2012 were taken from U.S. Fertilizer Import/Exports from USDA Economic Research Service Data Sets (U.S. Department of Agriculture 2012). USDA suspended updates to this data after 2012.

Table 4-29: Urea Production, Urea Applied as Fertilizer, Urea Imports, and Urea Exports (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Urea Production	7,450	5,270	10,700	11,400	11,500	10,521	11,272
Urea Applied as Fertilizer	3,296	4,779	6,732	6,865	6,998	7,131	7,265
Urea Imports	1,860	5,026	5,110	4,410	4,190	5,880	5,880
Urea Exports	854	536	743	559	777	270	270
Urea Consumed for Non-Agricultural Purposes	5,160	4,981	8,335	8,386	7,915	9,000	9,617

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. The methodology for urea consumption for non-agricultural purposes spliced activity data from different sources: USGS data for 1990 through 2008, U. S. Census Bureau data for 2009 and 2010, and GHGRP data beginning in 2011. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the data sets for years where there was overlap, with findings that the data sets were consistent and adjustments were not needed.

Uncertainty

There is limited publicly available data on the quantities of urea produced and consumed for non-agricultural purposes. Therefore, the amount of urea used for non-agricultural purposes is estimated based on a balance that relies on estimates of urea production, urea imports, urea exports, and the amount of urea used as fertilizer. EPA uses an uncertainty range of ±10 percent for urea production and ±5 percent for urea imports and urea exports, consistent with the ranges for activity data that are not obtained directly from plants, and using this suggested uncertainty provided in Section 3.2.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a normal probability density function was assigned for all activity data. The primary uncertainties associated with this source category are associated with the accuracy of these estimates as well as the fact that each estimate is obtained from a different data source. Because urea production estimates are no longer available from the USGS, there is additional uncertainty associated with urea produced beginning in 2011. There is also uncertainty associated with the assumption that all of the carbon in urea is released into the environment as CO_2 during use.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-30. Carbon dioxide emissions associated with urea consumption for non-agricultural purposes during 2022 were estimated to be between 6.8 and 7.3 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 4 percent below and 4 percent above the emission estimate of 7.1 MMT CO_2 Eq.

Table 4-30: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Urea Consumption for Non-Agricultural Purposes (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Urea Consumption for Non-Agricultural Purposes	CO_2	7.1	6.8	7.3	-4%	+4%

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

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to reporting of urea production occurring at ammonia facilities can be found under Subpart G (Ammonia Manufacturing) of the regulation (40 CFR Part 98).[29] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent.[30] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions. EPA also conducts QA checks of GHGRP reported urea production data against external datasets including the USGS *Minerals Yearbook* data. The comparison shows consistent trends in urea production over time.

Recalculations Discussion

Based on updated quantities of urea applied for agricultural uses for 2017 through 2021, updated urea imports from USGS for 2021, and updated urea exports from USGS for 2021, recalculations were performed for 2017 through 2021. Compared to the previous *Inventory*, CO_2 emissions from urea consumption for non-agricultural purposes increased by less than 1 percent for 2017 (46 kt CO_2) and 2018 (2 kt CO_2), decreased by less than 1 percent for 2019 (4 kt CO_2) and 2020 (10 kt CO_2) and increased by 32 percent for 2021 (1,611 kt CO_2).

Planned Improvements

At this time, there are no specific planned improvements for estimating CO_2 emissions from urea consumption for non-agricultural purposes.

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[29] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

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

4.7 Nitric Acid Production (CRT Source Category 2B2)

Nitrous oxide (N_2O) is emitted during the production of nitric acid (HNO_3), an inorganic compound used primarily to make synthetic commercial fertilizers. Nitric acid is also a major component in the production of adipic acid—a feedstock for nylon—and explosives. This reporting category (2B2) includes emissions from production of nitric acid. Emissions from fuels consumed for energy purposes during the production of nitric acid are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

There are two types of nitric acid: weak nitric acid and high-strength nitric acid. The weak nitric acid production method utilizes oxidation, condensation, and absorption to produce nitric acid at concentrations between 30 and 70 percent nitric acid. High-strength nitric acid (90 percent or greater nitric acid) can be produced by two methods: (1) through the dehydration, bleaching, condensing, and absorption of the weak nitric acid or (2) through the oxidation of ammonia into nitric oxide, which is oxidized and cooled into dinitrogen tetroxide and then pressurized and oxidized into high-strength nitric acid. Most U.S. plants were built between 1960 and 2000. As of 2022, there were 31 active nitric acid production plants that produce weak nitric acid in the United States (EPA 2023). One plant produces both weak and high-strength nitric acid (EPA 2010).

The basic process technology for producing nitric acid has not changed significantly over time. During this process, N_2O is formed as a byproduct and released from reactor vents into the atmosphere.

Nitric acid is made from the reaction of ammonia (NH_3) with oxygen (O_2) in two stages. The overall reaction is:

$$4NH_3 + 8O_2 \rightarrow 4HNO_3 + 4H_2$$

Currently, the nitric acid industry in the United States controls emissions of NO and NO_2 (i.e., NO_x), using a combination of non-selective catalytic reduction (NSCR) and selective catalytic reduction (SCR) technologies. In the process of destroying NO_x, NSCR systems are also very effective at destroying N_2O. Five nitric acid plants had NSCR systems installed between 1964 and 1977, over half due to the finalization of the Nitric Acid Plant New Source Performance Standards (NSPS) which went into effect in 1971. Four additional nitric acid plants had NSCR systems installed between 2016 and 2018, as a result of EPA Consent Decrees to control NO_X emissions more effectively. NSCR systems are used in approximately one-third of the weak acid production plants. For N_2O abatement, U.S. facilities are using both tertiary (i.e., NSCR and SCR) and secondary controls (i.e., catalysts added to the ammonia reactor to lessen potential N_2O production).

Emissions from the production of nitric acid are generally directly proportional to the annual amount of nitric acid produced because emissions are calculated as the product of the total annual production and plant-specific emission factors. There are a few instances, however, where that relationship has not been directly proportional. For example, in 2015 and 2019, nitric acid production decreased and emissions increased compared to the respective preceding years; in 2016, nitric acid production increased and emissions decreased compared to 2015. N_2O emissions for those years are calculated based on data from the GHGRP as discussed in the Methodology section below. According to data from plants reporting to GHGRP, plant-specific operations can affect the emission factor used, including: (1) site-specific fluctuations in ambient temperature and humidity, (2) catalyst age and condition, (3) process changes, such as fluctuations in process pressure or temperature and replacing the ammonia catalyst, (4) the addition, removal, maintenance, and utilization of abatement technologies, and (5) the number of nitric acid trains, which are reaction vessels where ammonia is oxidized to form nitric acid. Changes in those operating conditions for the years in question (2015, 2016, and 2019) caused changes in emission factors, which resulted in emissions changing disproportionally to production in those years.

Nitrous oxide emissions from this source were estimated to be 8.6 MMT CO_2 Eq. (33 kt of N_2O) in 2022 and are summarized in Table 4-31 and Table 4-32. Emissions from nitric acid production have decreased by 20 percent since 1990, while production has increased by 9 percent over the same time period (see Table 4-31 and Table

4-32). Emissions have decreased by 33 percent since 1997, the highest year of production in the time series. From 2021 to 2022, nitric acid production increased by 1 percent, while overall emissions from nitric acid production increased by 9.4 percent from 2021 to 2022.

Table 4-31: N_2O Emissions from Nitric Acid Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Nitric Acid Production	10.8	10.1	8.5	8.9	8.3	7.9	8.6

Table 4-32: N_2O Emissions from Nitric Acid Production (kt N_2O)

Year	1990	2005	2018	2019	2020	2021	2022
Nitric Acid Production	41	38	32	34	31	30	33

Methodology and Time-Series Consistency

Emissions of N_2O from nitric acid production are estimated using methods provided by the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. For 2010 through 2022, a Tier 3 method was used to estimate emissions based on GHGRP data. For 1990 through 2009, a Tier 2 method was used to estimate emissions from nitric acid production based on U.S. Census Bureau data.

2010 through 2022

Process N_2O emissions and nitric acid production data were obtained directly from EPA's GHGRP for 2010 through 2022 by aggregating reported facility-level data (EPA 2018; EPA 2023).[31]

Since 2010, in the United States, all nitric acid facilities that produce weak nitric acid (30 to 70 percent) have been required to report annual greenhouse gas emissions data to EPA as per the requirements of the GHGRP (Subpart V). Beginning with 2018, the rule was changed to include facilities that produce nitric acid of any strength. The only facility that produces high-strength nitric acid also produces weak nitric acid. All N_2O emissions from nitric acid production originate from the production of weak nitric acid.

Process emissions and nitric acid production reported to the GHGRP provide complete estimates of greenhouse gas emissions for the United States because there are no reporting thresholds. While facilities are allowed to stop reporting to the GHGRP if the total reported emissions from nitric acid production are less than 25,000 metric tons CO_2 Eq. per year for five consecutive years or less than 15,000 metric tons CO_2 Eq. per year for three consecutive years, no facilities have stopped reporting as a result of these provisions.[32] All nitric acid facilities are required to either calculate process N_2O emissions using a site-specific emission factor that is the average of the emission factor determined through annual performance tests for each nitric acid train under typical operating conditions or directly measure process N_2O emissions using monitoring equipment.[33]

Emissions from facilities vary from year to year, depending on the amount of nitric acid produced with and without abatement technologies and other conditions affecting the site-specific emission factor. To maintain consistency

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[31] National N_2O process emissions, national production, and national share of nitric acid production with abatement and without abatement technology were aggregated from the GHGRP facility-level data for 2010 to 2022 (i.e., percent production with and without abatement).

[32] See 40 CFR 98.2(i)(1) and 40 CFR 98.2(i)(2) for more information about these provisions.

[33] Facilities must use standard methods - either EPA Method 320 or ASTM D6348-03 for annual performance tests—and must follow associated QA/QC procedures consistent with category-specific QC of direct emission measurements during these performance tests.

across the time series and with the rounding approaches taken by other data sets, GHGRP nitric acid data are rounded and are shown in Table 4-33.

1990 through 2009

Using GHGRP data for 2010, country-specific N_2O emission factors were calculated for nitric acid production with abatement and without abatement (i.e., controlled and uncontrolled emission factors). The following 2010 emission factors were derived for production with abatement and without abatement: 3.3 kg N_2O/metric ton HNO_3 produced at plants using abatement technologies (e.g., tertiary systems such as NSCR systems) and 5.99 kg N_2O/metric ton HNO_3 produced at plants not equipped with abatement technology. Country-specific weighted emission factors were derived by weighting these emission factors by percent production with abatement and without abatement over time periods 1990 through 2008 and 2009. These weighted emission factors were used to estimate N_2O emissions from nitric acid production for years prior to the availability of GHGRP data (i.e., 1990 through 2008 and 2009). A separate weighted emission factor is included for 2009 due to data availability for that year.

EPA verified the installation dates of N_2O abatement technologies for all facilities based on GHGRP facility-level information and confirmed that all abatement technologies were accounted for in the derived emission factors (Icenhour 2020). Due to the lack of information on abatement equipment utilization, it is assumed that once abatement technology was installed in facilities, the equipment was consistently operational for the duration of the time series considered in this report (especially NSCRs).

The country-specific weighted N_2O emission factors were used in conjunction with annual production to estimate N_2O emissions for 1990 through 2009, using the following equations:

Equation 4-4: *2006 IPCC Guidelines* Tier 3: N_2O Emissions From Nitric Acid Production (Equation 3.6)

$$E_i = P_i \times EF_{weighted,i}$$

$$EF_{weighted,i} = \left[\left(\%P_{c,i} \times EF_c\right) + \left(\%P_{unc,i} \times EF_{unc}\right) \right]$$

where,

E_i = Annual N_2O Emissions for year i (kg/yr)

P_i = Annual nitric acid production for year i (metric tons HNO_3)

$EF_{weighted,i}$ = Weighted N_2O emission factor for year i (kg N_2O/metric ton HNO_3)

$\%P_{c,i}$ = Percent national production of HNO_3 with N_2O abatement technology (%)

EF_c = N_2O emission factor, with abatement technology (kg N_2O/metric ton HNO_3)

$\%P_{unc,i}$ = Percent national production of HNO_3 without N_2O abatement technology (%)

EF_{unc} = N_2O emission factor, without abatement technology (kg N_2O/metric ton HNO_3)

i = year from 1990 through 2009

- For 2009: Weighted N_2O emission factor = 5.46 kg N_2O/metric ton HNO_3.
- For 1990 through 2008: Weighted N_2O emission factor = 5.66 kg N_2O/metric ton HNO_3.

Nitric acid production data for the United States for 1990 through 2009 were obtained from the U.S. Census Bureau (U.S. Census Bureau 2008, 2009, 2010a, 2010b) (see Table 4-33). EPA used GHGRP facility-level information to verify that all reported N_2O abatement equipment were incorporated into the estimation of N_2O emissions from nitric acid production over the full time series (EPA 2021).

Table 4-33: Nitric Acid Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Production (kt)	7,200	6,710	8,210	8,080	7,970	7,800	7,860

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. The methodology for nitric acid production spliced activity data from two different sources: U.S. Census Bureau production data for 1990 through 2009 and GHGRP production data starting in 2010. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the two data sets for years where there was overlap, with findings that the data sets were consistent and adjustments were not needed.

Uncertainty

Uncertainty associated with the parameters used to estimate N_2O emissions includes the share of U.S. nitric acid production attributable to each emission abatement technology (i.e., utilization) over the time series (especially prior to 2010), and the associated emission factors applied to each abatement technology type. While some information has been obtained through outreach with industry associations, limited information is available over the time series (especially prior to 2010) for a variety of facility level variables, including plant-specific production levels, plant production technology (e.g., low or high pressure, etc.), and abatement technology destruction and removal efficiency rates. Production data prior to 2010 were obtained from National Census Bureau, which does not provide uncertainty estimates with their data. Facilities reporting to EPA's GHGRP must measure production using equipment and practices used for accounting purposes. While emissions are often directly proportional to production, the emission factor for individual facilities can vary significantly from year to year due to site-specific fluctuations in ambient temperature and humidity, catalyst age and condition, nitric acid production process changes, the addition or removal of abatement technologies, and the number of nitric acid trains at the facility. At this time, EPA does not estimate uncertainty of the aggregated facility-level information. As noted in the QA/QC and verification section below, EPA verifies annual facility-level reports through a multi-step process (e.g., combination of electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. The annual production reported by each nitric acid facility under EPA's GHGRP and then aggregated to estimate national N_2O emissions is assumed to have low uncertainty. EPA assigned an uncertainty range of ±5 percent for facility-reported N_2O emissions, and using this suggested uncertainty provided in section 3.4.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). EPA assigned an uncertainty range of ±2 percent for nitric acid production, and using this suggested uncertainty provided in section 3.3.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a normal probability density function was assigned for facility-reported N_2O emissions and nitric acid production.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-34. Nitrous oxide emissions from nitric acid production were estimated to be between 8.2 and 9.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 5 percent below to 5 percent above the 2022 emissions estimate of 8.6 MMT CO_2 Eq.

Table 4-34: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from Nitric Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Nitric Acid Production	N_2O	8.6	8.2	9.0	-5%	+5%

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

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to nitric acid facilities can be found under Subpart V: Nitric Acid Production of the GHGRP regulation (40 CFR Part 98). [34]

The main QA/QC activities are related to annual performance testing, which must follow either EPA Method 320 or ASTM D6348-03. EPA verifies annual facility-level GHGRP reports through a multi-step process that is tailored to the Subpart (e.g., combination of electronic checks including range checks, statistical checks, algorithm checks, year-to-year comparison checks, along with manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred (EPA 2015). [35] EPA's review of observed trends noted that while emissions have generally mirrored production, in 2015 and 2019 nitric acid production decreased compared to the previous year and emissions increased. While review is ongoing, based on feedback from the verification process to date, these changes are due to facility-specific changes (e.g., in the nitric production process and management of abatement equipment).

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

Pending resources, EPA is considering a near-term improvement to both review and refine quantitative uncertainty estimates and the associated qualitative discussion.

4.8 Adipic Acid Production (CRT Source Category 2B3)

Adipic acid is a white crystalline solid used in the manufacture of synthetic fibers, plastics, coatings, urethane foams, elastomers, and synthetic lubricants. This reporting category (2B3) includes emissions from the production of adipic acid. Emissions from fuels consumed for energy purposes during the production of adipic acid are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Adipic acid is produced through a two-stage process during which nitrous oxide (N_2O) is generated in the second stage. The first stage of manufacturing usually involves the oxidation of cyclohexane to form a cyclohexanone/cyclohexanol mixture. The second stage involves oxidizing this mixture with nitric acid to produce

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[34] See Subpart V monitoring and reporting regulation http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[35] See GHGRP Verification Factsheet https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

adipic acid. Nitrous oxide is generated as a byproduct of the nitric acid oxidation stage and is emitted in the waste gas stream (Thiemens and Trogler 1991). The second stage is represented by the following chemical reaction:

$$(CH_2)_5CO(cyclohexanone) + (CH_2)_5CHOH(cyclohexanol) + wHNO_3 \\ \rightarrow HOOC(CH_2)_4COOH(adipic\ acid) + xN_2O + yH_2O$$

Process emissions from the production of adipic acid vary with the types of technologies and level of emission controls employed by a facility. In 1990, two major adipic acid-producing plants had N_2O abatement technologies in place and, as of 1998, three major adipic acid production facilities had control systems in place (Reimer et al. 1999). In 2022, thermal reduction was applied as an N_2O abatement measure at one adipic acid facility (EPA 2023).

Worldwide, only a few adipic acid plants exist. The United States, Europe, and China are the major producers, with the United States accounting for the largest share of global adipic acid production capacity in recent years. In 2022, the United States had two companies with a total of two adipic acid production facilities (one in Texas and one in Florida), following the ceased operations of a third major production facility at the end of 2015 (EPA 2023).

Commercially, adipic acid is the most important of the aliphatic dicarboxylic acids, which are used to manufacture polyesters. Eighty-four percent of all adipic acid produced in the United States is used in the production of nylon 6,6; 9 percent is used in the production of polyester polyols; 4 percent is used in the production of plasticizers; and the remaining 4 percent is accounted for by other uses, including unsaturated polyester resins and food applications (ICIS 2007). Food grade adipic acid is used to provide some foods with a “tangy” flavor (Thiemens and Trogler 1991).

Compared to 1990, national adipic acid production in 2022 has increased by 3 percent to approximately 780,000 metric tons (ACC 2023). Nitrous oxide emissions from adipic acid production were estimated to be 2.1 MMT CO_2 Eq. (8 kt N_2O) in 2022 and are summarized in Table 4-35 and Table 4-36. Over the period 1990 through 2022, facilities have reduced emissions by 84.5 percent due to the widespread installation of pollution control measures in the late 1990s. The main reason for the 68 percent decrease in N_2O emissions from adipic acid production between 2021 and 2022 is increased utilization of N_2O abatement equipment at one adipic acid production facility.

EPA reviewed GHGRP facility reported information on the date of abatement technology installation in order to better reflect trends and changes in emissions abatement within the industry across the time series. The facility using the facility-specific emission factor developed through annual performance testing has reported no installation and no utilization of N_2O abatement technology. The facility using direct measurement of N_2O emissions has reported the use of thermal reduction as an N_2O abatement technology; the first unit began operation in 1980, and the second unit began operation in 2023 (Ard 2024; Ascend 2023).

Significant changes in the amount of time that the N_2O abatement device at one facility was in operation has been the main cause of fluctuating emissions in recent years. These fluctuations are most evident for years where trends in emissions and adipic acid production were not directly proportional: (1) between 2016 and 2017, (2) between 2017 and 2018, (3) between 2019 and 2020, (4) between 2020 and 2021, and (5) between 2021 and 2022. As noted above, changes in control measures and abatement technologies at adipic acid production facilities, including maintenance of equipment, can result in annual emission fluctuations. Little additional information is available on drivers of trends, and the amount of adipic acid produced is not reported under EPA’s GHGRP.

Table 4-35: N_2O Emissions from Adipic Acid Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Adipic Acid Production	13.5	6.3	9.3	4.7	7.4	6.6	2.1

Table 4-36: N_2O Emissions from Adipic Acid Production (kt N_2O)

Year	1990	2005	2018	2019	2020	2021	2022
Adipic Acid Production	51	24	35	18	28	25	8

Methodology and Time-Series Consistency

Emissions of N_2O from adipic acid production are estimated using methods provided by the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. For 2010 through 2022, a Tier 3 method was used to estimate emissions. For 1990 through 2009, emissions are estimated using both Tier 2 and Tier 3 methods. Due to confidential business information (CBI), plant names are not provided in this section; therefore, the four adipic acid-producing facilities that have operated over the time series will be referred to as Plants 1 through 4. As noted above, one currently operating facility uses thermal reduction as an N_2O abatement technology.

2010 through 2022

All emission estimates for 2010 through 2022 were obtained through analysis of GHGRP data (EPA 2010 through 2023). Facility-level greenhouse gas emissions data were obtained from EPA's GHGRP for the years 2010 through 2022 (EPA 2010 through 2023) and aggregated to national N_2O emissions. Consistent with IPCC Tier 3 methods, all adipic acid production facilities are required to either calculate N_2O emissions using a facility-specific emission factor developed through annual performance testing under typical operating conditions or directly measure N_2O emissions using monitoring equipment.[36]

1990 through 2009

For years 1990 through 2009, which were prior to EPA's GHGRP reporting, for both Plants 1 and 2, emission estimates were obtained directly from the plant engineers and account for reductions due to control systems in place at these plants during the time series. These prior estimates are considered CBI and hence are not published (Desai 2010, 2011). These estimates were based on continuous process monitoring equipment installed at the two facilities.

For Plant 4, 1990 through 2009 N_2O emissions were estimated using the following Tier 2 equation from the *2006 IPCC Guidelines*:

Equation 4-5: *2006 IPCC Guidelines* Tier 2: N_2O Emissions From Adipic Acid Production (Equation 3.8)

$$E_{aa} = Q_{aa} \times EF_{aa} \times (1 - [DF \times UF])$$

where,

E_{aa} = N_2O emissions from adipic acid production, metric tons
Q_{aa} = Quantity of adipic acid produced, metric tons
EF_{aa} = Emission factor, metric ton N_2O/metric ton adipic acid produced
DF = N_2O destruction factor
UF = Abatement system utility factor

The adipic acid production is multiplied by an emission factor (i.e., N_2O emitted per unit of adipic acid produced), which has been estimated to be approximately 0.3 metric tons of N_2O per metric ton of product (IPCC 2006). The "N_2O destruction factor" in the equation represents the percentage of N_2O emissions that are destroyed by the installed abatement technology. The "abatement system utility factor" represents the percentage of time that the

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[36] Facilities must use standard methods, either EPA Method 320 or ASTM D6348-03 for annual performance testing, and must follow associated QA/QC procedures during these performance tests consistent with category-specific QC of direct emission measurements.

abatement equipment operates during the annual production period. Plant-specific production data for Plant 4 were obtained across the time series through personal communications (Desai 2010, 2011). The plant-specific production data were then used for calculating emissions as described above.

For Plant 3, 2005 through 2009 emissions were obtained directly from the plant (Desai 2010, 2011). For 1990 through 2004, emissions were estimated using plant-specific production data and the IPCC factors as described above for Plant 4. Plant-level adipic acid production for 1990 through 2003 was estimated by allocating national adipic acid production data to the plant level using the ratio of known plant capacity to total national capacity for all U.S. plants (ACC 2023; CMR 2001, 1998; CW 1999; C&EN 1992 through 1995). For 2004, actual plant production data were obtained and used for emission calculations (CW 2005).

Plant capacities for 1990 through 1994 were obtained from *Chemical & Engineering News*, “Facts and Figures” and “Production of Top 50 Chemicals” (C&EN 1992 through 1995). Plant capacities for 1995 and 1996 were kept the same as 1994 data. The 1997 plant capacities were taken from *Chemical Market Reporter*, “Chemical Profile: Adipic Acid” (CMR 1998). The 1998 plant capacities for all four plants and 1999 plant capacities for three of the plants were obtained from *Chemical Week*, Product Focus: Adipic Acid/Adiponitrile (CW 1999). Plant capacities for the year 2000 for three of the plants were updated using *Chemical Market Reporter*, “Chemical Profile: Adipic Acid” (CMR 2001). For 2001 through 2003, the plant capacities for three plants were held constant at year 2000 capacities. Plant capacity for 1999 to 2003 for the one remaining plant was kept the same as 1998.

National adipic acid production data (see Table 4-37) from 1990 through 2022 were obtained from the American Chemistry Council (ACC 2023).

Table 4-37: Adipic Acid Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Production (kt)	755	865	825	810	710	760	780

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. The methodology for adipic acid production spliced activity data from multiple sources: plant-specific emissions data and publicly available plant capacity data for 1990 through 2009 and GHGRP emission data starting in 2010. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the two data sets for years where there was overlap, with findings that the data sets were consistent and adjustments were not needed.

Uncertainty

Uncertainty associated with N_2O emission estimates includes the methods used by companies to monitor and estimate emissions. While some information has been obtained through outreach with facilities, limited information is available over the time series on these methods, abatement technology destruction and removal efficiency rates, and plant-specific production levels. EPA assigned an uncertainty range of ±5 percent and a normal probability density function for facility-reported N_2O emissions, and using this suggested uncertainty provided in section 3.4.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023).

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-38. Nitrous oxide emissions from adipic acid production for 2022 were estimated to be between 2.0 and 2.2 MMT CO_2 Eq. at the 95 percent confidence level. These values indicate a range of approximately 4 percent below to 4 percent above the 2022 emission estimate of 2.1 MMT CO_2 Eq.

Table 4-38: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from Adipic Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Adipic Acid Production	N_2O	2.1	2.0	2.2	-4%	+4%

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

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to adipic acid facilities can be found under Subpart E (Adipic Acid Production) of the GHGRP regulation (40 CFR Part 98).[37] The main QA/QC activities are related to annual performance testing, which must follow either EPA Method 320 or ASTM D6348-03. EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[38] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year comparisons of reported data.

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

EPA has no specific planned improvements related to adipic acid.

4.9 Caprolactam, Glyoxal and Glyoxylic Acid Production (CRT Source Category 2B4)

This reporting category (2B4) includes emissions from the production of caprolactam, glyoxal (ethanedial), and glyoxylic acid. Emissions from fuels consumed for energy purposes during the production of caprolactam, glyoxal,

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[37] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

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

and glyoxylic acid are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Caprolactam

Caprolactam ($C_6H_{11}NO$) is a colorless monomer produced for nylon-6 fibers and plastics. A substantial proportion of the fiber is used in carpet manufacturing. Most commercial processes used for the manufacture of caprolactam begin with benzene, but toluene can also be used. The production of caprolactam can give rise to emissions of nitrous oxide (N_2O).

During the production of caprolactam, emissions of N_2O can occur from the ammonia oxidation step, emissions of carbon dioxide (CO_2) from the ammonium carbonate step, emissions of sulfur dioxide (SO_2) from the ammonium bisulfite step, and emissions of non-methane volatile organic compounds (NMVOCs). Emissions of CO_2, SO_2 and NMVOCs from the conventional process are unlikely to be significant in well-managed plants. Modified caprolactam production processes are primarily concerned with elimination of the high volumes of ammonium sulfate that are produced as a byproduct of the conventional process (IPCC 2006).

In the most commonly used process where caprolactam is produced from benzene, benzene is hydrogenated to cyclohexane which is then oxidized to produce cyclohexanone ($C_6H_{10}O$). The classical route (Raschig process) and basic reaction equations for production of caprolactam from cyclohexanone are (IPCC 2006):

$$Oxidation\ of\ NH_3\ to\frac{NO}{NO_2}$$

$$\downarrow$$

$$NH_3\ reacted\ with\frac{CO_2}{H_2O}to\ yield\ ammonium\ carbonate\ (NH_4)_2CO_3$$

$$\downarrow$$

$$(NH_4)_2CO_3\ reacted\ with\frac{NO}{NO_2}(from\ NH_3\ oxidation)to\ yield\ ammonium\ nitrite\ (NH_4NO_2)$$

$$\downarrow$$

$$NH_3\ reacted\ with\frac{SO_2}{H_2O}to\ yield\ ammonium\ bisulphite\ (NH_4HSO_3)$$

$$\downarrow$$

$$NH_4NO_2\ and\ (NH_4HSO_3)reacted\ to\ yield\ hydroxylamine\ disulphonate\ (NOH(SO_3NH_4)_2)$$

$$\downarrow$$

$$(NOH(SO_3NH_4)_2)\ hydrolised\ to\ yield\ hydroxylamine\ sulphate\ ((NH_2OH)_2.H_2SO_4)\ and\ ammonium\ sulphate\ ((NH_4)_2SO_4)$$

$$\downarrow$$

$$Cylohexanone\ reaction:$$

$$C_6H_{10}O\ +\frac{1}{2}(NH_2OH)_2.H_2SO_4(+NH_3\ and\ H_2SO_4)\rightarrow C_6H_{10}NOH\ +(NH_4)_2SO_4\ +H_2O$$

$$\downarrow$$

$$Beckmann\ rearrangement:$$

$$C_6H_{10}NOH\ \ (+H_2SO_4\ and\ SO_2)\rightarrow C_6H_{11}NO.H_2SO_4\ (+4NH_3\ and\ H_2O)\rightarrow C_6H_{11}NO\ +2(NH4)_2SO_4$$

In 2004, three facilities produced caprolactam in the United States (ICIS 2004). Another facility, Evergreen Recycling, was in operation from 2000 to 2001 (ICIS 2004; Textile World 2000) and from 2007 through 2015 (Shaw

2015). Caprolactam production at Fibrant LLC (formerly DSM Chemicals) in Georgia ceased in 2018 (Cline 2019). As of 2022, two companies in the United States produced caprolactam at two facilities: AdvanSix (formerly Honeywell) in Virginia (AdvanSix 2023) and BASF in Texas (BASF 2023).

Nitrous oxide emissions from caprolactam production in the United States were estimated to be 1.3 MMT CO_2 Eq. (5 kt N_2O) in 2022 and are summarized in Table 4-39 and Table 4-40. National emissions from caprolactam production decreased by approximately 10.5 percent over the period of 1990 through 2022. Emissions in 2022 increased by approximately 9.8 percent from the 2021 levels. This annual increase returned caprolactam production to levels consistent with 2017 before the COVID-19 pandemic.

Table 4-39: N_2O Emissions from Caprolactam Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Caprolactam Production	1.5	1.9	1.3	1.2	1.1	1.2	1.3

Table 4-40: N_2O Emissions from Caprolactam Production (kt N_2O)

Year	1990	2005	2018	2019	2020	2021	2022
Caprolactam Production	6	7	5	5	4	5	5

Glyoxal

Glyoxal is mainly used as a crosslinking agent for vinyl acetate/acrylic resins, disinfectant, gelatin hardening agent, textile finishing agent (permanent-press cotton, rayon fabrics), and wet-resistance additive (paper coatings) (IPCC 2006). It is also used for enhanced oil-recovery. It is produced from oxidation of acetaldehyde with concentrated nitric acid, or from the catalytic oxidation of ethylene glycol, and N_2O is emitted in the process of oxidation of acetaldehyde.

Glyoxal (ethanedial) ($C_2H_2O_2$) is produced from oxidation of acetaldehyde (ethanal) (C_2H_4O) with concentrated nitric acid (HNO_3). Glyoxal can also be produced from catalytic oxidation of ethylene glycol (ethanediol) (CH_2OHCH_2OH).

Glyoxylic Acid

Glyoxylic acid is produced by nitric acid oxidation of glyoxal. Glyoxylic acid is used for the production of synthetic aromas, agrochemicals, and pharmaceutical intermediates (IPCC 2006).

Preliminary data suggests that glyoxal and glyoxylic acid may be produced in small quantities domestically but are largely imported to the United States. EPA does not currently estimate the emissions associated with the production of glyoxal and glyoxylic acid because activity data are not available. See Annex 5 for more information.

Methodology and Time-Series Consistency

Emissions of N_2O from the production of caprolactam are calculated using the Tier 1 methodology from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. The Tier 1 equation is as follows:

Equation 4-6: *2006 IPCC Guidelines* Tier 1: N_2O Emissions From Caprolactam Production (Equation 3.9)

$$E_{N_2O} = EF \times CP$$

where,

E_{N_2O} = Annual N_2O Emissions (kg)

EF = N_2O emission factor (default) (kg N_2O/metric ton caprolactam produced)

CP = Caprolactam production (metric tons)

During the caprolactam production process, N_2O is generated as a byproduct of the high temperature catalytic oxidation of ammonia (NH_3), which is the first reaction in the series of reactions to produce caprolactam. The amount of N_2O emissions can be estimated based on the chemical reaction shown above. Based on this formula, which is consistent with an IPCC Tier 1 approach, approximately 111.1 metric tons of caprolactam are required to generate one metric ton of N_2O, resulting in an emission factor of 9.0 kg N_2O per metric ton of caprolactam (IPCC 2006). When applying the Tier 1 method, the *2006 IPCC Guidelines* state that it is good practice to assume that there is no abatement of N_2O emissions and to use the highest default emission factor available in the guidelines. In addition, EPA did not find support for the use of secondary catalysts to reduce N_2O emissions, such as those employed at nitric acid plants.

The activity data for caprolactam production (see Table 4-41) from 1990 to 2022 were obtained from the American Chemistry Council's *Guide to the Business of Chemistry* (ACC 2023). EPA will continue to analyze and assess alternative sources of production data as a quality control measure.

Table 4-41: Caprolactam Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Production (kt)	626	795	530	515	480	510	560

Carbon dioxide and methane (CH_4) emissions may also occur from the production of caprolactam, but currently the IPCC does not have methodologies for calculating these emissions associated with caprolactam production.

Methodological approaches, consistent with the *2006 IPCC Guidelines*, have been applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

Estimation of emissions of N_2O from caprolactam production can be treated as analogous to estimation of emissions of N_2O from nitric acid production. Both production processes involve an initial step of NH_3 oxidation, which is the source of N_2O formation and emissions (IPCC 2006). Therefore, uncertainties for the default emission factor values in the *2006 IPCC Guidelines* are an estimate based on default values for nitric acid plants. In general, default emission factors for gaseous substances have higher uncertainties because mass values for gaseous substances are influenced by temperature and pressure variations and gases are more easily lost through process leaks. The default values for caprolactam production have a relatively high level of uncertainty due to the limited information available (IPCC 2006). EPA assigned uncertainty bounds of ±5 percent for caprolactam production, based on expert judgment. EPA assigned an uncertainty range of ±40 percent for the N_2O emission factor, and using this suggested uncertainty provided in Section 3.5.2.1 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a normal probability density function was assigned for activity data, and a triangular probably density function was assigned for the emission factor.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-42. Nitrous oxide emissions from caprolactam, glyoxal and glyoxylic acid production for 2022 were estimated to be between 0.9 and 1.8 MMT CO_2 Eq. at the 95 percent confidence level. These values indicate a range of approximately 31 percent below to 31 percent above the 2022 emission estimate of 1.3 MMT CO_2 Eq.

Table 4-42: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from Caprolactam, Glyoxal and Glyoxylic Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Caprolactam Production	N_2O	1.3	0.9	1.8	-31%	+31%

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

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

Recalculations were performed for 2020 and 2021 to reflect updated caprolactam production data from the American Chemistry Council's *Guide to the Business of Chemistry* (ACC 2023). Compared to the previous *Inventory*, annual N_2O emissions decreased by 2 percent in 2020 and 2021, with a decrease of 0.02 MMT CO_2 Eq. in 2020 and 2021.

Planned Improvements

Pending resources, EPA will research other available datasets for caprolactam production and industry trends, including facility-level data. EPA continues to research available activity data and emissions associated with the production of glyoxal and glyoxylic acid. Preliminary data suggests that glyoxal and glyoxylic acid may be produced in small quantities domestically but are largely imported to the United States. See Annex 5 for more information. This planned improvement is subject to data availability and will be implemented in the medium- to long-term.

4.10 Carbide Production and Consumption (CRT Source Category 2B5 & 2B10)

Carbon dioxide (CO_2) and methane (CH_4) are emitted from the production of silicon carbide (SiC), a material used for industrial abrasive, metallurgical, and other non-abrasive applications in the United States, and CO_2 is emitted from the consumption of SiC. Per the IPCC methodological guidance, emissions from fuels consumed for energy purposes during the production of silicon carbide are accounted for in the industrial end-use sector reported under the Energy chapter. Additionally, some metallurgical and non-abrasive applications of SiC are emissive at high temperatures due to the SiC oxidation temperature (Biscay 2021). While emissions should be accounted for where they occur based on *2006 IPCC Guidelines*, emissions from SiC consumption are accounted for here until additional data on SiC consumption by end-use are available. The reporting category (2B5) includes emissions from the production of SiC, and the reporting category (2B10) includes emissions from the consumption of SiC.

To produce SiC, silica sand or quartz (SiO_2) is reacted with carbon (C) in the form of petroleum coke. A portion (about 35 percent) of the carbon contained in the petroleum coke is retained in the SiC. The remaining carbon is emitted as CO_2, CH_4, or carbon monoxide (CO). The overall reaction is shown below, but in practice, it does not proceed according to stoichiometry:

$$SiO_2 + 3C \rightarrow SiC + 2CO\ (+\ O_2 \rightarrow 2CO_2)$$

Carbon dioxide and CH_4 are also emitted during the production of calcium carbide, a chemical used to produce acetylene. Carbon dioxide is implicitly accounted for in the storage factor calculation for the non-energy use of petroleum coke in the Energy chapter.

Markets for manufactured abrasives, including SiC, are heavily influenced by activity in the U.S. manufacturing sector, especially in the aerospace, automotive, furniture, housing, and steel manufacturing sectors. Specific applications of abrasive-grade SiC in 2018 included antislip abrasives, blasting abrasives, bonded abrasives, coated abrasives, polishing and buffing compounds, tumbling media, and wire-sawing abrasives (USGS 2021). Approximately 50 percent of SiC is used in metallurgical applications, which include primarily iron and steel production, and other non-abrasive applications, which include use in advanced or technical ceramics and refractories (USGS 2023a; Washington Mills 2023).

As a result of the economic downturn in 2008 and 2009, demand for SiC decreased in those years. Low-cost imports, particularly from China, combined with high relative operating costs for domestic producers, continue to put downward pressure on the production of SiC in the United States. Consumption of SiC in the United States has recovered somewhat from its low in 2009 to 2020; 2021 consumption data was withheld to avoid disclosing company proprietary data (USGS 1991b through 2021), and 2022 USGS data has not yet been released.

Silicon carbide was manufactured by two facilities in the United States, one of which produced primarily non-abrasive SiC (USGS 2021). USGS production values for the United States consists of SiC used for abrasives and for metallurgical and other non-abrasive applications (USGS 2021). During the COVID-19 pandemic in 2020, the U.S. Department of Homeland Security considered abrasives manufacturing part of the critical manufacturing sector, and as a result, pandemic "stay-at-home" orders issued in March 2020 did not affect the abrasives manufacturing industry. These plants remained at full operation (USGS 2021a). In 2022, imports and exports continued to recover from the negative effects of the COVID-19 pandemic (USGS 2023b). Consumption of SiC increased by approximately 27 percent from 2021 to 2022, rising above pre-pandemic levels (U.S. Census Bureau 2005 through 2022).

Carbon dioxide emissions from SiC production and consumption in 2022 were 0.2 MMT CO_2 Eq. (210 kt CO_2), which are about 14 percent lower than emissions in 1990 (see Table 4-43 and Table 4-44). Approximately 50 percent of these emissions resulted from SiC production, while the remainder resulted from SiC consumption. Methane emissions from SiC production in 2022 were 0.01 MMT CO_2 Eq. (0.5 kt CH_4) (see Table 4-43 and Table 4-44). These tables indicate minor changes in emissions in recent years.

Table 4-43: CO_2 and CH_4 Emissions from Silicon Carbide Production and Consumption (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
SiC Production							
CO_2	0.2	0.1	0.1	0.1	0.1	0.1	0.1
CH_4	+	+	+	+	+	+	+
SiC Consumption							
CO_2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 4-44: CO_2 and CH_4 Emissions from Silicon Carbide Production and Consumption (kt)

Year	1990	2005	2018	2019	2020	2021	2022
SiC Production							
CO_2	170	92	92	92	92	92	105
CH_4	1	+	+	+	+	+	+
SiC Consumption							
CO_2	73	121	93	84	62	80	105

+ Does not exceed 0.5 kt.

Methodology and Time-Series Consistency

Emissions of CO_2 and CH_4 from the production of SiC are calculated using the Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. Emissions of CO_2 from the consumption of SiC are a country-specific source calculated using a country-specific methodology based on available data. The *2006 IPCC Guidelines* do not provide guidance for estimating emissions from use of SiC or SiC consumption, but the country-specific methodology used is based on the stoichiometry of SiC consumption and is compatible with the *2006 IPCC Guidelines* and consistent with a Tier 1 approach.

Annual estimates of SiC production were multiplied by the default emission factors, as shown below:

Equation 4-78: *2006 IPCC Guidelines* Tier 1: Emissions from Carbide Production (Equation 3.11)

$$E_{sc,CO2} = EF_{sc,CO2} \times Q_{sc}$$

$$E_{sc,CH4} = EF_{sc,CH4} \times Q_{sc} \times \left(\frac{1\ metric\ ton}{1000\ kg}\right)$$

where,

$E_{sc,CO2}$ = CO_2 emissions from production of SiC, metric tons

$EF_{sc,CO2}$ = Emission factor for production of SiC, metric ton CO_2/metric ton SiC

Q_{sc} = Quantity of SiC produced, metric tons

$E_{sc,CH4}$ = CH_4 emissions from production of SiC, metric tons

$EF_{sc,CH4}$ = Emission factor for production of SiC, kilogram CH_4/metric ton SiC

Emission factors were taken from the *2006 IPCC Guidelines*:

- 2.62 metric tons CO_2/metric ton SiC
- 11.6 kg CH_4/metric ton SiC

Production data includes silicon carbide manufactured for abrasive applications as well as for metallurgical and other non-abrasive applications (USGS 2021).

Silicon carbide industrial abrasives production data for 1990 through 2022 were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook: Manufactured Abrasives* (USGS 1991a through 2021; USGS 2023a). Silicon carbide production data published by USGS have been rounded to the nearest 5,000 metric tons to avoid disclosing company proprietary data. For the period 1990 through 2001, reported USGS production data include production from two facilities located in Canada that ceased operations in 1995 and 2001. Using SiC production data from Canada (ECCC 2022), U.S. SiC production for 1990 through 2001 was adjusted to reflect only U.S. production.

Emissions from SiC consumption are calculated by multiplying the annual SiC consumption for metallurgical and other non-abrasive uses by the carbon content of SiC (about 30.0 percent), which is based on the molecular weight of SiC, and converted to CO_2. This conversion calculation equates to 1.10 and is consistent with the IPCC default emission factor to calculate CO_2 emissions from the consumption of acetylene, a calcium carbide product, and demonstrates a methodology consistent with the *2006 IPCC Guidelines*. The amount of SiC used by other non-abrasive applications is determined by multiplying the annual SiC consumption by 50 percent (the percentage that the USGS allocates as usage by metallurgical and other non-abrasive applications) and then subtracting the amount of SiC used for metallurgical applications (USGS 1991a through 2021; USGS 2023a).

Emissions from SiC consumption are estimated for the entire time series using USGS consumption data (USGS 1991b through 2021) and data from the U.S. International Trade Commission (USITC) database on net imports and exports of SiC (U.S. Census Bureau 2005 through 2022) (Table 4-45). Total annual SiC consumption (utilization) was estimated by subtracting annual exports of SiC from the total of annual national SiC production and annual imports. Data on the annual consumption of SiC for metallurgical uses were obtained from USGS *Minerals Yearbook: Silicon* (USGS 1991b-2021; USGS 2023c). USGS withheld consumption data for metallurgical uses from publication for 2017, 2018, and 2021, and 2022 due to concerns of disclosing company-specific sensitive information, SiC consumption for 2017 and 2018 were estimated using 2016 values, and SiC consumption for 2021 and 2022 were estimated using the 2020 value (USGS 2023c). Additionally, as the USGS has not yet released the 2022 data, SiC consumption for 2022 was estimated using the 2020 value.

The petroleum coke portion of the total CO_2 process emissions from silicon carbide production is adjusted for within the Energy chapter, as these fuels were consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for non-energy use of fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (Section 3.1) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Table 4-45: Production and Consumption of Silicon Carbide (Metric Tons)

Year	1990	2005	2018	2019	2020	2021	2022
SiC Production	65,000	35,000	35,000	35,000	35,000	35,000	40,000
SiC Consumption	132,465	220,149	168,526	152,412	113,756	146,312	191,133

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

Silicon carbide production data published by the USGS is rounded to the nearest 5,000 tons and has been consistently reported at 35,000 tons since 2003 to avoid disclosure of company proprietary data. This translates to an uncertainty range of ±7 percent and a normal probability density function for SiC production (USGS 2021). There is uncertainty associated with the emission factors used because they are based on stoichiometry as opposed to monitoring of actual SiC production plants. An alternative is to calculate emissions based on the quantity of petroleum coke used during the production process rather than on the amount of silicon carbide produced; however, these data were not available. For CH_4, there is also uncertainty associated with the hydrogen-containing volatile compounds in the petroleum coke (IPCC 2006). EPA assigned an uncertainty of ±10 percent for the Tier 1 CO_2 and CH_4 emission factors for the SiC production processes, and using this suggested uncertainty provided in Section 3.6.3.1 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a triangular probability density function was assigned for emission factors. There is also uncertainty associated with the use or destruction of CH_4 generated from the process, in addition to uncertainty associated with levels of production, net imports, consumption levels, and the percent of total consumption that is attributed to metallurgical and other non-abrasive uses. EPA assigned an uncertainty range of ±5 percent for the primary data inputs for consumption (i.e., crude imports, ground and refined imports, crude exports, ground and refined exports, utilization [metallurgical applications]) to calculate overall uncertainty from SiC production, and using this suggested uncertainty provided in Section 3.6.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-46. Silicon carbide production and consumption CO_2 emissions from 2022 were estimated to be between 10 percent below and 10 percent above the emission estimate of 0.2 MMT CO_2 Eq. at the 95 percent confidence level. Silicon carbide production CH_4 emissions were estimated to be between 10 percent below and 11 percent above the emission estimate of 0.01 MMT CO_2 Eq. at the 95 percent confidence level.

Table 4-46: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Silicon Carbide Production and Consumption (MMT CO_2 Eq. and Percent)

Source	**Gas**	**2022 Emission Estimate (MMT CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)**		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Silicon Carbide Production and Consumption	CO_2	0.2	0.2	0.2	-10%	+10%
Silicon Carbide Production	CH_4	+	+	+	-10%	+11%

+ Does not exceed 0.05 MMT CO_2 Eq.

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

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

EPA is initiating research for data on SiC consumption by end-use for consideration in updating emissions estimates from SiC consumption and to account for emissions where they occur. This planned improvement is subject to data availability and will be implemented in the medium- to long-term given significance of emissions.

EPA has not integrated aggregated facility-level GHGRP information to inform estimates of CO_2 and CH_4 from SiC production and consumption. The aggregated information (e.g., activity data and emissions) associated with silicon carbide did not meet criteria to shield underlying confidential business information (CBI) from public disclosure. EPA plans to examine the use of GHGRP silicon carbide emissions data for possible use in emission estimates consistent with both Volume 1, Chapter 6 of the *2006 IPCC Guidelines* and the latest IPCC guidance on the use of facility-level data in national inventories. This planned improvement is ongoing and has not been incorporated into this *Inventory* report. This is a long-term planned improvement.

4.11 Titanium Dioxide Production (CRT Source Category 2B6)

Titanium dioxide (TiO_2) is manufactured using one of two processes: the chloride process and the sulfate process. The chloride process uses petroleum coke and chlorine as raw materials and emits process-related carbon dioxide

(CO_2). The sulfate process does not use petroleum coke or other forms of carbon as a raw material and does not emit CO_2. The reporting category (2B6) includes emissions from production of TiO_2. In accordance with the IPCC methodological guidance, emissions from fuels consumed for energy purposes during the production of titanium dioxide are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter. The chloride process is based on the following chemical reactions and does emit CO_2:

$$2FeTiO_3 + 7Cl_2 + 3C \rightarrow 2TiCl_4 + 2FeCl_3 + 3CO_2$$

$$2TiCl_4 + 2O_2 \rightarrow 2TiO_2 + 4Cl_2$$

The carbon in the first chemical reaction is provided by petroleum coke, which is oxidized in the presence of the chlorine and $FeTiO_3$ (rutile ore) to form CO_2. Since 2004, all TiO_2 produced in the United States has been produced using the chloride process, and a special grade of "calcined" petroleum coke is manufactured specifically for this purpose.

The principal use of TiO_2 is as a white pigment in paint, lacquers, and varnishes. It is also used as a pigment in the manufacture of plastics, paper, and other products. In 2022, U.S. TiO_2 production totaled 1,100,000 metric tons (USGS 2023b). Five plants produced TiO_2 in the United States in 2022.

Emissions of CO_2 from titanium dioxide production in 2022 were estimated to be 1.5 MMT CO_2 Eq. (1,474 kt CO_2), which represents an increase of 23 percent since 1990 (see Table 4-47 and Table 4-48). Compared to 2021, emissions from titanium dioxide production remained the same because production was consistent from 2021 to 2022. Annual production dipped in 2019 and 2020 and increased in 2021 and 2022.

Table 4-47: CO_2 Emissions from Titanium Dioxide (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Titanium Dioxide	1.2	1.8	1.5	1.3	1.3	1.5	1.5

Table 4-48: CO_2 Emissions from Titanium Dioxide (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Titanium Dioxide	1,195	1,755	1,541	1,340	1,340	1,474	1,474

Methodology and Time-Series Consistency

Emissions of CO_2 from TiO_2 production are calculated using a Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. Annual national TiO_2 production is multiplied by chloride process-specific emission factors provided by IPCC (IPCC 2006). The Tier 1 equation is as follows:

Equation 4-9: *2006 IPCC Guidelines* Tier 1: CO_2 Emissions from Titanium Production (Equation 3.12)

$$E_{td} = EF_{td} \times Q_{td}$$

where,

E_{td} = CO_2 emissions from TiO_2 production, metric tons

EF_{td} = Emission factor (chloride process), metric ton CO_2/metric ton TiO_2

Q_{td} = Quantity of TiO_2 produced, metric tons

The petroleum coke portion of the total CO_2 process emissions from TiO_2 production is adjusted for within the Energy chapter as these fuels were consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (Section 3.1 Fossil Fuel Combustion) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Data were obtained for the total amount of TiO_2 produced each year. For years prior to 2004, it was assumed that TiO_2 was produced using the chloride process and the sulfate process in the same ratio as the ratio of the total U.S. production capacity for each process. As of 2004, the last remaining sulfate process plant in the United States closed; therefore, 100 percent of production since 2004 used the chloride process (USGS 2005). An emission factor of 1.34 metric tons CO_2/metric ton TiO_2 was applied to the estimated chloride-process production (IPCC 2006). It was assumed that all TiO_2 produced using the chloride process was produced using petroleum coke, although some TiO_2 may have been produced with graphite or other carbon inputs.

The emission factor for the TiO_2 chloride process was taken from the *2006 IPCC Guidelines*. Titanium dioxide production data and the percentage of total TiO_2 production capacity that used the chloride process for 1990 through 2018 (see Table 4-49) were obtained through the U.S. Geological Survey (USGS) *Minerals Yearbook: Titanium* (USGS 1991 through 2022). Production data for 2019 and 2020 were obtained from the USGS Minerals Yearbook: Titanium, advanced data release of the 2020 tables (USGS 2023a). Production data for 2020 and 2021 were obtained from the *Minerals Commodity Summaries: Titanium and Titanium Dioxide* (USGS 2023b).[39] Data on the percentage of total TiO_2 production capacity that used the chloride process were not available for 1990 through 1993, so data from the 1994 USGS *Minerals Yearbook* were used for these years. Because a sulfate process plant closed in September 2001, the chloride process percentage for 2001 was estimated (Gambogi 2002). By 2002, only one sulfate process plant remained online in the United States, and this plant closed in 2004 (USGS 2005).

Table 4-49: Titanium Dioxide Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Production	979	1,310	1,150	1,000	1,000	1,100	1,100

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

Each year, the USGS collects titanium industry data for titanium mineral and pigment production operations. If TiO_2 pigment plants do not respond, production from the operations is estimated based on prior year production levels and industry trends. Variability in response rates fluctuates from 67 to 100 percent of TiO_2 pigment plants over the time series. EPA currently uses an uncertainty range of ±5 percent and a normal probability density function for the primary data inputs (i.e., TiO_2 production and chloride process capacity values) to calculate overall uncertainty from TiO_2 production, and using this suggested uncertainty provided in Section 3.7.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Additionally, the EPA uses an uncertainty range of ±15 percent and a triangular probability density function for the CO_2 chloride process carbon consumption rate, and using this uncertainty provided in Section 3.7.2.2 of the *2006 IPCC Guidelines* is representative of operations in the United States. based on expert judgment (RTI 2023).

Although some TiO_2 may be produced using graphite or other carbon inputs, information and data regarding these practices were not available. Titanium dioxide produced using graphite inputs, for example, may generate differing amounts of CO_2 per unit of TiO_2 produced as compared to that generated using petroleum coke in production. While the most accurate method to estimate emissions would be to base calculations on the amount of reducing

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[39] EPA has not integrated aggregated facility-level GHGRP information for titanium dioxide production facilities (40 CFR Part 98 Subpart EE). The relevant aggregated information (activity data, emission factor) from these facilities did not meet criteria to shield underlying CBI from public disclosure.

agent used in each process rather than on the amount of TiO_2 produced, sufficient data were not available to do so.

As of 2004, the last remaining sulfate-process plant in the United States closed. Since annual TiO_2 production was not reported by USGS by the type of production process used (chloride or sulfate) prior to 2004 and only the percentage of total production capacity by process was reported, the percent of total TiO_2 production capacity that was attributed to the chloride process was multiplied by total TiO_2 production to estimate the amount of TiO_2 produced using the chloride process. Finally, the emission factor was applied uniformly to all chloride-process production, and no data were available to account for differences in production efficiency among chloride-process plants. In calculating the amount of petroleum coke consumed in chloride-process TiO_2 production, literature data were used for petroleum coke composition. Certain grades of petroleum coke are manufactured specifically for use in the TiO_2 chloride process; however, this composition information was not available. EPA assigned an uncertainty range of ±15 percent and a triangular probability density function for the Tier 1 CO_2 emission factor for the titanium dioxide (chloride route) production process, and using this uncertainty provided in Table 3.9 of the *2006 IPCC Guidelines* is representative of operations in the United States based on expert judgment (RTI 2023).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-49. Titanium dioxide consumption CO_2 emissions from 2022 were estimated to be between 1.3 and 1.7 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below and 13 percent above the emission estimate of 1.5 MMT CO_2 Eq.

Table 4-50: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Titanium Dioxide Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Titanium Dioxide Production	CO_2	1.5	1.3	1.7	-12%	+13%

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

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

Updated USGS data on TiO_2 production was available for 2019 and 2020, resulting in updated emissions estimates for those years. Compared to the previous *Inventory*, emissions for 2019 decreased by 9 percent (134 kt CO_2), and emissions for 2020 increased by 12 percent (147 kt CO_2).

Planned Improvements

EPA plans to examine the use of GHGRP titanium dioxide emissions and other data for possible use in emission estimates consistent with both Volume 1, Chapter 6 of the *2006 IPCC Guidelines* and the latest IPCC guidance on the use of facility-level data in national inventories.[40] This planned improvement is ongoing and has not been

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

incorporated into this *Inventory* report. This is a long-term planned improvement given the significance of these emissions.

4.12 Soda Ash Production (CRT Source Category 2B7)

Carbon dioxide (CO_2) is generated as a byproduct of calcining trona ore to produce soda ash (sodium carbonate, Na_2CO_3) and is eventually emitted into the atmosphere. In addition, CO_2 may also be released when soda ash is consumed. This reporting category (2B7) includes emissions from the production of soda ash by any of four processes, of which calcining trona ore is the only emissive process used in the United States. Emissions from soda ash consumption associated with glass production are reported under Section 4.3, glass production. Emissions from soda ash consumption not associated with glass production are reported under Section 4.4, other process uses of carbonates. Emissions from fuels consumed for energy purposes during the production and consumption of soda ash are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Calcining involves placing crushed trona ore into a kiln to convert sodium bicarbonate into crude sodium carbonate that will later be filtered into pure soda ash. The emission of CO_2 during trona-based production is based on the following reaction:

$$2Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O(Trona) \rightarrow 3Na_2CO_3(Soda\ Ash) + 5H_2O + CO_2$$

Soda ash is a white crystalline solid that is readily soluble in water and strongly alkaline. Commercial soda ash is used as a raw material in a variety of industrial processes and in many familiar consumer products such as glass, soap and detergents, paper, textiles, and food. The largest use of soda ash is for glass manufacturing. Emissions from soda ash used in glass production are reported under Section 4.3. In addition, soda ash is used primarily to manufacture many sodium-based inorganic chemicals, including sodium bicarbonate, sodium chromates, sodium phosphates, and sodium silicates (USGS 2018b). Internationally, two types of soda ash are produced: natural and synthetic. The United States produces only natural soda ash and is second only to China in total soda ash production. Trona is the principal ore from which natural soda ash is made.

The United States represents about one-fifth of total world soda ash output (USGS 2023a). Only two states produce natural soda ash: Wyoming and California. Of these two states, net emissions of CO_2 from soda ash production were only calculated for Wyoming where trona ore is used.[41] Soda ash end uses in 2022 (excluding glass production) consisted of chemical production, 54 percent; other uses, 17 percent; wholesale distributors (e.g., for use in agriculture, water treatment, and grocery wholesale), 10 percent; soap and detergent manufacturing, 9 percent; flue gas desulfurization, 7 percent; water treatment, 2 percent; and pulp and paper production, 1 percent (USGS 2023b).[42]

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[41] In California, soda ash is manufactured using sodium carbonate-bearing brines instead of trona ore. To extract the sodium carbonate, the complex brines are first treated with CO_2 in carbonation towers to convert the sodium carbonate into sodium bicarbonate, which then precipitates from the brine solution. The precipitated sodium bicarbonate is then calcined back into sodium carbonate. Although CO_2 is generated as a byproduct, the CO_2 is recovered and recycled for use in the carbonation stage and is not emitted. A facility in a third state, Colorado, produced soda ash until the plant was idled in 2004. The lone producer of sodium bicarbonate no longer mines trona ore in the state. For a brief time, sodium bicarbonate was produced using soda ash feedstocks mined in Wyoming and shipped to Colorado. Prior to 2004, because the trona ore was mined in Wyoming, the production numbers given by the USGS included the feedstocks mined in Wyoming and shipped to Colorado. In this way, the sodium bicarbonate production that took place in Colorado was accounted for in the Wyoming numbers.

[42] Percentages may not add up to 100 percent due to independent rounding.

U.S. natural soda ash is competitive in world markets because it is generally considered a better-quality raw material than synthetically produced soda ash, and most of the world's soda ash is synthetic. Although the United States continues to be a major supplier of soda ash, China surpassed the United States in soda ash production in 2003, becoming the world's leading producer.

In 2022, CO_2 emissions from the production of soda ash from trona ore were 1.7 MMT CO_2 Eq. (1,704 kt CO_2) (see Table 4-51 and Table 4-52). Total emissions from soda ash production in 2022 decreased by approximately 1 percent compared to emissions in 2021, as soda ash production returned to 2018 levels observed before the COVID-19 pandemic. Emissions have increased by approximately 19 percent from 1990 levels.

Trends in emissions have remained relatively constant over the time series with some fluctuations since 1990. In general, these fluctuations were related to the behavior of the export market and the U.S. economy. The U.S. soda ash industry saw a decline in domestic and export sales caused by adverse global economic conditions in 2009, followed by a steady increase in production through 2019 before a significant decrease in 2020 due to the COVID-19 pandemic.

Table 4-51: CO_2 Emissions from Soda Ash Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Soda Ash Production	1.4	1.7	1.7	1.8	1.5	1.7	1.7

Table 4-52: CO_2 Emissions from Soda Ash Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Soda Ash Production	1,431	1,655	1,714	1,792	1,461	1,714	1,704

Methodology and Time-Series Consistency

Carbon dioxide emissions from soda ash production are calculated using a Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. During the soda ash production process, trona ore is calcined in a rotary kiln and chemically transformed into a crude soda ash that requires further processing. Carbon dioxide and water are generated as byproducts of the calcination process. Carbon dioxide emissions from the calcination of trona ore can be estimated based on the chemical reaction shown above. Based on this formula and the IPCC default emission factor of 0.0974 metric tons CO_2 per metric ton of trona ore, both of which are consistent with an IPCC Tier 1 approach, one metric ton of CO_2 is emitted when approximately 10.27 metric tons of trona ore are processed (IPCC 2006).

Data is not currently available for the quantity of trona used in soda ash production. Because trona ore is used primarily for soda ash production, EPA assumes that all trona ore production was used in soda ash production. The activity data for trona ore production (see Table 4-53) for 1990 through 2022 were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook for Soda Ash* (1994 through 2015b) and USGS *Mineral Industry Surveys for Soda Ash* (USGS 2016 through 2017, 2018a, 2019, 2020, 2021, 2022b, 2023b). Soda ash production[43] data were collected by the USGS from voluntary surveys of the U.S. soda ash industry. EPA will continue to analyze and assess opportunities to use facility-level data from EPA's GHGRP to improve the emission estimates for the soda ash production source category consistent with IPCC[44] and UNFCCC guidelines.

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[43] EPA has assessed the feasibility of using emissions information (including activity data) from EPA's GHGRP program. At this time, the aggregated information associated with production of soda ash did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

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

Table 4-53: Trona Ore Used in Soda Ash Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Trona Ore Use[a]	14,700	17,000	17,600	18,400	15,000	17,600	17,500

[a] Trona ore use is assumed to be equal to trona ore production.

Methodological approaches were applied to the entire time series to ensure consistency in emissions estimates from 1990 through 2022.

Uncertainty

Emission estimates from soda ash production have relatively low associated uncertainty levels because reliable and accurate data sources are available for the emission factor and activity data for trona-based soda ash production. One source of uncertainty is the purity of the trona ore used for manufacturing soda ash. The emission factor used for this estimate assumes the ore is 100 percent pure and likely overestimates the emissions from soda ash manufacture. The average water-soluble sodium carbonate-bicarbonate content for ore mined in Wyoming ranges from 85.5 to 93.8 percent (USGS 1995c).

EPA is aware of one facility producing soda ash from a liquid alkaline feedstock process, based on EPA's GHGRP. Soda ash production data was collected by the USGS from voluntary surveys. A survey request was sent to each of the five soda ash producers, all of which responded, representing 100 percent of the total production data (USGS 2023b). EPA assigned an uncertainty range of ±5 percent for trona production, and using the suggested uncertainty provided in Section 3.8.2.2 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). EPA assigned an uncertainty range of -15 percent to 0 percent range for the trona emission factor, based on expert judgment on the purity of mined trona (USGS 1995c). Per this expert judgment, a normal probability density function was assigned for activity data, and a triangular probability density function was assigned for the emission factor.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-54. Soda ash production CO_2 emissions for 2022 were estimated to be between 1.5 and 1.7 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 9 percent below and 8 percent above the emission estimate of 1.7 MMT CO_2 Eq.

Table 4-54: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Soda Ash Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Soda Ash Production	CO_2	1.7	1.5	1.7	-9%	+8%

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

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

EPA is assessing planned improvements for future reports, but at this time has no specific planned improvements for estimating CO_2 emissions from soda ash production.

4.13 Petrochemical Production (CRT Source Category 2B8)

The production of some petrochemicals results in carbon dioxide (CO_2) and methane (CH_4) emissions. Petrochemicals are chemicals isolated or derived from petroleum or natural gas. This reporting category (2B8) includes CO_2 emissions from the production of acrylonitrile, carbon black, ethylene, ethylene dichloride, ethylene oxide, and methanol, and CH_4 emissions from the production of acrylonitrile. The petrochemical industry uses primary fossil fuels (i.e., natural gas, coal, petroleum, etc.) for non-fuel purposes in the production of carbon black and other petrochemicals. Per the IPCC methodological guidance, emissions from fuels and feedstocks transferred out of the system for use in energy purposes (e.g., indirect or direct process heat or steam production) are currently accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Worldwide, more than 90 percent of acrylonitrile (vinyl cyanide, C_3H_3N) is made by way of direct ammoxidation of propylene with ammonia (NH_3) and oxygen over a catalyst. This process is referred to as the SOHIO process, named after the Standard Oil Company of Ohio (SOHIO) (IPCC 2006). The primary use of acrylonitrile is as the raw material for the manufacture of acrylic and modacrylic fibers. Other major uses include the production of plastics (acrylonitrile-butadiene-styrene [ABS] and styrene-acrylonitrile [SAN]), nitrile rubbers, nitrile barrier resins, adiponitrile, and acrylamide. All U.S. acrylonitrile facilities use the SOHIO process (AN 2014). The SOHIO process involves a fluidized bed reaction of chemical-grade propylene, ammonia, and oxygen over a catalyst. The process produces acrylonitrile as its primary product, and the process yield depends on the type of catalyst used and the process configuration. The ammoxidation process produces byproduct CO_2, carbon monoxide (CO), and water from the direct oxidation of the propylene feedstock and produces other hydrocarbons from side reactions.

Carbon black is a black powder generated by the incomplete combustion of an aromatic petroleum- or coal-based feedstock at a high temperature. Most carbon black produced in the United States is added to rubber to impart strength and abrasion resistance, and the tire industry is by far the largest consumer. The other major use of carbon black is as a pigment. The predominant process used in the United States to produce carbon black is the furnace black (or oil furnace) process. In the furnace black process, carbon black oil (a heavy aromatic liquid) is continuously injected into the combustion zone of a natural gas-fired furnace. Furnace heat is provided by the natural gas and a portion of the carbon black feedstock; the remaining portion of the carbon black feedstock is pyrolyzed to carbon black. The resultant CO_2 and uncombusted CH_4 are released from thermal incinerators used as control devices, process dryers, and equipment leaks. Three facilities in the United States use other types of carbon black processes. Specifically, one facility produces carbon black by the thermal cracking of acetylene-containing feedstocks (i.e., acetylene black process), a second facility produces carbon black by the thermal cracking of other hydrocarbons (i.e., thermal black process), and a third facility produces carbon black by the open burning of carbon black feedstock (i.e., lamp black process) (EPA 2000).

Ethylene (C_2H_4) is consumed in the production processes of the plastics industry including polymers such as high, low, and linear low density polyethylene (HDPE, LDPE, LLDPE); polyvinyl chloride (PVC); ethylene dichloride; ethylene oxide; and ethylbenzene. Virtually all ethylene is produced from steam cracking of ethane, propane, butane, naphtha, gas oil, and other feedstocks. The representative chemical equation for steam cracking of ethane to ethylene is shown below:

$$C_2H_6 \rightarrow C_2H_4 + H_2$$

Small amounts of CH_4 are also generated from the steam cracking process. In addition, CO_2 and CH_4 emissions result from combustion units.

Ethylene dichloride ($C_2H_4Cl_2$) is used to produce vinyl chloride monomer, which is the precursor to polyvinyl chloride (PVC). Ethylene dichloride was also used as a fuel additive until 1996 when leaded gasoline was phased out. Ethylene dichloride is produced from ethylene by either direct chlorination, oxychlorination, or a combination of the two processes (i.e., the "balanced process"); most U.S. facilities use the balanced process. The direct chlorination and oxychlorination reactions are shown below:

$$C_2H_4 + Cl_2 \rightarrow C_2H_4Cl_2 \text{ (direct chlorination)}$$

$$C_2H_4 + \tfrac{1}{2}O_2 + 2HCl \rightarrow C_2H_4Cl_2 + 2H_2O \text{ (oxychlorination)}$$

$$C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O \text{ (direct oxidation of ethylene during oxychlorination)}$$

In addition to the byproduct CO_2 produced from the direct oxidation of the ethylene feedstock, CO_2 and CH_4 emissions are also generated from combustion units.

Ethylene oxide (C_2H_4O) is used in the manufacture of glycols, glycol ethers, alcohols, and amines. Approximately 70 percent of ethylene oxide produced worldwide is used in the manufacture of glycols, including monoethylene glycol. Ethylene oxide is produced by reacting ethylene with oxygen over a catalyst. The oxygen may be supplied to the process through either an air (air process) or a pure oxygen stream (oxygen process). The byproduct CO_2 from the direct oxidation of the ethylene feedstock is removed from the process vent stream using a recycled carbonate solution, and the recovered CO_2 may be vented to the atmosphere or recovered for further utilization in other sectors, such as food production (IPCC 2006). The combined ethylene oxide reaction and byproduct CO_2 reaction is exothermic and generates heat, which is recovered to produce steam for the process. The ethylene oxide process also produces other liquid and off-gas byproducts (e.g., ethane that may be burned for energy recovery within the process. Almost all facilities, except one in Texas, use the oxygen process to manufacture ethylene oxide (EPA 2008).

Methanol (CH_3OH) is a chemical feedstock most often converted into formaldehyde, acetic acid and olefins. It is also an alternative transportation fuel, as well as an additive used by municipal wastewater treatment facilities in the denitrification of wastewater. Methanol is most commonly synthesized from a synthesis gas (i.e., "syngas" – a mixture containing H_2, CO, and CO_2) using a heterogeneous catalyst. There are a number of process techniques that can be used to produce syngas. Worldwide, steam reforming of natural gas is the most common method; most methanol producers in the United States also use steam reforming of natural gas to produce syngas. Other syngas production processes in the United States include partial oxidation of natural gas and coal gasification.

Emissions of CO_2 and CH_4 from petrochemical production in 2022 were 28.8 MMT CO_2 Eq. (28,788 kt CO_2) and 0.005 MMT CO_2 Eq. (0.17 kt CH_4), respectively (see Table 4-55 and Table 4-56). Carbon dioxide emissions from petrochemical production are driven primarily from ethylene production, while CH_4 emissions are only from acrylonitrile production. Since 1990, total CO_2 emissions from petrochemical production increased by 43 percent, and CH_4 emissions declined by 22 percent. Emissions of CO_2 were 6 percent lower in 2022 than in 2021, and emissions of CH_4 were 12 percent higher in 2022 than in 2021. The increase in CO_2 emissions since 1990 is due primarily to increased ethylene and methanol production, which have been driven by the increased natural gas production in the United States. The reduction in CO_2 emissions since 2021 is due to a reduction in emissions from ethylene production, despite an increase in ethylene production. Since CH_4 emissions from acrylonitrile are calculated using a Tier 1 approach based on production as the activity data, the decrease in CH_4 emissions since 1990 and the increase since 2021 correspond with changes in the production levels for acrylonitrile.

Table 4-55: CO_2 and CH_4 Emissions from Petrochemical Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
CO_2	**20.1**	**26.9**	**27.2**	**28.5**	**27.9**	**30.7**	**28.8**
Carbon Black	3.4	4.3	3.4	3.3	2.6	3.0	3.1
Ethylene	13.1	19.0	19.4	20.7	20.7	22.8	20.7

Ethylene Dichloride	0.3	0.5	0.4	0.5	0.5	0.4	0.4
Ethylene Oxide	1.1	1.5	1.3	1.4	1.7	1.9	1.7
Methanol	1.0	0.3	1.4	1.6	1.6	1.7	2.0
Acrylonitrile	1.2	1.3	1.3	1.0	0.9	0.9	1.0
CH_4	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Acrylonitrile	+	+	+	+	+	+	+
Total	**20.1**	**26.9**	**27.2**	**28.5**	**27.9**	**30.7**	**28.8**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 4-56: CO_2 and CH_4 Emissions from Petrochemical Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
CO_2	**20,075**	**26,882**	**27,200**	**28,483**	**27,926**	**30,656**	**28,788**
Carbon Black	3,381	4,269	3,440	3,300	2,610	3,000	3,060
Ethylene	13,126	19,024	19,400	20,700	20,700	22,800	20,700
Ethylene Dichloride	254	455	440	503	456	376	428
Ethylene Oxide	1,123	1,489	1,300	1,370	1,680	1,930	1,650
Methanol	977	319	1,370	1,620	1,630	1,700	2,000
Acrylonitrile	1,214	1,325	1,250	990	850	850	950
CH_4	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Acrylonitrile	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt CH_4.

Note: Totals by gas may not sum due to independent rounding.

Methodology and Time-Series Consistency

Emissions of CO_2 and CH_4 were calculated using the estimation methods provided by the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data, and country-specific methods from EPA's GHGRP. The *2006 IPCC Guidelines* Tier 1 method was used to estimate CO_2 and CH_4 emissions from production of acrylonitrile,[45] and a country-specific approach similar to the IPCC Tier 2 method was used to estimate CO_2 emissions from production of carbon black, ethylene oxide, ethylene, ethylene dichloride, and methanol, as CO_2 emissions from petrochemical production is a key category. The Tier 2 method for petrochemicals is a total feedstock carbon mass balance method used to estimate total CO_2 emissions, but it is not applicable for estimating CH_4 emissions.

As noted in the *2006 IPCC Guidelines*, the Tier 2 total feedstock carbon mass balance method is based on the assumption that all of the carbon input to the process is converted either into primary and secondary products or into CO_2. Further, the guideline states that while the total carbon mass balance method estimates total carbon emissions from the process, it does not directly provide an estimate of the amount of the total carbon emissions emitted as CO_2, CH_4, or non-CH_4 volatile organic compounds (NMVOCs). This method accounts for all the carbon as CO_2, including CH_4.

A methodology refinement for emissions from methanol production was implemented in this *Inventory* to transition from a Tier 1 method to a country-specific approach similar to a Tier 2 method, using the process CO_2 emissions reported to Subpart X of the GHGRP. As part of this refinement, CH_4 emissions from methanol production for every year in the time series are now included in the CO_2 emissions estimates to avoid double counting because the GHGRP reporting method is a mass balance method under which all carbon input to the process is assumed to be converted either into primary and secondary products or into CO_2.

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[45] EPA has not integrated aggregated facility-level GHGRP information for acrylonitrile production. The aggregated information associated with production of these petrochemicals did not meet criteria to shield underlying CBI from public disclosure.

Note, a subset of facilities reporting under EPA's GHGRP use Continuous Emission Monitoring Systems (CEMS) to monitor CO_2 emissions from process vents and/or stacks from stationary combustion units or use the optional combustion methodology for ethylene production facilities. These facilities are required to also report CO_2, CH_4 and N_2O emissions from combustion of process off-gas in flares. The CO_2 emissions from flares are included in aggregated CO_2 results. Analysis of aggregated annual reports from those facilities shows that flared CH_4 and N_2O emissions are less than 300 kt CO_2 Eq./year. Since data is only available from a subset of facilities and not consistently reported over time and since CH_4 and N_2O emissions are shown to be insignificant, they are excluded from this analysis. See the planned improvements section below and Annex 5.

Carbon Black, Ethylene, Ethylene Dichloride, and Ethylene Oxide

2010 through 2022

Carbon dioxide emissions and national production for carbon black, ethylene, ethylene dichloride, and ethylene oxide were aggregated directly from EPA's GHGRP dataset for 2010 through 2022 (EPA 2023).

These emissions reflect application of a country-specific approach similar to the IPCC Tier 2 method and were used to estimate CO_2 emissions from the production of carbon black, ethylene, ethylene dichloride, ethylene oxide. In 2022, data reported to the GHGRP included 3,060,000 metric tons of CO_2 emissions from carbon black production; 20,700,000 metric tons of CO_2 from ethylene production; 428,000 metric tons of CO_2 from ethylene dichloride production; and 1,650,000 metric tons of CO_2 from ethylene oxide production.

Since 2010, EPA's GHGRP requires all domestic producers of petrochemicals to report annual emissions and supplemental emissions information (e.g., production data, etc.) under Subpart X to facilitate verification of reported emissions. Most petrochemical production facilities are required to use either a mass balance approach or CEMS to measure and report emissions for each petrochemical process unit to estimate facility-level process CO_2 emissions; ethylene production facilities also have a third option. The mass balance method is used by most facilities[46] and assumes that all the carbon input is converted into primary and secondary products or is emitted to the atmosphere as CO_2. To apply the mass balance, facilities must measure the volume or mass of each gaseous and liquid feedstock and product, mass rate of each solid feedstock and product, and carbon content of each feedstock and product for each process unit and sum for their facility. To apply the optional combustion methodology, ethylene production facilities must measure the quantity, carbon content, and molecular weight of the fuel to a stationary combustion unit when that fuel includes any ethylene process off-gas. These data are used to calculate the total CO_2 emissions from the combustion unit. The facility must also estimate the fraction of the emissions that is attributable to burning the ethylene process off-gas portion of the fuel. This fraction is multiplied by the total emissions to estimate the emissions from ethylene production. The QA/QC and Verification section below has a discussion of non-CO_2 emissions from ethylene production facilities.

All non-energy uses of residual fuel and some non-energy uses of "other oil" are assumed to be used in the production of carbon black; therefore, consumption of these fuels is adjusted for within the Energy chapter to avoid double-counting of emissions from fuel used in the carbon black production presented here within IPPU sector. Additional information on the adjustments made within the Energy sector for non-energy use of fuels is described in both the Methodology section of CO_2 from Section 3.1 and Annex 2.1.

1990 through 2009

Prior to 2010, for carbon black, ethylene, ethylene dichloride, and ethylene oxide processes, an average national CO_2 emission factor was calculated based on the GHGRP data and applied to production for earlier years in the time series (i.e., 1990 through 2009) to estimate CO_2 emissions. For these 4 types of petrochemical processes, CO_2 emission factors were derived from EPA's GHGRP data by dividing annual CO_2 emissions for petrochemical type "i"

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[46] A few facilities producing ethylene dichloride, ethylene, and methanol used CO_2 CEMS; those CO_2 emissions have been included in the aggregated GHGRP emissions presented here.

with annual production for petrochemical type "i" and then averaging the derived emission factors obtained for each calendar year 2010 through 2013 (EPA 2023). The years 2010 through 2013 were used in the development of carbon dioxide emission factors as these years are more representative of operations in 1990 through 2009 for these facilities. The average emission factors for each petrochemical type were applied across all prior years because petrochemical production processes in the United States have not changed significantly since 1990, though some operational efficiencies have been implemented at facilities over the time series.

The average country-specific CO_2 emission factors that were calculated from the GHGRP data are as follows:

- 2.59 metric tons CO_2/metric ton carbon black produced
- 0.79 metric tons CO_2/metric ton ethylene produced
- 0.040 metric tons CO_2/metric ton ethylene dichloride produced
- 0.46 metric tons CO_2/metric ton ethylene oxide produced

Annual production data for carbon black for 1990 through 2009 were obtained from the International Carbon Black Association (Johnson 2003 and 2005 through 2010). Annual production data for ethylene, ethylene dichloride, and ethylene oxide for 1990 through 2009 were obtained from the American Chemistry Council's (ACC) *Business of Chemistry* (ACC 2023).

Methanol

2015 through 2022

Carbon dioxide emissions and national production for methanol were aggregated directly from EPA's GHGRP data for 2015 through 2022 (EPA 2023). These emissions reflect application of a country-specific approach similar to the IPCC Tier 2 method and were used to estimate CO_2 emissions from the production of methanol. In 2022, data reported to the GHGRP included 2,000,000 metric tons of CO_2 emissions from methanol production.

As noted above, since 2010, EPA's GHGRP requires all domestic producers of petrochemicals to report annual emissions and supplemental emissions information (e.g., production data, etc.) under Subpart X to facilitate verification of reported emissions. Methanol production facilities are required to use either a mass balance approach or CEMS to measure and report emissions for each methanol process unit to estimate facility-level process CO_2 emissions. Most methanol production facilities use the mass balance method. As noted above, when using the mass balance method, facilities must measure the volume or mass of each gaseous and liquid feedstock and product, mass rate of each solid feedstock and product, and carbon content of each feedstock and product for each process unit and sum for their facility. For 2010 to 2014, the methanol data reported to GHGRP is considered CBI; therefore, the direct use of the GHGRP data starts with the 2015 reported information.

1990 through 2014

In this *Inventory*, similar to the methodology for other petrochemicals that utilize GHGRP data, an average national CO_2 emission factor for years prior to 2015 was calculated for methanol production based on the GHGRP data and applied to production for earlier years in the time series (i.e., 1990 through 2014) to estimate CO_2 emissions. Methanol CO_2 emission factors were derived from EPA's GHGRP data by dividing annual CO_2 emissions for methanol with annual production for methanol and then averaging the derived emission factors obtained for each year 2015 through 2022. The average country-specific CO_2 emission factor from the GHGRP data for these years was determined to be 0.26 metric tons CO_2/metric ton methanol produced. Annual methanol production data for 1990 through 2014 were obtained from the ACC's *Business of Chemistry* (ACC 2023). The average country-specific CO_2 emission factor from the GHGRP data is lower than the IPCC Tier 1 emission factor of 0.67 metric tons CO_2/metric ton methanol produced value that was used in previous versions of the *Inventory*. The main difference between the IPCC Tier 1 emission factor and the GHGRP emission factor is that the IPCC emission factor includes emissions from combustion of natural gas fuel in the reformer as well as vented CO_2 from the process; therefore, the use of the IPCC Tier 1 emission factor would double count emissions from natural gas combustion in the IPPU chapter and the Energy chapter. EPA already accounts for emissions from combustion of natural gas fuel in the reformer as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Acrylonitrile

Carbon dioxide and methane emissions from acrylonitrile production were estimated using the Tier 1 method in the *2006 IPCC Guidelines*. Acrylonitrile emissions represent about 3 percent of total petrochemical emissions in 2022 so a Tier 1 approach is deemed acceptable, and higher Tier methods could not be used due to data sensitivities which are described below. Annual acrylonitrile production data were used with IPCC default Tier 1 CO_2 and CH_4 emission factors to estimate emissions for 1990 through 2022. Emission factors used to estimate acrylonitrile production emissions are as follows:

- 0.18 kg CH_4/metric ton acrylonitrile produced
- 1.00 metric tons CO_2/metric ton acrylonitrile produced

Annual acrylonitrile production data for 1990 through 2022 were obtained from ACC's *Business of Chemistry* (ACC 2023). EPA is unable to apply the aggregated facility-level GHGRP information for acrylonitrile production needed for a Tier 2 approach due to sensitive nature of reported data. The aggregated information associated with production of these petrochemicals did not meet criteria to shield underlying CBI from public disclosure.

Production of each type of petrochemical are shown in Table 4-57.

Table 4-57: Production of Selected Petrochemicals (kt)

Chemical	1990	2005	2018	2019	2020	2021	2022
Carbon Black	1,307	1,651	1,280	1,210	990	1,140	1,170
Ethylene	16,542	23,975	30,500	32,400	33,500	34,700	35,400
Ethylene Dichloride	6,283	11,260	12,500	12,600	11,900	11,500	12,100
Ethylene Oxide	2,429	3,220	3,310	3,800	4,680	4,860	5,310
Methanol	3,750	1,225	5,830	6,460	6,580	7,110	8,030
Acrylonitrile	1,214	1,325	1,250	990	850	850	950

As noted earlier in the introduction section of the Petrochemical Production section, the allocation and reporting of emissions from both fuels and feedstocks transferred out of the system for use in energy purposes to the Energy chapter differs slightly from the *2006 IPCC Guidelines*. According to the *2006 IPCC Guidelines*, emissions from fuel combustion from petrochemical production should be allocated to this source category within the IPPU chapter. Due to national circumstances, EIA data on primary fuel for feedstock use within the energy balance are presented by commodity only, with no resolution on data by industry sector (i.e., petrochemical production). In addition, under EPA's GHGRP, reporting facilities began reporting in 2014 on annual feedstock quantities for mass balance and CEMS methodologies (79 FR 63794), as well as the annual average carbon content of each feedstock (and molecular weight for gaseous feedstocks) for the mass balance methodology beginning in reporting year 2017 (81 FR 89260).[47] The United States is currently unable to report non-energy fuel use from petrochemical production under the IPPU chapter due to CBI issues. Therefore, consistent with *2006 IPCC Guidelines*, fuel consumption data reported by EIA are adjusted to account for these overlaps to avoid double-counting. More information on the non-energy use of fossil fuel feedstocks for petrochemical production can be found in Annex 2.3.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. The methodology for ethylene production, ethylene dichloride production, and ethylene oxide production spliced activity data from two different sources: ACC for 1990 through 2009 and GHGRP for 2010 through 2022. The methodology for methanol production spliced activity data from two different sources: ACC for 1990 through 2014 and GHGRP for 2015 through 2022. Consistent with the *2006 IPCC Guidelines*, the overlap

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[47] See https://www.epa.gov/ghgreporting/historical-rulemakings.

technique was applied to compare the two data sets for years where there was overlap. For ethylene production, the data sets were determined to be consistent, and adjustments were not needed. For ethylene dichloride production, ethylene oxide production, and methanol production, the data sets were determined to be inconsistent. The GHGRP data includes production of ethylene dichloride and ethylene oxide as intermediates, while it is unclear if the ACC data does. Methanol production data from GHGRP are significantly higher than the ACC data for every year since 2015; the reason for the difference is not clear. Therefore, no adjustments were made to the ethylene dichloride, ethylene oxide, and methanol activity data for 1990 through 2009 because the *2006 IPCC Guidelines* indicate that it is not good practice to use the overlap technique when the data sets are inconsistent. The methodology for carbon black production also spliced activity data from two different sources: ICBA for 1990 through 2009 and GHGRP for 2010 through 2022. The overlap technique was applied to these data for 2010 and 2011. The data sets were determined to be consistent, and adjustments were not needed.

Uncertainty

The CO_2 and CH_4 emission factors used for acrylonitrile production are based on a limited number of studies. Using plant-specific factors instead of default or average factors could increase the accuracy of the emission estimates; however, such data were not available for the current *Inventory* report. For acrylonitrile, EPA assigned an uncertainty range of ±60 percent for the CO_2 emission factor, ±10 percent for the CH_4 emission factor, and a normal probability density function for both, and using the suggested uncertainty provided in Table 3.27 of the *2006 IPCC Guidelines* is appropriate based on expert judgment, (RTI 2023). The results of the quantitative uncertainty analysis for the CO_2 emissions from carbon black production, ethylene, ethylene dichloride, ethylene oxide, and methanol are based on reported GHGRP data. Refer to the Methodology section for more details on how these emissions were calculated and reported to EPA's GHGRP. EPA assigned an uncertainty range of ±5 percent and a normal probability density function for CO_2 emissions from carbon black, ethylene, ethylene dichloride, and ethylene oxide production, and using the suggested uncertainty provided in Table 3.27 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). There is some uncertainty in the applicability of the average emission factors for each petrochemical type across all prior years. While petrochemical production processes in the United States have not changed significantly since 1990, some operational efficiencies have been implemented at facilities over the time series.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-58. Petrochemical production CO_2 emissions from 2022 were estimated to be between 27.6 and 30.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 4 percent below to 4 percent above the emission estimate of 28.8 MMT CO_2 Eq. Petrochemical production CH_4 emissions from 2022 were estimated to be between 0.0 and 0.01 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 14 percent below to 14 percent above the emission estimate of 0.005 MMT CO_2 Eq.

Table 4-58: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Petrochemical Production and CO_2 Emissions from Petrochemical Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Petrochemical Production	CO_2	28.8	27.6	30.0	-4%	+4%
Petrochemical Production	CH_4	+	0.0	0.01	-14%	+14%

+ Does not exceed 0.05 MMT CO_2 Eq.

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

QA/QC and Verification

For petrochemical production, QA/QC activities were conducted consistent with the U.S. Inventory QA/QC plan, as described in the QA/QC and Verification Procedures section of the IPPU chapter and Annex 8. Source-specific quality control measures for this category included the QA/QC requirements and verification procedures of EPA's GHGRP. More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to petrochemical facilities can be found under Subpart X (Petrochemical Production) of the regulation (40 CFR Part 98).[48] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[49] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions. EPA also conducts QA checks of GHGRP reported production data by petrochemical type against external datasets.

For ethylene, ethylene dichloride and ethylene oxide, it is possible to compare CO_2 emissions calculated using the GHGRP data to the CO_2 emissions that would have been calculated using the Tier 1 approach if GHGRP data were not available. For ethylene, the GHGRP emissions were within ±8 percent of the emissions calculated using the Tier 1 approach prior to 2018; for 2018 through 2022, the GHGRP emissions were between 76 percent and 87 percent of what would be calculated using the Tier 1 approach. For ethylene dichloride, the GHGRP emissions are typically higher than the Tier 1 emissions by up to 25 percent, but in 2010 and 2021, GHGRP emissions were slightly lower than the Tier 1 emissions. For ethylene oxide, GHGRP emissions typically vary from the Tier 1 emissions by up to ±20 percent, but in 2021 and 2022, the GHGRP emissions were significantly higher than the Tier 1 emissions. This was likely due to GHGRP data capturing the production of ethylene oxide as an intermediate in the onsite production of ethylene glycol.

For methanol, GHGRP production data was consistently higher than ACC production data in all years between 2015 and 2022. Even though the GHGRP production was higher than the ACC production, the GHGRP CO_2 emissions estimated using the methodology refinement in this *Inventory* are significantly lower than the emissions calculated using the Tier 1 approach in all years between 2015 and 2022. Additionally, there is a trend towards increasing differences over these years starting with an 873 kt CO_2 difference in 2015 and increasing to a 3,000 kt CO_2 difference in 2022. GHGRP emissions were between 43 percent and 61 percent of the Tier 1 emissions in 2015 and 2018, respectively. As discussed in the Methodology and Time-Series Consistency section above, EPA has determined that using the IPCC Tier 1 emissions factor to calculate methanol emissions results in double counting of natural gas combustion emissions in both this chapter and in the Energy chapter; therefore, use of the GHGRP derived emissions is deemed appropriate. For the years 1990 through 2014, the use of the GHGRP derived emission factor also results in lower emissions than those calculated using the IPCC Tier 1 emission factor. While this avoids the double counting of emissions with the Energy chapter, as described below in the Planned Improvements section, EPA intends to examine the emissions from methanol facilities that report to the GHGRP and may have been operating prior to 2010 to assess whether a more specific process-only emission factor can be developed from the GHGRP data for use in estimating CO_2 emissions from methanol production in 1990 through 2014.

EPA's GHGRP mandates that all petrochemical production facilities report their annual emissions of CO_2, CH_4, and N_2O from each of their petrochemical production processes. Source-specific quality control measures for the Petrochemical Production category included the QA/QC requirements and verification procedures of EPA's GHGRP. The QA/QC requirements differ depending on the calculation methodology used.

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[48] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

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

As part of a planned improvement effort, EPA has assessed the potential of using GHGRP data to estimate CH_4 emissions from ethylene production. As discussed in the Methodology section above, CO_2 emissions from ethylene production in this chapter are based on data reported under the GHGRP, and these emissions are calculated using a Tier 2 approach that assumes all of the carbon in the fuel (i.e., ethylene process off-gas) is converted to CO_2. Ethylene production facilities also calculate and report CH_4 emissions under the GHGRP when they use the optional combustion methodology. The facilities calculate CH_4 emissions from each combustion unit that burns off-gas from an ethylene production process unit using a Tier 1 approach based on the total quantity of fuel burned, a default or measured higher heating value, and a default emission factor. Because multiple other types of fuel in addition to the ethylene process unit off-gas may be burned in these combustion units, the facilities also report an estimate of the fraction of emissions that is due to burning the ethylene process off-gas component of the total fuel. Multiplying the total emissions by the estimated fraction provides an estimate of the CH_4 emissions from the ethylene production process unit. These ethylene production facilities also calculate CH_4 emissions from flares that burn process vent emissions from ethylene processes. The CO_2 emissions are calculated using either a Tier 2 approach based on measured gas volumes and measured carbon content or higher heating value, or a Tier 1 approach based on the measured gas flow and a default emission factor; the CH_4 emissions are calculated based on a Tier 1 approach using the CO_2 emissions and default emission factors. Nearly all ethylene production facilities use the optional combustion methodology under the GHGRP. 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). EPA continues to assess the GHGRP data for ways to better disaggregate the data and incorporate it into the *Inventory*.

These facilities are also required to report emissions of N_2O from combustion of ethylene process off-gas in both stationary combustion units and flares. Facilities using CEMS (consistent with a Tier 3 approach) are also required to report emissions of CH_4 and N_2O from combustion of petrochemical process-off gases in flares. Preliminary analysis of the aggregated reported CH_4 and N_2O emissions from facilities using CEMS and N_2O emissions from facilities using the optional combustion methodology suggests that these annual emissions are less than 0.4 percent of total petrochemical emissions, which is not significant enough to prioritize for inclusion in the report at this time. Pending resources and significance, EPA may include these N_2O emissions in future reports to enhance completeness. Future QC efforts to validate the use of Tier 1 default emission factors and report on the comparison of Tier 1 emission estimates and GHGRP data are described below in the Planned Improvements section.

Recalculations Discussion

A methodology refinement for calculating emissions from methanol production was implemented in this *Inventory*. As discussed in the Methodology and Time-Series Consistency section, the previously used Tier 1 approach was replaced with a country-specific approach similar to a Tier 2 method based on emissions aggregated directly from EPA's GHGRP data for 2015 through 2022 (EPA 2023) and an average country-specific CO_2 emission factor from the GHGRP data applied to production data from ACC's *Business of Chemistry* for 1990 through 2014 (ACC 2023). For 2015 through 2021, these changes resulted in a reduction in the reported CO_2 emissions between 43 percent (873 kt) in 2015 to 61 percent (2,110 kt) in 2018. For 1990 through 2014, the refinement resulted in a reduction of 61 percent each year (287 kt in 2011 to 2,449 kt in 1997).

Additionally, CH_4 emissions previously reported from methanol production were reduced to zero for all years of the time series because, as noted above in the Methodology and Time Series Consistency section, the methodology refinement is based on the assumption that all carbon input to the process is converted either to primary and secondary products or to CO_2.

Planned Improvements

Improvements include completing category-specific QC of activity data and emission factors, along with further assessment of CH_4 and N_2O emissions to enhance completeness in reporting of emissions from U.S. petrochemical production, pending resources, significance and time-series consistency considerations. For example, EPA is planning additional assessment of fuel combustion emissions data reported by methanol production facilities for ways to estimate process-based emissions in the *Inventory* separately from combustion emissions for 1990 through 2014. If the GHGRP data can be categorized by type of methanol process design, it may be possible to use GHGRP data for single reformer process units to develop a ratio of process-to-total emissions to adjust the IPCC emission factor. Potential difficulties with this analysis are that some of the methanol producing facilities also produce other chemicals and the combustion unit names may not clearly identify the process unit to which they apply, and some combustion unit data may be aggregated for multiple combustion units. The EPA is also planning additional assessment of ways to use CH_4 data from the GHGRP in the *Inventory*. One possible approach EPA is assessing would be to adjust the CO_2 emissions from the GHGRP downward by subtracting the carbon that is also included in the reported CH_4 emissions, per the discussion in the Petrochemical Production QA/QC and Verification section, above. As of this current report, timing and resources have not allowed EPA to complete these analyses of activity data, emissions, and emission factors but they remain priority improvements within the IPPU chapter.

Pending resources, a secondary potential improvement for this source category would focus on continuing to analyze the fuel and feedstock data from EPA's GHGRP to better disaggregate energy-related emissions and allocate them more accurately between the Energy and IPPU sectors of the *Inventory*. EPA will continue to look for ways to incorporate this data into future Inventories that will allow for easier data integration between the non-energy uses of fuels category and the petrochemicals category presented in this chapter. This planned improvement is still under development and has not been completed to report on progress in this current *Inventory*.

4.14 HCFC-22 Production (CRT Source Category 2B9a)

This reporting category (2B9a) includes by-product emissions of HCFC-23 (trifluoromethane or CHF_3) from production of HCFC-22 (chlorodifluoromethane). HFC-23 is generated as a byproduct during the manufacture of HCFC-22, which is primarily employed in refrigeration and air conditioning systems and as a chemical feedstock for manufacturing synthetic polymers. Between 1990 and 2000, U.S. production of HCFC-22 increased significantly as HCFC-22 replaced chlorofluorocarbons (CFCs) in many applications. Between 2000 and 2007, U.S. production fluctuated but generally remained above 1990 levels. In 2008 and 2009, U.S. production declined markedly and has remained near 2009 levels since. Because HCFC-22 depletes stratospheric ozone, its production for non-feedstock uses was phased out in 2020 under the U.S. Clean Air Act.[50] Feedstock production, however, is permitted to continue indefinitely. Per the IPCC methodological guidance, emissions from energy use are currently accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

HCFC-22 is produced by the reaction of chloroform ($CHCl_3$) and hydrogen fluoride (HF) in the presence of a catalyst, $SbCl_5$. The reaction of the catalyst and HF produces $SbCl_xF_y$, (where $x + y = 5$), which reacts with chlorinated hydrocarbons to replace chlorine atoms with fluorine. The HF and chloroform are introduced by submerged piping into a continuous-flow reactor that contains the catalyst in a hydrocarbon mixture of chloroform and partially fluorinated intermediates. The vapors leaving the reactor contain HCFC-21 ($CHCl_2F$), HCFC-22 ($CHClF_2$), HFC-23 (CHF_3), HCl, chloroform, and HF. The under-fluorinated intermediates (HCFC-21) and chloroform are then condensed and returned to the reactor, along with residual catalyst, to undergo further fluorination. The final vapors leaving the condenser are primarily HCFC-22, HFC-23, HCl and residual HF. The HCl is recovered as a useful

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[50] As construed, interpreted, and applied in the terms and conditions of the *Montreal Protocol on Substances that Deplete the Ozone Layer* [42 U.S.C. §7671m(b), CAA §614].

byproduct, and the HF is removed. Once separated from HCFC-22, the HFC-23 may be released to the atmosphere, recaptured for use in a limited number of applications, or destroyed.

Two facilities produced HCFC-22 in the United States in 2022. Emissions of HFC-23 from this activity in 2022 were estimated to be 1.8 MMT CO_2 Eq. (0.1 kt) (see Table 4-59 and Table 4-60). This quantity represents an 18 percent increase from 2021 emissions and a 95 percent decrease from 1990 emissions. The decrease from 1990 emissions was caused primarily by changes in the HFC-23 emission rate (kg HFC-23 emitted/kg HCFC-22 produced). The decrease from 2021 emissions was caused by both a decrease in the HFC-23 emission rate at one plant and a decrease in the total quantity of HCFC-22 produced. The long-term decrease in the emission rate is primarily attributable to six factors: (a) five plants that did not capture and destroy the HFC-23 generated have ceased production of HCFC-22 since 1990; (b) one plant that captures and destroys the HFC-23 generated began to produce HCFC-22; (c) one plant implemented and documented a process change that reduced the amount of HFC-23 generated; (d) the same plant began recovering HFC-23, primarily for destruction and secondarily for sale; (e) another plant began destroying HFC-23; and (f) the same plant, whose emission rate was higher than that of the other two plants, ceased production of HCFC-22 in 2013.

Emissions from HCFC-22 production are reported under fluorochemical production (CRT category 2B9) in this *Inventory*, which also includes the production of fluorochemicals other than HCFC-22 described further in section 4.15 of this chapter.

Table 4-59: HFC-23 Emissions from HCFC-22 Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
HCFC-22 Production	38.6	16.8	2.7	3.1	1.8	2.2	1.8

Table 4-60: HFC-23 Emissions from HCFC-22 Production (kt HFC-23)

Year	1990	2005	2018	2019	2020	2021	2022
HCFC-22 Production	3	1	+	+	+	+	+

+ Does not exceed 0.5 kt.

Methodology and Time-Series Consistency

To estimate HFC-23 emissions for five of the eight HCFC-22 plants that have operated in the United States since 1990, methods comparable to the Tier 3 methods in the *2006 IPCC Guidelines* (IPCC 2006) were used throughout the time series. Emissions for 2010 through 2022 were obtained through reports submitted by U.S. HCFC-22 production facilities to EPA's Greenhouse Gas Reporting Program (GHGRP). EPA's GHGRP mandates that all HCFC-22 production facilities report their annual emissions of HFC-23 from HCFC-22 production processes and HFC-23 destruction processes. Previously, data were obtained by EPA through collaboration with an industry association that received voluntarily reported HCFC-22 production and HFC-23 emissions annually from all U.S. HCFC-22 producers from 1990 through 2009. These emissions were aggregated and reported to EPA on an annual basis.

For the other three plants, the last of which closed in 1993, methods comparable to the Tier 1 method in the *2006 IPCC Guidelines* were used. Emissions from these three plants have been calculated using the recommended emission factor for unoptimized plants operating before 1995 (0.04 kg HCFC-23/kg HCFC-22 produced).

The five plants that have operated since 1994 measure (or, for the plants that have since closed, measured) concentrations of HFC-23 as well as mass flow rates of process streams to estimate their generation of HFC-23. Plants using thermal oxidation to abate their HFC-23 emissions monitor the performance of their oxidizers to verify that the HFC-23 is almost completely destroyed. One plant that releases a small fraction of its byproduct HFC-23 periodically measures HFC-23 concentrations at process vents using gas chromatography. This information is combined with information on quantities of products (e.g., HCFC-22) to estimate HFC-23 emissions.

To estimate 1990 through 2009 emissions, reports from an industry association were used that aggregated HCFC-22 production and HFC-23 emissions from all U.S. HCFC-22 producers and reported them to EPA (ARAP 1997, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, and 2010). To estimate 2010 through 2022 emissions, facility-level data (including both HCFC-22 production and HFC-23 emissions) reported through EPA's GHGRP were analyzed. In 1997 and 2008, comprehensive reviews of plant-level estimates of HFC-23 emissions and HCFC-22 production were performed (RTI 1997; RTI 2008). The 1997 and 2008 reviews enabled U.S. totals to be reviewed, updated, and where necessary, corrected. The reviews also allowed plant-level uncertainty analyses (Monte-Carlo simulations) to be performed for 1990, 1995, 2000, 2005, and 2006. Estimates of annual U.S. HCFC-22 production are presented in Table 4-61.

Table 4-61: HCFC-22 Production (kt)

Year	1990	2005	2012	2018	2019	2020	2021	2022
Production	139	156	96	C	C	C	C	C

C (CBI)

Note: HCFC-22 production in 2013 through 2022 is considered confidential business information (CBI) as there were only two producers of HCFC-22 in those years.

Uncertainty

The uncertainty analysis presented in this section was based on a plant-level Monte Carlo stochastic simulation for 2006. The Monte Carlo analysis used estimates of the uncertainties in the individual variables in each plant's estimating procedure. This analysis was based on the generation of 10,000 random samples of model inputs from the probability density functions for each input. A normal probability density function was assumed for all measurements and biases except the equipment leak estimates for one plant; a log-normal probability density function was used for this plant's equipment leak estimates. The simulation for 2006 yielded a 95-percent confidence interval for U.S. emissions of 6.8 percent below to 9.6 percent above the reported total.

The relative errors yielded by the Monte Carlo stochastic simulation for 2006 were applied to the U.S. emission estimate for 2022. The resulting estimates of absolute uncertainty are likely to be reasonably accurate because (1) the methods used by the two remaining plants to estimate their emissions are not believed to have changed significantly since 2006, and (2) although the distribution of emissions among the plants has changed between 2006 and 2022 (because one plant has closed), the plant that currently accounts for most emissions had a relative uncertainty in its 2006 (as well as 2005) emissions estimate that was similar to the relative uncertainty for total U.S. emissions. Thus, the closure of one plant is not likely to have a large impact on the uncertainty of the national emission estimate.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-62. HFC-23 emissions from HCFC-22 production were estimated to be between 1.7 and 2.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 7 percent below and 10 percent above the emission estimate of 1.8 MMT CO_2 Eq.

Table 4-62: Approach 2 Quantitative Uncertainty Estimates for HFC-23 Emissions from HCFC-22 Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
HCFC-22 Production	HFC-23	1.8	1.7	2.0	-7%	+10%

[a] Range of emissions reflects a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). Under the GHGRP, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[51] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

The GHGRP also requires source-specific quality control measures for the HCFC-22 Production category. Under EPA's GHGRP, HCFC-22 producers are required to (1) measure concentrations of HFC-23 and HCFC-22 in the product stream at least weekly using equipment and methods (e.g., gas chromatography) with an accuracy and precision of 5 percent or better at the concentrations of the process samples, (2) measure mass flows of HFC-23 and HCFC-22 at least weekly using measurement devices (e.g., flowmeters) with an accuracy and precision of 1 percent of full scale or better, (3) calibrate mass measurement devices at the frequency recommended by the manufacturer using traceable standards and suitable methods published by a consensus standards organization, (4) calibrate gas chromatographs at least monthly through analysis of certified standards, and (5) document these calibrations.

Recalculations Discussion

The 2019 emissions estimate increased by 0.05 kg of HFC-23 to reflect newly reported emissions from a facility that destroys HFC-23. This increased the 2019 emissions estimate by two ten thousandths of a percent.

Planned Improvements

At this time, there are no specific planned improvements for estimating HFC-23 emissions from HCFC-22 production.

4.15 Production of Fluorochemicals Other Than HCFC-22 (CRT Source Category 2B9b)

This reporting category, fluorochemical production (2B9b), facilities in the United States produced or transformed approximately 200 fluorinated gases other than HCFC-22 in 2022, including saturated and unsaturated hydrofluorocarbons (HFCs), saturated and unsaturated perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), nitrogen trifluoride (NF_3), hydrofluoroethers (HFEs), perfluoroalkylamines, and dozens of others. Emissions from fluorochemical production may include emissions of the intentionally manufactured chemical as well as reactant and by-product emissions. The compounds emitted depend upon the production or transformation process, but may include, e.g., HFCs, PFCs, SF_6, nitrous oxide (N_2O), NF_3, and many others. Potential sources of fluorinated GHG emissions at fluorochemical production facilities include process vents, equipment leaks, and evacuating returned

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[51] EPA (2015). Greenhouse Gas Reporting Program Report Verification. Available online at: https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

containers[52] Production-related emissions of fluorinated GHGs occur from both process vents and equipment leaks. Process vent emissions occur from manufacturing equipment such as reactors, distillation columns, and packaging equipment. Equipment leak emissions, or fugitive emissions, occur from valves, flanges, pump seals, compressor seals, pressure relief valves, connectors, open-ended lines, and sampling connections. In addition, users of fluorinated GHGs may return empty containers (e.g., cylinders) to the production facility for reuse; prior to reuse, the residual fluorinated GHGs (often termed "heels") may be evacuated from the container and are a potential emission source. In many cases, these "heels" are recovered or exhausted to a treatment device for destruction. In other cases, however, they are released into the atmosphere.[53]

Emissions of all HFCs, PFCs, NF_3, and SF_6 from production of fluorochemicals other than hydrochlorofluorocarbon (HCFC)-22 are presented in Table 4-63 below for the years 1990, 2005, and the period 2018 to 2022. Per the IPCC methodological guidance, emissions from energy use are currently accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

The fluorinated GHG emissions reported under the Greenhouse Gas Reporting Program (GHGRP) include emissions of HFCs, PFCs, SF_6, NF_3, and numerous "other" fluorinated GHGs, such as octafluorotetrahydrofuran (C_4F_8O), trifluoromethyl sulfur pentafluoride (SF_5CF_3), and hexafluoropropylene oxide. Because they are not included among the seven UNFCCC-reportable gases or gas groups, the "other" fluorinated GHGs are not included in *Inventory* totals. However, their emissions are presented below because they often have high GWPs and large GWP-weighted emissions.

Total emissions of HFCs, PFCs, SF_6, and NF_3 from fluorochemical production are estimated to have increased from 32 MMT CO_2 Eq. (3,400 MT) in 1990 to a peak of 45 MMT CO_2 Eq. (5,700 MT) in 1999, declining to 3.9 MMT CO_2 Eq. (860 MT) in 2016[54] and rising again to 6.0 MMT CO_2 Eq. (1,200 MT) in 2022. These trends reflect estimated changes in fluorinated gas production and increasing use of control devices. Prior to 2000, only 2 facilities are known to have operated control devices to destroy fluorinated GHG emissions. After 2000, additional production facilities began to install and use control devices to destroy fluorinated GHG emissions,[55] and fluorinated GHG emissions declined sharply from 45 MMT CO_2 Eq. (5,700 MT) in 1999 to 13 MMT CO_2 Eq. (2,300 MT) in 2005. Emissions continued to fall more slowly through 2016, reflecting the installation of controls at an additional 4 facilities in 2011, 2012, 2015, and 2016. Total fluorinated GHG emissions rose from 2017 to 2022 as production increased at some facilities.

Emissions from the production of fluorochemicals other than HCFC-22 are reported under fluorochemical production (CRT category 2B9) in conjunction with emissions from HCFC-22 production described in Section 4.14 of this chapter.

HFC Emissions

Estimated emissions of HFCs increased from 8.7 MMT CO_2 Eq. in 1990 to a peak of 14 MMT CO_2 Eq. in 1999 (1,200 to 2,600 MT), declining with some fluctuation to 2.5 MMT CO_2 Eq. in 2022. Emissions in 1990 were primarily from facilities producing compounds other than saturated HFCs. The subsequent trends in emissions were driven by the growth in production of saturated HFCs and the imposition of controls. Production of saturated HFCs is estimated to have increased from around 0.3 MMT CO_2 Eq. (2,000 MT) in 1990 to over 300 MMT CO_2 Eq. (100,000 MT) by

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[52] The totals presented below also include emissions from destruction of previously produced fluorinated GHGs that are shipped to production facilities for destruction, e.g., because they are found to be irretrievably contaminated.

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

[54] Emissions in MMT CO_2 Eq. were similar in 2017, but the 2017 emissions in MT were considerably higher (4,500 MT) due to anomalously high emissions of one low-GWP, unsaturated HFC at one facility.

[55] One facility is assumed to have installed controls in 2000, another installed controls in 2003, and three facilities are assumed to have installed controls in 2005.

2010 as HFCs replaced ozone-depleting substances, which were being phased out under the Montreal Protocol and Clean Air Act (EPA 2023a; EPA 2023b). This increase in HFC production drove HFC emissions to their 1999 peak. However, estimated emissions declined significantly from 1999 to 2005 due to the assumed addition of controls in 2000 and subsequent years. Estimated emissions of HFCs resumed their increase from 2005 to 2010, reaching 7.2 MMT CO_2 Eq. (2,300 MT), but again declined sharply in 2011 to 4.6 MMT CO_2 Eq. (1,200 MT) based on addition of controls. Since 2012, HFC emissions have continued to trend downward with some fluctuations, hitting a minimum of 1.7 MMT CO_2 Eq. in 2021. With the phase-out of production of saturated HFCs (Kigali Amendment, and U.S. AIM program), the downward trend of HFC emissions is expected to continue, but the share of HFC emissions that are not associated with saturated HFC production (approximately 0.7 MMT CO_2 Eq. in 2022) is likely to persist in the absence of additional controls.

PFC Emissions

Emissions of PFCs increased gradually from 18 MMT CO_2 Eq. (2,000 MT) in 1990 to 24 MMT CO_2 Eq. (2,800 MT) in 1999 but dropped to 4.0 MMT CO_2 Eq. (490 MT) by 2005, reflecting the addition of controls at high-emitting facilities and apparent changes to the mix of products produced at another facility.[56] Overall PFC emissions from 2005 to 2022 have remained relatively steady, oscillating around 2.5 MMT CO_2 Eq. The upward trend between 1990 and 1999 was largely driven by the three facilities that reported their historical emissions to the EPA. In the absence of historical emissions data for other facilities, the quantities of fluorinated GHGs produced or transformed at other facilities emitting PFCs are estimated to have remained generally steady between 1990 and 2009 and therefore do not contribute to the emissions trend before 2010. For most of the fluorinated GHGs produced at these facilities, there was no available industry information to inform activity estimates or trends for 1990 to 2009. Therefore, as discussed in the Methodology section below, 2010 production values from EPA's GHGRP were assumed to have held constant for these compounds from 1990 to 2010.

SF_6 Emissions

Emissions of SF_6 are estimated to have risen gradually from 5.8 MMT CO_2 Eq. (250 MT) in 1990 to a peak of 7.5 MMT CO_2 Eq. (320 MT) in 1995, to have declined slowly to 7.0 MMT CO_2 Eq. in 2000, and then to have declined more rapidly to a minimum of 0.0004 MMT CO_2 Eq. (0.01 MT) in 2017, after which emissions rose and fluctuated between 0.056 MMT CO_2 Eq. (in 2020) and 0.0024 MMT CO_2 Eq. (in 2022). The rapid emissions decline after 2000 was driven first by the imposition of controls at one facility and then by the cessation of production in 2010 at a major U.S. SF_6-producing facility.

NF_3 Emissions

Since 1990, estimated emissions of NF_3 have fluctuated between 0.11 MMT CO_2 Eq. and 0.72 MMT CO_2 Eq., with peaks occurring in 2000 (0.71 MMT CO_2 Eq.), 2010 (0.70 MMT CO_2 Eq.), and 2020 (0.72 MMT CO_2 Eq.), and lows occurring in 1990 (0.29 MMT CO_2 Eq.), 2003 (0.33 MMT CO_2 Eq.), and 2018 (0.11 MMT CO_2 Eq.). NF_3 may be emitted both from the production of NF_3 and from the production of other fluorochemicals. The dominant source since 2010 has been production of NF_3. Trends after 2010 were driven by changes both in NF_3 production and in

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[56] In a summary of 1990 through 2010 emissions submitted to EPA (described more below), 3M, which owns several facilities that historically emitted PFCs, noted that the mix of products produced at its various facilities had changed over time, leading to changes in the magnitude and contents of emissions. This change in magnitude and contents was particularly pronounced at 3M's Decatur facility (referred to elsewhere in this document as "3M Company"), where emissions declined from 15.8 MMT CO_2 Eq. in 2000 to 0.53 MMT CO_2 Eq. in 2002, and where the contents of emissions changed from HFCs, PFCs, SF_6 and other fluorinated GHGs in 2000 to PFCs and other fluorinated GHGs in 2003. (Emissions in 2002 were not differentiated by group). Emissions were also reduced after the installation of a control device at the Cordova facility. 3M noted that Initial start-up of the thermal oxidizer occurred in 2003, but that it took time to optimize the operation of the thermal oxidizer and treatment of the various gas streams, leading to a decrease in emissions over several years.

the emission rate (kg NF_3 emitted/kg NF_3 produced) for NF_3 production, with both contributing to increased emissions since 2018. For 1990 through 2009, the NF_3 that is emitted from the production of NF_3 is assumed to be influenced by the trajectory of NF_3 production, which is generally assumed to follow production trends in the semiconductor industry except where NF_3 facility capacity limits production further. Semiconductor production increased steadily from 1995 to 2007 but is estimated to have declined from 2007 through 2010. As described in the Methodology section under "Estimated Emissions for 3M facilities," the NF_3 that is emitted from production of other fluorochemicals is assumed to have been emitted as a constant fraction of the "other" fluorinated GHGs whose 1990 through 2010 emissions were reported by 3M facilities. This fraction was estimated based on the fraction of "other" fluorinated GHG emissions accounted for by NF_3 between 2011 and 2015 and is highly uncertain. Nevertheless, because the highest-emitting 3M facilities reported decreasing emissions of all other fluorinated GHG groups between 2000 and 2005 (due to the installation of a control device at one facility and apparent production changes at another), NF_3 emissions also appear likely to have decreased during this period.

Other Fluorinated GHG Emissions

Other fluorinated GHGs, i.e., those not included in the UNFCCC-reportable gases or gas groups, are also emitted in significant quantities from fluorinated gas production and transformation processes. Estimated emissions of these other fluorinated GHGs are provided in Table 4-64 for the years 1990, 2005, and the period 2018 to 2022. The other fluorinated GHGs with the highest estimated emissions in 2022 are presented separately, and the remaining other fluorinated GHGs are aggregated.

Total emissions of other fluorinated GHGs increased from 4.7 MMT CO_2 Eq. (450 MT) in 1990 to a peak of 10.1 MMT CO_2 (870 MT) in 2000, declining rapidly to 0.90 MMT CO_2 Eq. in 2009 and then declining more slowly to 0.13 MMT CO_2 Eq. (40 MT) in 2021 and 2022. Between 1990 and 2009, estimated emissions of other fluorinated GHGs were primarily driven by the emissions reported by 3M facilities, which showed significant declines between 2000 and 2005, reflecting apparent production changes at one facility and the installation of a control device at another. The decline in emissions from 2019 to 2020 was due to a decrease in the emission rate at one facility.

Table 4-63: Emissions of HFCs, PFCs, SF_6, and NF_3 from Production of Fluorochemicals Other Than HCFC-22 (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
HFC-23	6.7	1.7	1.3	1.1	0.9	0.7	1.0
HFC-125	0.1	1.9	0.4	0.4	0.4	0.4	0.3
HFC-143a	0.1	0.8	0.7	0.6	0.3	0.2	0.3
HFC-134a	+	0.4	0.3	0.3	0.2	0.2	0.3
1H,4H-Perfluorobutane	0.0	0.0	0.0	+	+	+	0.2
1H,6H-Perfluorohexane	0.0	0.0	0.0	+	+	+	0.2
Other HFCs	1.6	0.5	0.2	0.2	0.2	0.2	0.3
Perfluorocyclobutane	11.2	0.7	1.3	1.4	1.1	1.3	1.3
PFC-14 (Perfluoromethane)	2.4	1.4	1.0	0.9	0.9	0.9	1.0
Other PFCs	3.9	1.9	0.7	0.7	0.4	0.4	0.6
Nitrogen trifluoride	0.3	0.6	0.1	0.6	0.7	0.5	0.5
Sulfur hexafluoride	5.8	3.3	+	+	+	+	+
Total	**32.3**	**13.2**	**5.9**	**6.2**	**5.2**	**4.9**	**5.9**

+ Does not exceed 0.05 MMT CO_2 Eq.
Note: Table does not sum due to independent rounding.

Table 4-64: Emissions of HFCs, PFCs, SF_6, and NF_3 from Production of Fluorochemicals Other Than HCFC-22 (Metric Tons)

Gas	1990	2005	2018	2019	2020	2021	2022
HFC-23	540	140	100	89	71	56	77
HFC-125	43	600	130	130	120	110	105
HFC-143a	30	160	160	120	63	49	57
HFC-134a	37	340	200	220	180	180	190
1H,4H-Perfluorobutane	0	0	0	1.2	0.60	1.2	53
1H,6H-Perfluorohexane	0	0	0	0.92	0.47	0.90	41
Other HFCs	500	400	270	260	230	250	270
Perfluorocyclobutane	1,200	70	130	150	120	130	140
PFC-14 (Perfluoromethane)	360	210	150	130	140	140	160
Other PFCs	420	210	71	77	41	49	59
Nitrogen trifluoride	18	37	6.7	35	45	31	31
Sulfur hexafluoride	250	140	0.15	0.17	0.24	0.21	0.10
Total HFCs, PFCs, SF_6, and NF_3	**3,400**	**2,300**	**1,200**	**1,200**	**1,000**	**1,000**	**1,200**

+ Does not exceed 0.5 MT.

Note: Table does not sum due to independent rounding.

Table 4-65: Emissions of Other Fluorinated GHGs from Production of Fluorochemicals Other Than HCFC-22 (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
Octafluorotetrahydrofuran	2.4	1.9	+	0.1	+	+	+
1,1,1,2,2,3,3-Heptafluoro-3-(1,2,2,2-tetrafluoroethoxy)-propane	+	+	+	+	+	+	+
Trifluoromethyl sulphur pentafluoride	1.2	0.9	+	0.1	+	+	+
Hexafluoropropylene oxide	0.3	0.3	0.3	0.3	+	+	+
FC-3283/FC-8270 (Perfluorotripropylamine)	+	+	+	+	+	+	+
Others	0.8	0.5	0.1	0.1	0.1	+	+
Total Other Fluorinated GHGs	**4.7**	**3.7**	**0.6**	**0.6**	**0.1**	**0.1**	**0.1**

+ Does not exceed 0.5 MT.

Note: Table does not sum due to independent rounding.

Table 4-66: Emissions of Other Fluorinated GHGs from Production of Fluorochemicals Other Than HCFC-22 (Metric Tons)

Gas	1990	2005	2018	2019	2020	2021	2022
Octafluorotetrahydrofuran	170	140	4	4	2	1	2
1,1,1,2,2,3,3-Heptafluoro-3-(1,2,2,2-tetrafluoroethoxy)-propane	6	4	5	6	3	6	3
Trifluoromethyl sulphur pentafluoride	66	53	3	4	1	1	1
Hexafluoropropylene oxide	34	34	32	32	2	2	2

FC-3283/FC-8270 (Perfluorotripropylamine)	+	+	+	+	1	1	1
Others	170	120	76	84	35	33	35
Total Other Fluorinated GHGs	450	350	120	130	43	43	45

+ Does not exceed 0.5 MT.

Note: Table does not sum due to independent rounding.

Table 4-67: Production and Transformation of Fluorinated GHGs (kt)[a]

Set of Facilities	**1990**	**2005**	**2018**	**2019**	**2020**	**2021**	**2022**
Facilities reporting their F-GHG emissions, production, and transformation to GHGRP after 2010[b]	86	271	376	371	352	348	370
Facilities reporting only their F-GHG production and transformation to GHGRP after 2010	3.3	3.3	11.2	9.7	8.2	7.5	11.2
Total Production and Transformation	89	274	387	381	360	356	381

[a] Totals are presented across species to protect confidential business information.

[b] Includes 1 facility that reported production, but not emissions, of SF_6 through 2010.

Note: Tables may not sum due to independent rounding.

Methodology

The *2006 IPCC Guidelines* as elaborated by the 2019 Refinement include Tier 1, Tier 2, and Tier 3 methods for estimating fluorinated GHG emissions from production of fluorinated compounds. The Tier 1 method calculates emissions by multiplying a default emission factor by total production. Specific default emission factors exist for production of SF_6 and NF_3; a more general default emission factor covers production of all other fluorinated GHGs. (The more general default emission factor was developed based on data from U.S. facilities collected under the GHGRP between 2011 and 2016.) The Tier 2 method calculates emissions using a mass-balance approach. The Tier 3 method is based on the collection of plant-specific data on the types and quantities of fluorinated GHGs emitted from process vents, leaks, container venting, and other sources, considering any abatement technology. The Tier 3 method is often implemented by developing and applying facility-specific emission factors indexed to production.

Based on available data on emissions and activity, EPA used a form of the IPCC Tier 3 method to estimate fluorinated GHG emissions from most U.S. production of fluorinated compounds. Emissions from U.S. production for which there are fewer data are based on the Tier 1 method.

Overview of GHGRP Data for this Source Category

As discussed further below, much of the data used to develop the estimates presented here come from the GHGRP. The data were collected under two sections of the GHGRP regulation—Subpart L, Fluorinated Gas Production; and Subpart OO, Suppliers of Industrial Greenhouse Gases. Under Subpart L, certain fluorinated gas production facilities must report their emissions from a range of processes and sources, detailed further below. Data collected under Subpart L include emissions data for calendar years 2011 through 2022. Under Subpart OO, fluorinated GHG suppliers (including fluorinated GHG producers) must report the quantities of each fluorinated GHG that they produce, transform, destroy, import, or export. Data collected under Subpart OO include production and transformation data for calendar years 2010 through 2022. Facilities' production and transformation data are not shown here because they are considered confidential business information under the GHGRP.

Emissions Reported Under Subpart L of the GHGRP

Under Subpart L, facilities that produce a fluorinated gas must report their greenhouse gas emissions if the facility emits 25,000 MT CO_2 Eq. or more per year in combined emissions from fluorinated gas production, stationary fuel combustion units, miscellaneous uses of carbonate, and all other applicable source categories listed in the rule. (For purposes of calculating emissions from fluorinated gas production for inclusion in the total that is compared to the threshold, emissions are assumed to be uncontrolled.) Facilities must report their fluorinated GHG emissions from the production and transformation of fluorinated gases, from venting of residual fluorinated GHGs from containers, and from destruction of previously produced fluorinated GHGs. The emissions reported from production and transformation include both emissions from process vents and emissions from equipment leaks.

Under the GHGRP, "fluorinated GHGs," whose emissions must be reported, include SF_6, NF_3, and any fluorocarbon except for substances with vapor pressures below 1 Torr at 25 degrees C and substances that are regulated as "controlled substances" under EPA's ozone-protection regulations at 40 CFR Part 82, Subpart A (e.g., chlorofluorocarbons [CFCs], hydrochlorofluorocarbons [HCFCs], and halons). In addition to SF_6 and NF_3, this definition includes hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), hydrofluoroethers (HFEs), fully fluorinated tertiary amines, perfluoropolyethers (including PFPMIE), and hydrofluoropolyethers, and others. "Fluorinated gases," from whose production or transformation emissions must be reported, include the fluorinated GHGs detailed above as well as CFCs and HCFCs.[57]

Facilities calculate emissions from process vents using one of two methods. For vents that emit 10,000 MT CO_2 Eq. or more (considering controls) of fluorinated GHGs from continuous processes, facilities must use emissions testing to establish an emission factor at least every ten years, or sooner if the process changes in a way that will significantly affect emissions from the vent. For other process vents, facilities may use measurements, engineering calculations, or engineering assessments to establish the emission factor. Facilities then calculate their annual emissions based on the measured or calculated emission factor and related activity data, considering the extent to which the process is controlled and any destruction device or process malfunctions.

To calculate emissions from equipment leaks, facilities that report under Subpart L are required to collect information on the number and type of pieces of equipment; service of each piece of equipment; concentration of each fluorinated GHG in the stream; and the time period each piece of equipment was in service. Facilities use one or more of the following methods to calculate emissions from equipment leaks (EPA 1995):

- Average Emission Factor Approach in EPA Protocol for Equipment Leak Estimates.
- Other Approaches in EPA Protocol for Equipment Leak Estimates in conjunction with EPA Method 21.
- Other Approaches in EPA Protocol for Equipment Leak Estimates in conjunction with site-specific leak detection methods.
- Site-specific leak detection methods.

Most emissions are reported by chemical; the exceptions are (1) fluorinated GHGs that are emitted in quantities of 1,000 MT CO_2 Eq. or less across all production and transformation processes at a facility and (2) fluorinated GHGs that are emitted from facilities that produce only one fluorinated GHG, where the emitted fluorinated GHG is not the fluorinated gas produced. In these cases, the emissions are reported in CO_2 Eq. by fluorinated GHG group. There are 12 fluorinated GHG groups, each of which encompasses a set of GHGs with roughly similar atmospheric behavior, including similar GWPs and atmospheric lifetimes. These include, e.g., fully fluorinated GHGs such as PFCs and SF_6, saturated HFCs with two or fewer hydrogen-carbon bonds, saturated HFCs with more than two carbon-hydrogen bonds, unsaturated HFCs and PFCs, and others (see Table 4-68 for a full list).

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[57] HCFC-22 is considered a fluorinated gas under the GHGRP, but emissions from HCFC-22 production are reported separately from emissions from production of other fluorinated gases.

Table 4-68: Fluorinated GHG Groups Under Which Certain Emissions Are Reported Under Subpart L of the GHGRP and Associated GWPs

Fluorinated GHG Group	GHGRP Default Global Warming Potential (100-yr.)
Fully fluorinated GHGs	10,000
Saturated hydrofluorocarbons (HFCs) with 2 or fewer carbon-hydrogen bonds	3,700
Saturated HFCs with 3 or more carbon-hydrogen bonds	930
Saturated hydrofluoroethers (HFEs) and hydrochlorofluoroethers (HCFEs) with 1 carbon-hydrogen bond	5,700
Saturated HFEs and HCFEs with 2 carbon-hydrogen bonds	2,600
Saturated HFEs and HCFEs with 3 or more carbon-hydrogen bonds	270
Fluorinated formates	350
Fluorinated acetates, carbonofluoridates, and fluorinated alcohols other than fluorotelomer alcohols	30
Unsaturated PFCs, unsaturated HFCs, unsaturated HCFCs, unsaturated halogenated ethers, unsaturated halogenated esters, fluorinated aldehydes, and fluorinated ketones	1
Fluorotelomer alcohols	1
Fluorinated GHGs with carbon-iodine bond(s)	1
Other fluorinated GHGs	2,000

Two other datasets reported under Subpart L are relevant to estimating uncontrolled emission factors. (As discussed further below, such uncontrolled emission factors are applied to years before Subpart L reporting began (for CY 2011) and before emission controls were put into place.) First, in addition to reporting emissions by chemical at the facility level, facilities report emissions from each production and transformation process at the facility in tons of CO_2 Eq. by fluorinated GHG group. To calculate CO_2 Eq. emissions, facilities use a chemical-specific 100-year GWP where one is available for the compound of interest. If no chemical-specific 100-year GWP is available for the compound of interest, facilities use the GHGRP default GWP for the fluorinated GHG group of which the compound is a member. These default GWPs are shown in Table 4-63.

Second, for each process, facilities also report the extent to which emissions are abated (the effective destruction efficiency or EDE) as a range. The EDE is calculated as follows:

$$EDE = 1 - \frac{CE_{PV}}{UE_{PV}}$$

where:

EDE = Effective destruction efficiency of the process

CE_{PV} = Actual GWP-weighted controlled emissions from all vents for the process, MT CO_2 Eq.

UE_{PV} = Hypothetical GWP-weighted uncontrolled emissions from all vents for the process, MT CO_2 Eq. (CE_{PV} will equal UE_{PV} if the process is not controlled, resulting in a calculated EDE of 0).

Note that the EDE is based on the extent to which emissions from process vents are controlled. Emissions from equipment leaks are not included in the EDE calculation. Table 4-69 provides the EDE ranges available for facilities to report and the arithmetic means of each range. The use of these datasets to calculate uncontrolled emission factors is discussed in more detail in the “1990-2010 Emissions Estimates” section below.

Verification of GHGRP Reports

Data reported under the GHGRP, including emissions and production, are electronically verified using range checks, internal consistency checks, and time-series consistency checks. Where the data fail a preliminary check, EPA contacts the facility to see whether there is an explanation for the issue or whether the data are indeed erroneous. In the latter case, facilities are required to correct the data. Where one or more of the anomalous data elements is not explained or corrected, the report for that facility for that year is considered unverified.

1990-2010 Emissions Estimates

For 14 of the 17 fluorinated gas production facilities that have reported their emissions under the GHGRP, 1990 through 2010 emissions are estimated using (1) facility- and chemical-specific emission factors based on the emissions data discussed under “2011-2022 Emissions” below, (2) reported or estimated production and transformation of fluorinated GHGs at each facility in each year, i.e., activity data, and (3) reported and estimated levels of emissions control at each facility in each year. (For the other 3 fluorinated ga production facilities that have reported their emissions under the GHGRP, 1990 through 2010 emissions were estimated using data submitted by the company, as explained further below.)

Facility- and Chemical-Specific Emission Factors Reflecting Emissions Controls

Facility- and chemical-specific emission factors were developed based on the 2011 to 2015 emissions reported under the GHGRP (discussed above) and the 2011 to 2015 production and transformation of fluorinated GHGs reported under the GHGRP. (Production and transformation of CFCs and HCFCs are not reported under the GHGRP.) For each emitted fluorinated GHG at each facility, emissions of the fluorinated GHG were summed over the five-year period. This sum was then divided by the sum of the quantities of all fluorinated GHGs produced or transformed at the facility over the five-year period.[58] As discussed further below in the Uncertainty section, emissions of any particular fluorinated GHG are likely to occur only from a subset of the production or transformation processes at each facility, but in the absence of information on chemical-specific emissions at the process level, it was assumed that all fluorinated GHG production and transformation processes at the facility emit all fluorinated GHGs at the facility. This yielded the emission factors for each fluorinated GHG at each facility. Both emissions and activity (production + transformation) totals were summed over the five-year period to account for the intermittent and variable nature of some emissions and production/transformation processes. Compounds that were not emitted or produced/transformed between 2011 and 2015 but that were emitted or produced/transformed later were assumed not to have been emitted or produced/transformed (as applicable) before 2011.

Facility- and Chemical-Specific Emission Factors Reflecting No Emissions Controls

The 2011 to 2015 emissions reported under the GHGRP reflect emissions controls to the extent those are implemented at each facility. Because facilities have not always controlled their fluorinated GHG emissions since 1990, uncontrolled emission factors were developed for each facility to apply to years when the facility’s emissions were not believed to be controlled. To estimate uncontrolled emissions, GHGRP data were first used to assess the 2011 to 2015 levels of control for each production or transformation process at each facility.

To calculate uncontrolled emissions from each process and fluorinated GHG group, a point estimate of the effective destruction efficiency (EDE, described above) was required and was estimated using the arithmetic mean

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[58] Permit data for two facilities indicated that they began controlling emissions at some point between 2011 and 2015. However, the actual emissions reported by these facilities did not change substantially after the date when the permit indicated that controls were imposed. For this reason, the reported 2011 to 2015 emissions and emission factors are believed to be representative of emissions for these facilities before 2011.

of the lower and upper bounds of the EDE range reported for the process.[59] This was consistent with the approach taken in the *2019 Refinement* to develop the Tier 1 factor for fluorinated gas production facilities. The reported vented emissions for each process and fluorinated GHG group were divided by (1 - arithmetic mean EDE) to obtain the estimated uncontrolled emissions from process vents for that process and fluorinated GHG group. For each fluorinated GHG group, the controlled emissions across processes (including emissions from both vents and leaks) and the uncontrolled emissions across processes (including emissions from both vents and leaks) were then summed, and the first was divided by the second. This yielded an average level of control for each fluorinated GHG group at each facility. All fluorinated GHGs within each fluorinated GHG group at each facility were assumed to be controlled to the same level. To estimate the uncontrolled emissions of each fluorinated GHG within each group at each facility, the emissions of each fluorinated GHG were divided by the level of control estimated for its fluorinated GHG group at the facility. The same procedure was used to estimate uncontrolled emission factors as had been used to estimate controlled emission factors: the estimated uncontrolled 2011 to 2015 emissions of each fluorinated GHG were summed, and this sum was divided by the sum of the quantities of all fluorinated GHGs produced or transformed at the facility from 2011 to 2015.

Table 4-69: Destruction Efficiency Range Values Used to Estimate Pre-Abatement Emissions for Production and Transformation Processes

DE ranges	Lower Bound	Upper Bound	Arithmetic Mean of Bounds
>=0% to <75%	0.0	0.75	0.375
>=75% to <95%	0.75	0.95	0.85
>=95% to <99%	0.95	0.99	0.97
>=99%	0.99	0.9999	0.995

Estimated Levels of Emissions Controls

As discussed above, both uncontrolled emission factors and controlled emission factors were developed for each facility and fluorinated GHG; these emission factors were developed for estimating emissions from production and transformation processes for years 1990 to 2010. The following information and assumptions were used to determine whether and when emissions from facilities were likely to have been controlled from 1990 to 2010. For the estimated status of emissions controls at each facility reporting under Subpart L, and, where relevant, the starting year for those controls, see Table 4-70.

- Facilities with publicly available information on the presence and use of control devices were assumed to control their emissions starting in the year specified in the publicly available information. Publicly available information included operating permits, news articles on facility modifications, company press releases, etc. Where the publicly available information documents that a control device was in place beginning in a certain year, the facility was assumed to control process emissions beginning in that year, and the controlled emission factor was used in estimating emissions for that year and the following years. The uncontrolled emission factor was used to estimate emissions in earlier years.
- In the absence of other control information, facilities that never reported DRE ranges other than “>=0% to <75%” for their production and transformation processes during reporting years 2011 and 2012 were assumed to have no control devices in place during the time period 1990 to 2012.
- Facilities that reported DRE ranges other than “>=0% to <75%” for at least one production or transformation process for 2011 or 2012 but for which other control information was not available were assumed to have begun controlling their emissions in 2005.

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[59] Note that facilities would report a range of 0% to 75% even if they do not abate emissions at all; thus, the assumption that emissions are 37.5 percent controlled may overestimate the hypothetical uncontrolled emissions of some facilities, e.g., those that do not abate any emissions.

Table 4-70: Estimated Starting Years for Emission Controls at Each Fluorinated Gas Production Facility Reporting under Subpart L of the GHGRP

Facility Name	Estimated Start Year	Basis of Estimation
3M COMPANY	No controls	Never reported a DRE range other than ">=0% to <75%"
3M CORDOVA	2003	Climate News Article[60]
3M Cottage Grove Center - Site	2016	Reported a DRE range other than ">=0% to <75%" for the first time in 2016
Airgas Therapeutics LLC - Scott Medical Products	No controls	Never reported a DRE range other than ">=0% to <75%"
ANDERSON DEVELOPMENT COMPANY	No controls	Never reported a DRE range other than ">=0% to <75%"
ARKEMA, INC.	2005	Reported a DRE range other than ">=0% to <75%" in 2011
Chemours - Corpus Christi Plant	No controls	Never reported a DRE range other than ">=0% to <75%"
CHEMOURS CHAMBERS WORKS	2005	Reported a DRE range other than ">=0% to <75%" in 2011
CHEMOURS COMPANY - FAYETTEVILLE WORKS	2015	Reported a DRE range other than ">=0% to <75%" for the first time in 2015
CHEMOURS EL DORADO	2005	Reported a DRE range other than ">=0% to <75%" in 2011
CHEMOURS LOUISVILLE WORKS	No controls	Never reported a DRE range other than ">=0% to <75%"
CHEMOURS WASHINGTON WORKS	2005	Reported a DRE range other than ">=0% to <75%" in 2011
DAIKIN AMERICA INC.	1993	Title V operating permit[61]
HONEYWELL INTERNATIONAL INC - BATON ROUGE PLANT	2012	Title V operating permit[62]
HONEYWELL INTERNATIONAL INC - GEISMAR COMPLEX	2011	Title V operating permit[63]
Honeywell Metropolis	No controls	Never reported a DRE range other than ">=0% to <75%" (did not report under Subpart L)
MEXICHEM FLUOR INC.	1993	Title V operating permit[64]
Versum Materials US, LLC	No controls	Never reported a DRE range other than ">=0% to <75%"

Activity Data

The activity data for production and transformation of fluorinated compounds for 1990 to 2010 are based on production and transformation data reported to EPA by certain facilities for certain years, on production capacity data, and on fluorinated GHG production and consumption trends estimated for the various fluorinated GHG-consuming industries.

Production and Production Capacity Data

Production data are available from reporting to the U.S. GHGRP under Subpart OO, Suppliers of Industrial Greenhouse Gases, and from an industry survey conducted by U.S. EPA in 2008 and 2009. Production and transformation data were reported under Subpart OO for 2010 and later years. The responses to the industry survey included production data for certain fluorinated gases at certain facilities for the years 2004, 2005, and

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[60] See https://insideclimatenews.org/news/29122022/3m-cordova-illinois-pfas-cf4-pollution/.

[61] Daikin (2013) http://lf.adem.alabama.gov/WebLink/DocView.aspx?id=29951882&dbid=0.

[62] Honeywell (2011) https://edms.deq.louisiana.gov/app/doc/view?doc=8579001.

[63] Honeywell (2012) https://edms.deq.louisiana.gov/app/doc/view?doc=7812895.

[64] See https://edms.deq.louisiana.gov/app/doc/view?doc=1309650.

2006. 2004 to 2006 production data are available for 15 fluorinated compounds. Year 2006 production at an SF_6-producing facility was estimated based on production capacity data as described below (Rand 2007). Production of certain compounds at one other facility was estimated based on 2003 production capacity estimates from SRI 2004.

Estimated Production

Estimated production for facilities and fluorinated GHGs for which production or production capacity data were available for some years before 2010.

For facilities and fluorinated GHGs for which production or production capacity data were available for 2006 or 2003, production between 2006 or 2003 (as applicable) and 2010 (or 2011) was estimated by interpolating between the 2006 production or 2003 production capacity value and the 2010 (or 2011) production value reported under Subpart OO.

For the years before the earliest year with production or production capacity data (e.g., years 1990 to 2002 or 2003), production was estimated based on growth or consumption trends for the major industries using each fluorinated GHG.

- For fluorinated compounds that are commonly emitted in the semiconductor industry, estimates of U.S. layer-weighted semiconductor production (Total Manufactured Layer Area, or TMLA) were used to inform the fluorinated compound production estimates (EPA 2023c). Fluorinated compound production values were assumed to vary with TMLA from 1990 to 2002 or 2003. For example, 1998 production of PFC-14 at a particular facility was estimated by multiplying the 2003 production of PFC-14 at that facility by the ratio between the TMLA estimated for 1998 and the TMLA estimated for 2003. Fluorinated compounds for which TMLA was used to estimate production include PFC-14, PFC-116, PFC-218, perfluorocyclobutane (c-C_4F_8), and NF_3. (Note that the TMLA data were also extrapolated from year 1995 to 1990 based on the average change per year from 1995 to 2009.)

- SF_6 is commonly used in electric power systems, magnesium production, and electronics manufacturing. SF_6 consumption estimates across these three industries for 1990 to 2003 were used to inform the SF_6 production data (EPA 2023d); SF_6 production was assumed to vary with consumption totals from 1990 to 2003.

- For HFCs commonly used as replacements for ozone-depleting substances (ODS), such as HFCs used as substitutes for CFCs and HCFCs in air-conditioning and refrigeration equipment, HFC production data for certain fluorinated compounds from the Vintaging Model (VM) were used to inform the HFC production estimates (EPA 2023b). HFC production values were assumed to vary with the VM estimates of production. The industry trend data were applied to the list of HFCs in Table 4-71.

Table 4-71: List of Saturated HFCs, Unsaturated HFCs (Hydrofluoroolefins or HFOs), and Unsaturated HCFCs (Hydrochlorofluoroolefins or HCFOs) whose 1990-2009 Production Was Estimated Using Vintaging Model, Virgin Manufacturing by Chemical

Fluorinated Gas
HFC-23
HFC-32
HFC-125
HFC-134a
HFC-143a
HFC-152a
HFC-236fa
HFC-245fa
HFC-365mfc
HCFO-1233zd(E)
HFO-1234yf
HFO-1234ze
HFO-1336mzz(Z)
HFC-4310mee

Estimated production for facilities and fluorinated GHGs for which production data before 2010 were not available.

In the absence of production data for the period 1990 to 2009, the production data reported to the GHGRP under Subpart OO were extrapolated backward based on the industry trends discussed above. For compounds for which industry trend data were unavailable, production was assumed to have remained constant over the time series.

In both cases, 2009 production was estimated by conducting a trend analysis on the Subpart OO production data for years 2010 to 2015. In instances where there did not appear to be a trend, the average of the production values for years 2010 to 2015 was used as the estimated production for year 2009. In instances where there was a trend, the year 2010 (or 2011) production value was used as the estimated production for year 2009.

If the industry trend information discussed above was applicable to a fluorinated compound, it was assumed that production varied with the industry trend from 1990 to 2009. If no industry trend information was available, it was assumed that production from 1990 to 2008 remained constant at the 2009 value.

For facilities and fluorinated compounds where information was available on annual production capacity, the estimated activity data was reviewed and compared to the known production capacity. For instances where the estimated activity data exceeded known production capacity for a certain year, the production estimate was set equal to the capacity value. In addition, where information was available on the starting year for production of a fluorinated GHG at a facility, production was only estimated beginning in the process startup year through 2009.

Estimated Emissions for 3M Facilities

3M provided 1990, 1995, 2000, and 2002 through 2010 emissions data for three facilities: 3M Cordova, 3M Company, and 3M Cottage Grove Center - Site.[65] Therefore, speciated 1990-2010 emissions at these facilities were estimated using a different methodology than that described above.[66]

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[65] For 1990, 1995, and 2000, 3M provided emissions data for a Pilot Development Center in addition to the other three facilities. Emissions by group from the Pilot Development Center were added to and are represented by the emissions by group for 3M Cottage Grove Center – Site.

[66] 3M's methods for estimating its emissions are described in detail in "3M Global EHS Laboratory Response to EPA Data Request on Fluorochemical Emissions," February 2024 (3M, 2024). In brief, 3M estimated emissions from its processes using

3M emissions data were provided by facility and by fluorinated GHG group in metric tons of CO_2 Eq., weighted by 100-year GWPs from various IPCC Assessment Reports. The fluorinated GHG groups included HFCs, PFCs, SF_6, HFEs, and other fluorinated GHGs. (3M noted that the "other fluorinated GHG" category included NF_3.) GWPs from the IPCC *Third Assessment Report* (TAR) were used to report totals for 1990, 1995, 2000, and 2003 to 2006. GWPs from the IPCC *Fifth Assessment Report* (AR5) was used to report totals for 2002, and GWPs from the IPCC *Fourth Assessment Report* (AR4) were used to report totals for 2007 to 2010. The emissions were also categorized as emissions from electrochemical fluorination (ECF) processes and downstream (DS) emissions. The DS emissions for 1990, 1995, and 2000 were reported as a total for each facility rather than by fluorinated GHG group.

To present emissions estimates by compound, EPA needed to disaggregate the data provided by 3M. The first step was to disaggregate the 1990, 1995, and 2000 DS emissions into fluorinated GHG groups. Since the 2003 to 2006 data were calculated using the same set of GWPs as the 1990, 1995, and 2000 data, the DS emissions of each group at each facility for 2003 to 2006 were divided by the total DS 2003 to 2006 emissions at that facility to obtain a set of fractions. These fractions were then multiplied by the 1990, 1995, and 2000 DS totals to sort those emissions into groups.

For 2002, ECF and DS emissions were only reported under the PFC group. (3M noted that chemical classifications were not preserved when 2002 emissions were recalculated using GWP values from AR5.) Since data for every other year showed emissions reported from multiple fluorinated GHG groups, and since 2004 was the closest year with emissions well sorted into fluorinated GHG groups, the ECF and DS emissions for 2002 were separated into multiple fluorinated GHG groups using the 2004 ECF and DS groups shares for each facility.

The next step was to disaggregate the emissions of each fluorinated GHG group into emissions of the relevant compounds in that group. To accomplish this, EPA assumed that emissions of each fluorinated GHG group before 2011 consisted of the same fluorinated GHGs, in the same proportions, as from 2011 through 2015. However, each compound's share of the GWP-weighted emissions of the group in a given year depends on the GWPs used for that compound and for the other compounds in the group in that year. To account for this, EPA multiplied the reported 2011 to 2015 emissions of each compound in metric tons by the corresponding GWPs for that compound from the TAR, AR4, and AR5 to generate three sets of emissions by compound in metric tons of CO_2 Eq. For each set, the sum of emissions across 2011 to 2015 for each compound were divided by the total emissions for the corresponding fluorinated GHG group for those five years to calculate shares for each group.

The 3M emissions data by group for 1990, 1995, 2000, and 2002 to 2010 were then speciated by compound using the appropriate set of share values for each year. Since 3M Company only reported emissions of one compound in 2011 to 2015 but had emissions from multiple fluorinated GHG groups in 1990, 1995, 2000, and 2002 to 2010, the share values for 3M Cordova were used to speciate the 1990, 1995, 2000, and 2002-2010 emissions by group for 3M COMPANY. The speciated emissions in metric tons of CO_2 Eq. by compound for each facility were then divided by the appropriate TAR, AR4, or AR5 GWP for each compound to obtain the estimated emissions in metric tons of each compound for 1990, 1995, 2000, and 2002 to 2010.

Linear interpolation was then used to estimate emissions for 1991 to 1994, 1996 to 1999, and 2001 for each compound for these three facilities.

Estimated Emissions for Facilities that Produce Fluorinated GHGs but Do Not Report Under Subpart L

There is a subset of facilities that report production and transformation of fluorinated gases under Subpart OO and that also have emission levels less than the threshold value for reporting under Subpart L (i.e., uncontrolled emissions below the 25,000-MT CO_2 Eq. threshold). For these facilities, EPA developed emission estimates based on aggregated production estimates and the Tier 1 default emission factor in the 2019 Refinement. Because the

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emission factors that were developed using methods similar to those used for developing emission factors under the GHGRP. As under the GHGRP, emission factors were multiplied by different types of activity data (e.g., production) to estimate emissions for each facility and year. In 2003 and later years, 3M also accounted for emission reductions attributable to operation of the thermal oxidizer at the Cordova plant.

specific fluorinated GHGs emitted are not known, the emissions were assumed to consist of the fluorinated GHGs shown in Table 3.28b of chapter 3.10.2 of Volume 3 IPPU (IPCC 2019), in the proportions shown in that table. Emissions are assumed to have been flat at the 2010 value in the years before 2010.

Estimated Emissions for SF_6 Production Facility

For an SF_6 production facility that ceased production in 2010, the year before emissions from fluorinated gas production were required to be reported under the GHGRP, SF_6 emissions were estimated using historical production capacity, the global growth rate of SF_6 sales reported in RAND 2007, and the Tier 1 default emission factor for production of SF_6 in the 2019 Refinement. For this plant, a 1982 SF_6 production capacity of 1,200 short tons (Perkins 1982) was multiplied by the ratio between the RAND survey SF_6 sales totals for 2006 and 1982, 1.52 (RAND 2007), resulting in estimated production of 1,652 metric tons in 2006. This production was assumed to have declined linearly to zero in 2011.

2011-2022 Emissions Estimates

For the 17 fluorinated gas production facilities that have reported their emissions under the GHGRP, 2011 to 2022 emissions are estimated using the fluorinated GHG emissions reported under Subpart L of the GHGRP.

As discussed above, most emissions reported under Subpart L are reported by chemical, but some emissions are reported only by fluorinated GHG group in MT CO_2 Eq. Between 2011 and 2022, the share of total CO_2 Eq. emissions reported only by fluorinated GHG group has ranged between 1 and 2 percent. In this analysis, to ensure that all emissions are reported by species, emissions that are reported only by fluorinated GHG group are assumed to consist of the fluorinated GHGs in that group that are reported by chemical at the facility. As discussed further in the Uncertainty section, this is likely to result in incorrect speciation of some emissions, but the impact of this incorrect speciation is expected to be small.

Estimated Emissions for Facilities that Produce Fluorinated GHGs but Do Not Report Under Subpart L

As discussed above, for facilities that produce fluorinated GHGs but that do not report their emissions under subpart L, EPA developed emission estimates based on aggregated production estimates and the Tier 1 default emission factor in the 2019 Refinement. Because the specific fluorinated GHGs emitted are not known, the emissions were assumed to consist of the fluorinated GHGs shown in Table 3.28b of chapter 3.10.2 of Volume 3 IPPU (IPCC 2019), in the proportions shown in that table.

Uncertainty

The estimates in this memo are subject to a number of uncertainties. These uncertainties are generally greater for years before 2011, when reporting of fluorinated GHG emissions from fluorinated gas production began under the GHGRP, than for 2011 and following years. However, the emissions estimated from 2011 to 2022 are also subject to various uncertainties. The uncertainties for both the 1990 to 2010 and 2011 to 2022 periods are discussed in more detail below.

1990-2010 Uncertainty

The uncertainty of emissions estimated for 1990 through 2010 is considerably greater than that for emissions for 2011 through 2022 because emissions were not reported under the GHGRP. EPA has estimated emissions using estimated emission rates, fluorochemical production and transformation activity, and levels of control, and each set of estimates is subject to uncertainty.

Uncertainty regarding activity data

Identity of emitting processes

In reality, emissions of particular fluorinated GHGs are linked to production and/or transformation of particular fluorinated gases at facilities. However, GHGRP information/data does not link emissions of specific fluorinated GHGs to production or transformation of specific fluorinated gases. For the estimates presented here, therefore, all emissions are indexed to total production across all fluorinated gases. This may not capture trends in emissions that are driven by trends in production or transformation of subsets of the fluorinated gases produced at a facility.

Produced and emitted gases change over time

The set of gases produced at a facility, and therefore the set of fluorinated GHGs that are emitted by that facility, may change over time. It is likely that certain production and transformation processes that existed from 2011 to 2015 (the basis of the emission factors used to back-cast emissions in this analysis) did not exist throughout the entire previous time series (1990 to 2010). In such cases, emissions of the fluorinated GHGs emitted from the new processes will be overestimated by this analysis for certain years before 2011. On the other hand, it is also likely that some production and transformation processes, and their associated fluorinated GHG emissions, occurred only during the 1990 to 2010 period and not later, meaning that their emissions are not represented in the emission factors developed based on the 2011 to 2015 emissions and production data collected under the GHGRP. Such emissions will therefore not be captured by this analysis. The most prominent example of the second situation is probably production of CFCs and HCFCs other than HCFC-22 between 1990 and 2009, which has declined steadily since 1990 as the production of CFCs and HCFCs for emissive uses has been phased out under the Montreal Protocol and Clean Air Act. Production of CFCs and HCFCs can sometimes result in emissions of HFCs or PFCs.

Quantity of produced gases

Where production or production capacity data were available for certain fluorinated gases, facilities, and years before 2010, those data were incorporated into this analysis. However, even for facilities and compounds for which data were available in certain years, there were several years for which data were not available. For multiple produced compounds, data were available only in 2010. To estimate trends in production of compounds for years before production or production capacity data were available, production of certain compounds was indexed to known national production or consumption trends for those compounds. This is the case for most HFCs, several PFCs, SF_6, and NF_3. National production estimates are available for HFCs, increasing confidence in country-level production estimates, but the distribution of production among the various HFC-producing facilities is uncertain. Where estimated production was indexed to consumption (for several PFCs, SF_6, and NF_3), the uncertainty is larger than for HFCs because changes in net imports/exports (which are not known) may also affect the production trend.

For certain fluorinated gases, trend information was not available; therefore, production was back-cast by assuming that it had remained constant at the 2010 level from 1990 through 2009. This is a highly uncertain assumption.

Some production and transformation activity is not reported under Subpart OO or modeled in back-casting

Under Subpart OO, quantities of fluorinated GHGs that are produced and transformed at the same facility are not reported to us, although any emissions from such processes are reported under Subpart L. Such unreported production and transformation are therefore not captured in the 1990 to 2010 activity estimates used to estimate 1990 through 2010 emissions. To the extent that such unreported production and transformation drive emissions and change over time, the trends will not be captured by this analysis.

Facilities that no longer produce fluorinated gases or that started producing them after 1990

Some facilities may have produced fluorinated gases at some point between 1990 and 2010 that no longer produced those compounds after 2010. One SF_6 producer is known to fall into this category and its 1990 to 2010 emissions were estimated, but there may be other facilities that are not included in this analysis. On the other hand, some facilities for which 1990 to 2010 emissions were estimated may not have produced them over the entire time series, in which case emissions of the compounds those facilities are assumed to have emitted could be overestimated.

Uncertainty regarding emission factors

Emission rates change over time

The emission factors used to estimate 1990 to 2010 emissions are based on the emissions and production reported from 2011 to 2015, reflecting emission rates during that period. For processes that have been used throughout the timeseries, emission rates may have changed over time as the process was optimized to increase efficiency, decreasing by-product emissions, or alternatively, as the process was optimized to maximize production, which sometimes increases by-product emissions. Emission rates also depend on the extent to which emissions are controlled at the facility, the uncertainties for which are discussed further below.

Emissions from container venting and destruction may not scale with production

In this analysis, emissions from container venting and destruction of previously produced fluorinated GHGs were included in the emission factors used to estimate 1990 to 2010 emissions. This implicitly assumes that such emissions scale with production and transformation. While this seems likely to be broadly true, there may be exceptions. However, since emissions from container venting and destruction are generally a small share of facility emissions (2 percent, on average), the impact of such exceptions is expected to be small.

Uncertainty regarding levels of control

In this analysis, the arithmetic mean of the DRE range reported by each facility for each process was used to estimate the DRE for that process and the uncontrolled emissions for that process. Since the emissions implied by the bounds of each DRE range span at least a factor of four,[67] this is an uncertain assumption. The uncertainty is mitigated somewhat by the fact that there are generally several processes at each facility, meaning that departures from the assumed mean average out to some extent. There is also uncertainty in the assumptions that (1) all fluorinated GHGS within a particular fluorinated GHG group are abated to the same extent and (2) facilities for which control device start dates are unavailable began to control emissions in 2005.

Quantitative uncertainty estimate for uncontrolled emission factors from *2019 Refinement*

As noted above, 2011 to 2016 data from the GHGRP was used to develop the Tier 1 default uncontrolled emission factor for the *2019 Refinement*, using methods similar to those described here. A Monte Carlo analysis performed to assess the uncertainty of the Tier 1 default factor indicated that the uncertainty for each facility's uncontrolled emission factor was less than 50 percent. This uncertainty estimate considered the uncertainty regarding the levels of control, but not the uncertainty of applying factors from one time period at the facility to much earlier time period (although the variability of each facility's emission factor over the 6-year span of the *2019 Refinement* analysis was found to be relatively low).

Uncertainty regarding the identity of 3M emitted compounds

For the three 3M facilities that submitted their 1990 through 2010 emissions by fluorinated GHG group, it is assumed that the emissions of each group consist of the compounds in that group that were reported by species by the facility from 2011 through 2014. However, 3M indicated that the mix of products made at its facilities had changed over time, which would have affected the identities of the fluorinated GHGs emitted. For example, at one facility, only one compound was reported to be emitted for 2011-2015 but 3M's historical emissions data showed multiple fluorinated GHG groups for that facility for 1990 to 2010. For that facility, it is assumed that emissions consisted of the compounds in each gas type that were reported by species by the 3M facility that was determined to be the most similar. Additionally, there were a few years of data for these three facilities where some emissions were reported as a total rather than separated by group. For these years, the group shares were assumed to be

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[67] For example, the DRE range 0 to 75% implies emissions of (1-0) x uncontrolled emissions to (1-75%) x uncontrolled emissions, or, rearranging and calculating, 0.25 x uncontrolled emissions to 1 x uncontrolled emissions, a factor of four.

the same as in nearby years. There is uncertainty involved with each of the assumptions made while speciating emissions for these three facilities, though the uncertainty is minimal regarding total emissions in metric tons of CO_2 Eq. In at least one case, the speciation method appears to have resulted in an overestimate for an individual compound. In this analysis, 3M's emissions of C_4F_8O are estimated to have peaked at around 410 MT in 2000, but at least one study has inferred considerably lower global emissions (around 120 MT) for that year based on atmospheric measurements of C_4F_8O (Vollmer et al. 2019).

2011-2022 Uncertainty

Emissions from 2011 to 2022 reflect reporting by fluorinated gas production facilities under the GHGRP. As discussed above, emissions reported under the GHGRP are based on facility- and process-specific measurements or calculations and are therefore expected to be reasonably accurate for the reporting facilities. (Emissions from the largest sources, process vents emitting 10,000 MT CO_2 Eq. or more annually, are estimated using Tier 3 methods.)

Unverified reports

Ninety-five percent (171/180) of the Subpart L reports submitted by fluorinated gas production facilities from 2011 to 2022 are considered to be fully verified; five percent (9/180) of the reports include one or more data elements that are not verified. One facility accounts for two thirds (6/9) of the unverified reports. Many of the issues in the unverified reports for this facility relate to time-series inconsistencies that have arisen as the facility updates reports for recent years, but not previous years, to reflect refinements to estimated emission rates. This facility has accounted for between 6 percent (in 2011) and 29 percent (in 2022) of the GWP-weighted emissions reported for this source category. The uncertainties for this facility therefore have an appreciable impact on the uncertainty of the estimates for the source category as a whole, particularly in years before 2022.

Facilities that do not produce fluorinated gases but may emit fluorinated GHGs from other fluorochemical production processes

Under the GHGRP, EPA collects information from facilities that produce fluorinated gases. While this likely includes most, and possibly all, U.S. facilities that produce fluorochemicals of any kind, it is possible that some fluorochemical producers do not report either their production of fluorochemicals or their emissions of fluorinated GHGs to EPA under the GHGRP. In this case, emissions estimates based only on GHGRP reporting would underestimate actual emissions.

At fluorinated gas production facilities that currently report their emissions under the GHGRP, it is possible that some processes that emit fluorinated GHGs neither produce nor transform a fluorinated gas, in which case their emissions would not be reported under the GHGRP. In that case, emissions estimates based only on GHGRP reporting would underestimate actual emissions.

Exclusion of nitrous oxide

The GHGRP does not currently require facilities to report emissions of nitrous oxide (N_2O) from fluorinated gas production or transformation, but the IPCC *2019 Refinement* includes a default emission factor for N_2O from production of NF_3, implying such emissions may occur. The GHGRP data (and this analysis) may therefore underestimate emissions of N_2O from fluorinated gas production. Because the GWP of N_2O is considerably lower than that of saturated HFCs, PFCs, and other fluorinated GHGs, any underestimate is expected to be relatively small.

Identity of emitted compounds

In this analysis, it is assumed that emissions that are reported only in MT CO_2 Eq. by fluorinated GHG group consist of the compounds in that group that are reported by species by the facility. However, if that were actually the case, emissions of those compounds would have been included in the speciated emissions rather than reported separately in MT CO_2 Eq. This analysis therefore incorrectly speciates some emissions. As noted in the Methodology section, the share of total CO_2 Eq. emissions reported only by fluorinated GHG group is small, ranging between 1 and 2 percent. Moreover, while the emissions are not assigned to the exact species emitted, they are assigned to a species that is closely related and likely to have similar atmospheric impacts (e.g., another saturated HFC with two or fewer carbon-hydrogen bonds). The impact of this uncertainty is therefore limited.

Quantities of Reactants Consumed or Fluorinated Gases Produced

The emissions reported under Subpart L are required to be calculated using process activity data, such as the quantity of reactants consumed or the quantity of the fluorinated gas product produced. In general, the uncertainties in process activity levels are expected to be small. The *2019 Refinement* places such uncertainties "in the region of 1 percent."

Because the uncertainties enumerated above are either small or difficult to quantify, EPA did not attempt to include them in the 2022 quantitative uncertainty estimate for this source category. The 2022 quantitative uncertainty estimate includes the following uncertainties:

Process Vent Emission Factors

Process vent emission factors that were developed based on stack testing (for continuous process vents emitting 10,000 MT CO_2 Eq. or more) were estimated to have an uncertainty (95-percent confidence interval) of ±35 percent based on Subpart L requirements.[68] Process vent emission factors that were developed based on calculations (for batch process vents and for continuous process vents emitting less than 10,000 MT CO_2 Eq.) were estimated to have a larger uncertainty of ±50 percent. Continuous processes were assumed to have two vents per process; batch processes were assumed to have five vents per process.[69]

Equipment Leak Estimates

The estimated equipment leaks reported by each facility for each process were estimated to have an uncertainty of ± 90 percent. The uncertainty of leak estimates depends on the method used to estimate leaks; there are multiple methods. For simplicity, this analysis uses a conservatively high uncertainty estimate that is appropriate for the Average EF Approach.

Venting of Residual Gas in Containers

The reported emissions of fluorinated GHGs from venting of residual gas in returned containers were estimated to have an uncertainty of ± 30 percent for each facility. This estimate is based on the Subpart L requirement to either measure the contents of each container or to measure the contents of at least 30 representative containers for each compound and container size and type.

Facilities that produce fluorinated gases but do not report their emissions to the GHGRP

EPA estimated emissions for fluorinated gas production facilities that do not report their emissions under Subpart L of the GHGRP. The estimates presented here for 2011 to 2022 are based on aggregated production estimates, the Tier 1 default emission factor in the *2019 Refinement*, and the default fluorinated GHG speciation from Table 3.28b (chapter 3.10.2 of *2019 Refinement*). There is considerable uncertainty in both the magnitude of the emissions and the identity of the emitted compounds. The *2019 Refinement* estimates the uncertainty of the Tier 1 emission factor as -98 percent to +470 percent. (In the quantitative uncertainty estimate below, which is based on error propagation, values of ±98 percent were used because error propagation requires the assumption of symmetric uncertainty bounds.) In 2022, estimated emissions from the six non-reporting facilities accounted for 44 percent of total estimated U.S. emissions from fluorinated gas production and transformation. In contrast,

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[68] *Technical Support Document for Emissions from Production of Fluorinated Gases*, Office of Air and Radiation, U.S. Environmental Protection Agency, November 5, 2010. Available online at: https://www.epa.gov/sites/default/files/2015-02/documents/subpart-l_techsuppdoc.pdf.

[69] *Economic Impact Analysis for the Mandatory Reporting of Greenhouse Gas Emissions F-Gases: Subparts I, L, DD, QQ, SS*, U.S. Environmental Protection Agency, November 2010. Available online at: https://www.regulations.gov/document/EPA-HQ-OAR-2009-0927-0179.

production and transformation by these facilities accounted for just three percent of total fluorinated GHG production and transformation across all facilities. Because the emissions estimated for several of the six facilities exceeded the 25,000 MT CO_2 Eq. reporting threshold under Subpart L, but these facilities have not reported their emissions under Subpart L, it appears likely that emissions from at least some facilities are overestimated.

The four uncertainties listed immediately above were convolved using error propagation to arrive at an overall uncertainty estimate for 2022. The results of the Approach 1 quantitative uncertainty analysis are summarized in Table 4-72. Emissions of HFCs, PFCs, SF_6, and NF_3 from production of fluorochemicals other than HCFC-22 were estimated to fall between 4.83 and 7.08 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 19 percent below and 19 percent above the emission estimate of 5.95 MMT CO_2 Eq.

Table 4-72: Approach 1 Quantitative Uncertainty Estimates for HFC, PFC, SF_6, and NF_3 from Production of Fluorochemicals other than HCFC-22 (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate (%)	
			Lower Bound[a]	Upper Bound[a]	Lower Bound	Upper Bound
Production of Fluorochemicals other than HCFC-22	HFCs, PFCs, SF_6, and NF_3	5.95	4.83	7.08	-19%	+19%

[a] Absolute lower and upper bounds were calculated using the corresponding lower and upper bounds in percentages.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). Under the GHGRP, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[70] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

The GHGRP also requires source-specific quality control measures for the Fluorinated Gas Production category. Under the GHGRP, fluorinated gas producers are required to (1) develop and periodically update process vent-specific emission factors using either measurements or engineering calculations, depending on the nature of the process (continuous vs. batch) and the magnitude of emissions from the vent, (2) take more measurements of vent emissions where variability is high, (3) use methods for sampling, measuring volumetric flow rates, non-fluorinated-GHG gas analysis, and measuring stack gas moisture that have been validated using a scientifically sound validation protocol, (4) use a quality-assured analytical measurement technology capable of detecting the analyte of interest at the concentration of interest and use a sampling and analytical procedure validated with the analyte of interest at the concentration of interest, (5) periodically test the performance of destruction devices used to control emissions, (6) account for any malfunctions in the process or destruction device, (6) account for emissions from equipment leaks, (7) measure the quantities of residual gas that are vented from returned containers (or develop an emission factor based on at least 30 measurements per gas and container size and type), (8) calibrate mass measurement devices at the frequency recommended by the manufacturer using traceable

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[70] EPA (2015). Greenhouse Gas Reporting Program Report Verification. Available online at: https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

standards and suitable methods published by a consensus standards organization, (9) calibrate analytical equipment used to determine the concentration of fluorinated GHGs, and (10) document all measurements and calibrations.

The 1990, 1995, 2000, and 2002 through 2010 emissions data reported by 3M for three facilities was compared to the 1990 through 2010 emissions previously calculated for those facilities using the same calculation method used for other facilities that have reported their emissions under the GHGRP since 2011. The overall trajectory of the 3M-reported emissions, as well as the minima and maxima of those emissions, were similar to those previously calculated, but the increases and decreases in the 3M-reported emissions were more gradual. 3M explained that the gradual changes were due to changes in the compounds and quantities produced and to the gradual deployment and optimization of the destruction device at the 3M Cordova facility.

Recalculations

This is a new category included for the current (i.e., 1990 to 2022) *Inventory*, thus, no recalculations were performed.

Planned Improvements

EPA is planning to refine its estimates of emissions from non-reporting facilities after confirming with the facilities that their actual per-facility uncontrolled emissions fall below 25,000 MT CO_2 Eq.. EPA is also planning to refine its estimates of emissions for other facilities between 1990 and 2009, e.g., by comparing these against emissions inferred from atmospheric measurements. Moreover, EPA is continuing to seek datasets that can be used to improve and/or QA/QC emissions estimates, particularly for the years 1990 to 2009. These datasets may include, for example, real-time facility-specific estimates or additional global “top-down,” atmosphere-based emissions estimates that could be used to establish an upper limit on emissions of certain compounds.

4.16 Carbon Dioxide Consumption (CRT Source Category 2B10)

Carbon dioxide (CO_2) is used for a variety of commercial applications, including food processing, chemical production, carbonated beverage production, and refrigeration, and is also used in petroleum production for enhanced oil recovery (EOR). CO_2 used for EOR is injected underground to enable additional petroleum to be produced. For the purposes of this analysis, CO_2 used in food and beverage applications is assumed to be emitted to the atmosphere. This reporting category (2B10) includes emissions from IPCC assessment reports that do not fall within any other CRT source category, which includes emissions from CO_2 consumption. A further discussion of CO_2 used in EOR is described in the Energy chapter in Box 3-6 titled “Carbon Dioxide Transport, Injection, and Geological Storage” and is not included in this section.

Carbon dioxide is produced from naturally-occurring CO_2 reservoirs, as a byproduct from the energy and industrial production processes (e.g., ammonia production, fossil fuel combustion, ethanol production), and as a byproduct from the production of crude oil and natural gas, which contain naturally occurring CO_2 as a component.

In 2022, the amount of CO_2 produced and captured for commercial applications and subsequently emitted to the atmosphere was 5.0 MMT CO_2 Eq. (5,000 kt) (see Table 4-73 and Table 4-74). This is less than a 1 percent increase (10 kt) from 2021 levels and is an increase of approximately 240 percent (3,528 kt) since 1990.

Table 4-73: CO_2 Emissions from CO_2 Consumption (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
CO_2 Consumption	1.5	1.4	4.1	4.9	5.0	5.0	5.0

Table 4-74: CO_2 Emissions from CO_2 Consumption (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
CO_2 Consumption	1,472	1,375	4,130	4,870	4,970	4,990	5,000

Methodology and Time-Series Consistency

Carbon dioxide emission estimates for 1990 through 2022 utilize a country-specific method and were based on the quantity of CO_2 extracted and transferred for industrial applications (i.e., non-EOR end-uses). Some of the CO_2 produced by these facilities is used for EOR, and some is used in other commercial applications (e.g., chemical manufacturing, food and beverage). The IPCC does not have specific methodological guidelines for CO_2 consumption, but the country-specific methodology used is consistent with a Tier 3 approach since it relies on facility-specific information.

2010 through 2022

For 2010 through 2022, data from EPA's GHGRP (Subpart PP) were aggregated from facility-level reports to develop a national-level estimate for use in the *Inventory* (EPA 2023). Facilities report CO_2 extracted or produced from natural reservoirs and industrial sites, and CO_2 captured from energy and industrial processes and transferred to various end-use applications to EPA's GHGRP. This analysis includes only reported CO_2 transferred to food and beverage end-uses. EPA is continuing to analyze and assess integration of CO_2 transferred to other end-uses to enhance the completeness of estimates under this source category. Other end-uses include industrial applications, such as metal fabrication. EPA is analyzing the information reported to ensure that other end-use data excludes non-emissive applications and publication will not reveal CBI. Additionally, a small amount of CO_2 is used as a refrigerant; use and emissions from this application are reported under Section 4.25 Substitution of Ozone Depleting Substances (CRT Source Category 2F). Reporters subject to EPA's GHGRP Subpart PP are also required to report the quantity of CO_2 that is imported and/or exported. Currently, these data are not publicly available through the GHGRP due to data confidentiality reasons and hence are excluded from this analysis.

Facilities subject to Subpart PP of EPA's GHGRP are required to measure CO_2 extracted or produced. More details on the calculation and monitoring methods applicable to extraction and production facilities can be found under Subpart PP: Suppliers of Carbon Dioxide of the regulation, Part 98[71] The number of facilities that reported data to EPA's GHGRP Subpart PP (Suppliers of Carbon Dioxide) for 2010 through 2022 is much higher (ranging from 44 to 53) than the number of facilities included in the *Inventory* for the 1990 to 2009 time period prior to the availability of GHGRP data (4 facilities). The difference is largely due to the fact the 1990 to 2009 data includes only CO_2 transferred to end-use applications from naturally occurring CO_2 reservoirs and excludes industrial sites.

1990 through 2009

For 1990 through 2009, data from EPA's GHGRP are not available. For this time period, CO_2 production data from four naturally-occurring CO_2 reservoirs were used to estimate annual CO_2 emissions. These facilities were Jackson Dome in Mississippi, Bravo and West Bravo Domes in New Mexico, and McCallum Dome in Colorado. The facilities in Mississippi and New Mexico produced CO_2 for use in both EOR and in other commercial applications (e.g.,

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[71] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

chemical manufacturing, food production). The fourth facility in Colorado (McCallum Dome) produced CO_2 for commercial applications only (New Mexico Bureau of Geology and Mineral Resources 2006).

Carbon dioxide production data and the percentage of production that was used for non-EOR applications for the Jackson Dome, Mississippi facility were obtained from Advanced Resources International (ARI 2006, 2007) for 1990 to 2000, and from the Annual Reports of Denbury Resources (Denbury Resources 2002 through 2010) for 2001 to 2009 (see Table 4-75). Denbury Resources reported the average CO_2 production in units of MMCF CO_2 per day for 2001 through 2009 and reported the percentage of the total average annual production that was used for EOR. Production from 1990 to 1999 was set equal to 2000 production, due to lack of publicly available production data for 1990 through 1999. Carbon dioxide production data for the Bravo Dome and West Bravo Dome were obtained from ARI for 1990 through 2009 (ARI 1990 to 2010). Data for the West Bravo Dome facility were only available for 2009. The percentage of total production that was used for non-EOR applications for the Bravo Dome and West Bravo Dome facilities for 1990 through 2009 were obtained from New Mexico Bureau of Geology and Mineral Resources (Broadhead 2003; New Mexico Bureau of Geology and Mineral Resources 2006). Production data for the McCallum Dome (Jackson County), Colorado facility were obtained from the Colorado Oil and Gas Conservation Commission (COGCC) for 1999 through 2009 (COGCC 2014). Production data for 1990 to 1998 and percentage of production used for EOR were assumed to be the same as for 1999, due to lack of publicly available data.

Table 4-75: CO_2 Production (kt CO_2) and the Percent Used for Non-EOR Applications

Year	Jackson Dome, MS CO_2 Production (kt) (% Non-EOR)	Bravo Dome, NM CO_2 Production (kt) (% Non-EOR)	West Bravo Dome, NM CO_2 Production (kt) (% Non-EOR)	McCallum Dome, CO CO_2 Production (kt) (% Non-EOR)	Total CO_2 Production from Extraction and Capture Facilities (kt)	% Non-EOR[a]
1990	1,344 (100%)	63 (1%)	+	65 (100%)	NE	NE
2005	1,254 (27%)	58 (1%)	+	63 (100%)	NE	NE
2018	IE	IE	IE	IE	58,400[b]	7%
2019	IE	IE	IE	IE	61,300[b]	8%
2020	IE	IE	IE	IE	44,700[b]	11%
2021	IE	IE	IE	IE	43,980[b]	11%
2022	IE	IE	IE	IE	46,800[b]	11%

+ Does not exceed 0.5 percent.

NE (Not Estimated)

IE (Included Elsewhere)

[a] Includes only food and beverage applications.

[b] For 2010 through 2022, the publicly available GHGRP data were aggregated at the national level based on GHGRP CBI criteria. The Dome-specific CO_2 production values are accounted for (i.e., included elsewhere) in the Total CO_2 Production from Extraction and Capture Facilities values starting in 2010 and are not able to be disaggregated.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022. The methodology for CO_2 consumption spliced activity data from two different sources: Industry data for 1990 through 2009 and GHGRP data starting in 2010. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the two data sets for years where there was overlap (IPCC 2006). The data sets were determined to be inconsistent; the GHGRP data include CO_2 from industrial sources while the industry data do not. No adjustments were made to the activity data for 1990 through 2009 because the *2006 IPCC Guidelines* indicate that it is not good practice to use the overlap technique when the data sets are inconsistent.

Uncertainty

There is uncertainty associated with the data reported through EPA's GHGRP. Specifically, there is uncertainty associated with the amount of CO_2 consumed for food and beverage applications, given the GHGRP does have provisions that Subpart PP reporters are not required to report to the GHGRP if their emissions fall below certain thresholds, in addition to the exclusion of the amount of CO_2 transferred to all other end-use categories. This latter category might include CO_2 quantities that are being used for non-EOR industrial applications such as firefighting. Second, uncertainty is associated with the exclusion of imports/exports data for CO_2 suppliers. Currently these data are not publicly available through EPA's GHGRP and hence are excluded from this analysis. EPA verifies annual facility-level reports through a multi-step process (e.g., combination of electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred.[72] Given the lack of specific uncertainty ranges available on the data used, EPA assigned an uncertainty range of ±5 percent and a normal probability density function for CO_2 consumed for food and beverage applications. The uncertainty range is derived from the default range for solvent use in Section 5.5 of Chapter 3 of the *2006 IPCC Guidelines*. These values are representative of CO_2 used in food and beverage based on expert judgment (RTI 2023).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-76. Carbon dioxide consumption CO_2 emissions for 2022 were estimated to be between 4.8 and 5.2 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 5 percent below to 5 percent above the emission estimate of 5.0 MMT CO_2 Eq.

Table 4-76: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from CO_2 Consumption (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
CO_2 Consumption	CO_2	5.0	4.8	5.2	-5%	+5%

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

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to CO_2 Consumption can be found under Subpart PP (Suppliers of Carbon Dioxide) of the regulation (40 CFR Part 98).[73] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[74] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

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

[73] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

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

Planned Improvements

EPA will continue to evaluate the potential to include additional GHGRP data on other emissive end-uses to improve the accuracy and completeness of estimates for this source category. Particular attention will be made to ensuring time-series consistency of the emissions estimates presented in future *Inventory* reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this *Inventory*. In implementing improvements and integration of data from EPA's GHGRP, EPA will rely on the latest guidance from the IPCC on the use of facility-level data in national inventories.[75]

These improvements are still in process and will be incorporated into future *Inventory* reports. These are near-to medium-term improvements.

4.17 Phosphoric Acid Production (CRT Source Category 2B10)

Phosphoric acid (H_3PO_4) is a basic raw material used in the production of phosphate-based fertilizers. Phosphoric acid production from natural phosphate rock is a source of carbon dioxide (CO_2) emissions, due to the chemical reaction of the inorganic carbon (calcium carbonate) component of the phosphate rock. This reporting category (2B10) includes emissions that do not fall within any other CRT source category, which includes production of phosphoric acid. Emissions from fuels consumed for energy purposes during the production of phosphoric acid are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Phosphate rock is mined in Florida and North Carolina, which account for more than 75 percent of total domestic output, and in Idaho and Utah (USGS 2023). It is used primarily as a raw material for wet-process phosphoric acid production. The composition of natural phosphate rock varies, depending on the location where it is mined. Natural phosphate rock mined in the United States generally contains inorganic carbon in the form of calcium carbonate (limestone) and may also contain organic carbon.

The phosphoric acid production process involves chemical reaction of the calcium phosphate ($Ca_3(PO_4)_2$) component of the phosphate rock with sulfuric acid (H_2SO_4) and recirculated phosphoric acid (H_3PO_4) (EFMA 2000). Phosphate rock also contains naturally occurring limestone ($CaCO_3$), ranging from 0.2 to 4.5 percent (as CO_2), with domestic phosphate rock from Florida containing 3.1 percent limestone (as CO_2) (EFMA 2000). The generation of CO_2 from limestone in the phosphate rock is from the associated limestone-sulfuric acid reaction, as shown below:

$$CaCO_3 + H_2SO_4 + H_2O \rightarrow CaSO_4 \cdot 2H_2O + CO_2$$

Total U.S. phosphate rock production in 2022 was an estimated 21 million metric tons (USGS 2023). Between 1990 and 2022, domestic phosphate rock production decreased by approximately 58 percent. Total imports of phosphate rock to the United States in 2022 were 2.4 million metric tons (USGS 2023). Between 2018 and 2021, most of the imported phosphate rock (95 percent) came from Peru, with 5 percent from Morocco (USGS 2023). All phosphate rock mining companies in the United States are vertically integrated with fertilizer plants that produce phosphoric acid located near the mines.

Total CO_2 emissions from phosphoric acid production were 0.8 MMT CO_2 Eq. (840 kt CO_2) in 2022 (see Table 4-77 and Table 4-78). Domestic consumption of phosphate rock in 2022 was estimated to have decreased 3.9 percent

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

relative to 2021 levels. The COVID-19 pandemic did not impact the domestic phosphate rock market as both the fertilizer industry and related agricultural businesses were considered essential industries and were unaffected by pandemic "stay-at-home" orders issued in March 2020 (USGS 2021a).

Table 4-77: CO_2 Emissions from Phosphoric Acid Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Phosphoric Acid Production	1.5	1.3	0.9	0.9	0.9	0.9	0.8

Table 4-78: CO_2 Emissions from Phosphoric Acid Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Phosphoric Acid Production	1,529	1,342	937	909	901	874	840

Methodology and Time-Series Consistency

The United States uses a country-specific methodology consistent with and comparable to an IPCC Tier 1 approach to calculate emissions from production of phosphoric acid from phosphate rock based on the stoichiometry of the process reaction shown above. The *2006 IPCC Guidelines* do not provide a method for estimating process emissions (CO_2) from phosphoric acid production. Carbon dioxide emissions from production of phosphoric acid from phosphate rock are estimated by multiplying the average amount of inorganic carbon (expressed as CO_2) contained in the natural phosphate rock as calcium carbonate by the amount of phosphate rock that is used annually to produce phosphoric acid, accounting for domestic production and net imports for consumption. The estimation methodology is as follows:

Equation 4-10: CO_2 Emissions from Phosphoric Acid Production

$$E_{pa} = C_{pr} \times Q_{pr}$$

where,

E_{pa} = CO_2 emissions from phosphoric acid production, metric tons

C_{pr} = Average amount of carbon (expressed as CO_2) in natural phosphate rock, metric ton CO_2/ metric ton phosphate rock

Q_{pr} = Quantity of phosphate rock used to produce phosphoric acid

The CO_2 emissions calculation methodology assumes that all of the inorganic carbon (calcium carbonate) content of the phosphate rock reacts to produce CO_2 in the phosphoric acid production process and is emitted with the stack gas. The methodology also assumes that none of the organic carbon content of the phosphate rock is converted to CO_2 and that all of the organic carbon content remains in the phosphoric acid product.

From 1993 to 2004, the U.S. Geological Survey (USGS) *Mineral Yearbook: Phosphate Rock* disaggregated phosphate rock mined annually in Florida and North Carolina from phosphate rock mined annually in Idaho and Utah, and reported the annual amounts of phosphate rock exported and imported for consumption (see Table 4-79). For the years 1990 through 1992, and 2005 through 2022, only nationally aggregated mining data was reported by USGS. For the years 1990, 1991, and 1992, the breakdown of phosphate rock mined in Florida and North Carolina and the amount mined in Idaho and Utah are approximated using data reported by USGS for the average share of U.S. production in those states from 1993 to 2004. For the years 2005 through 2022, the same approximation method is used, but the share of U.S. production was assumed to be consistent with the ratio of production capacity in those states, which were obtained from the USGS commodity specialist for phosphate rock (USGS 2012; USGS 2021b). For 1990 through 2022, data on U.S. domestic consumption of phosphate rock, consisting of domestic reported sales and use of phosphate rock, exports of phosphate rock (primarily from Florida and North Carolina), and imports of phosphate rock for consumption, were obtained from USGS *Minerals Yearbook: Phosphate Rock*

(USGS 1994 through 2015b) and from USGS *Minerals Commodity Summaries: Phosphate Rock* (USGS 2016 through 2021a, 2022). From 2004 through 2022, the USGS reported no exports of phosphate rock from U.S. producers (USGS 2022).

The carbonate content of phosphate rock varies depending upon where the material is mined. Composition data for domestically mined and imported phosphate rock were provided by the Florida Institute of Phosphate Research, now known as the Florida Industrial and Phosphate Research Institute (FIPR 2003a). Phosphate rock mined in Florida contains approximately 1 percent inorganic C, and phosphate rock imported from Morocco contains approximately 1.46 percent inorganic C. Calcined phosphate rock mined in North Carolina and Idaho contains approximately 0.41 percent and 0.27 percent inorganic C, respectively (see Table 4-79). Similar to the phosphate rock mined in Morocco, phosphate rock mined in Peru contains approximately 5 percent CO_2 (Golder Associates and M3 Engineering 2016).

Carbonate content data for phosphate rock mined in Florida are used to calculate the CO_2 emissions from consumption of phosphate rock mined in Florida and North Carolina (more than 75 percent of domestic production), and carbonate content data for phosphate rock mined in Morocco and Peru are used to calculate CO_2 emissions from consumption of imported phosphate rock. The CO_2 emissions calculation assumes that all of the domestic production of phosphate rock is used in uncalcined form. As of 2006, the USGS noted that one phosphate rock producer in Idaho produces calcined phosphate rock; however, no production data were available for this single producer (USGS 2006). The USGS confirmed that no significant quantity of domestic production of phosphate rock is in the calcined form (USGS 2012).

Table 4-79: Phosphate Rock Domestic Consumption, Exports, and Imports (kt)

Location/Year	1990	2005	2018	2019	2020	2021	2022
U.S. Domestic Consumption[a]	49,800	35,200	23,300	23,400	22,600	21,900	21,000
FL and NC	*42,494*	*28,160*	*18,170*	*18,250*	*17,630*	*17,080*	*16,380*
ID and UT	*7,306*	*7,040*	*5,130*	*5,150*	*4,970*	*4,820*	*4,620*
Exports—FL and NC	6,240	0	0	0	0	0	0
Imports	451	2,630	2,770	2,140	2,520	2,460	2,400
Total U.S. Consumption	**44,011**	**37,830**	**26,070**	**25,540**	**25,120**	**24,360**	**23,400**

[a] U.S. domestic consumption values are based on reported phosphate rock sold or used by producers.

Note: Totals may not sum due to independent rounding.

Table 4-80: Chemical Composition of Phosphate Rock (Percent by Weight)

Composition	Central Florida	North Florida	North Carolina (calcined)	Idaho (calcined)	Morocco	Peru
Total Carbon (as C)	1.60	1.76	0.76	0.60	1.56	NA
Inorganic Carbon (as C)	1.00	0.93	0.41	0.27	1.46	NA
Organic Carbon (as C)	0.60	0.83	0.35	0.00	0.10	NA
Inorganic Carbon (as CO_2)	3.67	3.43	1.50	1.00	5.00	5.00

NA (Not Available)

Sources: FIPR (2003a), Golder Associates and M3 Engineering (2016)

Methodological approaches were applied to the entire time series to ensure consistency in emissions estimates from 1990 through 2022.

Uncertainty

Phosphate rock production data used in the emission calculations were developed by the USGS through monthly and semiannual voluntary surveys of the active phosphate rock mines during 2021. Prior to 2006, USGS provided the data disaggregated regionally; however, beginning in 2006, only total U.S. phosphate rock production was reported. Regional production for 2021 was estimated based on regional production data from 2017 to 2020 and multiplied by regionally-specific emission factors. There is uncertainty associated with the degree to which the estimated 2021 regional production data represents actual production in those regions. Total U.S. phosphate rock production data are not considered to be a significant source of uncertainty because all the domestic phosphate rock producers report their annual production to the USGS. Data for exports of phosphate rock used in the emission calculations are reported to the USGS by phosphate rock producers and are not considered to be a significant source of uncertainty. Data for imports for consumption are based on international trade data collected by the U.S. Census Bureau. These U.S. government economic data are not considered to be a significant source of uncertainty. Based on expert judgement of the USGS, EPA assigned an uncertainty range of ±5 percent to the percentage of phosphate rock produced from Florida and North Carolina, and ±5 percent to phosphoric acid production and imports (USGS 2012). Per this expert judgment, a normal probability density function was assigned for all activity data.

An additional source of uncertainty in the calculation of CO_2 emissions from phosphoric acid production is the carbonate composition of phosphate rock, as the composition of phosphate rock varies depending upon where the material is mined and may also vary over time. The *Inventory* relies on one study (FIPR 2003a) of chemical composition of the phosphate rock; limited data are available beyond this study. Another source of uncertainty is the disposition of the organic carbon content of the phosphate rock. A representative of FIPR indicated that in the phosphoric acid production process, the organic carbon content of the mined phosphate rock generally remains in the phosphoric acid product, which is what produces the color of the phosphoric acid product (FIPR 2003b). Organic carbon is therefore not included in the calculation of CO_2 emissions from phosphoric acid production.

A third source of uncertainty is the assumption that all domestically-produced phosphate rock is used in phosphoric acid production and used without first being calcined. Calcination of the phosphate rock would result in conversion of some of the organic carbon in the phosphate rock into CO_2; however, according to air permit information available to the public, at least one facility has calcining units permitted for operation (NCDENR 2013).

Finally, USGS indicated that in 2021 less than 5 percent of domestically-produced phosphate rock was used to manufacture elemental phosphorus and other phosphorus-based chemicals, rather than phosphoric acid (USGS 2022). According to USGS, there is only one domestic producer of elemental phosphorus, in Idaho, and no data were available concerning the annual production of this single producer. Elemental phosphorus is produced by reducing phosphate rock with coal coke, and it is therefore assumed that 100 percent of the carbonate content of the phosphate rock will be converted to CO_2 in the elemental phosphorus production process. The calculation for CO_2 emissions assumes that phosphate rock consumption, for purposes other than phosphoric acid production, results in CO_2 emissions from 100 percent of the inorganic carbon content in phosphate rock, but none from the organic carbon content.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-81. 2022 phosphoric acid production CO_2 emissions were estimated to be between 0.7 and 1.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 18 percent below and 20 percent above the emission estimate of 0.8 MMT CO_2 Eq.

Table 4-81: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Phosphoric Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Phosphoric Acid Production	CO_2	0.8	0.7	1.1	-18%	+20%

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

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

Recalculations were performed for 2021 to reflect updated USGS data on the total U.S. production of phosphate rock. This update resulted in a decrease of 35 kt CO_2 in 2021.

Planned Improvements

EPA continues to evaluate potential improvements to the *Inventory* estimates for this source category, which include direct integration of EPA's GHGRP data for 2010 through 2022 along with assessing applicability of reported GHGRP data to update the inorganic carbon content of phosphate rock for prior years to ensure time-series consistency. Specifically, EPA would need to assess that averaged inorganic carbon content data (by region or other approaches) meets GHGRP confidential business information (CBI) screening criteria. EPA would then need to assess the applicability of GHGRP data for the averaged inorganic carbon content (by region or other approaches) from 2010 through 2022, along with other information to inform estimates in prior years in the time series (1990 through 2009) based on the sources of phosphate rock used in production of phosphoric acid over time. In implementing improvements and integration of data from EPA's GHGRP, EPA will rely upon the latest guidance from the IPCC on the use of facility-level data in national inventories.[76] These long-term planned improvements are still in development by EPA and have not been implemented into the current *Inventory* report.

4.18 Iron and Steel Production (CRT Source Category 2C1) and Metallurgical Coke Production

Iron and steel production is a multi-step process that generates process-related emissions of carbon dioxide (CO_2) and methane (CH_4) as raw materials are refined into iron and then transformed into crude steel. This reporting category (2C1) includes emissions from the production of iron and steel. Per the IPCC methodological guidance, emissions from conventional fuels (e.g., natural gas, fuel oil) consumed for energy purposes during the production of iron and steel are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Iron and steel production includes seven distinct production processes: metallurgical coke production, sinter production, direct reduced iron (DRI) production, pellet production, pig iron.[77] production, electric arc furnace

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[76] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf and the *2019 Refinement*, Volume 1, Chapter 2, Section 2.3, *Use of Facility Data in Inventories* at https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch02_DataCollection.pdf.

[77] Pig iron is the common industry term to describe what should technically be called crude iron. Pig iron is a subset of crude iron that has lost popularity over time as industry trends have shifted. Throughout this report, pig iron will be used

(EAF) steel production, and basic oxygen furnace (BOF) steel production. The number of production processes at a particular plant is dependent upon the specific plant configuration. Most process CO_2 generated from the iron and steel industry is a result of the production of crude iron.

In addition to the production processes mentioned above, CO_2 is also generated at iron and steel mills through the consumption of process byproducts (e.g., blast furnace gas, coke oven gas) used for various purposes including heating, annealing, and electricity generation. Process byproducts sold off-site for use as synthetic natural gas are also accounted for in these calculations. In general, CO_2 emissions are generated in these production processes through the reduction and consumption of various carbon-containing inputs (e.g., ore, scrap, flux, coke byproducts). Fugitive CH_4 emissions can also be generated from these processes, as well as from sinter, direct iron, and pellet production.

In 2022, approximately eleven integrated iron and steel steelmaking facilities utilized BOFs to refine and produce steel from iron, and raw steel was produced at 101 facilities across the United States. As of 2020, approximately 29 percent of steel production was attributed to BOFs and 71 percent to EAFs (AISI 2020). The trend in the United States for integrated facilities has been a shift towards fewer BOFs and more EAFs. EAFs use scrap steel as their main input and use significantly less energy than BOFs. There are also 14 cokemaking facilities, of which 3 facilities are co-located with integrated iron and steel facilities (ACCCI 2021). In the United States, seven states account for roughly 61 percent of total raw steel production: Indiana, Alabama, Tennessee, Kentucky, Mississippi, Arkansas, and Ohio (AISI 2023).

Total annual production of crude steel in the United States was fairly constant between 2000 and 2008 and ranged from a low of 99,320,000 tons to a high of 109,880,000 tons (2001 and 2004, respectively). Due to the decrease in demand caused by the global economic downturn (particularly from the automotive industry), crude steel production in the United States sharply decreased to 65,459,000 tons in 2009. Crude steel production was fairly constant from 2011 through 2014, and after a dip in production from 2014 to 2015, crude steel production steadily increased. Crude steel production dipped again in 2020 due to the COVID-19 pandemic and returned to pre-pandemic levels in 2021. Production declined by approximately 6 percent in 2022 (AISI 2023). This decline may be attributable to projections for decreased global end-use consumption due to multiple factors including the conflict in Ukraine, continuing coronavirus disease 2019 (COVID-19) mitigation measures in China, rising energy costs and interest rates, and global inflation (USGS 2023a). The United States was the fourth largest producer of raw steel in the world, behind China, India, and Japan, accounting for approximately 4.3 percent of world production in 2022 (AISI 2004 through 2023).

The majority of CO_2 emissions from the iron and steel production process come from the use of metallurgical coke in the production of pig iron and from the consumption of other process byproducts, with lesser amounts emitted from the use of carbon-containing flux and from the removal of carbon from pig iron used to produce steel.

According to the *2006 IPCC Guidelines*, the production of metallurgical coke from coking coal is considered to be an energy use of fossil fuel, and the use of coke in iron and steel production is considered to be an industrial process source. The *2006 IPCC Guidelines* suggest that emissions from the production of metallurgical coke should be reported separately in the Energy sector, while emissions from coke consumption in iron and steel production should be reported in the Industrial Processes and Product Use sector. The approaches and emission estimates for both metallurgical coke production and iron and steel production, however, are presented here because much of the relevant activity data is used to estimate emissions from both metallurgical coke production and iron and steel production. For example, some byproducts (e.g., coke oven gas) of the metallurgical coke production process are consumed during iron and steel production, and some byproducts of the iron and steel production process (e.g., blast furnace gas) are consumed during metallurgical coke production. Emissions associated with the consumption of these byproducts are attributed at the point of consumption. Emissions associated with the use of conventional

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interchangeably with crude iron, but it should be noted that in other data sets or reports pig iron and crude iron may not be used interchangeably and may provide different values.

fuels (e.g., natural gas, fuel oil) for electricity generation, heating and annealing, or other miscellaneous purposes downstream of the iron and steelmaking furnaces are reported in the Energy chapter.

Metallurgical Coke Production

Emissions of CO_2 from metallurgical coke production in 2022 were 3.0 MMT CO_2 Eq. (2,954 kt CO_2) (see Table 4-82 and Table 4-83). Emissions decreased by 8 percent from 2021 to 2022 and have decreased by 47 percent since 1990. Coke production in 2022 was about 9 percent lower than in 2021 and 59 percent below 1990 (EIA 2023, AISI 2023).

Significant activity data for 2020 through 2022 were not available in time for publication of this report due to industry consolidation that impacts the publication of data without revealing confidential business information. Activity data for these years were estimated using 2019 values adjusted based on GHGRP emissions data, as described in the Methodology and Time-Series Consistency section below.

Table 4-82: CO_2 Emissions from Metallurgical Coke Production (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	5.6	3.9	1.3	3.0	2.3	3.2	3.0

Table 4-83: CO_2 Emissions from Metallurgical Coke Production (kt CO_2)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	5,608	3,921	1,282	3,006	2,325	3,224	2,954

Iron and Steel Production

Emissions of CO_2 and CH_4 from iron and steel production in 2022 were 37.7 MMT CO_2 Eq. (37,718 kt) and 0.0077 MMT CO_2 Eq. (0.3 kt CH_4), respectively (see Table 4-84 through Table 4-87). Emissions from iron and steel production decreased by 2 percent from 2021 to 2022 and have decreased by 62 percent since 1990, due to restructuring of the industry, technological improvements, and increased scrap steel utilization. Carbon dioxide emission estimates include emissions from the consumption of carbonaceous materials in the blast furnace, EAF, and BOF, as well as blast furnace gas and coke oven gas consumption for other activities at the steel mill.

Significant activity data for 2020 through 2022 were not available in time for publication of this report due to industry consolidation that impacts the publication of data without revealing confidential business information. Activity data for these years were estimated using 2019 values adjusted based on GHGRP emissions data, as described in the Methodology and Time-Series Consistency section below.

In 2022, domestic production of pig iron decreased by 11 percent from 2021 levels. Overall, domestic pig iron production has declined since the 1990s; pig iron production in 2022 was 59 percent lower than in 2000 and 60 percent below 1990. Carbon dioxide emissions from iron production have decreased by 81 percent (37.0 MMT CO_2 Eq.) since 1990. Carbon dioxide emissions from steel production have decreased by 16 percent (1.3 MMT CO_2 Eq.) since 1990, while overall CO_2 emissions from iron and steel production have declined by 62 percent (61.4 MMT CO_2 Eq.) from 1990 to 2022.

Table 4-84: CO_2 Emissions from Iron and Steel Production (MMT CO_2 Eq.)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Sinter Production	2.4	1.7	0.9	0.9	0.7	0.8	0.8
Iron Production	45.7	17.7	9.6	9.4	8.4	9.0	8.7
Pellet Production	1.8	1.5	0.9	0.9	0.8	0.8	0.8
Steel Production	8.0	9.4	6.0	5.8	5.7	5.8	6.7
Other Activities[a]	41.2	35.9	24.1	23.2	19.8	22.1	20.8
Total	**99.1**	**66.2**	**41.6**	**40.1**	**35.4**	**38.6**	**37.7**

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[a] Includes emissions from blast furnace gas and coke oven gas combustion for activities at the steel mill other than consumption in blast furnace, EAFs, or BOFs.

Note: Totals may not sum due to independent rounding.

Table 4-85: CO_2 Emissions from Iron and Steel Production (kt CO_2)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Sinter Production	2,448	1,663	937	876	749	836	787
Iron Production	45,709	17,666	9,589	9,365	8,420	9,038	8,673
Pellet Production	1,817	1,503	924	878	751	838	789
Steel Production	7,964	9,395	5,982	5,812	5,657	5,816	6,655
Other Activities[a]	41,194	35,934	24,149	23,158	19,820	22,119	20,814
Total	**99,132**	**66,161**	**41,581**	**40,089**	**35,398**	**38,648**	**37,718**

[a] Includes emissions from blast furnace gas and coke oven gas combustion for activities at the steel mill other than consumption in blast furnace, EAFs, or BOFs.

Note: Totals may not sum due to independent rounding.

Table 4-86: CH_4 Emissions from Iron and Steel Production (MMT CO_2 Eq.)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Sinter Production	+	+	+	+	+	+	+

+ Does not exceed 0.05 MMT CO_2 Eq.

Table 4-87: CH_4 Emissions from Iron and Steel Production (kt CH_4)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Sinter Production	0.9	0.6	+	+	+	+	+

+ Does not exceed 0.5 kt.

Methodology and Time-Series Consistency

Emission estimates for metallurgical coke, EAF steel production, and BOF steel production presented in this chapter utilize a country-specific approach based on Tier 2 methodologies provided by the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. These Tier 2 methodologies call for a mass balance accounting of the carbonaceous inputs and outputs during the iron and steel production process and the metallurgical coke production process. Estimates for pig iron production apply Tier 2 methods consistent with the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. Tier 1 methods are used for certain iron and steel production processes (i.e., sinter production, pellet production and DRI production) for which available data are insufficient to apply a Tier 2 method (e.g., country-specific carbon contents of inputs and outputs are not known). The majority of emissions are captured with higher tier methods, as sinter production, pellet production, and DRI production only account for roughly 8 percent of total iron and steel production emissions.

The Tier 2 methodology equation is as follows:

Equation 4-11: CO_2 Emissions from Coke, Pig Iron, EAF Steel, and BOF Steel Production, based on *2006 IPCC Guidelines* Tier 2 Methodologies

$$E_{CO_2} = \left[\sum_a (Q_a \times C_a) - \sum_b (Q_b \times C_b)\right] \times \frac{44}{12}$$

where,

E_{CO2} = Emissions from coke, pig iron, EAF steel, or BOF steel production, metric tons

a = Input material *a*

b = Output material *b*

Q_a = Quantity of input material *a*, metric tons

C_a = Carbon content of input material *a*, metric tons C/metric ton material

Q_b = Quantity of output material *b*, metric tons

C_b = Carbon content of output material *b*, metric tons C/metric ton material

44/12 = Stoichiometric ratio of CO_2 to C

The Tier 1 methodology equations are as follows:

Equation 4-12: *2006 IPCC Guidelines* Tier 1: Emissions from Sinter, Direct Reduced Iron, and Pellet Production (Equations 4.6, 4.7, and 4.8)

$$E_{s,p} = Q_s \times EF_{s,p}$$

$$E_{d,CO2} = Q_d \times EF_{d,CO2}$$

$$E_{p,CO2} = Q_p \times EF_{p,CO2}$$

where,

$E_{s,p}$ = Emissions from sinter production process for pollutant *p* (CO_2 or CH_4), metric ton

Q_s = Quantity of sinter produced, metric tons

$EF_{s,p}$ = Emission factor for pollutant *p* (CO_2 or CH_4), metric ton *p*/metric ton sinter

$E_{d,CO2}$ = Emissions from DRI production process for CO_2, metric ton

Q_d = Quantity of DRI produced, metric tons

$EF_{d,CO2}$ = Emission factor for CO_2, metric ton CO_2/metric ton DRI

$E_{p,CO2}$ = Emissions from pellet production process for CO_2, metric ton

Q_p = Quantity of pellets produced, metric tons

$EF_{p,CO2}$ = Emission factor for CO_2, metric ton CO_2/metric ton pellets produced

A significant number of activity data that serve as inputs to emissions calculations were unavailable for 2020 through 2022 at the time of publication and were estimated using 2019 values. To estimate annual emissions for these years, the EPA used process emissions data from the EPA's Greenhouse Gas Reporting Program (GHGRP) subpart Q for the iron and steel sector to adjust the estimated values for 2020 through 2022. GHGRP process emissions data decreased by approximately 14 percent from 2019 to 2020, increased by approximately 12 percent from 2020 to 2021, and decreased by approximately 6 percent from 2021 to 2022 (EPA 2023). These percentage changes were applied to 2019 activity data values to produce estimates for 2020 through 2022.

Metallurgical Coke Production

Coking coal is used to manufacture metallurgical coke which is used primarily as a reducing agent in the production of iron and steel but is also used in the production of other metals including zinc and lead (see Zinc Production and Lead Production sections of this chapter). Emissions associated with producing metallurgical coke from coking coal are estimated and reported separately from emissions that result from the iron and steel production process. To estimate emissions from metallurgical coke production, a Tier 2 method provided by the *2006 IPCC Guidelines* was utilized. The amount of carbon contained in materials produced during the metallurgical coke production process (i.e., coke, coke breeze and coke oven gas) is deducted from the amount of carbon contained in materials consumed during the metallurgical coke production process (i.e., natural gas, blast furnace gas, and coking coal). For calculations, activity data for these inputs, including natural gas, blast furnace gas, and coking coke consumed for metallurgical coke production, are in units consistent with the carbon content values. Light oil, which is produced during the metallurgical coke production process, is excluded from the deductions due to data limitations. The amount of carbon contained in these materials is calculated by multiplying the material-specific carbon content by the amount of material consumed or produced (see Table 4-88). The amount of coal tar produced was approximated using a production factor of 0.03 tons of coal tar per ton of coking coal consumed. The amount of coke breeze produced was approximated using a production factor of 0.075 tons of coke breeze per ton of coking coal consumed (Steiner 2008; DOE 2000). Data on the consumption of carbonaceous materials (other than coking coal) as well as coke oven gas production were available for integrated steel mills only (i.e., steel mills with co-located coke plants); therefore, carbonaceous material (other than coking coal) consumption and coke oven gas production were excluded from emission estimates for merchant coke plants. Carbon contained in coke oven gas used for coke-oven underfiring was not included in the deductions to avoid double-counting.

Table 4-88: Material Carbon Contents for Metallurgical Coke Production

Material	kg C/kg
Coal Tar[a]	0.62
Coke[a]	0.83
Coke Breeze[a]	0.83
Coking Coal[b]	0.75
Material	**kg C/GJ**
Coke Oven Gas[c]	12.1
Blast Furnace Gas[c]	70.8

[a] Source: IPCC (2006), Vol. 3 Chapter 4, Table 4.3

[b] Source: EIA (2017b)

[c] Source: IPCC (2006), Vol. 2 Chapter 1, Table 1.3

Although the *2006 IPCC Guidelines* provide a Tier 1 CH_4 emission factor for metallurgical coke production (i.e., 0.1 g CH_4 per metric ton of coke production), it is not appropriate to use because CO_2 emissions were estimated using the Tier 2 mass balance methodology. The mass balance methodology makes a basic assumption that all carbon that enters the metallurgical coke production process either exits the process as part of a carbon-containing output or as CO_2 emissions. This is consistent with a preliminary assessment of aggregated facility-level greenhouse gas CH_4 emissions reported by coke production facilities under EPA's GHGRP. The assessment indicates that CH_4 emissions from coke production are insignificant and below 500 kt or 0.05 percent of total national emissions. Pending resources and significance, EPA continues to assess the possibility of including these emissions in future Inventories to enhance completeness but has not incorporated these emissions into this report.

Data relating to the mass of coking coal consumed at metallurgical coke plants and the mass of metallurgical coke produced at coke plants were taken from the Energy Information Administration (EIA) *Quarterly Coal Report: October through December* (EIA 1998 through 2019) and EIA *Quarterly Coal Report: January through March* (EIA 2021 through 2023) (see Table 4-89). Data on the volume of natural gas consumption, blast furnace gas consumption, and coke oven gas production for metallurgical coke production at integrated steel mills were obtained from the American Iron and Steel Institute (AISI) *Annual Statistical* Report (AISI 2004 through 2023) and through personal communications with AISI (Steiner 2008) (see Table 4-90). These data from the AISI *Annual Statistical Report* were withheld for 2020 through 2022, so the 2019 values were used as estimated data for the missing 2020 through 2022 values and adjusted using GHGRP emissions data, as described earlier in this Methodology and Time-Series Consistency section.

The factor for the quantity of coal tar produced per ton of coking coal consumed was provided by AISI (Steiner 2008). The factor for the quantity of coke breeze produced per ton of coking coal consumed was obtained through Table 2-1 of the report *Energy and Environmental Profile of the U.S. Iron and Steel Industry* (DOE 2000). Data on natural gas consumption and coke oven gas production at merchant coke plants were not available and were excluded from the emission estimate. Carbon contents for metallurgical coke, coal tar, coke oven gas, and blast furnace gas were provided by the *2006 IPCC Guidelines*. The carbon content for coke breeze was assumed to equal the carbon content of coke. Carbon contents for coking coal was from EIA.

Table 4-89: Production and Consumption Data for the Calculation of CO_2 Emissions from Metallurgical Coke Production (Thousand Metric Tons)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Metallurgical Coke Production							
Coking Coal Consumption at Coke Plants	35,269	21,259	16,635	16,261	13,076	15,957	14,523
Coke Production at Coke Plants	25,054	15,167	12,525	11,676	9,392	11,381	10,337
Coke Breeze Production	2,645	1,594	1,248	1,220	981	1,197	1,089
Coal Tar Production	1,058	638	499	488	392	479	436

Table 4-90: Production and Consumption Data for the Calculation of CO_2 Emissions from Metallurgical Coke Production (Million ft^3)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Metallurgical Coke Production							
Coke Oven Gas Production	250,767	114,213	80,750	77,692	66,492	74,206	69,829
Natural Gas Consumption	599	2,996	2,275	2,189	1,873	2,091	1,967
Blast Furnace Gas Consumption	24,602	4,460	4,022	3,914	3,350	3,738	3,518

Iron and Steel Production

To estimate emissions from pig iron production in the blast furnace, the amount of carbon contained in the produced pig iron and blast furnace gas were deducted from the amount of carbon contained in inputs (i.e., metallurgical coke, sinter, natural ore, pellets, natural gas, fuel oil, coke oven gas, carbonate fluxes or slagging materials, and direct coal injection). For calculations, activity data for these inputs, including coke consumed for pig iron production, are in units consistent with the carbon content values. The carbon contained in the pig iron, blast furnace gas, and blast furnace inputs was estimated by multiplying the material-specific carbon content by each material type (see Table 4-91). In the absence of a default carbon content value from the *2006 IPCC Guidelines* for pellet, sinter, or natural ore consumed for pig iron production, a country-specific approach based on Tier 2 methodology is used. Pellet, sinter, and natural ore used as an input for pig iron production is assumed to have the same carbon content as direct reduced iron (2 percent), based on expert judgment (RTI 2024). Carbon in blast furnace gas used to pre-heat the blast furnace air is combusted to form CO_2 during this process. Carbon contained in blast furnace gas used as a blast furnace input was not included in the deductions to avoid double-counting.

Emissions from steel production in EAFs were estimated by deducting the carbon contained in the steel produced from the carbon contained in the EAF anode, charge carbon, and scrap steel added to the EAF. Small amounts of carbon from DRI and pig iron to the EAFs were also included in the EAF calculation. For BOFs, estimates of carbon contained in BOF steel were deducted from carbon contained in inputs such as natural gas, coke oven gas, fluxes (i.e., limestone and dolomite), and pig iron. In each case, the carbon was calculated by multiplying material-specific carbon contents by each material type (see Table 4-91). For EAFs, the amount of EAF anode consumed was approximated by multiplying total EAF steel production by the amount of EAF anode consumed per metric ton of steel produced (0.002 metric tons EAF anode per metric ton steel produced [Steiner 2008]). The amount of carbon-containing flux (i.e., limestone and dolomite) used in EAF and BOF steel production was deducted from the “Other Process Uses of Carbonates” source category (CRT Source Category 2A4) to avoid double-counting.

Carbon dioxide emissions from the consumption of blast furnace gas and coke oven gas for other activities occurring at the steel mill were estimated by multiplying the amount of these materials consumed for these purposes by the material-specific carbon content (see Table 4-91).

Table 4-91: Material Carbon Contents for Iron and Steel Production

Material	kg C/kg
Coke	0.83
Direct Reduced Iron	0.02
Dolomite	0.13
EAF Carbon Electrodes	0.82
EAF Charge Carbon	0.83
Limestone	0.12
Pig Iron	0.04
Steel	0.01
Material	**kg C/GJ**
Coke Oven Gas	12.1
Blast Furnace Gas	70.8

Source: IPCC (2006), Table 4.3. Coke Oven Gas and Blast Furnace Gas, Table 1.3.

Carbon dioxide emissions associated with sinter production, direct reduced iron production, pellet production, pig iron production, steel production, and other steel mill activities were summed to calculate the total CO_2 emissions from iron and steel production (see Table 4-84 and Table 4-85).

The sinter production process results in fugitive emissions of CH_4, which are emitted via leaks in the production equipment, rather than through the emission stacks or vents of the production plants. The fugitive emissions were calculated by applying Tier 1 emission factors taken from the *2006 IPCC Guidelines* for sinter production (see Table 4-92). Although the *2006 IPCC Guidelines* also provide a Tier 1 methodology for CH_4 emissions from pig iron production, it is not appropriate to use because CO_2 emissions for pig iron production are estimated using the Tier 2 mass balance methodology. The mass balance methodology makes a basic assumption that all carbon that enters the pig iron production process either exits the process as part of a carbon-containing output or as CO_2 emissions; the estimation of CH_4 emissions is precluded. Annual analysis of facility-level emissions reported during iron production further supports this assumption and indicates that CH_4 emissions are below 500 kt CO_2 Eq. and well below 0.05 percent of total national emissions. The production of direct reduced iron could also result in emissions of CH_4 through the consumption of fossil fuels (e.g., natural gas, etc.); however, these emission estimates are excluded due to data limitations. Pending further analysis and resources, EPA may include these emissions in future reports to enhance completeness. EPA is still assessing the possibility of including these emissions in future reports and have not included this data in the current report.

Table 4-92: CH_4 Emission Factors for Sinter and Pig Iron Production

Material Produced	Factor	Unit
Sinter	0.07	kg CH_4/metric ton

Source: IPCC (2006), Table 4.2.

Emissions of CO_2 from sinter production, direct reduced iron production, and pellet production were estimated by multiplying total national sinter production, total national direct reduced iron production, and total national pellet production by Tier 1 CO_2 emission factors (see Table 4-93). Because estimates of sinter production, direct reduced iron production, and pellet production were not available, production was assumed to equal consumption.

Table 4-93: CO_2 Emission Factors for Sinter Production, Direct Reduced Iron Production, and Pellet Production

Material Produced	Metric Ton CO_2/Metric Ton
Sinter	0.2
Direct Reduced Iron	0.7
Pellet Production	0.03

Source: IPCC (2006), Table 4.1.

The consumption of coking coal, natural gas, distillate fuel, and coal used in iron and steel production are adjusted for within the Energy chapter to avoid double-counting of emissions reported within the IPPU chapter as these fuels were consumed during non-energy related activities. More information on this methodology and examples of adjustments made between the IPPU and Energy chapters are described in Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Sinter consumption and pellet consumption data for 1990 through 2020 were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2022) and through personal communications with AISI (Steiner 2008) (see Table 4-94). These data from the AISI *Annual Statistical Report* were withheld for 2020 through 2022, so the 2019 values were used as estimated data for the missing 2020 through 2022 values and adjusted using GHGRP emissions data, as described earlier in this Methodology and Time-Series Consistency section.

In general, direct reduced iron (DRI) consumption data were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook – Iron and Steel Scrap* (USGS 1991 through 2022; USGS 2023b) and personal communication with the USGS Iron and Steel Commodity Specialist (Tuck 2023a). Data for DRI consumed in EAFs were not available for the years 1990 and 1991. EAF DRI consumption in 1990 and 1991 was calculated by multiplying the total DRI consumption for all furnaces by the EAF share of total DRI consumption in 1992. Data for DRI consumed in BOFs were not available for the years 1990 through 1993. BOF DRI consumption in 1990 through 1993 was calculated by multiplying the total DRI consumption for all furnaces (excluding EAFs and cupola) by the BOF share of total DRI consumption (excluding EAFs and cupola) in 1994.

The Tier 1 CO_2 emission factors for sinter production, direct reduced iron production and pellet production were obtained through the *2006 IPCC Guidelines* (IPCC 2006). Time-series data for pig iron production, coke, natural gas, fuel oil, sinter, and pellets consumed in the blast furnace; pig iron production; and blast furnace gas produced at the iron and steel mill and used in the metallurgical coke ovens and other steel mill activities were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2021) and through personal communications with AISI (Steiner 2008) (see Table 4-94 and Table 4-95). Data including blast furnace gas, coke oven gas, natural gas, limestone, sinter, and natural ore consumption for blast furnaces, coke production, and steelmaking furnaces (EAFs and BOFs) from the AISI *Annual Statistical Report* were withheld for 2020 through 2022, so the 2019 values were used as estimated data for the missing 2020 through 2022 values and adjusted using GHGRP emissions data, as described earlier in this Methodology and Time-Series Consistency section. Similarly, the percent of total steel production for EAF and BOF steelmaking processes were withheld for 2021 and 2022, so the 2020 values were used as estimated data for the missing 2021 values and adjusted using GHGRP emissions data, as described earlier in this Methodology and Time-Series Consistency section.

Data for EAF steel production, carbon-containing flux, EAF charge carbon, and natural gas consumption were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2022) and through personal communications with AISI (AISI 2006 through 2016, Steiner 2008). The factor for the quantity of EAF anode consumed per ton of EAF steel produced was provided by AISI (Steiner 2008). Data for BOF steel production, carbon-containing flux, natural gas, natural ore, pellet, sinter consumption as well as BOF steel production were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2023) and through personal communications with AISI (Steiner 2008). Data for EAF consumption of natural gas and BOF consumption of coke oven gas, limestone, and natural ore from the AISI *Annual Statistical Report* were not available for 2021 and 2022, so 2020 values were used as estimated data for the missing 2021 and 2022 values and adjusted using GHGRP emissions data, as described earlier in this

Methodology and Time-Series Consistency section. Data for EAF and BOF scrap steel, pig iron, and DRI consumption were obtained from the USGS *Minerals Yearbook – Iron and Steel Scrap* (USGS 1991 through 2022; USGS 2023b) and personal communication with the USGS Iron and Steel Commodity Specialist (Tuck 2023a). Data on coke oven gas and blast furnace gas consumed at the iron and steel mill (other than in the EAF, BOF, or blast furnace) were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2021) and through personal communications with AISI (Steiner 2008). These data were not available for 2021 and 2022, so 2020 values were used as estimated data for the missing 2021 and 2022 values and adjusted using GHGRP emissions data, as described earlier in this Methodology and Time-Series Consistency section. Some data from the *AISI Annual Statistical Report* on natural gas consumption were withheld for 2020 through 2022, so the 2019 values were used as estimated data for the missing 2020 through 2022 values and adjusted using GHGRP emissions data, as described earlier in this Methodology and Time-Series Consistency section.

Data on blast furnace gas and coke oven gas sold for use as synthetic natural gas were obtained from EIA's *Natural Gas Annual 2019* (EIA 2020). Carbon contents for direct reduced iron, EAF carbon electrodes, EAF charge carbon, limestone, dolomite, pig iron, and steel were provided by the *2006 IPCC Guidelines*. The carbon contents for natural gas, fuel oil, and direct injection coal were obtained from EIA (EIA 2017b) and EPA (EPA 2010). Heat contents for fuel oil and direct injection coal were obtained from EIA (EIA 1992, 2011); natural gas heat content was obtained from Table 37 of AISI's *Annual Statistical Report* (AISI 2004 through 2021). Heat contents for coke oven gas and blast furnace gas were provided in Table 37 of AISI's *Annual Statistical Report* (AISI 2004 through 2021) and confirmed by AISI staff (Carroll 2016).

Table 4-94: Production and Consumption Data for the Calculation of CO_2 and CH_4 Emissions from Iron and Steel Production (Thousand Metric Tons)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Sinter Production	12,239	8,315	4,687	4,378	3,747	4,182	3,935
Direct Reduced Iron Production	517	1,303	C	C	C	C	C
Pellet Production	60,563	50,096	30,793	29,262	25,044	27,949	26,300
Pig Iron Production							
Coke Consumption	24,946	13,832	7,618	7,291	6,240	6,964	6,553
Pig Iron Production	49,669	37,222	24,058	22,302	18,320	22,246	19,791
Direct Injection Coal Consumption	1,485	2,573	2,569	2,465	2,110	2,354	2,216
EAF Steel Production							
EAF Anode and Charge Carbon Consumption	67	1,127	1,133	1,137	1,118	1,129	1,123
Scrap Steel Consumption	42,691	46,600	C	C	C	C	C
Flux Consumption	319	695	998	998	998	998	998
EAF Steel Production	33,511	52,194	58,904	61,172	51,349	57,307	53,926
BOF Steel Production							
Pig Iron Consumption	47,307	34,400	C	C	C	C	C
Scrap Steel Consumption	14,713	11,400	C	C	C	C	C
Flux Consumption	576	582	408	363	311	347	326
BOF Steel Production	43,973	42,705	27,704	26,591	21,384	23,865	22,457

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Table 4-95: Production and Consumption Data for the Calculation of CO_2 Emissions from Iron and Steel Production (Million ft^3 unless otherwise specified)

Source/Activity Data	1990	2005	2018	2019	2020	2021	2022
Pig Iron Production							
Natural Gas Consumption	56,273	59,844	40,204	37,934	32,465	36,232	34,095
Fuel Oil Consumption (thousand gallons)	163,397	16,170	3,365	2,321	1,986	2,217	2,086

Coke Oven Gas Consumption	22,033	16,557	13,337	12,926	11,063	12,346	11,618
Blast Furnace Gas Production	1,439,380	1,299,980	871,860	836,033	715,509	798,522	751,418
EAF Steel Production							
Natural Gas Consumption	15,905	19,985	8,556	9,115	7,801	8,706	8,192
BOF Steel Production							
Coke Oven Gas Consumption	3,851	524	405	389	333	372	350
Other Activities							
Coke Oven Gas Consumption	224,883	97,132	67,008	64,377	55,096	61,489	57,861
Blast Furnace Gas Consumption	1,414,778	1,295,520	867,838	832,119	712,159	794,783	747,900

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

The estimates of CO_2 emissions from metallurgical coke production are based on assessing uncertainties in material production and consumption data and average carbon contents. Uncertainty is associated with the total U.S. coking coal consumption, total U.S. coke production, and materials consumed during this process. Data for coking coal consumption and metallurgical coke production are from different data sources (EIA) than data for other carbonaceous materials consumed at coke plants (AISI), which does not include data for merchant coke plants. There is uncertainty associated with the fact that coal tar and coke breeze production were estimated based on coke production because coal tar and coke breeze production data were not available. Since merchant coke plant data is not included in the estimate of other carbonaceous materials consumed at coke plants, the mass balance equation for CO_2 from metallurgical coke production cannot be reasonably completed; therefore, for the purpose of this analysis, uncertainty parameters are applied to primary data inputs to the calculation (i.e., coking coal consumption and metallurgical coke production) only.

The estimates of CO_2 emissions from iron and steel production are based on material production and consumption data and average carbon contents. There is uncertainty associated with the assumption that pellet production, direct reduced iron and sinter consumption are equal to production. There is uncertainty with the representativeness of the associated IPCC default emission factors. There is uncertainty associated with the assumption that all coal used for purposes other than coking coal is for direct injection coal. There is also uncertainty associated with the carbon contents for pellets, sinter, and natural ore, which are assumed to equal the carbon contents of direct reduced iron, when consumed in the blast furnace. There is uncertainty associated with the consumption of natural ore under current industry practices. For EAF steel production, there is uncertainty associated with the amount of EAF anode and charge carbon consumed due to inconsistent data throughout the time series. Also for EAF steel production, there is uncertainty associated with the assumption that 100 percent of the natural gas attributed to “steelmaking furnaces” by AISI is process-related and nothing is combusted for energy purposes. Uncertainty is also associated with the use of process gases such as blast furnace gas and coke oven gas. Data are not available to differentiate between the use of these gases for processes at the steel mill versus for energy generation (i.e., electricity and steam generation); therefore, all consumption is attributed to iron and steel production. These data and carbon contents produce a relatively accurate estimate of CO_2 emissions; however, there are uncertainties associated with each.

For calculating the emissions estimates from iron and steel and metallurgical coke production, EPA utilizes a number of data points taken from the AISI *Annual Statistical Report* (ASR). This report serves as a benchmark for information on steel companies in United States, regardless if they are a member of AISI, which represents integrated producers (i.e., blast furnace and EAF). During the compilation of the 1990 through 2016 *Inventory* report EPA initiated conversation with AISI to better understand and update the qualitative and quantitative uncertainty metrics associated with AISI data elements. AISI estimates their data collection response rate to range from 75 to 90 percent, with certain sectors of the iron and steel industry not being covered by the ASR; therefore, there is some inherent uncertainty in the values provided in the AISI ASR, including material production and consumption data. There is also some uncertainty to which materials produced are exported to Canada. As indicated in the introduction to this section, the trend for integrated facilities has moved to more use of EAFs and fewer BOFs. This trend may not be completely captured in the current data which also increases uncertainty. EPA assigned an uncertainty range of ±10 percent for the primary data inputs (i.e., consumption and production values for each production process, heat and carbon content values), a normal probability density function for consumption and production values for each production process, and a triangular probability density function for heat and carbon content values to calculate overall uncertainty from iron and steel production, and using this suggested uncertainty provided in Table 4.4 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). During EPA's discussion with AISI, AISI noted that an uncertainty range of ±5 percent would be a more appropriate approximation to reflect their coverage of integrated steel producers in the United States. EPA will continue to assess the best range of uncertainty for these values. EPA assigned an uncertainty range of ±25 percent and a triangular probability density function for the Tier 1 CO_2 emission factors for the sinter, direct reduced iron, and pellet production processes, and using this suggested uncertainty provided in Table 4.4 of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-96 for metallurgical coke production and iron and steel production. Total CO_2 emissions from metallurgical coke production and iron and steel production for 2022 were estimated to be between 34.3 and 47.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 16 percent below and 16 percent above the emission estimate of 40.7 MMT CO_2 Eq. Total CH_4 emissions from metallurgical coke production and iron and steel production for 2022 were estimated to be between 0.007 and 0.008 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 7 percent below and 7 percent above the emission estimate of 0.0077 MMT CO_2 Eq.

Table 4-96: Approach 2 Quantitative Uncertainty Estimates for CO_2 and CH_4 Emissions from Iron and Steel Production and Metallurgical Coke Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Metallurgical Coke & Iron and Steel Production	CO_2	40.7	34.3	47.1	-16%	+16%
Metallurgical Coke & Iron and Steel Production	CH_4	+	+	+	-7%	+7%

+ Does not exceed 0.05 MMT CO_2 Eq.

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

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). As part of a multiyear improvement effort, EPA is reviewing the iron and steel methodology and available data, conducting additional category specific QC checks and will report on findings when that review is complete (i.e., projected to be complete at earliest for the 2025 report). More information is provided under Planned Improvements below.

Recalculations Discussion

Recalculations were performed for the year 2021 with updated USGS values for DRI, pig iron, and scrap steel consumption for both BOF and EAF steel production. Additionally, revisions to GHGRP data for 2020 and 2021 resulted in minor changes to activity data that were adjusted using GHGRP data, as described in the Methodology and Time-Series Consistency section. Compared to the previous *Inventory*, CO_2 emissions from steel production increased by less than 1 percent (7 kt CO_2) in 2020 and by less than 1 percent (211 kt CO_2) in 2021.

Planned Improvements

Significant activity data for 2020 through 2022 were not available for this report and were estimated using 2019 values and adjusted using GHGRP emissions data. EPA will continue to explore sources of 2020 through 2022 data and other estimation approaches. EPA will evaluate and analyze data reported under EPA's GHGRP to improve the emission estimates for Iron and Steel Production process categories. Particular attention will be made to ensure time-series consistency of the emissions estimates presented in future *Inventory* reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this *Inventory*. In implementing improvements and integration of data from EPA's GHGRP, EPA will rely on the latest guidance from the IPCC on the use of facility-level data in national inventories.[78] This is a near to medium-term improvement, and per preliminary work, EPA estimates that the earliest this improvement could be incorporated is the next (i.e., 2025) *Inventory* submission.

Additional improvements include accounting for emission estimates for the production of metallurgical coke in the Energy chapter as well as identifying the amount of carbonaceous materials, other than coking coal, consumed at merchant coke plants. Other potential improvements include identifying the amount of coal used for direct injection and the amount of coke breeze, coal tar, and light oil produced during coke production. Efforts will also be made to identify information to better characterize emissions from the use of process gases and fuels within the Energy and IPPU chapters. Additional efforts will be made to improve the reporting and transparency in accounting for fuels between the IPPU and Energy chapters, particularly the inclusion of a quantitative summary of the carbon balance in the United States. This planned improvement is a long-term improvement and is still in development. It is not included in this current *Inventory* report. EPA estimates that the earliest this improvement could be incorporated is the next (i.e., 2025) *Inventory* submission.

4.19 Ferroalloy Production (CRT Source Category 2C2)

Ferroalloys are composites of iron (Fe) and other elements such as silicon (Si), manganese (Mn), and chromium (Cr). This reporting category (2C2) includes emissions of carbon dioxide (CO_2) and methane (CH_4) from the production of several ferroalloys. Per the IPCC methodological guidance, emissions from fuels consumed for energy purposes during the production of ferroalloys are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter. Emissions from the production of two types of ferrosilicon (25 to 55 percent and 56 to 95 percent silicon), silicon metal (96 to 99 percent silicon), and miscellaneous alloys (32 to 65 percent silicon) have been calculated.

Emissions from the production of ferrochromium and ferromanganese are not included because of the small number of manufacturers of these materials in the United States. Government information disclosure rules prevent the publication of production data for these production facilities. Additionally, production of ferrochromium in the United States ceased in 2009 (USGS 2013a).

Similar to emissions from the production of iron and steel, CO_2 is emitted when metallurgical coke is oxidized during a high-temperature reaction with iron and the selected alloying element. Due to the strong reducing

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[78] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf and the *2019 Refinement*, Volume 1, Chapter 2, Section 2.3, *Use of Facility Data in Inventories* at https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch02_DataCollection.pdf.

environment, CO is initially produced and eventually oxidized to CO_2. A representative reaction equation for the production of 50 percent ferrosilicon (FeSi) is given below:

$$\mathrm{Fe_2O_3 + 2SiO_2 + 7C \rightarrow 2FeSi + 7CO}$$

While most of the carbon contained in the process materials is released to the atmosphere as CO_2, a percentage is also released as CH_4 and other volatiles. The amount of CH_4 that is released is dependent on furnace efficiency, operation technique, and control technology.

Ferroalloys are used to alter the material properties of the steel. Ferroalloys are produced in conjunction with the iron and steel industry, often at co-located facilities, and production trends closely follow that of the iron and steel industry. As of 2020, 11 facilities in the United States produce ferroalloys (USGS 2022b).

Emissions of CO_2 from ferroalloy production in 2022 were 1.3 MMT CO_2 Eq. (1,327 kt CO_2) (see Table 4-97 and Table 4-98), which is a 15 percent reduction since 2021 and a 38 percent reduction since 1990. Emissions of CH_4 from ferroalloy production in 2022 were 0.01 MMT CO_2 Eq. (0.4 kt CH_4), which is a 15 percent decrease since 2021 and a 45 percent decrease since 1990. Variability in emissions over the past five years is attributable to facility shutdowns in 2018 and 2020 (USGUS 2020; USGS 2021). The latter facility reopened its ferrosilicon production facility in 2021, owing to increased demand for ferrosilicon products and improved domestic pricing (USGS 2022c).

Table 4-97: CO_2 and CH_4 Emissions from Ferroalloy Production (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	2.2	1.4	2.1	1.6	1.4	1.6	1.3
CH_4	+	+	+	+	+	+	+
Total	**2.2**	**1.4**	**2.1**	**1.6**	**1.4**	**1.6**	**1.3**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 4-98: CO_2 and CH_4 Emissions from Ferroalloy Production (kt)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	2,152	1,392	2,063	1,598	1,377	1,567	1,327
CH_4	1	+	1	+	+	+	+

+ Does not exceed 0.5 kt

Methodology and Time-Series Consistency

Emissions of CO_2 and CH_4 from ferroalloy production are calculated[79] using a Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. Annual ferroalloy production is multiplied by material-specific emission factors provided by IPCC (IPCC 2006). The Tier 1 equations for CO_2 and CH_4 emissions are as follows:

Equation 4-13: *2006 IPCC Guidelines* Tier 1: CO_2 Emissions for Ferroalloy Production (Equation 4.15)

$$E_{CO_2} = \sum_i (MP_i \times EF_i)$$

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[79] EPA has not integrated aggregated facility-level GHGRP information to inform these estimates. The aggregated information (e.g., activity data and emissions) associated with production of ferroalloys did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

where,

E_{CO2} = CO_2 emissions, metric tons

MP_i = Production of ferroalloy type *i*, metric tons

EF_i = Generic emission factor for ferroalloy type *i*, metric tons CO_2/metric ton specific ferroalloy product

Equation 4-14: *2006 IPCC Guidelines* Tier 1: CH_4 Emissions for Ferroalloy Production (Equation 4.18)

$$E_{CH_4} = \sum_i (MP_i \times EF_i)$$

where,

E_{CH4} = CH_4 emissions, kg

MP_i = Production of ferroalloy type *i*, metric tons

EF_i = Generic emission factor for ferroalloy type *i*, kg CH_4/metric ton specific ferroalloy product

Default emission factors were used because country-specific emission factors are not currently available. The following emission factors were used to develop annual CO_2 and CH_4 estimates:

- Ferrosilicon, 25 to 55 percent Si and Miscellaneous Alloys, 32 to 65 percent Si: 2.5 metric tons CO_2/metric ton of alloy produced, 1.0 kg CH_4/metric ton of alloy produced.
- Ferrosilicon, 56 to 95 percent Si: 4.0 metric tons CO_2/metric ton alloy produced, 1.0 kg CH_4/metric ton of alloy produced.
- Silicon Metal: 5.0 metric tons CO_2/metric ton metal produced, 1.2 kg CH_4/metric ton metal produced.

It was assumed that 100 percent of the ferroalloy production was produced using petroleum coke in an electric arc furnace process (IPCC 2006), although some ferroalloys may have been produced with coking coal, wood, other biomass, or graphite carbon inputs. The amount of petroleum coke consumed in ferroalloy production was calculated assuming that the petroleum coke used is 90 percent carbon (C) and 10 percent inert material (Onder and Bagdoyan 1993).

The use of petroleum coke for ferroalloy production is adjusted for within the Energy chapter as this fuel was consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for non-energy use of fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion [CRT Source Category 1A]) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Ferroalloy production data for 1990 through 2022 (see Table 4-99) were obtained from the U.S. Geological Survey (USGS) through the *Minerals Yearbook: Silicon* (USGS 1996 through 2022) and the *Minerals Industry Survey: Silicon* (USGS 2023a). The following data were available from the USGS publications for the time series:

- Ferrosilicon, 25 to 55 percent Si: Annual production data were available from 1990 through 2010.
- Ferrosilicon, 56 to 95 percent Si: Annual production data were available from 1990 through 2010.
- Silicon Metal: Annual production data were available from 1990 through 2005. Production data for 2005 were used as estimates for 2006 through 2010 because data for these years were not available due to government information disclosure rules.
- Miscellaneous Alloys, 32 to 65 percent Si: Annual production data were available from 1990 through 1998. Starting 1999, USGS reported miscellaneous alloys and ferrosilicon containing 25 to 55 percent silicon as a single category.

Starting with the 2011 publication, USGS ceased publication of production quantity by ferroalloy product and began reporting all the ferroalloy production data as a single category (i.e., Total Silicon Materials Production). This is due to the small number of ferroalloy manufacturers in the United States and government information disclosure rules. Ferroalloy product shares developed from the 2010 production data (i.e., ferroalloy product production divided by total ferroalloy production) were used with the total silicon materials production quantity to estimate the production quantity by ferroalloy product type for 2011 through 2022 (USGS 2017 through 2022).

Table 4-99: Production of Ferroalloys (Metric Tons)

Year	1990	2005	2018	2019	2020	2021	2022
Ferrosilicon 25%-55%	321,385	123,000	189,846	147,034	126,681	144,227	122,119
Ferrosilicon 56%-95%	109,566	86,100	167,511	129,736	111,778	127,259	107,752
Silicon Metal	145,744	148,000	183,642	142,229	122,541	139,514	118,128
Misc. Alloys 32-65%	72,442	NA	NA	NA	NA	NA	NA

NA (Not Available) for product type, aggregated with ferrosilicon (25-55% Si)

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

Annual ferroalloy production was reported by the USGS in three broad categories until the 2010 publication: ferroalloys containing 25 to 55 percent silicon (including miscellaneous alloys), ferroalloys containing 56 to 95 percent silicon, and silicon metal (through 2005 only, 2005 value used as an estimate for 2006 through 2010). Starting with the *2011 Minerals Yearbook: Silicon*, USGS started reporting all the ferroalloy production under a single category: total silicon materials production. The total silicon materials quantity was allocated across the three categories, based on the 2010 production shares for the three categories. Refer to the Methodology section for further details. Additionally, production data for silvery pig iron (alloys containing less than 25 percent silicon) are not reported by the USGS to avoid disclosing proprietary company data. Emissions from this production category, therefore, were not estimated.

Some ferroalloys may be produced using wood or other biomass as a primary or secondary carbon source (carbonaceous reductants); however, information and data regarding these practices were not available. Emissions from ferroalloys produced with wood or other biomass would not be counted under this source because wood-based carbon is of biogenic origin.[80] Even though emissions from ferroalloys produced with coking coal or graphite inputs would be counted in national trends, they may be generated with varying amounts of CO_2 per unit of ferroalloy produced. The most accurate method for these estimates would be to base calculations on the amount of reducing agent used in the process, rather than the amount of ferroalloys produced. These data, however, were not available, and are also often considered confidential business information.

Emissions of CH_4 from ferroalloy production will vary depending on furnace specifics, such as type, operation technique, and control technology. Higher heating temperatures and techniques such as sprinkle charging would reduce CH_4 emissions; however, specific furnace information was not available or included in the CH_4 emission estimates.

EPA assigned a uncertainty range of ±25 percent for the primary emission factors (i.e., ferrosilicon 25-55% Si, ferrosilicon 56-95% Si, and silicon metal), and an uncertainty range of ±5 percent for the 2010 production values for ferrosilicon 25-55% Si, ferrosilicon 56-95% Si, and silicon metal production and the 2021 total silicon materials production value used to calculate emissions from overall ferroalloy production. Using these suggested uncertainties provided in in Table 4.9 of Section 4.3.3.2 of the *2006 IPCC Guidelines* is appropriate based on expert

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[80] Emissions and sinks of biogenic carbon are accounted for in the Land Use, Land-Use Change, and Forestry chapter.

judgment (RTI 2023). Per this expert judgment, a normal probability density function was assumed for all activity data, and a triangular probability density function was assumed for emission factors.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-100. Ferroalloy production CO_2 emissions from 2022 were estimated to be between 1.2 and 1.5 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 13 percent below and 13 percent above the emission estimate of 1.3 MMT CO_2 Eq. Ferroalloy production CH_4 emissions were estimated to be between a range of approximately 12 percent below and 13 percent above the emission estimate of 0.01 MMT CO_2 Eq.

Table 4-100: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Ferroalloy Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Ferroalloy Production	CO_2	1.3	1.2	1.5	-13%	+13%
Ferroalloy Production	CH_4	+	+	+	-12%	+13%

+ Does not exceed 0.05 MMT CO_2 Eq.

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

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

No recalculations were performed for the 1990 to 2021 portion of the time series.

Planned Improvements

Pending available resources and prioritization of improvements for more significant sources, EPA will continue to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates and category-specific QC procedures for the Ferroalloy Production source category. Given the small number of facilities and reporting thresholds, particular attention will be made to ensure completeness and time-series consistency of the emissions estimates presented in future *Inventory* reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this *Inventory*. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[81] This is a long-term planned improvement, and EPA is still assessing the possibility of incorporating this improvement into the *Inventory*. This improvement has not been included in the current *Inventory* report.

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[81] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf and the *2019 Refinement*, Volume 1, Chapter 2, Section 2.3, *Use of Facility Data in Inventories* at https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch02_DataCollection.pdf.

4.20 Aluminum Production (CRT Source Category 2C3)

Aluminum is a lightweight, malleable, and corrosion-resistant metal that is used in many manufactured products, including aircraft, automobiles, bicycles, and kitchen utensils. As of recent reporting, the United States was the ninth[82] largest producer of primary aluminum with an estimated aluminum production of 860 thousand metric tons, with approximately 1.2 percent of the world total production (USGS 2022). The United States was also a major importer of primary aluminum. This reporting category (2C3) includes emissions from the production of primary aluminum—in addition to consuming large quantities of electricity—results in process-related emissions of carbon dioxide (CO_2) and two perfluorocarbons (PFCs): perfluoromethane (CF_4) and perfluoroethane (C_2F_6).

Carbon dioxide is emitted during the aluminum smelting process when alumina (aluminum oxide, Al_2O_3) is reduced to aluminum using the Hall-Héroult reduction process. The reduction of the alumina occurs through electrolysis in a molten bath of natural or synthetic cryolite (Na_3AlF_6). The reduction cells contain a carbon (C) lining that serves as the cathode. Carbon is also contained in the anode, which can be a carbon mass of paste, coke briquettes, or prebaked carbon blocks from petroleum coke. During reduction, most of this carbon is oxidized and released to the atmosphere as CO_2.

Process emissions of CO_2 from aluminum production were estimated to be 1.4 MMT CO_2 Eq. (1,446 kt) in 2022 (see Table 4-101 and Table 4-102). The carbon anodes consumed during aluminum production consist of petroleum coke and, to a minor extent, coal tar pitch. The petroleum coke portion of the total CO_2 process emissions from aluminum production is considered to be a non-energy use of petroleum coke and is accounted for here and not under the CO_2 from fossil fuel combustion source category of the Energy sector. Similarly, the coal tar pitch portion of these CO_2 process emissions is accounted for here.

Table 4-101: CO_2 Emissions from Aluminum Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Aluminum Production	6.8	4.1	1.5	1.9	1.7	1.5	1.4

Table 4-102: CO_2 Emissions from Aluminum Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Aluminum Production	6,831	4,142	1,455	1,880	1,748	1,541	1,446

In addition to CO_2 emissions, the aluminum production industry is also a source of PFC emissions. During the smelting process, when the alumina ore content of the electrolytic bath falls below critical levels required for electrolysis, rapid voltage increases occur, which are termed High Voltage Anode Effects (HVAEs). HVAEs cause carbon from the anode and fluorine from the dissociated molten cryolite bath to combine, thereby producing fugitive emissions of CF_4 and C_2F_6. In general, the magnitude of emissions for a given smelter and level of production depends on the frequency and duration of these anode effects. As the frequency and duration of the anode effects increase, emissions increase. Another type of anode effect, Low Voltage Anode Effects (LVAEs), became a concern in the early 2010s as the aluminum industry increasingly began to use cell technologies with higher amperage and additional anodes (IPCC 2019). LVAEs emit CF_4 and are included in PFC emission totals from 2006 forward.

Since 1990, emissions of CF_4 and C_2F_6 have both declined by 96 and 97 percent respectively, to 0.62 MMT CO_2 Eq.

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[82] Based on the U.S. USGS (2022) Aluminum factsheet, assuming all countries grouped under the "other countries" categories all have lower production than the U.S. Available at: https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-aluminum.pdf.

of CF_4 (0.1 kt) and 0.08 MMT CO_2 Eq. of C_2F_6 (0.01 kt) in 2022, respectively, as shown in Table 4-103 and Table 4-104. This decline is due both to reductions in domestic aluminum production and to actions taken by aluminum smelting companies to reduce the frequency and duration of anode effects. These actions include technology and operational changes such as employee training, use of computer monitoring, and changes in alumina feeding techniques. Since 1990, aluminum production has declined by 78 percent, while the combined CF_4 and C_2F_6 emission rate (per metric ton of aluminum produced) has been reduced by 78 percent. PFC emissions decreased by approximately 18 percent between 2021 and 2022. Aluminum production also decreased in 2022, down 3 percent from 2021.

Table 4-103: PFC Emissions from Aluminum Production (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
CF_4	16.1	2.6	1.0	1.1	1.2	0.8	0.7
C_2F_6	3.2	0.5	0.4	0.3	0.2	0.1	0.1
Total	**19.3**	**3.1**	**1.4**	**1.4**	**1.4**	**0.9**	**0.8**

Note: Totals may not sum due to independent rounding.

Table 4-104: PFC Emissions from Aluminum Production (kt)

Gas	1990	2005	2018	2019	2020	2021	2022
CF_4	2.4	0.4	0.2	0.2	0.2	0.1	0.1
C_2F_6	0.29	0.05	0.03	0.03	0.02	0.01	0.01

In 2022, U.S. primary aluminum production totaled approximately 0.86 million metric tons, a 3 percent decrease from 2021 production levels (USGS 2023). In 2022, three companies managed production at six operational primary aluminum smelters in five states. Two smelters operated at full capacity during 2022.The other four smelters operated at reduced capacity and one of these four smelters began a temporary shutdown in June (USGS 2023). Domestic smelters were operating at about 52 percent of capacity of 1.64 million tons per year at year end 2022 (USGS 2023).

Methodology and Time-Series Consistency

Process CO_2 and PFC (i.e., CF_4 and C_2F_6) emission estimates from primary aluminum production for 2010 through 2022 are available from EPA's GHGRP Subpart F (Aluminum Production) (EPA 2023). Under EPA's GHGRP, facilities began reporting primary aluminum production process emissions (for 2010) in 2011; as a result, GHGRP data (for 2010 through 2022) are available to be incorporated into the *Inventory*. EPA's GHGRP mandates that all facilities that contain an aluminum production process must report: CF_4 and C_2F_6 emissions from anode effects in all prebake and Søderberg electrolysis cells, CO_2 emissions from anode consumption during electrolysis in all prebake and Søderberg cells, and all CO_2 emissions from onsite anode baking. To estimate the process emissions, EPA's GHGRP uses the process-specific equations detailed in Subpart F (aluminum production).[83] These equations are based on the Tier 2/Tier 3 IPCC (2006) methods for primary aluminum production, and Tier 1 methods when estimating missing data elements. It should be noted that the same methods (i.e., *2006 IPCC Guidelines*) were used for estimating the emissions prior to the availability of the reported GHGRP data in the *Inventory*. Prior to 2010, aluminum production data were provided through EPA's Voluntary Aluminum Industrial Partnership (VAIP).

As previously noted, the use of petroleum coke for aluminum production is adjusted for within the Energy chapter to avoid double counting emissions as this fuel was consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for non-energy use of fuels is described in both the

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[83] Code of Federal Regulations, Title 40: Protection of Environment, Part 98: Mandatory Greenhouse Gas Reporting, Subpart F—Aluminum Production. See https://www.ecfr.gov/cgi-bin/text-idx?SID=24a41781dfe4218b339e914de03e8727&mc=true&node=pt40.23.98&rgn=div5#sp40.23.98.f.

Methodology section of CO_2 from Fossil Fuel Combustion (3.2 Carbon Emitted from Non-Energy Uses of Fossil Fuels [CRT Source Category 1A]) and Annex 2.3, Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels.

Process CO_2 Emissions from Anode Consumption and Anode Baking

Carbon dioxide emission estimates for the years prior to the introduction of EPA's GHGRP in 2010 were estimated using *2006 IPCC Guidelines* methods, but individual facility reported data were combined with process-specific emissions modeling. These estimates were based on information previously gathered from EPA's Voluntary Aluminum Industrial Partnership (VAIP) program, U.S. Geological Survey (USGS) Mineral Commodity reviews, and The Aluminum Association (USAA) statistics, among other sources. Since pre- and post-GHGRP estimates use the same methodology, emission estimates are comparable across the time series.

Most of the CO_2 emissions released during aluminum production occur during the electrolysis reaction of the carbon anode, as described by the following reaction:

$$2\mathrm{Al_2O_3} + 3\mathrm{C} \rightarrow 4\mathrm{Al} + 3\mathrm{CO_2}$$

For prebake smelter technologies, CO_2 is also emitted during the anode baking process. These emissions can account for approximately 10 percent of total process CO_2 emissions from prebake smelters.

Depending on the availability of smelter-specific data, the CO_2 emitted from electrolysis at each smelter was estimated from: (1) the smelter's annual anode consumption, (2) the smelter's annual aluminum production and rate of anode consumption (per ton of aluminum produced) for previous and/or following years, or (3) the smelter's annual aluminum production and IPCC default CO_2 emission factors. The first approach tracks the consumption and carbon content of the anode, assuming that all carbon in the anode is converted to CO_2. Sulfur, ash, and other impurities in the anode are subtracted from the anode consumption to arrive at a carbon consumption figure. This approach corresponds to either the IPCC Tier 2 or Tier 3 method, depending on whether smelter-specific data on anode impurities are used. The second approach interpolates smelter-specific anode consumption rates to estimate emissions during years for which anode consumption data are not available. This approach avoids substantial errors and discontinuities that could be introduced by reverting to Tier 1 methods for those years. The last approach corresponds to the IPCC Tier 1 method (IPCC 2006) and is used in the absence of present or historic anode consumption data.

The equations used to estimate CO_2 emissions in the Tier 2 and 3 methods vary depending on smelter type (IPCC 2006). For Prebake cells, the process formula accounts for various parameters, including net anode consumption, and the sulfur, ash, and impurity content of the baked anode. For anode baking emissions, the formula accounts for packing coke consumption, the sulfur and ash content of the packing coke, as well as the pitch content and weight of baked anodes produced. For Søderberg cells, the process formula accounts for the weight of paste consumed per metric ton of aluminum produced, and pitch properties, including sulfur, hydrogen, and ash content.

Through the VAIP, anode consumption (and some anode impurity) data have been reported for 1990, 2000, 2003, 2004, 2005, 2006, 2007, 2008, and 2009. Where available, smelter-specific process data reported under the VAIP were used; however, if the data were incomplete or unavailable, information was supplemented using industry average values recommended by IPCC (2006). Smelter-specific CO_2 process data were provided by 18 of the 23 operating smelters in 1990 and 2000, by 14 out of 16 operating smelters in 2003 and 2004, 14 out of 15 operating smelters in 2005, 13 out of 14 operating smelters in 2006, 5 out of 14 operating smelters in 2007 and 2008, and 3 out of 13 operating smelters in 2009. For years where CO_2 emissions data or CO_2 process data were not reported by these companies, estimates were developed through linear interpolation, and/or assuming representative (e.g., previously reported or industry default) values.

In the absence of any previous historical smelter-specific process data (i.e., 1 out of 13 smelters in 2009; 1 out of 14 smelters in 2006, 2007, and 2008; 1 out of 15 smelters in 2005; and 5 out of 23 smelters between 1990 and

2003), CO_2 emission estimates were estimated using Tier 1 Søderberg and/or Prebake emission factors (metric ton of CO_2 per metric ton of aluminum produced) from IPCC (2006).

Process PFC Emissions from Anode Effects

High Voltage Anode Effects

Smelter-specific PFC emissions from aluminum production for 2010 through 2022 were reported to EPA under its GHGRP. To estimate their PFC emissions from HVAEs and report them under EPA's GHGRP, smelters use an approach identical to the Tier 3 approach in the *2006 IPCC Guidelines* (IPCC 2006). Specifically, they use a smelter-specific slope coefficient as well as smelter-specific operating data to estimate an emission factor using the following equation:

$$PFC = S \times AE$$

$$AE = F \times D$$

where,

PFC = CF_4 or C_2F_6, kg/MT aluminum

S = Slope coefficient, PFC/AE

AE = Anode effect, minutes/cell-day

F = Anode effect frequency per cell-day

D = Anode effect duration, minutes

They then multiply this emission factor by aluminum production to estimate PFC emissions from HVAEs. All U.S. aluminum smelters are required to report their emissions under EPA's GHGRP.

Perfluorocarbon emissions for the years prior to 2010 were estimated using the same equation, but the slope-factor used for some smelters was technology-specific rather than smelter-specific, making the method a Tier 2 rather than a Tier 3 approach for those smelters. Emissions and background data were reported to EPA under the VAIP. For 1990 through 2009, smelter-specific slope coefficients were available and were used for smelters representing between 30 and 94 percent of U.S. primary aluminum production. The percentage changed from year to year as some smelters closed or changed hands and as the production at remaining smelters fluctuated. For smelters that did not report smelter-specific slope coefficients, IPCC technology-specific slope coefficients were applied (IPCC 2006). The slope coefficients were combined with smelter-specific anode effect data collected by aluminum companies and reported under the VAIP to estimate emission factors over time. For 1990 through 2009, smelter-specific anode effect data were available for smelters representing between 80 and 100 percent of U.S. primary aluminum production. Where smelter-specific anode effect data were not available, representative values (e.g., previously reported or industry averages) were used.

For all smelters, emission factors were multiplied by annual production to estimate annual emissions at the smelter level. For 1990 through 2009, smelter-specific production data were available for smelters representing between 30 and 100 percent of U.S. primary aluminum production. (For the years after 2000, this percentage was near the high end of the range.) Production at non-reporting smelters was estimated by calculating the difference between the production reported under VAIP and the total U.S. production supplied by USGS, and then allocating this difference to non-reporting smelters in proportion to their production capacity. Emissions were then aggregated across smelters to estimate national emissions (see Table 1-5).

Table 4-105: Summary of HVAE Emissions (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
HVAE Emissions	19.3	3.1	1.4	1.4	1.4	0.9	0.7

Low Voltage Anode Effects

LVAE emissions of CF_4 were estimated for 2006 through 2022 (see Table 1-6) based on the Tier 1 (technology-specific, production-based) method in the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019). Prior to 2006, LVAE emissions are believed to have been negligible.[84] The Tier 1 method is used in the LVAE emissions calculations from aluminum production in the absence of smelter-specific data available to quantify the LVAE-specific process emissions. National aluminum production estimates (allocated to smelters as described below) and the technology used in individual smelters were the best available data to perform the emissions calculations, as smelter-specific production data is not publicly available.

The following equation was used to estimate LVAE PFC emissions:

Equation 4-15: CF_4 Emissions Resulting from Low Voltage Anode Effects

$$LVAE\ E_{CF4} = LVAE\ EF_{CF4} \times MP$$

where,

LVAE E_{CF4} = LVAE emissions of CF_4 from aluminum production, kg CF_4

LVAE EF_{CF4} = LVAE emission factor for CF_4 (default by cell technology type)

MP = Metal production by cell technology type, tons Al.

In the LVAE emissions calculations, the Metal Production (MP) factor is calculated differently for the years 2006 through 2009 than for 2010 and beyond. For years prior to GHGRP reporting (2006 through 2009), the MP factor is calculated by dividing the annual production reported by USGS with the total U.S. capacity reported for this specific year, based on the USGS yearbook and applying this national utilization factor to each facility's production capacity to obtain an estimated facility production value. For GHGRP reporting years (2010+), the methodology to calculate the MP value was changed to allocate the total annual production reported by USAA, based on the distribution of CO_2 emissions amongst the operating smelters in a specific year. The latter improves the accuracy of the LVAE emissions estimates over assuming capacity utilization is the same at all smelters. The main drawback of using this methodology to calculate the MP factor is that, in some instances, it led to production estimates that are slightly larger (less than six percent) than the production capacity reported that year. In practice, this is most likely explained by the differences in process efficiencies at each facility and to a lesser extent, differences in measurements and methods used by each facility to obtain their CO_2 estimates and the degree of uncertainty in the USGS annual production reporting.

Once LVAE emissions were estimated, they were then combined with HVAE emissions estimates to calculate total PFC emissions from aluminum production.

Table 4-106: Summary of LVAE Emissions (MMT CO_2 Eq.)

Year	2006	2018	2019	2020	2021	2022
LVAE Emissions	0.13	0.05	0.07	0.06	0.05	0.05

Production Data

Between 1990 and 2009, production data were provided under the VAIP by 21 of the 23 U.S. smelters that operated during at least part of that period. For the non-reporting smelters, production was estimated based on

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[84] The *2019 Refinement* states, "Since 2006, the global aluminum industry has undergone changes in technology and operating conditions that make LVAE emissions much more prevalent[12]; these changes have occurred not only through uptake of newer technologies (e.g., $PFPB_L$ to $PFPB_M$) but also during upgrades within the same technology in order to maximize productivity and reduce energy use" (IPCC 2019). Footnote #12 uses the example of $PFPB_L$, which is prevalent in the United States, as an older technology that has been upgraded.

the difference between reporting smelters and national aluminum production levels as reported to USGS, with allocation to specific smelters based on reported production capacities (USGS 1990 through 2009).

National primary aluminum production data for 2010 through 2022 were compiled using USGS Mineral Industry Surveys, and the USGS Mineral Commodity Summaries (see Table 1-7).

Table 4-107: Production of Primary Aluminum (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Production (kt)	4,048	2,481	891	1,093	1,012	889	860

Methodological approaches were applied to the entire time-series to ensure time-series consistency from 1990 through 2022.

Uncertainty

Uncertainty was estimated for the CO_2, CF_4, and C_2F_6 emission values reported by each individual facility to EPA's GHGRP, taking into consideration the uncertainties associated with aluminum production, anode effect minutes, and slope factors. The uncertainty bounds used for these parameters were established based on information collected under the VAIP and held constant through 2022. Uncertainty surrounding the reported CO_2, CF_4, and C_2F_6 emission values were determined to have a normal distribution with uncertainty ranges of approximately 6 percent below to 6 percent above, 16 percent below to 16 percent above, and 20 percent below to 20 percent above their 2022 emission estimates, respectively.

For LVAE, since emission values were not reported through EPA's GHGRP but estimated instead through a Tier 1 methodology, the uncertainty analysis examined uncertainty associated with primary capacity data as well as technology-specific emission factors. Uncertainty for each facility's primary capacity, reported in the USGS Yearbook, was estimated to have a Pert Beta distribution with an uncertainty range of 7 percent below to 7 percent above the capacity estimates based on the uncertainty of reported capacity data, the number of years since the facility reported new capacity data, and uncertainty in capacity utilization. Uncertainty was applied to LVAE emission factors according to technology using the uncertainty ranges provided in the *2019 Refinement to the 2006 IPCC Guidelines*. An uncertainty range for Horizontal Stud Søderberg (HSS) technology was not provided in the *2019 Refinement to the 2006 IPCC Guidelines* due to insufficient data, so a normal distribution and uncertainty range of ±99 percent was applied for that technology based on expert judgment. A Monte Carlo analysis was applied to estimate the overall uncertainty of the CO_2, CF_4, and C_2F_6 emission estimates for the U.S. aluminum industry as a whole, and the results are provided below.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-108. Aluminum production-related CO_2 emissions were estimated to be between 1.41 and 1.48 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 3 percent below to 3 percent above the emission estimate of 1.446 MMT CO_2 Eq. Also, production-related CF_4 emissions were estimated to be between 0.62 and 0.73 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 8 percent below to 8 percent above the emission estimate of 0.676 MMT CO_2 Eq. Aluminum production-related C_2F_6 emissions were estimated to be between 0.075 and 0.09 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 9 percent below to 9 percent above the emission estimate of 0.083 MMT CO_2 Eq. Finally, Aluminum production-related aggregated PFCs emissions were estimated to be between 0.71 and 0.82 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 7 percent below to 7 percent above the emission estimate of 0.759 MMT CO_2 Eq.

Table 4-108: Approach 2 Quantitative Uncertainty Estimates for CO_2 and PFC Emissions from Aluminum Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Aluminum Production	CO_2	1.446	1.41	1.48	-3%	+3%
Aluminum Production	CF_4	0.676	0.62	0.73	-8%	+8%
Aluminum Production	C_2F_6	0.083	0.075	0.09	-9%	+9%
Aluminum Production	PFCs	0.759	0.71	0.82	-7%	+7%

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

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[85] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

Recalculations Discussion

No recalculations were performed for the 1990 through 2021 portion of the time series.

Planned Improvements

EPA is assessing planned improvements for future reports, but at this time has no specific planned improvements for estimating CO_2 and PFC emissions from aluminum production.

4.21 Magnesium Production and Processing (CRT Source Category 2C4)

The magnesium metal production and casting industry uses sulfur hexafluoride (SF_6) as a cover gas to prevent the rapid oxidation of molten magnesium in the presence of air. This reporting category (2C4) includes emissions from magnesium metal production and processing. Sulfur hexafluoride has been used in this application around the world for more than 30 years. A dilute gaseous mixture of SF_6 with dry air and/or carbon dioxide (CO_2) is blown over molten magnesium metal to induce and stabilize the formation of a protective crust. A small portion of the SF_6 reacts with the magnesium to form a thin molecular film of mostly magnesium oxide and magnesium fluoride.

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[85] GHGRP Report Verification Factsheet. See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

The amount of SF_6 reacting in magnesium production and processing is considered to be negligible and thus all SF_6 used is assumed to be emitted into the atmosphere. Alternative cover gases, such as AM-cover™ (containing HFC-134a), Novec™ 612 (FK-5-1-12) and dilute sulfur dioxide (SO_2) systems can and are being used by some facilities in the United States. However, many facilities in the United States are still using traditional SF_6 cover gas systems. Carbon dioxide is also released during primary magnesium production if carbonate based raw materials, such as dolomite, are used. During the processing of these raw materials to produce magnesium, calcination occurs which results in a release of CO_2 emissions.

The magnesium industry emitted 1.1 MMT CO_2 Eq. (0.05 kt) of SF_6, 0.03 MMT CO_2 Eq. (0.02 kt) of HFC-134a, and 0.003 MMT CO_2 Eq. (2.9 kt) of CO_2 in 2022. This represents a decrease of approximately 4 percent from total 2021 emissions (see Table 4-109 and Table 4-110) and a decrease in SF_6 emissions by 3 percent. In 2022, total HFC-134a emissions decreased from 0.040 MMT CO_2 Eq. to 0.029 MMT CO_2 Eq., or a 28 percent decrease as compared to 2021 emissions. FK 5-1-12 emissions in 2022 were consistent with 2021. The emissions of the carrier gas, CO_2, increased from 2.91 kt in 2021 to 2.94 kt in 2022, or 1 percent.

Table 4-109: SF_6, HFC-134a, FK 5-1-12 and CO_2 Emissions from Magnesium Production and Processing (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
SF_6	5.6	3.0	1.1	0.9	0.9	1.2	1.1
HFC-134a	0.0	0.0	0.1	0.1	0.1	+	+
CO_2	0.1	+	+	+	+	+	+
FK 5-1-12[a]	*0.0*	*0.0*	*+*	*+*	*+*	*+*	*+*
Total	**5.7**	**3.0**	**1.1**	**1.0**	**0.9**	**1.2**	**1.2**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Emissions of FK 5-1-12 are not included in totals.

Note: Totals may not sum due to independent rounding.

Table 4-110: SF_6, HFC-134a, FK 5-1-12 and CO_2 Emissions from Magnesium Production and Processing (kt)

Year	1990	2005	2018	2019	2020	2021	2022
SF_6	0.2	0.1	+	+	+	+	+
HFC-134a	0.0	0.0	0.1	+	+	+	+
CO_2	129.0	3.6	1.6	2.4	3.0	2.9	2.9
FK 5-1-12[a]	*0.0*	*0.0*	*+*	*+*	*+*	*+*	*+*

+ Does not exceed 0.5 kt

[a] Emissions of FK 5-1-12 are not included in totals.

Methodology and Time-Series Consistency

Emission estimates for the magnesium industry incorporate information provided by industry participants in EPA's SF_6 Emission Reduction Partnership for the Magnesium Industry as well as emissions data reported through Subpart T (Magnesium Production and Processing) of EPA's GHGRP. The Partnership started in 1999 and, in 2010, participating companies represented 100 percent of U.S. primary and secondary production and 16 percent of the casting sector production (i.e., die, sand, permanent mold, wrought, and anode casting). SF_6 emissions for 1999 through 2010 from primary production, secondary production (i.e., recycling), and die casting were generally reported by Partnership participants. Partners reported their SF_6 consumption, which is assumed to be equivalent to emissions. Along with SF_6, some Partners reported their HFC-134a and FK 5-1-12 consumed, which is also assumed to be equal to emissions. The last reporting year under the Partnership was 2010. Emissions data for 2011 through 2020 are obtained through EPA's GHGRP. Under the program, owners or operators of facilities that have a magnesium production or casting process must report emissions from use of cover or carrier gases, which include SF_6, HFC-134a, FK 5-1-12 and CO_2. Consequently, cover and carrier gas emissions from magnesium production and processing were estimated for three time periods, depending on the source of the emissions data: 1990 through 1998 (pre-EPA Partnership), 1999 through 2010 (EPA Partnership), and 2011 through 2022 (EPA GHGRP). The methodologies described below also make use of magnesium production data published by the U.S. Geological Survey (USGS) as available.

1990 through 1998

To estimate emissions for 1990 through 1998, industry SF_6 emission factors were multiplied by the corresponding metal production and consumption (casting) statistics from USGS. For this period, it was assumed that there was no use of HFC-134a or FK 5-1-12 cover gases, and hence emissions were not estimated for these alternatives.

Sulfur hexafluoride emission factors from 1990 through 1998 were based on a number of sources and assumptions. Emission factors for primary production were available from U.S. primary producers for 1994 and 1995. The primary production emission factors were 1.2 kg SF_6 per metric ton for 1990 through 1993, and 1.1 kg SF_6 per metric ton for 1994 through 1997. The emission factor for secondary production from 1990 through 1998 was assumed to be constant at the 1999 average Partner value. An emission factor for die casting of 4.1 kg SF_6 per metric ton, which was available for the mid-1990s from an international survey (Gjestland and Magers 1996), was used for years 1990 through 1996. For 1996 through 1998, the emission factor for die casting was assumed to decline linearly to the level estimated based on Partner reports in 1999. This assumption is consistent with the trend in SF_6 sales to the magnesium sector that was reported in the RAND survey of major SF_6 manufacturers, which showed a decline of 70 percent from 1996 to 1999 (RAND 2002). Sand casting emission factors for 1990 through 2001 were assumed to be the same as the 2002 emission factor for all but one facility, which used an emission factor derived from 2011 GHGRP data and held constant to back cast emissions for 1990-1998. The emission factors for the other processes (i.e., permanent mold, wrought, and anode casting), about which less is known, were assumed to remain constant at levels defined in Table 4-110. The emission factors for the other processes (i.e., permanent mold, wrought, and anode casting) were based on discussions with industry representatives.

The quantities of CO_2 carrier gas used for each production type have been estimated using the 1999 estimated CO_2 emissions data and the annual calculated rate of change of SF_6 use in the 1990 through 1999 time period. For each year and production type, the rate of change of SF_6 use between the current year and the subsequent year was first estimated. This rate of change was then applied to the CO_2 emissions of the subsequent year to determine the CO_2 emission of the current year.

Carbon dioxide emissions from the calcination of dolomite in the primary production of magnesium were calculated based on the *2006 IPCC Guidelines* Tier 2 method by multiplying the estimated primary production of magnesium by an emissions factor of 3.62 kilogram of CO_2 per kilogram of magnesium produced.[86] For 1990 through 1998, production was estimated to be equal to the production capacity of the facility.

1999 through 2010

The 1999 through 2010 emissions from primary and secondary production were based on information provided by EPA's industry Partners. In some instances, there were years of missing Partner data, including SF_6 consumption and metal processed. For these situations, emissions were estimated through interpolation where possible, or by holding company-reported emissions (as well as production) constant from the previous year. For alternative cover gases, including HFC-134a and FK 5-1-12, mainly reported data was relied upon. That is, unless a Partner reported using an alternative cover gas, it was not assumed it was used. Emissions of alternate gases were also estimated through linear interpolation where possible.

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[86] See https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/3_Volume3/V3_4_Ch4_Metal_Industry.pdf.

The die casting emission estimates for 1999 through 2010 were also based on information supplied by industry Partners. When a Partner was determined to be no longer in production, its metal production and usage rates were set to zero. Missing data on emissions or metal input was either interpolated or held constant at the last available reported value. In 1999 through 2010, Partners were assumed to account for all die casting tracked by USGS. For 1999, die casters who were not Partners were assumed to be similar to Partners who cast small parts. Due to process requirements, these casters consume larger quantities of SF_6 per metric ton of processed magnesium than casters that process large parts. Consequently, emission estimates from this group of die casters were developed using an average emission factor of 5.2 kg SF_6 per metric ton of magnesium. This emission factor was developed using magnesium production and SF_6 usage data for the year 1999. In 2008, the derived emission factor for die casting began to increase after many years of largely decreasing emission factors. As determined through an analysis of activity data reported from the USGS, this increase is due to a temporary decrease in production at many facilities between 2008 and 2010, which reflects the change in production that occurred during the recession.

The emissions from other casting operations were estimated by multiplying emission factors (kg SF_6 per metric ton of metal produced or processed) by the amount of metal produced or consumed from USGS, with the exception of some years for which Partner sand casting emissions data are available. The emission factors for sand casting activities were acquired through the data reported by the Partnership for 2002 to 2006. For 1999 through 2001, the sandcasting emission factor was held constant at the 2002 Partner-reported level. For 2007 through 2010, the sandcasting Partner did not report and the reported emission factor from 2005 was applied to the Partner and to a non GHGRP sand casters. Activity data for 2005 was obtained from USGS (USGS 2005b). One non partner sand casting facility reported to GHGRP in 2011 and had an emission factor derived for 2011, this factor was used to back cast emissions for this facility from 1999 to 2010.

The emission factors for primary production, secondary production and sand casting for the 1999 to 2010 are not published to protect company-specific production information. However, the emission factor for primary production has not risen above the average 1995 Partner value of 1.1 kg SF_6 per metric ton. The emission factors for the other industry sectors (i.e., permanent mold, wrought, and anode casting) were based on discussions with industry representatives. The emission factors for casting activities are provided below in Table 4-111.

The emissions of HFC-134a and FK-5-1-12 were included in the estimates for only instances where Partners reported that information to the Partnership. Emissions of these alternative cover gases were not estimated for instances where emissions were not reported.

Carbon dioxide carrier gas emissions were estimated using the emission factors developed based on GHGRP-reported carrier gas and cover gas data, by production type. It was assumed that the use of carrier gas, by production type, is proportional to the use of cover gases. Therefore, an emission factor, in kg CO_2 per kg cover gas and weighted by the cover gases used, was developed for each of the production types. GHGRP data, on which these emissions factors are based, was available for primary, secondary, die casting and sand casting. The emission factors were applied to the quantity of all cover gases used (SF_6, HFC-134a, and FK-5-1-12) by production type in this time period for producers that reported CO_2 emissions from 2011-2022 through the GHGP. Carrier gas emissions for the 1999 through 2010 time period were only estimated for those Partner companies that reported using CO_2 as a carrier gas through the GHGRP. Using this approach helped ensure time-series consistency. Emissions of carrier gases for permanent mold, wrought, and anode processes were estimated using the ratio of total CO_2 emissions to total cover gas emissions for primary, secondary, die and sand in a given year and the total SF_6 emissions from each permanent mold, wrought, and anodes processes respectively in that same year. CO_2 emissions from the calcination of dolomite were estimated using the same approach as described above. At the end of 2001, the sole magnesium production plant operating in the United States that produced magnesium metal using a dolomitic process that resulted in the release of CO_2 emissions ceased its operations (USGS 1995b through 2023).

Table 4-111: SF_6 Emission Factors (kg SF_6 per metric ton of magnesium)

Year	Die Casting[a]	Permanent Mold	Wrought	Anodes
1999	1.75[b]	2	1	1
2000	0.72	2	1	1
2001	0.72	2	1	1
2002	0.71	2	1	1
2003	0.81	2	1	1
2004	0.79	2	1	1
2005	0.77	2	1	1
2006	0.88	2	1	1
2007	0.64	2	1	1
2008	0.97	2	1	1
2009	1.41	2	1	1
2010	1.43	2	1	1

[a] Weighted average includes all die casters, Partners and non-Partners. For the majority of the time series (2000 through 2010), Partners made up 100 percent of die casters in the United States.

[b] Weighted average that includes an estimated emission factor of 5.2 kg SF_6 per metric ton of magnesium for die casters that do not participate in the Partnership.

2011 through 2022

For 2011 through 2022, for the primary and secondary producers, GHGRP-reported cover and carrier gases emissions data were used. For sand and die casting, some emissions data was obtained through EPA's GHGRP. Additionally, in 2018 a new GHGRP reporter began reporting permanent mold emissions. The balance of the emissions for this industry segment was estimated based on previous Partner reporting (i.e., for Partners that did not report emissions through EPA's GHGRP) or were estimated by multiplying emission factors by the amount of metal produced or consumed. Partners who did not report through EPA's GHGRP were assumed to have continued to emit SF_6 at the last reported level, which was from 2010 in most cases, unless publicly available sources indicated that these facilities have closed or otherwise eliminated SF_6 emissions from magnesium production (ARB 2015). Many Partners that did report through the GHGRP showed increases in SF_6 emissions driven by increased production related to a continued economic recovery after the 2008 recession. One Partner in particular reported an anonymously large increase in SF_6 emissions from 2010 to 2011, further driving increases in emissions between the two time periods of inventory estimates. All Partners were assumed to have continued to consume magnesium at the last reported level. Where the total metal consumption estimated for the Partners fell below the U.S. total reported by USGS, the difference was multiplied by the emission factors discussed in the section above, i.e., non-partner emission factors. For the other types of production and processing (i.e., permanent mold, wrought, and anode casting), emissions were estimated by multiplying the industry emission factors with the metal production or consumption statistics obtained from USGS (USGS 1995b-2023). USGS data for 2022 were not yet available at the time of the analysis, so the 2021 values were held constant through 2022 as an estimate.

Emissions of carrier gases for permanent mold, wrought, and anode processes were estimated using an approach consistent with the 1999 through 2010 time series.

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2022. 2006 IPCC Guidance methodologies were used throughout the time series, mainly either a Tier 2 or Tier 3 approach depending on available data.

Uncertainty

Uncertainty surrounding the total estimated emissions in 2022 is attributed to the uncertainties around SF_6, HFC-134a, and CO_2 emission estimates. To estimate the uncertainty surrounding the estimated 2022 SF_6 emissions from magnesium production and processing, the uncertainties associated with three variables were estimated: (1) emissions reported by magnesium producers and processors for 2022 through EPA's GHGRP, (2) emissions estimated for magnesium producers and processors that reported via the Partnership in prior years but did not report 2022 emissions through EPA's GHGRP, and (3) emissions estimated for magnesium producers and processors that did not participate in the Partnership or report through EPA's GHGRP. An uncertainty of 5 percent was assigned to the emissions (usage) data reported by each GHGRP reporter for all the cover and carrier gases (per the *2006 IPCC Guidelines*). If facilities did not report emissions data during the current reporting year through EPA's GHGRP, SF_6 emissions data were held constant at the most recent available value reported through the Partnership. The uncertainty associated with these values was estimated to be 30 percent for each year of extrapolation (per the *2006 IPCC Guidelines*). The uncertainty of the total inventory estimate remained relatively constant between 2021 and 2022.

Alternate cover gas and carrier gases data was set equal to zero if the facilities did not report via the GHGRP. For those industry processes that are not represented in the Partnership, such as permanent mold and wrought casting, SF_6 emissions were estimated using production and consumption statistics reported by USGS and estimated process-specific emission factors (see Table 4-111). The uncertainties associated with the emission factors and USGS-reported statistics were assumed to be 75 percent and 25 percent, respectively. Emissions associated with die casting and sand casting activities utilized emission factors based on Partner reported data with an uncertainty of 75 percent. In general, where precise quantitative information was not available on the uncertainty of a parameter, a conservative (upper-bound) value was used.

Additional uncertainties exist in these estimates that are not addressed in this methodology, such as the basic assumption that SF_6 neither reacts nor decomposes during use. The melt surface reactions and high temperatures associated with molten magnesium could potentially cause some gas degradation. Previous measurement studies have identified SF_6 cover gas degradation in die casting applications on the order of 20 percent (Bartos et al. 2007). Sulfur hexafluoride may also be used as a cover gas for the casting of molten aluminum with high magnesium content; however, the extent to which this technique is used in the United States is unknown.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-112. Total emissions associated with magnesium production and processing were estimated to be between 1.06 and 1.24 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 7.9 percent below to 7.7 percent above the 2022 emission estimate of 1.15 MMT CO_2 Eq. The uncertainty estimates for 2022 are slightly higher to the uncertainty reported for 2021 in the previous *Inventory*. This increase in uncertainty is attributed to the increased number of facilities with interpolated emissions and the increasing number of years for facilities with emissions held constant.

Table 4-112: Approach 2 Quantitative Uncertainty Estimates for SF_6, HFC-134a and CO_2 Emissions from Magnesium Production and Processing (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Magnesium Production	SF_6, HFC-134a, CO_2	1.2	1.1	1.2	-7.9%	+7.7%

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

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[87] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

Recalculations Discussion

One die casting facility which had previously had emissions back cast at a constant level had its back casting methodology updated using linear growth from 0 to reported emissions levels between 2001 and 2014, resulting in decreases in SF_6 emissions across 2001 to 2013.

Sand Casting Emissions for 2021 were updated based on 2021 specific data available in the 2021 data tables release from USGS's Mineral Yearbook. 2021 data was previously held constant at 2020 levels due to USGS Mineral Yearbook data only going through 2020. The updated production of sand cast magnesium was larger than what was estimated for 2021 in the previous *Inventory* cycle leading to an increase in SF_6 emissions in 2021.

One sand casting facility, which had previously only been estimated from 2011 onward, was confirmed to have emissions across the time series, an updated emission factor for 2011 was calculated and used to back cast emissions from 1990 to 2010.

Review of facility responses indicate that changes over time in the emission factors for this industry have occurred as facilities switch to using systems with cover gases other than SF_6 (e.g. SO_2) and also during time-periods where back-up SF_6-based systems are used due to the failure of the primary (non-SF_6) system have occurred, leading to the periodic spike in SF_6 usage rates.

Planned Improvements

Cover gas research conducted over the last decade has found that SF_6 used for magnesium melt protection can have degradation rates on the order of 20 percent in die casting applications (Bartos et al. 2007). Current emission estimates assume (per the *2006 IPCC Guidelines*) that all SF_6 utilized is emitted to the atmosphere. Additional research may lead to a revision of the *2006 IPCC Guidelines* to reflect this phenomenon and until such time, developments in this sector will be monitored for possible application to the *Inventory* methodology.

Additional emissions are generated as byproducts from the use of alternate cover gases, which are not currently accounted for. Research on this topic is developing, and as reliable emission factors become available, these emissions will be incorporated into the *Inventory.*

4.22 Lead Production (CRT Source Category 2C5)

In 2022, lead was produced in the United States using only secondary production processes. Until 2014, lead production in the United States involved both primary and secondary processes—both of which emit carbon

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[87] GHGRP Report Verification Factsheet. See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

dioxide (CO_2) (Sjardin 2003). This reporting category (2C5) includes emissions from the production of lead. Per the IPCC methodological guidance, emissions from fuels consumed for energy purposes during the production of lead are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

Primary production of lead through the direct smelting of lead concentrate produces CO_2 emissions as the lead concentrates are reduced in a furnace using metallurgical coke (Sjardin 2003). Primary lead production, in the form of direct smelting, previously occurred at a single smelter in Missouri. This primary lead smelter was closed at the end of 2013, and a small amount of residual lead was processed during demolition of the facility in 2014 (USGS 2015). Beginning in 2015, primary lead production no longer occurred in the United States.

Similar to primary lead production, CO_2 emissions from secondary lead production result when a reducing agent, usually metallurgical coke, is added to the smelter to aid in the reduction process. Carbon dioxide emissions from secondary production also occur through the treatment of secondary raw materials (Sjardin 2003). Secondary production primarily involves the recycling of lead acid batteries and post-consumer scrap at secondary smelters. Secondary lead production in the United States has fluctuated over the past 20 years, reaching a high of 1,180,000 metric tons in 2007 and again in 2019. In 2022, secondary lead production accounted for 100 percent of total U.S. lead production. The lead-acid battery industry accounted for about 92 percent of the reported U.S. lead consumption in 2022 (USGS 2023a).

In 2022, secondary lead production in the United States decreased by approximately 3 percent compared to 2021 (USGS 2023a). Secondary lead production in 2022 is 3 percent higher than in 1990 (USGS 1994 and 2023a). The United States has become more reliant on imported refined lead, owing to the closure of the last primary lead smelter in 2013. Exports of spent starting-lighting-ignition (SLI) batteries decreased between 2014 and 2017, and subsequently recovered beginning in 2018. Exports were 10 percent higher in the first 9 months of 2021 compared to the same time period in 2014 (USGS 2015 through 2023b). In the first 9 months of 2022, 24.6 million spent SLI lead-acid batteries were exported, 4 percent less than that in the same time period in 2021 (USGS 2023b).

Emissions of CO_2 from lead production in 2022 were 0.4 MMT CO_2 Eq. (428 kt), which is a 3 percent decrease compared to 2021 and a 17 percent decrease compared to 1990 (see Table 4-113 and Table 4-114) (USGS 1994; USGS 2023a; USGS 2023b).

The United States was the third largest mine producer of lead in the world, behind China and Australia, and accounted for approximately 6 percent of world production in 2022 (USGS 2023a).

Table 4-113: CO_2 Emissions from Lead Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Lead Production	0.5	0.6	0.5	0.5	0.5	0.4	0.4

Table 4-114: CO_2 Emissions from Lead Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Lead Production	516	553	527	531	450	439	428

Methodology and Time-Series Consistency

Carbon dioxide emissions from lead production[88] are calculated based on Sjardin's work (Sjardin 2003) for lead production emissions and use Tier 1 methods from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data. The Tier 1 equation is as follows:

Equation 4-16: *2006 IPCC Guidelines* Tier 1: CO_2 Emissions From Lead Production (Equation 4.32)

$$CO_2\ Emissions = (DS\ \times EF_{DS})\ + (S\ \times EF_S)$$

where,

DS = Lead produced by direct smelting, metric ton

S = Lead produced from secondary materials

EF_{DS} = Emission factor for direct smelting, metric tons CO_2/metric ton lead product

EF_S = Emission factor for secondary materials, metric tons CO_2/metric ton lead product

For primary lead production using direct smelting, Sjardin (2003) and the *2006 IPCC Guidelines* provide an emission factor of 0.25 metric tons CO_2/metric ton lead. For secondary lead production, Sjardin (2003) and the *2006 IPCC Guidelines* provide an emission factor of 0.25 metric tons CO_2/metric ton lead for direct smelting, as well as an emission factor of 0.2 metric tons CO_2/metric ton lead produced for the treatment of secondary raw materials (i.e., pretreatment of lead acid batteries). Since the secondary production of lead involves both the use of the direct smelting process and the treatment of secondary raw materials, Sjardin recommends an additive emission factor to be used in conjunction with the secondary lead production quantity. The direct smelting factor (0.25) and the sum of the direct smelting and pretreatment emission factors (0.45) are multiplied by total U.S. primary and secondary lead production, respectively, to estimate CO_2 emissions.

The production and use of coking coal for lead production is adjusted for within the Energy chapter as this fuel was consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (Section 3.1 Fossil Fuel Combustion (CRT Source Category 1A)) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

The 1990 through 2022 activity data for primary and secondary lead production (see Table 4-115) were obtained from the U.S. Geological Survey (USGS 1994 through 2023a).

Table 4-115: Lead Production (Metric Tons)

Year	1990	2005	2018	2019	2020	2021	2022
Primary	404,000	143,000	0	0	0	0	0
Secondary	922,000	1,150,000	1,170,000	1,180,000	1,000,000	975,000	950,000

Methodological approaches discussed below were applied to applicable years to ensure time-series consistency in emissions from 1990 through 2022.

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[88] EPA has not integrated aggregated facility-level Greenhouse Gas Reporting Program (GHGRP) information to inform these estimates. The aggregated information (e.g., activity data and emissions) associated with Lead Production did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

Uncertainty

Uncertainty associated with lead production relates to the emission factors and activity data used. The direct smelting emission factor used in primary production is taken from Sjardin (2003) who averaged the values provided by three other studies (Dutrizac et al. 2000; Morris et al. 1983; Ullman 1997). For secondary production, Sjardin (2003) added a CO_2 emission factor associated with battery treatment. The applicability of these emission factors to plants in the United States is uncertain. EPA assigned an uncertainty range of ±20 percent for these emission factors, and using this suggested uncertainty provided in Table 4.23 of the *2006 IPCC Guidelines* for a Tier 1 emission factor by process type is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a triangular probability density function was assumed for emission factors.

There is also a smaller level of uncertainty associated with the accuracy of primary and secondary production data provided by the USGS which is collected via voluntary surveys; the uncertainty of the activity data is a function of the reliability of reported plant-level production data and the completeness of the survey response. EPA currently uses an uncertainty range of ±10 percent for primary and secondary lead production, and using this suggested uncertainty provided in Table 4.23 of the *2006 IPCC Guidelines* for Tier 1 national production data is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a normal probability density function was assumed for all activity data.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-116. Lead production CO_2 emissions in 2022 were estimated to be between 0.4 and 0.5 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 15 percent below and 16 percent above the emission estimate of 0.4 MMT CO_2 Eq.

Table 4-116: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Lead Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Lead Production	CO_2	0.4	0.4	0.5	-15%	+16%

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

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Initial review of activity data show that EPA's GHGRP Subpart R lead production data and resulting emissions are fairly consistent with those reported by USGS. EPA is still reviewing available GHGRP data, reviewing QC analysis to understand differences in data reporting (i.e., threshold implications), and assessing the possibility of including this planned improvement in future *Inventory* reports (see Planned Improvements section below). Currently, GHGRP data are used for QA purposes only.

Recalculations Discussion

Recalculations were implemented for 2020 and 2021 based on revised USGS data for secondary lead production. Compared to the previous *Inventory*, emissions decreased by 3 percent (14 kt CO_2) for 2020 and by 2 percent (7 kt CO_2) for 2021 (USGS 2023b).

Planned Improvements

Pending resources and prioritization of improvements for more significant sources, EPA will continue to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates and category-specific QC for the Lead Production source category, in particular considering completeness of reported lead production given the reporting threshold. Particular attention will be made to ensuring time-series consistency of the emissions estimates presented in future *Inventory* reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this *Inventory*. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[89]

4.23 Zinc Production (CRT Source Category 2C6)

Zinc production in the United States consists of both primary and secondary processes. Of the primary and secondary processes currently used in the United States, only the electrothermic and Waelz kiln secondary processes result in non-energy carbon dioxide (CO_2) emissions (Viklund-White 2000). This reporting category (2C6) includes emissions from the production of zinc. Per the IPCC methodological guidance, emissions from fuels consumed for energy purposes during the production of zinc are accounted for as part of fossil fuel combustion in the industrial end-use sector reported under the Energy chapter.

The majority of zinc produced in the United States is used for galvanizing. Galvanizing is a process where zinc coating is applied to steel in order to prevent corrosion. Zinc is used extensively for galvanizing operations in the automotive and construction industry. Zinc is also used in the production of zinc alloys and brass and bronze alloys (e.g., brass mills, copper foundries, and copper ingot manufacturing). Zinc compounds and dust are also used, to a lesser extent, by the agriculture, chemicals, paint, and rubber industries.

Production of zinc can be conducted with a range of pyrometallurgical (e.g., electrothermic furnace, Waelz kiln, flame reactor, batch retorts, Pinto process, and PIZO process) and hydrometallurgical (e.g., hydrometallurgical recovery, solvent recovery, solvent extraction-electrowinning, and electrolytic) processes. Hydrometallurgical production processes are assumed to be non-emissive since no carbon is used in these processes (Sjardin 2003). Primary production in the United States is conducted through the non-emissive electrolytic process, while secondary techniques include the electrothermic and Waelz kiln processes, as well as a range of other processes. Worldwide primary zinc production also employs a pyrometallurgical process using an Imperial Smelting Furnace; however, this process is not used in the United States (Sjardin 2003).

In the electrothermic process, roasted zinc concentrate and secondary zinc products enter a sinter feed where they are burned to remove impurities before entering an electric retort furnace. Metallurgical coke is added to the electric retort furnace as a carbon-containing reductant. This concentration step, using metallurgical coke and high temperatures, reduces the zinc oxides and produces vaporized zinc, which is then captured in a vacuum condenser. This reduction process also generates non-energy CO_2 emissions.

$$ZnO + C \rightarrow Zn(gas) + CO_2 \qquad \text{(Reaction 1)}$$

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

$$ZnO + CO \rightarrow Zn(gas) + CO_2 \quad \text{(Reaction 2)}$$

In the Waelz kiln process, electric arc furnace (EAF) dust, which is captured during the recycling of galvanized steel, enters a kiln along with a reducing agent (typically carbon-containing metallurgical coke). When kiln temperatures reach approximately 1,100 to 1,200 degrees Celsius, zinc fumes are produced, which are combusted with air entering the kiln. This combustion forms zinc oxide, which is collected in a baghouse or electrostatic precipitator, and is then leached to remove chloride and fluoride. The use of carbon-containing metallurgical coke in a high-temperature fuming process results in non-energy CO_2 emissions. Through this process, approximately 0.33 metric tons of zinc is produced for every metric ton of EAF dust treated (Viklund-White 2000).

In the flame reactor process, a waste feed stream, which can include EAF dust, is processed in a high-temperature environment (greater than 2,000 °C) created by the combustion of natural gas or coal and oxygen-enriched air. Volatile metals, including zinc, are forced into the gas phase and drawn into a combustion chamber, where air is introduced and oxidation occurs. The metal oxide product is then collected in a dust collection system (EPA 1992).

In 2022, the only companies in the United States that used emissive technology to produce secondary zinc products were Befesa Holding US Inc (Befesa) and Steel Dust Recycling (SDR). The secondary zinc facilities operated by Befesa were acquired from American Zinc Recycling (AZR) (formerly "Horsehead Corporation") in 2021. PIZO Operating Company, LLC (PIZO) operated a secondary zinc production facility that processed EAF dust in Blytheville, AR from 2009 to 2012.

For Befesa, EAF dust is recycled in Waelz kilns at their Calumet, IL; Palmerton, PA; Rockwood, TN; and Barnwell, SC facilities. The former AZR facility in Beaumont, TX processed EAF dust via flame reactor from 1993 through 2009 (AZR 2021, Horsehead 2014). These Waelz kiln and flame reactor facilities produce intermediate zinc products (crude zinc oxide or calcine). Prior to 2014, most of output from these facilities were transported to their Monaca, PA facility where the products were smelted into refined zinc using electrothermic technology. In April 2014, the Monaca smelter was permanently closed and replaced by a new facility in Mooresboro, NC in 2014.

The Mooresboro facility uses a hydrometallurgical process (i.e., solvent extraction with electrowinning technology) to produce zinc products, which is assumed to be non-emissive as described above. Production at the Mooresboro facility was idled in April 2016 and re-started in March 2020 (Recycling Today 2020). Direct consumption of coal, coke, and natural gas were replaced with electricity consumption (Horsehead 2012b). The Mooresboro facility uses leaching and solvent extraction (SX) technology combined with electrowinning, melting, and casting technology. In this process, Waelz Oxide (WOX) is first washed in water to remove soluble elements such as chlorine, potassium, and sodium, and then is leached in a sulfuric acid solution to dissolve the contained zinc creating a pregnant liquor solution (PLS). The PLS is then processed in a solvent extraction step in which zinc is selectively extracted from the PLS using an organic solvent creating a purified zinc-loaded electrolyte solution. The loaded electrolyte solution is then fed into the electrowinning process in which electrical energy is applied across a series of anodes and cathodes submerged in the electrolyte solution causing the zinc to deposit on the surfaces of the cathodes. As the zinc metal builds up on these surfaces, the cathodes are periodically harvested in order to strip the zinc from their surfaces (Horsehead 2015).

SDR recycles EAF dust into intermediate zinc products using Waelz kilns and sells the intermediate products to companies who smelt it into refined products.

Emissions of CO_2 from zinc production in 2022 were estimated to be 0.9 MMT CO_2 Eq. (947 kt CO_2) (see Table 4-117). All 2022 CO_2 emissions resulted from secondary zinc production processes. Emissions from zinc production in the United States have increased overall since 1990 due to a gradual shift from non-emissive primary production to emissive secondary production. In 2022, emissions were estimated to be 50 percent higher than they were in 1990. Emissions decreased 6 percent from 2021 levels.

Table 4-117: CO_2 Emissions from Zinc Production (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Zinc Production	0.6	1.0	1.0	1.0	1.0	1.0	0.9

Table 4-118: CO_2 Emissions from Zinc Production (kt CO_2)

Year	1990	2005	2018	2019	2020	2021	2022
Zinc Production	632	1,030	999	1,026	977	1,007	947

U.S. zinc mine production increased by 9 percent in 2022 compared to 2021, due in part to higher mill throughput and zinc ore grades at the Red Dog Mine in Alaska, the largest zinc mine in the United States. In 2022, United States primary and secondary refined zinc production were estimated to total 220,000 metric tons (USGS 2023) (see Table 4-119), remaining at approximately the same production level as in 2021. Secondary zinc production fell to its lowest point in the time series in 2019, following the closure of the Monaca, PA smelter in 2014 and issues with the AZR secondary zinc refinery in Mooresboro, NC. Secondary zinc production has increased significantly since the reopening of the idled Mooresboro facility in March 2020 (USGS 2021; AZP 2021).

Table 4-119: Zinc Production (Metric Tons)

Year	1990	2005	2018	2019	2020	2021	2022
Primary	262,704	191,120	101,000	101,000	101,000	101,000	101,000
Secondary	95,708	156,000	15,000	14,000	79,000	119,000	119,000
Total	**358,412**	**347,120**	**116,000**	**115,000**	**180,000**	**220,000**	**220,000**

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Emissions of CO_2 emissions from zinc production[90] using the electrothermic primary production and Waelz kiln secondary production processes are calculated using a Tier 1 method from the *2006 IPCC Guidelines*, in accordance with the IPCC methodological decision tree and available data (IPCC 2006). The Tier 1 equation used to estimate emissions from zinc production is as follows:

Equation 4-17: *2006 IPCC Guidelines* Tier 1: CO_2 Emissions from Zinc Production (Equation 4.33)

$$E_{CO2} = Zn \times EF_{default}$$

where,

E_{CO_2} = CO_2 emissions from zinc production, metric tons

Zn = Quantity of zinc produced, metric tons

$EF_{default}$ = Default emission factor, metric tons CO_2/metric ton zinc produced

The Tier 1 emission factors provided by IPCC for Waelz kiln-based secondary production were derived from metallurgical coke consumption factors and other data presented in Vikland-White (2000). These coke consumption factors as well as other inputs used to develop the Waelz kiln emission factors are shown below. IPCC does not provide an emission factor for electrothermic processes due to limited information; therefore, the Waelz kiln-specific emission factors were also applied to zinc produced from electrothermic processes. Starting in 2014, refined zinc produced in the United States used hydrometallurgical processes and is assumed to be non-emissive.

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[90] EPA has not integrated aggregated facility-level Greenhouse Gas Reporting Program (GHGRP) information to inform these estimates. The aggregated information (e.g., activity data and emissions) associated with Zinc Production did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

For Waelz kiln-based production, IPCC recommends the use of emission factors based on EAF dust consumption, if possible, rather than the amount of zinc produced since the amount of reduction materials used is more directly dependent on the amount of EAF dust consumed. Since only a portion of emissive zinc production facilities consume EAF dust, the emission factor based on zinc production is applied to the non-EAF dust consuming facilities, while the emission factor based on EAF dust consumption is applied to EAF dust consuming facilities.

The Waelz kiln emission factor based on the amount of zinc produced was developed based on the amount of metallurgical coke consumed for non-energy purposes per ton of zinc produced (i.e., 1.19 metric tons coke/metric ton zinc produced) (Viklund-White 2000), and the following equation:

Equation 4-18: Waelz Kiln CO_2 Emission Factor for Zinc Produced

$$EF_{Waelz\ Kiln} = \frac{1.19\ metric\ tons\ coke}{metric\ tons\ zinc} \times \frac{0.85\ metric\ tons\ C}{metric\ tons\ coke} \times \frac{3.67\ metric\ tons\ CO_2}{metric\ tons\ C} = \frac{3.70\ metric\ tons\ CO_2}{metric\ tons\ zinc}$$

Refined zinc production levels for AZR’s Monaca, PA facility (utilizing electrothermic technology) were available from the company for years 2005 through 2013 (Horsehead 2008, 2011, 2012, 2013, and 2014). The Monaca facility was permanently shut down in April 2014 and replaced by AZR’s new facility in Mooresboro, NC. The new facility uses hydrometallurgical process to produce refined zinc products. Hydrometallurgical production processes are assumed to be non-emissive since no carbon is used in these processes (Sjardin 2003).

Metallurgical coke consumption for non-EAF dust consuming facilities for 1990 through 2004 were extrapolated using the percentage change in annual refined zinc production at secondary smelters in the United States, as provided by the U.S. Geological Survey (USGS) *Minerals Yearbook: Zinc* (USGS 1994 through 2006). Metallurgical coke consumption for 2005 through 2013 were based on the secondary zinc production values obtained from the Horsehead Corporation Annual Report Form 10-K: 2005 through 2008 from the 2008 10-K (Horsehead Corp 2009); 2009 and 2010 from the 2010 10-K (Horsehead Corp. 2011); and 2011 through 2013 from the associated 10-K (Horsehead Corp. 2012a, 2013, 2014). Metallurgical coke consumption levels for 2014 and later were zero due to the closure of the AZR (formerly “Horsehead Corporation”) electrothermic furnace facility in Monaca, PA. The secondary zinc produced values for each year were then multiplied by the 3.70 metric tons CO_2/metric ton zinc produced emission factor to develop CO_2 emission estimates for the AZR electrothermic furnace facility.

The Waelz kiln emission factor based on the amount of EAF dust consumed was developed based on the amount of metallurgical coke consumed per ton of EAF dust consumed (i.e., 0.4 metric tons coke/metric ton EAF dust consumed) (Viklund-White 2000), and the following equation:

Equation 4-19: Waelz Kiln CO_2 Emission Factor for EAF Dust Consumed

$$EF_{EAF\ Dust} = \frac{0.4\ metric\ tons\ coke}{metric\ tons\ EAF\ Dust} \times \frac{0.85\ metric\ tons\ C}{metric\ tons\ coke} \times \frac{3.67\ metric\ tons\ CO_2}{metric\ tons\ C} = \frac{1.24\ metric\ tons\ CO_2}{metric\ tons\ EAF\ Dust}$$

Metallurgical coke consumption for EAF dust consuming facilities for 1990 through 2022 were calculated based on the values of EAF dust consumed. The total amount of EAF dust consumed by the Waelz kilns currently operated by Befesa was available from AZR (formerly “Horsehead Corporation”) in financial reports for years 2006 through 2015 (Horsehead 2007, 2008, 2010a, 2011, 2012a, 2013, 2014, 2015, and 2016), from correspondence with AZR for 2016 through 2019 (AZR 2020), and from correspondence with Befesa for 2020 through 2022 (Befesa 2022, 2023). The EAF dust consumption values for each year were then multiplied by the 1.24 metric tons CO_2/metric ton EAF dust consumed emission factor to develop CO_2 emission estimates for Befesa’s Waelz kiln facilities.

The amount of EAF dust consumed by SDR and their total production capacity were obtained from SDR’s facility in Alabama for the years 2011 through 2022 (SDR 2012, 2014, 2015, 2017, 2018, 2021, 2022, 2023). The SDR facility has been operational since 2008, underwent expansion in 2011 to include a second unit (operational since early- to mid-2012), and expanded its capacity again in 2017 (SDR 2018). Annual consumption data for SDR was not publicly available for the years 2008, 2009, and 2010. These data were estimated using data for AZR's Waelz kilns for 2008 through 2010 (Horsehead 2007, 2008, 2010a, 2010b, 2011). Annual capacity utilization ratios were calculated using AZR's annual consumption and total capacity for the years 2008 through 2010. AZR's annual capacity utilization ratios were multiplied with SDR's total capacity to estimate SDR's consumption for each of the years, 2008 through 2010 (SDR 2013). The 1.24 metric tons CO_2/metric ton EAF dust consumed emission factor was then applied to SDR's estimated EAF dust consumption to develop CO_2 emission estimates for those Waelz kiln facilities.

PIZO's facility in Arkansas was operational from 2009 to 2012 (PIZO 2021). The amount of EAF dust consumed by PIZO's facility for 2009 through 2012 was not publicly available. EAF dust consumption for PIZO's facility for 2009 and 2010 were estimated by calculating annual capacity utilization of AZR's Waelz kilns and multiplying this utilization ratio by PIZO's total capacity (PIZO 2012). EAF dust consumption for PIZO's facility for 2011 through 2012 were estimated by applying the average annual capacity utilization rates for AZR and SDR (Grupo PROMAX) to PIZO's annual capacity (Horsehead 2012; SDR 2012; PIZO 2012). The 1.24 metric tons CO_2/metric ton EAF dust consumed emission factor was then applied to PIZO's estimated EAF dust consumption to develop CO_2 emission estimates for those Waelz kiln facilities.

The production and use of coking coal for zinc production is adjusted for within the Energy chapter as this fuel was consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for non-energy use of fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion (CRT Source Category 1A)) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Beginning with the 2017 USGS *Minerals Commodity Summary: Zinc*, United States primary and secondary refined zinc production were reported as one value, total refined zinc production. Prior to this publication, primary and secondary refined zinc production statistics were reported separately. For years 2016 through 2022, only one facility produced primary zinc. Primary zinc produced from this facility was subtracted from the USGS 2016 to 2022 total zinc production statistic to estimate secondary zinc production for these years.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

There is uncertainty associated with the amount of EAF dust consumed in the United States to produce secondary zinc using emission-intensive Waelz kilns. The estimate for the total amount of EAF dust consumed in Waelz kilns is based on combining the totals for (1) the EAF dust consumption value obtained for the kilns currently operated by Befesa (and formerly operated by AZR or Horsehead Corporation) and (2) an EAF dust consumption value obtained from the Waelz kiln facility operated by SDR. For the 1990 through 2015 estimates, EAF dust consumption values for the kilns currently operated by Befesa were obtained from annual financial reports to the Securities and Exchange Commission (SEC) by AZR. In 2016, AZR reorganized as a private company and ceased providing annual reports to the SEC (Recycling Today 2017). EAF dust consumption values for subsequent years from the Befesa kilns and SDR have been obtained from personal communication with facility representatives. Since actual EAF dust consumption information is not available for PIZO's facility (2009 through 2010) and SDR's facility (2008 through 2010), the amount is estimated by multiplying the EAF dust recycling capacity of the facility (available from the company's website) by the capacity utilization factor for AZR (which was available from Horsehead Corporation financial reports).The EAF dust consumption for PIZO's facility for 2011 through 2012 was estimated by multiplying the average capacity utilization factor developed from AZR and SDR's annual capacity utilization rates by PIZO's EAF dust recycling capacity. Therefore, there is uncertainty associated with the assumption used to estimate PIZO's annual EAF dust consumption values for 2009 through 2012 and SDR's annual EAF dust consumption values for 2008 through 2010. EPA uses an uncertainty range of ±5 percent for these EAF dust consumption data inputs, based upon expert elicitation from the USGS commodity specialist. Per this expert judgment, a normal probability density function was assigned for EAF dust consumption data inputs.

There is also uncertainty associated with the emission factors used to estimate CO_2 emissions from secondary zinc production processes. The Waelz kiln emission factors are based on materials balances for metallurgical coke and EAF dust consumed as provided by Viklund-White (2000). Therefore, the accuracy of these emission factors depends upon the accuracy of these materials balances. Data limitations prevented the development of emission factors for the electrothermic process. Therefore, emission factors for the Waelz kiln process were applied to both electrothermic and Waelz kiln production processes. Consistent with the ranges in Table 4.25 of the *2006 IPCC Guidelines*, EPA assigned an uncertainty range of ±20 percent for the Tier 1 Waelz kiln emission factors, which are provided by Viklund-White in the form of metric tons of coke per metric ton of EAF dust consumed and metric tons of coke per metric ton of zinc produced. In order to convert coke consumption rates to CO_2 emission rates, values for the heat and carbon content of coke were obtained from Table 4.2 – Tier 2 of the *2006 IPCC Guidelines*. An uncertainty range of ±10 percent was assigned to these coke data elements, and using the suggested uncertainty provided in Table 4.25, Tier 2 – National Reducing Agent & Process Materials Data of the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023). Per this expert judgment, a triangular probability density function was assigned for emission factors and the heat and carbon content of coke.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-120. Zinc production CO_2 emissions from 2022 were estimated to be between 0.8 and 1.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 18 percent below and 20 percent above the emission estimate of 0.9 MMT CO_2 Eq.

Table 4-120: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Zinc Production (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Zinc Production	CO_2	0.9	0.8	1.1	-18%	+20%

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

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

Recalculations were performed for the year 2021 based on updated EAF dust consumption data. Compared to the previous *Inventory*, 2021 emissions from zinc production increased by 4 percent (38 kt CO_2).

Planned Improvements

Pending resources and prioritization of improvements for more significant sources, EPA will continue to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates and category-specific QC for zinc production, in particular considering completeness of reported zinc production given the reporting threshold. Given the small number of facilities in the United States, particular attention will be made to risks for disclosing CBI and ensuring time-series consistency of the emissions estimates presented in future *Inventory* reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this *Inventory*. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[91] This is a long-term planned improvement, and EPA is still assessing the possibility of including this improvement in future *Inventory* reports.

4.24 Electronics Industry (CRT Source Category 2E)

The electronics industry uses multiple greenhouse gases in its manufacturing processes. In semiconductor manufacturing, these include long-lived fluorinated greenhouse gases used for plasma etching and chamber cleaning (CRT Source Category 2E1), fluorinated heat transfer fluids used for temperature control and other applications (CRT Source Category 2E4), and nitrous oxide (N_2O) used to produce thin films through chemical vapor deposition and in other applications (reported under CRT Source Category 2H3). Similar to semiconductor manufacturing, the manufacturing of micro-electro-mechanical systems (MEMS) devices (reported under CRT Source Category 2E5 Other) and photovoltaic (PV) cells (CRT Source Category 2E3) requires the use of multiple long-lived fluorinated greenhouse gases for various processes.

The gases most commonly employed in the electronics industry are trifluoromethane (hydrofluorocarbon (HFC)-23 or CHF_3), perfluoromethane (CF_4), perfluoroethane (C_2F_6), nitrogen trifluoride (NF_3), and sulfur hexafluoride (SF_6), although other fluorinated compounds such as perfluoropropane (C_3F_8) and perfluorocyclobutane (c-C_4F_8) are also used. The exact combination of compounds is specific to the process employed.

In addition to emission estimates for these seven commonly used fluorinated gases, this *Inventory* contains emissions estimates for N_2O and other HFCs and unsaturated, low-GWP PFCs including C_5F_8, C_4F_6, HFC-32, HFC-41, and HFC-134a. These additional HFCs and PFCs are emitted from etching and chamber cleaning processes in much smaller amounts, accounting for 0.02 percent of emissions (in CO_2 Eq.) from these processes.

For semiconductors, a single 300 mm silicon wafer that yields between 400 to 600 semiconductor products (devices or chips) may require more than 100 distinct fluorinated-gas-using process steps, principally to deposit and pattern dielectric films. Plasma etching (or patterning) of dielectric films, such as silicon dioxide and silicon nitride, is performed to provide pathways for conducting material to connect individual circuit components in each device. The patterning process uses plasma-generated fluorine atoms, which chemically react with exposed dielectric film to selectively remove the desired portions of the film. The material removed as well as undissociated fluorinated gases flow into waste streams and, unless emission abatement systems are employed, into the atmosphere. Plasma enhanced chemical vapor deposition (PECVD) chambers, used for depositing dielectric films, are cleaned periodically using fluorinated and other gases. During the cleaning cycle the gas is converted to fluorine atoms in plasma, which etches away residual material from chamber walls, electrodes, and chamber hardware. Undissociated fluorinated gases and other products pass from the chamber to waste streams and, unless abatement systems are employed, into the atmosphere.

In addition to emissions of unreacted gases, some fluorinated compounds can also be transformed in the plasma processes into different fluorinated compounds which are then exhausted, unless abated, into the atmosphere. For example, when C_2F_6 is used in cleaning or etching, CF_4 is typically generated and emitted as a process byproduct. In some cases, emissions of the byproduct gas can rival or even exceed emissions of the input gas, as is the case for NF_3 used in remote plasma chamber cleaning, which often generates CF_4 as a byproduct.

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[91] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf and the *2019 Refinement*, Volume 1, Chapter 2, Section 2.3, *Use of Facility Data in Inventories* at https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/1_Volume1/19R_V1_Ch02_DataCollection.pdf.

Besides dielectric film etching and PECVD chamber cleaning, much smaller quantities of fluorinated gases are used to etch polysilicon films and refractory metal films like tungsten.

Nitrous oxide is used in manufacturing semiconductor devices to produce thin films by CVD and nitridation processes as well as for N-doping of compound semiconductors and reaction chamber conditioning (Doering 2000).

Liquid perfluorinated compounds are also used as heat transfer fluids (F-HTFs) for temperature control, device testing, cleaning substrate surfaces and other parts, and soldering in certain types of semiconductor manufacturing production processes. Leakage and evaporation of these fluids during use is a source of fluorinated gas emissions (EPA 2006). Unweighted F-HTF emissions consist primarily of perfluorinated amines, hydrofluoroethers, perfluoropolyethers (specifically, PFPMIEs), and perfluoroalkylmorpholines. Three percent or less consist of HFCs, PFCs, and SF_6 (where PFCs are defined as compounds including only carbon and fluorine). With the exceptions of the hydrofluoroethers and most of the HFCs, all of these compounds are very long-lived in the atmosphere and have global warming potentials (GWPs) near 10,000.[92]

MEMS and photovoltaic cell manufacturing require thin film deposition and etching of material with a thickness of one micron or more, so the process is less intricate and complex than semiconductor manufacturing. The manufacturing process is different than semiconductors, but generally employs similar techniques. Like semiconductors, MEMS and photovoltaic cell manufacturers use fluorinated compounds for etching, cleaning reactor chambers, and temperature control. CF_4, SF_6, and the Bosch process (which consists of alternating steps of SF_6 and C_4F_8) are used to manufacture MEMS (EPA 2010). Photovoltaic cell manufacturing predominately uses CF_4, to etch crystalline silicon wafers, and C_2F_6 or NF_3 during chamber cleaning after deposition of SiN_x films (IPCC 2006), although other F-GHGs may be used. Similar to semiconductor manufacturing, both MEMS and photovoltaic cell manufacturing use N_2O in depositing films and other manufacturing processes. MEMS and photovoltaic manufacturing may also employ HTFs for cooling process equipment (EPA 2010).

Emissions from all fluorinated greenhouse gases (including F-HTFs) and N_2O for semiconductors, MEMS and photovoltaic cells manufacturing are presented in Table 4-121 below for the years 1990, 2005, and the period 2018 to 2022. The rapid growth of the electronics industry and the increasing complexity (growing number of layers and functions)[93] of electronic products led to an increase in emissions of 152 percent between 1990 and 1999, when emissions peaked at 8.4 MMT CO_2 Eq. Emissions began to decline after 1999, reaching a low point in 2009 before rebounding to 2006 emission levels and more or less plateauing at the current level, which represents a 43 percent decline from 1999 to 2022. Together, industrial growth, adoption of emissions reduction technologies (including but not limited to abatement technologies) and shifts in gas usages resulted in a net increase in emissions of approximately 43 percent between 1990 and 2022. Total emissions from semiconductor manufacture in 2022 were lower than 2021 emissions, decreasing by 2.2 percent, largely due to a large decrease in SF_6 emissions. The decrease in SF_6 are seen in facilities that manufacture 200 mm wafer size that do not have abatement systems installed as well as 300 mm wafer size that have abatement systems installed.

For U.S. semiconductor manufacturing in 2022, total CO_2-equivalent emissions of all fluorinated greenhouse gases and N_2O from deposition, etching, and chamber cleaning processes were estimated to be 4.7 MMT CO_2 Eq. This is a

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[92] The GWP of PFPMIE, a perfluoropolyether used as an F-HTF, is included in the IPCC *Fourth Assessment Report* with a value of 10,300. The GWPs of the perfluorinated amines and perfluoroalkylmorpholines that are used as F-HTFs have not been evaluated in the peer-reviewed literature. However, evaluations by the manufacturer indicate that their GWPs are near 10,000 (78 FR 20632), which is expected given that these compounds are both saturated and fully fluorinated. EPA assigns a default GWP of 10,000 to compounds that are both saturated and fully fluorinated and that do not have chemical-specific GWPs in either the Fourth or the Fifth Assessment Reports.

[93] Complexity is a term denoting the circuit required to connect the active circuit elements (transistors) on a chip. Increasing miniaturization, for the same chip size, leads to increasing transistor density, which, in turn, requires more complex interconnections between those transistors. This increasing complexity is manifested by increasing the levels (i.e., layers) of wiring, with each wiring layer requiring fluorinated gas usage for its manufacture.

decrease in emissions from 1999 of 44 percent, and an increase in emissions from 1990 of 42 percent. These trends are driven by the above stated reasons.

Photovoltaic cell and MEMS manufacturing emissions of all fluorinated greenhouse gases are in Table 4-121. While EPA has developed a simple methodology to estimate emissions from non-reporters and to back-cast emissions from these sources for the entire time series, there is very high uncertainty associated with these emission estimates.

The emissions reported by facilities manufacturing MEMS included emissions of C_2F_6, C_3F_8, c-C_4F_8, CF_4, HFC-23, NF_3, N_2O and SF_6,[94] and were equivalent to only 0.110 percent to 0.260 percent of the total reported emissions from electronics manufacturing in 2011 to 2022. F-GHG emissions, the primary type of emissions for MEMS, ranged from 0.0003 to 0.012 MMT CO_2 Eq. from 1991 to 2022. Based upon information in the World Fab Forecast (WFF), it appears that some GHGRP reporters that manufacture both semiconductors and MEMS are reporting their emissions as only from semiconductor manufacturing (GHGRP reporters must choose a single classification per fab). Emissions from non-reporters have not been estimated.

Total CO_2-equivalent emissions from manufacturing of photovoltaic cells were estimated to range from 0.0003 MMT CO_2 Eq. to 0.0320 MMT CO_2 Eq. from 1998 to 2022 and were equivalent to between 0.003 percent to 0.77 percent of the total reported emissions from electronics manufacturing. F-GHG emissions, the primary type of emissions for photovoltaic cells, ranged from 0.0003 to 0.032 MMT CO_2 Eq. from 1998 to 2022. Emissions from manufacturing of photovoltaic cells were estimated using an emission factor developed from reported data from a single manufacturer between 2015 and 2016. This emission factor was then applied to production capacity estimates from non-reporting facilities. Reported emissions from photovoltaic cell manufacturing consisted of CF_4, C_2F_6, c-C_4F_8, CHF_3, NF_3, and N_2O.[95]

Emissions of F-HTFs, grouped by HFCs, PFCs or SF_6 are presented in Table 4-121. Emissions of F-HTFs that are not HFCs, PFCs or SF_6 are not included in inventory totals and are included for informational purposes only.

Since reporting of F-HTF emissions began under EPA's GHGRP in 2011, total F-HTF emissions (reported and estimated non-reported) have fluctuated between 0.4 MMT CO_2 Eq. and 0.9 MMT CO_2 Eq., with an overall declining trend between 2011 to 2022. An analysis of the data reported to EPA's GHGRP indicates that F-HTF emissions account for anywhere between 9 percent and 17 percent of total annual emissions (F-GHG, N_2O and F-HTFs) from semiconductor manufacturing.[96] Table 4-123 shows F-HTF emissions in tons by compound group based on reporting to EPA's GHGRP and the interpolated share of F-HTF emissions to F-GHG emissions for select years prior to reporting. [97]

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[94] Gases not reported by MEMS manufacturers to the GHGRP are currently listed as "NE" in the CRTs. Since no facilities report using these gases, emissions of these gases are not estimated for this sub-sector. However, there is insufficient data to definitively conclude that they are not used by non-reporting facilities.

[95] Gases not reported by PV manufacturers to the GHGRP are currently listed as "NE" in the CRTs. Since no facilities report using these gases, emissions of these gases are not estimated for this sub-sector. However, there is insufficient data to definitively conclude that they are not used by non-reporting facilities.

[96] Emissions data for HTFs (in tons of gas) from the semiconductor industry from 2011 through 2022 were obtained from the EPA GHGRP annual facility emissions reports.

[97] Many fluorinated heat transfer fluids consist of perfluoropolymethylisopropyl ethers (PFPMIEs) of different molecular weights and boiling points that are distilled from a mixture. "BP 200 °C" (and similar terms below) indicate the boiling point of the fluid in degrees Celsius. For more information, see https://www.regulations.gov/document?D=EPA-HQ-OAR-2009-0927-0276.

Table 4-121: PFC, HFC, SF_6, NF_3, and N_2O Emissions from Electronics Industry (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
CF_4	0.8	1.0	1.6	1.5	1.5	1.6	1.6
C_2F_6	1.8	1.8	1.1	0.9	0.8	0.9	0.9
C_3F_8	+	0.1	0.1	0.1	0.1	0.1	0.1
C_4F_8	0.0	0.1	0.1	0.1	0.1	0.1	0.1
HFC-23	0.2	0.2	0.3	0.3	0.3	0.4	0.3
SF_6	0.5	0.8	0.8	0.8	0.8	0.9	0.7
NF_3	+	0.4	0.5	0.5	0.6	0.6	0.6
C_4F_6	+	+	+	+	+	+	+
C_5F_8	+	+	+	+	+	+	+
CH_2F_2	+	+	+	+	+	+	+
CH_3F	+	+	+	+	+	+	+
CH_2FCF_3	+	+	+	+	+	+	0.0
Total Semiconductors	**3.3**	**4.3**	**4.5**	**4.2**	**4.2**	**4.5**	**4.4**
CF_4	0.0	+	+	+	+	+	+
C_2F_6	0.0	+	+	+	+	+	+
C_3F_8	0.0	+	0.0	0.0	0.0	0.0	0.0
C_4F_8	0.0	+	+	+	+	+	+
HFC-23	0.0	+	+	+	+	+	+
SF_6	0.0	+	+	+	+	+	+
NF_3	0.0	0.0	+	+	+	+	+
Total MEMS	**0.0**	**+**	**+**	**+**	**+**	**+**	**+**
CF_4	0.0	+	+	+	+	+	+
C_2F_6	0.0	+	+	+	+	+	+
C_4F_8	0.0	+	+	+	+	+	+
HFC-23	0.0	+	+	+	+	+	+
SF_6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NF_3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total PV	**0.0**	**+**	**+**	**+**	**+**	**+**	**+**
N_2O (Semiconductors)	+	0.1	0.2	0.2	0.3	0.3	0.3
N_2O (MEMS)	0.0	+	+	+	+	+	+
N_2O (PV)	0.0	+	+	+	+	+	+
Total N_2O	**+**	**0.1**	**0.2**	**0.2**	**0.3**	**0.3**	**0.3**
HFC, PFC and SF_6 F-HTFs	0.0	+	+	+	+	+	+
Total Electronics Industry	**3.3**	**4.5**	**4.8**	**4.5**	**4.5**	**4.8**	**4.7**

+ Does not exceed 0.05 MMT CO_2 Eq.

Table 4-122: PFC, HFC, SF_6, NF_3, and N_2O Emissions from Semiconductor Manufacture (Metric Tons)

Year	1990	2005	2018	2019	2020	2021	2022
CF_4	114.8	145.3	236.7	223.9	227.6	238.2	247.2
C_2F_6	160.0	163.4	99.1	85.0	75.9	78.7	81.6
C_3F_8	0.4	7.3	12.2	10.7	9.6	11.2	13.6
C_4F_8	0.0	10.9	6.0	5.7	5.8	6.3	6.1
HFC-23	14.6	14.1	26.5	25.7	26.6	30.4	25.2
SF_6	21.7	33.4	33.4	33.3	32.3	38.4	31.4
NF_3	2.8	26.2	34.1	33.5	36.2	39.2	39.4
C_4F_6	0.7	0.9	0.8	0.9	0.8	1.0	0.9
C_5F_8	0.5	0.6	0.5	0.4	0.4	0.4	0.4
CH_2F_2	0.6	0.8	0.9	1.0	1.0	1.0	1.0
CH_3F	1.4	1.8	2.4	2.5	2.8	2.9	2.4
CH_2FCF_3	+	+	+	+	+	+	0.0
N_2O	135.9	463.3	883.4	816.0	1,020.8	1,083.0	1,113.2

+ Does not exceed 0.05 MT.

Table 4-123: F-HTF Emissions from Electronics Manufacture by Compound Group (kt CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
HFCs	0.0	0.9	2.7	1.1	0.9	1.1	1.5
PFCs	0.0	3.8	10.0	8.5	7.8	5.5	7.4
SF_6	0.0	5.6	13.2	6.1	12.9	9.0	4.2
HFEs	0.0	39.4	4.6	1.3	5.4	3.8	14.4
PFPMIEs	0.0	110.5	182.8	174.8	151.0	149.4	165.3
Perfluoalkylromorpholines	0.0	66.4	58.4	57.1	61.3	53.7	19.7
Perfluorotrialkylamines	0.0	209.9	413.7	367.5	382.0	367.5	237.1
Total F-HTFs	**0.0**	**436.5**	**685.4**	**616.5**	**621.2**	**590.1**	**449.6**

Note: Emissions of F-HTFs that are not HFCs, PFCs or SF_6 are not included in inventory totals and are included for informational purposes only. Emissions presented for informational purposes include HFEs, PFPMIEs, perfluoroalkylmorpholines, and perfluorotrialkylamines.

Methodology and Time-Series Consistency

Emissions are based on data reported through Subpart I, Electronics Manufacture, of EPA's GHGRP, semiconductor manufacturing Partner-reported emissions data received through EPA's PFC[98] Reduction/Climate Partnership, EPA's PFC Emissions Vintage Model (PEVM)—a model that estimates industry emissions from etching and chamber cleaning processes in the absence of emission control strategies (Burton and Beizaie 2001)[99]—and estimates of industry activity (i.e., total manufactured layer area and manufacturing capacity). The availability and applicability of reported emissions data from the EPA Partnership and EPA's GHGRP and activity data differ across the 1990 through 2022 time series. Consequently, fluorinated greenhouse gas (F-GHG) emissions from etching and chamber cleaning processes for semiconductors were estimated using seven distinct methods, one each for the periods 1990 through 1994, 1995 through 1999, 2000 through 2006, 2007 through 2010, 2011 and 2012, 2013 and 2014, and 2015 through 2022. Nitrous oxide emissions were estimated using five distinct methods, one each for the period 1990 through 1994, 1995 through 2010, 2011 and 2012, 2013 and 2014, and 2015 through 2022. The methodology discussion below for these time periods focuses on semiconductor emissions from etching, chamber cleaning, and uses of N_2O. Other emissions for MEMS, photovoltaic cells, and HTFs were estimated using the approaches described immediately below.

MEMS

GHGRP-reported emissions (F-GHG and N_2O) from the manufacturing of MEMS are available for the years 2011 to 2022. Emissions from manufacturing of MEMS for years prior to 2011 were calculated by linearly interpolating emissions between 1990 (at zero MMT CO_2 Eq.) and 2011, the first year where emissions from manufacturing of MEMS was reported to the GHGRP. Based upon information in the World Fab Forecast (WFF), it appears that some GHGRP reporters that manufacture both semiconductors and MEMS are reporting their emissions as only from semiconductor manufacturing; however, emissions from MEMS manufacturing are likely being included in semiconductor totals. Emissions were not estimated for non-reporters.

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[98] In the context of the EPA Partnership and PEVM, PFC refers to perfluorocompounds, not perfluorocarbons.

[99] A Partner refers to a participant in the U.S. EPA PFC Reduction/Climate Partnership for the Semiconductor Industry. Through a Memorandum of Understanding (MoU) with the EPA, Partners voluntarily reported their PFC emissions to the EPA by way of a third party, which aggregated the emissions through 2010.

Photovoltaic Cells

GHGRP-reported emissions (F-GHG and N_2O) from the manufacturing of photovoltaic cells are available for 2011, 2012, 2015, and 2016 from two manufacturers. EPA estimates the emissions from manufacturing of PVs from non-reporting facilities by multiplying the estimated capacity of non-reporters by a calculated F-GHG emission factor and N_2O emission factor based on GHGRP reported emissions from the manufacturer (in MMT CO_2 Eq. per megawatt) that reported emissions in 2015 and 2016. This manufacture's emissions are expected to be more representative of emissions from the sector, as their emissions were consistent with consuming only CF_4 for etching processes and are a large-scale manufacturer, representing 28 percent of the U.S. production capacity in 2016. The second photovoltaic manufacturer only produced a small fraction of U.S. production (<4 percent). They also reported the use of NF_3 in remote plasma cleaning processes, which does not have an emission factor in Part 98 for PV manufacturing, requiring them to report emissions equal to consumption. The total F-GHG emissions from non-reporters are then disaggregated into individual gases using the gas distribution from the 2015 to 2016 manufacturer. Manufacturing capacities in megawatts were drawn from DisplaySearch, a 2015 Congressional Research Service Report on U.S. Solar Photovoltaic Manufacturing, and self-reported capacity by GHGRP reporters. EPA estimated that during the 2015 to 2016 period, 28 percent of manufacturing capacity in the United States was represented through reported GHGRP emissions. Capacities are estimated for the full time series by linearly scaling the total U.S. capacity between zero in 1997 to the total capacity reported of crystalline silicon (c-Si) PV manufacturing in 2000 in DisplaySearch and then linearly scaling between the total capacity of c-Si PV manufacturing in DisplaySearch in 2009 to the total capacity of c-Si PV manufacturing reported in the Congressional Research Service report in 2012. Capacities were held constant for non-reporters for 2012 to 2019. In 2020, non-reporter capacity declined due to the closure of several PV manufacturing plants. This capacity was held constant for 2021 and 2022. Average emissions per MW from the GHGRP reporter in 2015 and 2016 were then applied to the total capacity prior to 2015. Emissions for 2014 from the GHGRP reporter that reported in 2015 and 2016 were scaled to the number of months open in 2014. For 1998 through 2022, emissions per MW (capacity) from the GHGRP reporter were applied to the non-reporters. For 2017 through 2022, there are no reported PV emissions. Therefore, emissions were estimated using the EPA-derived emission factor and estimated manufacturing capacity from non-reporters only.

HTFs

Facility emissions of F-HTFs from semiconductor manufacturing are reported to EPA under its GHGRP and are available for the years 2011 through 2022. EPA estimates the emissions of F-HTFs from non-reporting semiconductor facilities by calculating the ratio of GHGRP-reported fluorinated HTF emissions to GHGRP reported F-GHG emissions from etching and chamber cleaning processes, and then multiplying this ratio by the F-GHG emissions from etching and chamber cleaning processes estimated for non-reporting facilities. Fluorinated HTF use in semiconductor manufacturing is assumed to have begun in the early 2000s and to have gradually displaced other HTFs (e.g., de-ionized water and glycol) in semiconductor manufacturing (EPA 2006). For time-series consistency, EPA interpolated the share of F-HTF emissions to F-GHG emissions between 2000 (at 0 percent) and 2011 (at 17 percent) and applied these shares to the unadjusted F-GHG emissions during those years to estimate the emissions.

Semiconductors

1990 through 1994

From 1990 through 1994, Partnership data were unavailable, and emissions were modeled using PEVM (Burton and Beizaie 2001).[100] The 1990 to 1994 emissions are assumed to be uncontrolled, since reduction strategies such as chemical substitution and abatement were yet to be developed.

PEVM is based on the recognition that fluorinated greenhouse gas emissions from semiconductor manufacturing vary with: (1) the number of layers that comprise different kinds of semiconductor devices, including both silicon wafer and metal interconnect layers, and (2) silicon consumption (i.e., the area of semiconductors produced) for each kind of device. The product of these two quantities, Total Manufactured Layer Area (TMLA), constitutes the activity data for semiconductor manufacturing. PEVM also incorporates an emission factor that expresses emissions per unit of manufactured layer-area. Emissions are estimated by multiplying TMLA by this emission factor.

PEVM incorporates information on the two attributes of semiconductor devices that affect the number of layers: (1) linewidth technology (the smallest manufactured feature size),[101] and (2) product type (discrete, memory or logic).[102] For each linewidth technology, a weighted average number of layers is estimated using VLSI product-specific worldwide silicon demand data in conjunction with complexity factors (i.e., the number of layers per Integrated Circuit (IC) specific to product type (Burton and Beizaie 2001; ITRS 2007). PEVM derives historical consumption of silicon (i.e., square inches) by linewidth technology from published data on annual wafer starts and average wafer size (VLSI Research, Inc. 2012).

The emission factor in PEVM is the average of four historical emission factors, each derived by dividing the total annual emissions reported by the Partners for each of the four years between 1996 and 1999 by the total TMLA estimated for the Partners in each of those years. Over this period, the emission factors varied relatively little (i.e., the relative standard deviation for the average was 5 percent). Since Partners are believed not to have applied significant emission reduction measures before 2000, the resulting average emission factor reflects uncontrolled emissions and hence may be use here to estimate 1990 through 1994 emissions. The emission factor is used to estimate U.S. uncontrolled emissions using publicly available data on world (including U.S.) silicon consumption.

As it was assumed for this time period that there was no consequential adoption of fluorinated-gas-reducing measures, a fixed distribution of fluorinated-gas use was assumed to apply to the entire U.S. industry to estimate gas-specific emissions. This distribution was based upon the average fluorinated-gas purchases made by semiconductor manufacturers during this period and the application of IPCC default emission factors for each gas (Burton and Beizaie 2001).

PEVM only addressed the seven main F-GHGs (CF_4, C_2F_6, C_3F_8, c-C_4F_8, HFC-23, SF_6, and NF_3) used in semiconductor manufacturing. Through reporting under Subpart I of EPA's GHGRP, data on other F-GHGs (C_4F_6, C_5F_8, HFC-32, HFC-41, HFC-134a) used in semiconductor manufacturing became available and EPA was therefore able to extrapolate this data across the entire 1990 to 2022 timeseries. To estimate emissions for these "other F-GHGs", emissions data from Subpart I between 2014 to 2016 were used to estimate the average share or percentage contribution of these gases as compared to total F-GHG emissions. Subpart I emission factors were updated for 2014 by EPA as a

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[100] Various versions of the PEVM exist to reflect changing industrial practices. From 1990 to 1994 emissions estimates are from PEVM v1.0, completed in September 1998. The emission factor used to estimate 1990 to 1994 emissions is an average of the 1995 and 1996 emissions factors, which were derived from Partner reported data for those years.

[101] By decreasing features of Integrated Circuit components, more components can be manufactured per device, which increases its functionality. However, as those individual components shrink it requires more layers to interconnect them to achieve the functionality. For example, a microprocessor manufactured with 65 nm feature sizes might contain as many as 1 billion transistors and require as many as 11 layers of component interconnects to achieve functionality, while a device manufactured with 130 nm feature size might contain a few hundred million transistors and require 8 layers of component interconnects (ITRS 2007).

[102] Memory devices manufactured with the same feature sizes as microprocessors (a logic device) require approximately one-half the number of interconnect layers, whereas discrete devices require only a silicon base layer and no interconnect layers (ITRS 2007). Since discrete devices did not start using PFCs appreciably until 2004, they are only accounted for in the PEVM emissions estimates from 2004 onwards.

result of a larger set of emission factor data becoming available, so reported data from 2011 through 2013 was not utilized for the average. To estimate non-reporter emissions from 2011-2022, the average emissions data from Subpart I of 2011 to 2022 was used.

To estimate N_2O emissions, it was assumed the proportion of N_2O emissions estimated for 1995 (discussed below) remained constant for the period of 1990 through 1994.

1995 through 1999

For 1995 through 1999, total U.S. emissions were extrapolated from the total annual emissions reported by the Partners (1995 through 1999). Partner-reported emissions are considered more representative (e.g., in terms of capacity utilization in a given year) than PEVM-estimated emissions and are used to generate total U.S. emissions when applicable. The emissions reported by the Partners were divided by the ratio of the total capacity of the plants operated by the Partners and the total capacity of all of the semiconductor plants in the United States; this ratio represents the share of capacity attributable to the Partnership. This method assumes that Partners and non-Partners have identical capacity utilizations and distributions of manufacturing technologies. Plant capacity data is contained in the World Fab Forecast (WFF) database and its predecessors, which is updated quarterly. Gas-specific emissions were estimated using the same method as for 1990 through 1994.

For this time period emissions of other F-GHGs (C_4F_6, C_5F_8, HFC-32, HFC-41, HFC-134a) were estimated using the method described above for 1990 to 1994.

For this time period, the N_2O emissions were estimated using an emission factor that was applied to the annual, total U.S. TMLA manufactured. The emission factor was developed using a regression-through-the-origin (RTO) model: GHGRP reported N_2O emissions were regressed against the corresponding TMLA of facilities that reported no use of abatement systems. Details on EPA's GHGRP reported emissions and development of emission factor using the RTO model are presented in the 2011 through 2012 section. The total U.S. TMLA for 1995 through 1999 was estimated using PEVM.

2000 through 2006

Emissions for the years 2000 through 2006—the period during which Partners began the consequential application of fluorinated greenhouse gas-reduction measures—were estimated using a combination of Partner-reported emissions and adjusted PEVM modeled emissions. The emissions reported by Partners for each year were accepted as the quantity emitted from the share of the industry represented by those Partners. Remaining emissions, those from non-Partners, were estimated using PEVM, with one change. To ensure time-series consistency and to reflect the increasing use of remote clean technology (which increases the efficiency of the production process while lowering emissions of fluorinated greenhouse gases), the average non-Partner emission factor (PEVM emission factor) was assumed to begin declining gradually during this period. Specifically, the non-Partner emission factor for each year was determined by linear interpolation, using the end points of 1999 (the original PEVM emission factor) and 2011 (a new emission factor determined for the non-Partner population based on GHGRP-reported data, described below).

The portion of the U.S. total emissions attributed to non-Partners is obtained by multiplying PEVM's total U.S. emissions figure by the non-Partner share of U.S. total silicon capacity for each year as described above.[103] Gas-specific emissions from non-Partners were estimated using linear interpolation between the gas-specific emissions distributions of 1999 (assumed to be the same as that of the total U.S. Industry in 1994) and 2011 (calculated from a subset of non-Partners that reported through the GHGRP as a result of emitting more than 25,000 MT CO_2 Eq. per year). Annual updates to PEVM reflect published figures for actual silicon consumption from VLSI Research, Inc., revisions and additions to the world population of semiconductor manufacturing plants, and changes in IC

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[103] This approach assumes that the distribution of linewidth technologies is the same between Partners and non-Partners. As discussed in the description of the method used to estimate 2007 emissions, this is not always the case.

fabrication practices within the semiconductor industry (see ITRS 2008 and Semiconductor Equipment and Materials Industry 2011).[104, 105, 106] For this time period emissions of other F-GHGs (C_4F_6, C_5F_8, HFC-32, HFC-41, HFC-134a) were estimated using the method described above for 1990 to 1994.

Nitrous oxide emissions were estimated using the same methodology as the 1995 through 1999 methodology.

2007 through 2010

For the years 2007 through 2010, emissions were also estimated using a combination of Partner reported emissions and adjusted PEVM modeled emissions to provide estimates for non-Partners; however, two improvements were made to the estimation method employed for the previous years in the time series. First, the 2007 through 2010 emission estimates account for the fact that Partners and non-Partners employ different distributions of manufacturing technologies, with the Partners using manufacturing technologies with greater transistor densities and therefore greater numbers of layers.[107] Second, the scope of the 2007 through 2010 estimates was expanded relative to the estimates for the years 2000 through 2006 to include emissions from research and development (R&D) fabs. This additional enhancement was feasible through the use of more detailed data published in the WFF. PEVM databases were updated annually as described above. The published world average capacity utilization for 2007 through 2010 was used for production fabs, while for R&D fabs a 20 percent figure was assumed (SIA 2009).

In addition, publicly available utilization data was used to account for differences in fab utilization for manufacturers of discrete and IC products for 2010 emissions for non-Partners. The Semiconductor Capacity Utilization (SICAS) Reports from SIA provides the global semiconductor industry capacity and utilization, differentiated by discrete and IC products (SIA 2009 through 2011). PEVM estimates were adjusted using technology-weighted capacity shares that reflect the relative influence of different utilization. Gas-specific emissions for non-Partners were estimated using the same method as for 2000 through 2006.

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[104] Special attention was given to the manufacturing capacity of plants that use wafers with 300 mm diameters because the actual capacity of these plants is ramped up to design capacity, typically over a 2 to 3 year period. To prevent overstating estimates of partner-capacity shares from plants using 300 mm wafers, *design* capacities contained in WFF were replaced with estimates of *actual installed* capacities for 2004 published by Citigroup Smith Barney (2005). Without this correction, the partner share of capacity would be overstated, by approximately 5 percent. For perspective, approximately 95 percent of all new capacity additions in 2004 used 300 mm wafers, and by year-end those plants, on average, could operate at approximately 70 percent of the design capacity. For 2005, actual installed capacities were estimated using an entry in the World Fab Watch database (April 2006 Edition) called "wafers/month, 8-inch equivalent," which denoted the actual installed capacity instead of the fully-ramped capacity. For 2006, actual installed capacities of new fabs were estimated using an average monthly ramp rate of 1100 wafer starts per month (wspm) derived from various sources such as semiconductor fabtech, industry analysts, and articles in the trade press. The monthly ramp rate was applied from the first-quarter of silicon volume (FQSV) to determine the average design capacity over the 2006 period.

[105] In 2006, the industry trend in co-ownership of manufacturing facilities continued. Several manufacturers, who are Partners, now operate fabs with other manufacturers, who in some cases are also Partners and in other cases are not Partners. Special attention was given to this occurrence when estimating the Partner and non-Partner shares of U.S. manufacturing capacity.

[106] Two versions of PEVM are used to model non-Partner emissions during this period. For the years 2000 to 2003 PEVM v3.2.0506.0507 was used to estimate non-Partner emissions. During this time, discrete devices did not use PFCs during manufacturing and therefore only memory and logic devices were modeled in the PEVM v3.2.0506.0507. From 2004 onwards, discrete device fabrication started to use PFCs, hence PEVM v4.0.0701.0701, the first version of PEVM to account for PFC emissions from discrete devices, was used to estimate non-Partner emissions for this time period.

[107] EPA considered applying this change to years before 2007 but found that it would be difficult due to the large amount of data (i.e., technology-specific global and non-Partner TMLA) that would have to be examined and manipulated for each year. This effort did not appear to be justified given the relatively small impact of the improvement on the total estimate for 2007 and the fact that the impact of the improvement would likely be lower for earlier years because the estimated share of emissions accounted for by non-Partners is growing as Partners continue to implement emission-reduction efforts.

For this time period emissions of other F-GHGs (C_5F_8, CH_2F_2, CH_3F, CH_2FCF_3, $C_2H_2F_4$) were estimated using the method described above for 1990 to 1994. Nitrous oxide emissions were estimated using the same methodology as the 1995 through 1999 methodology.

2011 through 2012

The fifth method for estimating emissions from semiconductor manufacturing covers the period 2011 through 2012. This methodology differs from previous years because the EPA's Partnership with the semiconductor industry ended (in 2010) and reporting under EPA's GHGRP began. Manufacturers whose estimated uncontrolled emissions equal or exceed 25,000 MT CO_2 Eq. per year (based on default F-GHG-specific emission factors and total capacity in terms of substrate area) are required to report their emissions to EPA. This population of reporters to EPA's GHGRP included both historical Partners of EPA's PFC Reduction/Climate Partnership as well as non-Partners some of which use gallium arsenide (GaAs) technology in addition to Si technology.[108] Emissions from the population of manufacturers that were below the reporting threshold were also estimated for this time period using EPA-developed emission factors and estimates of facility-specific production obtained from WFF. Inventory totals reflect the emissions from both reporting and non-reporting populations.

Under EPA's GHGRP, semiconductor manufacturing facilities report emissions of F-GHGs (for all types of F-GHGs) used in etch and clean processes as well as emissions of fluorinated heat transfer fluids. (Fluorinated heat transfer fluids are used to control process temperatures, thermally test devices, and clean substrate surfaces, among other applications.) They also report N_2O emissions from CVD and other processes. The F-GHGs and N_2O were aggregated, by gas, across all semiconductor manufacturing GHGRP reporters to calculate gas-specific emissions for the GHGRP-reporting segment of the U.S. industry. At this time, emissions that result from heat transfer fluid use that are HFC, PFC and SF_6 are included in the total emission estimates from semiconductor manufacturing, and these GHGRP-reported emissions have been compiled and presented in Table 4-121. F-HTF emissions resulting from other types of gases (e.g., HFEs) are not presented in semiconductor manufacturing totals in Table 4-121 and Table 4-122 but are shown in Table 4-123 for informational purposes.

Changes to the default emission factors and default destruction or removal efficiencies (DREs) used for GHGRP reporting affected the emissions trend between 2013 and 2014. These changes did not reflect actual emission rate changes but data improvements. Therefore, for the current *Inventory*, EPA adjusted the time series of GHGRP-reported data for 2011 through 2013 to ensure time-series consistency using a series of calculations that took into account the characteristics of a facility (e.g., wafer size and abatement use). To adjust emissions for facilities that did not report abatement in 2011 through 2013, EPA simply applied the revised emission factors to each facility's estimated gas consumption by gas, process type and wafer size. In 2014, EPA also started collecting information on fab-wide DREs and the gases abated by process type, which were used in calculations for adjusting emissions from facilities that abated F-GHGs in 2011 through 2013.

- To adjust emissions for facilities that abated emissions in 2011 through 2013, EPA first calculated the quantity of gas abated in 2014 using reported F-GHG emissions, the revised default DREs (or the estimated site-specific DRE,[109] if a site-specific DRE was indicated), and the fab-wide DREs reported in 2014.[110] To adjust emissions for facilities that abated emissions in 2011 through 2013, EPA first estimated

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[108] GaAs and Si technologies refer to the wafer on which devices are manufactured, which use the same PFCs but in different ways.

[109] EPA generally assumed site-specific DREs were as follows: CF_4, Etch (90 percent); all other gases, Etch (98 percent); NF_3, Clean (95 percent); CF_4, Clean (80 percent), and all other gases, Clean (80 percent). There were a few exceptions where a higher DRE was assumed to ensure the calculations operated correctly when there was 100 percent abatement.

[110] If abatement information was not available for 2014 or the reported incorrectly in 2014, data from 2015 or 2016 was substituted.

the percentage of gas passing through abatement systems for remote plasma clean in 2014 using the ratio of emissions reported for CF_4 and NF_3.

- EPA then estimated the quantity of NF_3 abated for remote plasma clean in 2014 using the ratio of emissions reported for CF_4 (which is not abated) and NF_3. This abated quantity was then subtracted from the total abated quantity calculated as described in the bullet above.
- To account for the resulting remaining abated quantity, EPA assumed that the percentage of gas passing through abatement systems was the same across all remaining gas and process type combinations where abatement was reported for 2014.
- The percentage of gas abated was then assumed to be the same in 2011 through 2013 (if the facility claimed abatement that year) as in 2014 for each gas abated in 2014.

The revised emission factors and DREs were then applied to the estimated gas consumption for each facility by gas, process type and wafer size.[111]

For the segment of the semiconductor industry that is below EPA's GHGRP reporting threshold, and for R&D facilities, which are not covered by EPA's GHGRP, emission estimates are based on EPA-developed emission factors for the F-GHGs and N_2O and estimates of manufacturing activity. The new emission factors (in units of mass of CO_2 Eq./TMLA [million square inches (MSI)]) are based on the emissions reported under EPA's GHGRP by facilities without abatement and on the TMLA estimates for these facilities based on the WFF (SEMI 2012, 2013).[112] In a refinement of the method used to estimate emissions for the non-Partner population for prior years, different emission factors were developed for different subpopulations of fabs, disaggregated by wafer size (200 mm and 300 mm). For each of these groups, a subpopulation-specific emission factor was obtained using a regression-through-the-origin (RTO) model: facility-reported aggregate emissions of seven F-GHGs (CF_4, C_2F_6, C_3F_8, c-C_4F_8, CHF_3, SF_6 and NF_3)[113] were regressed against the corresponding TMLA to estimate an aggregate F-GHG emissions factor (CO_2 Eq./MSI TMLA), and facility-reported N_2O emissions were regressed against the corresponding TMLA to estimate a N_2O emissions factor (CO_2 Eq./MSI TMLA). For each subpopulation, the slope of the RTO model is the emission factor for that subpopulation. Information on the use of point-of-use abatement by non-reporting fabs was not available; thus, EPA conservatively assumed that non-reporting facilities did not use point-of-use abatement.

For 2011 and 2012, estimates of TMLA relied on the capacity utilization of the fabs published by the U.S. Census Bureau's Historical Data Quarterly Survey of Plant Capacity Utilization (USCB 2011, 2012). Similar to the assumption for 2007 through 2010, facilities with only R&D activities were assumed to utilize only 20 percent of their manufacturing capacity. All other facilities in the United States are assumed to utilize the average percent of the manufacturing capacity without distinguishing whether fabs produce discrete products or logic products.

Non-reporting fabs were then broken out into subpopulations by wafer size (200 mm and 300 mm). using information available through the WFF. The appropriate emission factor was applied to the total TMLA of each subpopulation of non-reporting facilities to estimate the CO_2-equivalent emissions of that subpopulation.

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[111] Since facilities did not report by fab before 2014, fab-wide DREs were averaged if a facility had more than one fab. For facilities that reported more than one wafer size per facility, the percentages of a facility's emissions per wafer size were estimated in 2014 and applied to earlier years, if possible. If the percentage of emissions per wafer size were unknown, a 50/50 split was used.

[112] EPA does not have information on fab-wide DREs for this time period, so it is not possible to estimate uncontrolled emissions from fabs that reported point-of-use abatement. These fabs were therefore excluded from the regression analysis. (They are still included in the national totals.)

[113] Only seven gases were aggregated because inclusion of F-GHGs that are not reported in the *Inventory* results in overestimation of emission factor that is applied to the various non-reporting subpopulations.

Gas-specific, CO_2-equivalent emissions for each subpopulation of non-reporting facilities were estimated using the corresponding reported distribution of gas-specific, CO_2-equivalent emissions from which the aggregate emission factors, based on GHGRP-reported data, were developed. Estimated in this manner, the non-reporting population accounted for 4.9 and 5.0 percent of U.S. emissions in 2011 and 2012, respectively. The GHGRP-reported emissions and the calculated non-reporting population emissions are summed to estimate the total emissions from semiconductor manufacturing.

2013 and 2014

For 2013 and 2014, as for 2011 and 2012, F-GHG and N_2O emissions data received through EPA's GHGRP were aggregated, by gas, across all semiconductor-manufacturing GHGRP reporters to calculate gas-specific emissions for the GHGRP-reporting segment of the U.S. industry. However, for these years WFF data was not available. Therefore, an updated methodology that does not depend on the WFF derived activity data was used to estimate emissions for the segment of the industry that are not covered by EPA's GHGRP. For the facilities that did not report to the GHGRP (i.e., which are below EPA's GHGRP reporting threshold or are R&D facilities), emissions were estimated based on the proportion of total U.S. emissions attributed to non-reporters for 2011 and 2012. EPA used a simple averaging method by first estimating this proportion for both F-GHGs and N_2O for 2011, 2012, and 2015 and 2016, resulting in one set of proportions for F-GHGs and one set for N_2O, and then applied the average of each set to the 2013 and 2014 GHGRP reported emissions to estimate the non-reporters' emissions. Fluorinated gas-specific, CO_2-equivalent emissions for non-reporters were estimated using the corresponding reported distribution of gas-specific, CO_2-equivalent emissions reported through EPA's GHGRP for 2013 and 2014.

GHGRP-reported emissions in 2013 were adjusted to capture changes to the default emission factors and default destruction or removal efficiencies used for GHGRP reporting, affecting the emissions trend between 2013 and 2014. EPA used the same method to make these adjustments as described above for 2011 and 2012 GHGRP data.

2015 through 2022

Similar to the methods described above for 2011 and 2012, and 2013 and 2014, EPA relied upon emissions data reported directly through the GHGRP. For 2015 through 2022, EPA took an approach similar to the one used for 2011 and 2012 to estimate emissions for the segment of the semiconductor industry that is below EPA's GHGRP reporting threshold, and for R&D facilities, which are not covered by EPA's GHGRP. However, in a change from previous years, EPA was able to develop new annual emission factors for 2015 through 2022 using TMLA from WFF and a more comprehensive set of emissions, i.e., fabs with as well as without abatement control, as new information about the use of abatement in GHGRP fabs and fab-wide were available. Fab-wide DREs represent total fab CO_2 Eq.-weighted controlled F-GHG and N_2O emissions (emissions after the use of abatement) divided by total fab CO_2 Eq.-weighted uncontrolled F-GHG and N_2O emissions (emission prior to the use of abatement).

Using information about reported emissions and the use of abatement and fab-wide DREs, EPA was able to calculate uncontrolled emissions (each total F-GHG and N_2O) for every GHGRP reporting fab. Using this, coupled with TMLA estimated using methods described above (see 2011 through 2012), EPA derived emission factors by year, gas type (F-GHG or N_2O), and wafer size (200 mm and less or 300 mm) by dividing the total annual emissions reported by GHGRP reporters by the total TMLA estimated for those reporters. These emission factors were multiplied by estimates of non-reporter TMLA to arrive at estimates of total F-GHG and N_2O emissions for non-reporters for each year. For each wafer size, the total F-GHG emissions were disaggregated into individual gases using the shares of total emissions represented by those gases in the emissions reported to the GHGRP by unabated fabs producing that wafer size.

Data Sources

GHGRP reporters, which consist of former EPA Partners and non-Partners, estimated their emissions using a default emission factor method established by EPA. Like the Tier 2c Method in the *2019 Refinement to the 2006 IPCC Guidelines*, this method uses different emission and byproduct generation factors for different F-GHGs and process types and uses factors for different wafer sizes (i.e., 300mm vs. 150 and 200mm) and CVD clean subtypes (in situ thermal, in situ plasma, and remote plasma). Starting with 2014 reported emissions, EPA's GHGRP required semiconductor manufacturers to apply updated emission factors to estimate their F-GHG emissions. For the years 2011 through 2013 reported emissions, semiconductor manufacturers used older emission factors to estimate their F-GHG emissions (Federal Register / Vol. 75, No. 230 /December 1, 2010, 74829). Subpart I emission factors were updated for 2014 by EPA as a result of a larger set of emission factor data becoming available as part of the Subpart I petition process, which took place from 2011 through 2013. In addition to semiconductor manufacturing, GHGRP also includes reported emissions from MEMS and PV producers.

Historically, semiconductor industry partners estimated and reported their emissions using a range of methods and uneven documentation. It is assumed that most Partners used a method at least as accurate as the IPCC's Tier 2a Methodology, recommended in the *2006 IPCC Guidelines*. Partners are estimated to have accounted for between 56 and 79 percent of F-GHG emissions from U.S. semiconductor manufacturing between 1995 and 2010, with the percentage declining in recent years as Partners increasingly implemented abatement measures.

Estimates of operating plant capacities and characteristics for Partners and non-Partners were derived from the Semiconductor Equipment and Materials Industry (SEMI) WFF (formerly World Fab Watch) database (1996 through 2012, 2013, 2016, 2018, 2021, and 2023) (e.g., Semiconductor Materials and Equipment Industry 2021). Actual worldwide capacity utilizations for 2008 through 2010 were obtained from Semiconductor International Capacity Statistics (SICAS) (SIA 2009 through 2011). Estimates of the number of layers for each linewidth was obtained from International Technology Roadmap for Semiconductors: 2013 Edition (Burton and Beizaie 2001; ITRS 2007; ITRS 2008; ITRS 2011; ITRS 2013). PEVM utilized the WFF, SICAS, and ITRS, as well as historical silicon consumption estimates published by VLSI. Actual quarterly U.S. capacity utilizations for 2011, 2012, 2014 to 2022 were obtained from the U.S. Census Bureau's Historical Data Quarterly Survey of Plant Capacity Utilization (USCB 2011, 2012, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022).

Estimates of PV manufacturing capacity, which are used to calculate emissions from non-reporting facilities, are based on data from two sources. A historical market analysis from DisplaySearch provided estimates of U.S. manufacturing capacity from 2000 to 2009 (DisplaySearch 2010). Domestic PV cell production for 2012 was obtained from a Congressional Research Service report titled *U.S. Solar Photovoltaic Manufacturing: Industry Trends, Global Competition, Federal Support* (Platzer 2015).

Uncertainty

A quantitative uncertainty analysis of this source category was performed using the IPCC-recommended Approach 2 uncertainty estimation methodology, the Monte Carlo stochastic simulation technique. The Monte Carlo stochastic simulation was performed on the total emissions estimate from the electronics industry, represented in equation form as:

Equation 4-20: Total Emissions from Electronics Industry

$$\begin{aligned}\text{Total Emissions } (\mathrm{E}_T) &\\ &= \text{Semiconductors F-GHG and N}_2\text{O Emissions } (\mathrm{E}_{Semi})\\ &+ \text{MEMS F-GHG and N}_2\text{O Emissions } (\mathrm{E}_{MEMS}) + \text{PV F-GHG and N}_2\text{O Emissions } (\mathrm{E}_{PV})\\ &+ \text{HFC, PFC and SF}_6\text{ F-HTFs Emissions } (\mathrm{E}_{HTF})\end{aligned}$$

The uncertainty in the total emissions for the electronics industry, presented in Table 4-124 below, results from the convolution of four distributions of emissions, namely from semiconductors manufacturing, MEMS manufacturing, PV manufacturing and emissions of heat transfer fluids. The approaches for estimating uncertainty in each of the sources are described below:

Semiconductors Manufacture Emission Uncertainty

The Monte Carlo stochastic simulation was performed on the emissions estimate from semiconductor manufacturing, represented in equation form as:

Equation 4-21: Total Emissions from Semiconductor Manufacturing

$$\begin{aligned}\text{Semiconductors F-GHG and N}_2\text{O Emissions }(\text{E}_{Semi})\\ &= \text{ GHGRP Reported F-GHG Emissions (ER,F-GHG, Semi)}\\ &+ \text{ Non-Reporters' Estimated F-GHG Emissions }\left(\text{E}_{\text{NR,F-GHG,}Semi}\right)\\ &+ \text{ GHGRP Reported N}_2\text{O Emissions }\left(\text{E}_{\text{R,N}_2\text{O,}Semi}\right)\\ &+ \text{ Non-Reporters' Estimated N}_2\text{O Emissions }\left(\text{E}_{\text{NR,N}_2\text{O,}Semi}\right)\end{aligned}$$

The uncertainty in E_{Semi} results from the convolution of four distributions of emissions, $E_{R,F\text{-}GHG}$,$_{Semi}$ $E_{R,N2O,Semi}$ $E_{NR,F\text{-}GHG}$,$_{Semi}$ and $E_{NR,N2O,Semi}$. The approaches for estimating each distribution and combining them to arrive at the reported 95 percent confidence interval (CI) for E_{Semi} are described in the remainder of this section.

The uncertainty estimate of $E_{R,\ F\text{-}GHG,Semi}$, or GHGRP-reported F-GHG emissions, is developed based on gas-specific uncertainty estimates of emissions for two industry segments, one processing 200 mm or less wafers and one processing 300 mm wafers. Uncertainties in emissions for each gas and industry segment are based on an uncertainty analysis conducted during the assessment of emission estimation methods for the Subpart I rulemaking in 2012 (see Technical Support for Modifications to the Fluorinated Greenhouse Gas Emission Estimation Method Option for Semiconductor Facilities under Subpart I, docket EPA–HQ–OAR–2011–0028).[114] This assessment relied on facility-specific gas information by gas and wafer size, and incorporated uncertainty associated with both emission factors and gas consumption quantities. The 2012 analysis did not consider the use of abatement.

For the industry segment that manufactured 200 mm wafers, estimates of uncertainty at a 95 percent CI ranged from ±29 percent for C_3F_8 to ±10 percent for CF_4. For the corresponding 300 mm industry segment, estimates of uncertainty at the 95 percent CI ranged from ±36 percent for C_4F_8 to ±16 percent for CF_4. For gases for which uncertainty was not analyzed in the 2012 assessment (e.g., CH_2F_2), EPA applied the 95 percent CI range equivalent to the range for the gas and industry segment with the highest uncertainty from the 2012 assessment. These gas and wafer-specific uncertainty estimates were developed to represent uncertainty at a facility-level, but they are applied to the total emissions across all the facilities that did not abate emissions as reported under EPA's GHGRP at a national-level. Hence, it is noted that the uncertainty estimates used may be overestimating the uncertainties at a national-level.

For those facilities reporting abatement of emissions under EPA's GHGRP, estimates of uncertainties for the no abatement industry segments are modified to reflect the use of full abatement (abatement of all gases from all cleaning and etching equipment) and partial abatement. These assumptions used to develop uncertainties for the partial and full abatement facilities are identical for 200 mm and 300 mm wafer processing facilities. For all facilities reporting gas abatement, a triangular distribution of destruction or removal efficiency is assumed for each gas. The triangular distributions range from an asymmetric and highly uncertain distribution of zero percent minimum to 90 percent maximum with 70 percent most likely value for CF_4 to a symmetric and less uncertain distribution of 85 percent minimum to 95 percent maximum with 90 percent most likely value for C_4F_8, NF_3, and SF_6. For facilities reporting partial abatement, the distribution of fraction of the gas fed through the abatement device, for each gas, is assumed to be triangularly distributed as well. It is assumed that no more than 50 percent

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[114] On November 13, 2013, EPA published a final rule revising Subpart I (Electronics Manufacturing) of the GHGRP (78 FR 68162). The revised rule includes updated default emission factors and updated default destruction and removal efficiencies that are slightly different from those that semiconductor manufacturers were required to use to report their 2012 emissions. The uncertainty analyses that were performed during the development of the revised rule focused on these updated defaults but are expected to be reasonably representative of the uncertainties associated with the older defaults, particularly for estimates at the country level. (They may somewhat underestimate the uncertainties associated with the older defaults at the facility level.) For simplicity, the 2012 estimates are assumed to be unbiased although in some cases, the updated (and therefore more representative) defaults are higher or lower than the older defaults. Multiple models and sensitivity scenarios were run for the Subpart I analysis. The uncertainty analysis presented here made use of the Input gas and wafer size model (Model 1) under the following conditions: Year = 2010, f = 20, n = SIA3.

of the gases are abated (i.e., the maximum value) and that 50 percent is the most likely value, and the minimum is zero percent. Consideration of abatement then resulted in four additional industry segments, two 200-mm wafer-processing segments (one fully and one partially abating each gas) and two 300-mm wafer-processing segment (one fully and the other partially abating each gas). Gas-specific emission uncertainties were estimated by convolving the distributions of unabated emissions with the appropriate distribution of abatement efficiency for fully and partially abated facilities using a Monte Carlo simulation.

The uncertainty in $E_{R,F\text{-}GHG,Semi}$ is obtained by allocating the estimates of uncertainties to the total GHGRP-reported emissions from each of the six industry segments, and then running a Monte Carlo simulation which results in the 95 percent CI for emissions from GHGRP-reporting facilities ($E_{R,F\text{-}GHG,Semi}$).

The uncertainty in $E_{R,N2O,Semi}$ is obtained by assuming that the uncertainty in the emissions reported by each of the GHGRP reporting facilities results from the uncertainty in quantity of N_2O consumed and the N_2O emission factor (or utilization). Similar to analyses completed for Subpart I (see Technical Support for Modifications to the Fluorinated Greenhouse Gas Emission Estimation Method Option for Semiconductor Facilities under Subpart I, docket EPA–HQ–OAR–2011–0028), the uncertainty of N_2O consumed was assumed to be 20 percent. Consumption of N_2O for GHGRP reporting facilities was estimated by back-calculating from emissions reported and assuming no abatement. The quantity of N_2O utilized (the complement of the emission factor) was assumed to have a triangular distribution with a minimum value of zero percent, mode of 20 percent and maximum value of 84 percent. The minimum was selected based on physical limitations, the mode was set equivalent to the Subpart I default N_2O utilization rate for chemical vapor deposition, and the maximum was set equal to the maximum utilization rate found in ISMI Analysis of Nitrous Oxide Survey Data (ISMI 2009). The inputs were used to simulate emissions for each of the GHGRP reporting, N_2O-emitting facilities. The uncertainty for the total reported N_2O emissions was then estimated by combining the uncertainties of each facilities' reported emissions using Monte Carlo simulation.

The estimate of uncertainty in $E_{NR,\ F\text{-}GHG,Semi}$ and $E_{NR,\ N2O,Semi}$ entailed developing estimates of uncertainties for the emissions factors and the corresponding estimates of TMLA.

The uncertainty in TMLA depends on the uncertainty of two variables—an estimate of the uncertainty in the average annual capacity utilization for each level of production of fabs (e.g., full scale or R&D production) and a corresponding estimate of the uncertainty in the number of layers manufactured. For both variables, the distributions of capacity utilizations and number of manufactured layers are assumed triangular for all categories of non-reporting fabs. The most probable utilization is assumed to be 82 percent, with the highest and lowest utilization assumed to be 89 percent, and 70 percent, respectively. For the triangular distributions that govern the number of possible layers manufactured, it is assumed the most probable value is one layer less than reported in the ITRS; the smallest number varied by technology generation between one and two layers less than given in the ITRS and largest number of layers corresponded to the figure given in the ITRS.

The uncertainty bounds for the average capacity utilization and the number of layers manufactured are used as inputs in a separate Monte Carlo simulation to estimate the uncertainty around the TMLA of both individual facilities as well as the total non-reporting TMLA of each sub-population.

The uncertainty around the emission factors for non-reporting facilities is the total combined uncertainties of individual gases and the TMLA of each reporting facility in that category. The combined uncertainty of emissions of individual gases from non-reporters is equal to the uncertainty of total emissions for non-reporting facilities.

The uncertainty around the emission factors for non-reporting facilities is the total combined uncertainties of individual gases (MT units) and the TMLA of each reporting facility in that category. The combined uncertainty of emissions of individual gases from non-reporters is equal to the uncertainty of total emissions for non-reporting facilities. For each wafer size for reporting facilities, emissions of individual gases were regressed on TMLA (with an intercept forced to zero) for 10,000 emission and 10,000 TMLA values in a Monte Carlo simulation, which results in 10,000 total regression coefficients (emission factors). The 2.5th and the 97.5th percentile of these emission factors are determined, and the bounds are assigned as the percent difference from the estimated emission factor.

The next step in estimating the uncertainty in emissions of reporting and non-reporting facilities in semiconductor manufacture is convolving the distribution of reported emissions, emission factors, and TMLA using Monte Carlo simulation. For this Monte Carlo simulation, the distributions of the reported F-GHG gas- and wafer size-specific emissions are assumed to be normally distributed, and the uncertainty bounds are assigned at 1.96 standard deviations around the estimated mean. The were some instances, though, where departures from normality were observed for variables, including for the distributions of the gas- and wafer size-specific N_2O emissions, TMLA, and non-reporter emission factors, both for F-GHGs and N_2O. As a result, the distributions for these parameters were assumed to follow a PERT beta distribution.

MEMS Manufacture Emission Uncertainty

The Monte Carlo stochastic simulation was performed on the emissions estimate from MEMS manufacturing, represented in equation form as:

Equation 4-22: Total Emissions from MEMS Manufacturing

$$\text{MEMS F-GHG and N}_2\text{O Emissions } (\text{E}_{MEMS}) = \text{GHGRP Reported F-GHG Emissions } (\text{E}_{\text{R,F-GHG},MEMS}) + \text{GHGRP Reported N}_2\text{O Emissions } (\text{E}_{\text{R,N}_2\text{O},\ MEMS})$$

$$\begin{aligned}\text{MEMS F-GHG and N}_2\text{O Emissions } (\text{E}_{MEMS})& \\ = \ & \text{GHGRP Reported F-GHG Emissions } \left(\text{E}_{\text{R, F-GHG},MEMS}\right) \\ + \ & \text{GHGRP Reported N}_2\text{O Emissions } \left(\text{E}_{\text{R},N_2\text{O},MEMS}\right)\end{aligned}$$

Emissions from MEMS manufacturing are only quantified for GHGRP reporters. MEMS manufacturers that report to the GHGRP all report the use of 200 mm wafers. Some MEMS manufacturers report using abatement equipment. Therefore, the estimates of uncertainty at the 95 percent CI for each gas emitted by MEMS manufacturers are set equal to the gas-specific uncertainties for manufacture of 200mm semiconductor wafers with partial abatement. The same assumption is applied for uncertainty levels for GHGRP reported MEMS N_2O emissions ($E_{R,N2O,MEMS}$).

PV Manufacture Emission Uncertainty

The Monte Carlo stochastic simulation was performed on the emissions estimate from PV manufacturing, represented in equation form as:

Equation 4-23: Total Emissions from PV Manufacturing

$$\text{PV F-GHG and N}_2\text{O Emissions } (\text{E}_{PV}) = \text{Non-Reporters' Estimated F-GHG Emissions } (\text{E}_{\text{NR,F-GHG},PV}) + \text{Non-Reporters' Estimated N}_2\text{O Emissions } (\text{E}_{\text{NR,N}_2\text{O},PV})$$

$$\begin{aligned}&\text{PV F-GHG and N}_2\text{O Emissions } (\text{E}_{PV}) \\ = \ & \text{Non-Reporters' Estimated F-GHG Emissions } \left(\text{E}_{\text{NR,F-GHG},PV}\right) \\ + \ & \text{Non-Reporters' Estimated N2O Emissions } \left(\text{E}_{\text{NR,N}_2\text{O},PV}\right)\end{aligned}$$

Emissions from PV manufacturing are only estimated for non-GHGRP reporters in 2022. There were no reported emissions from PV manufacturing in GHGRP in 2022. The "Non-Reporters' Estimated F-GHG Emissions" term in Equation 4-23 was estimated using an emission factor developed using emissions from reported data in 2015 and 2016 and total non-reporters' capacity. Due to a lack of information and data and because they represent similar physical and chemical processes, the uncertainty at the 95 percent CI level for non-reporter PV capacity is assumed to be the same as the uncertainty in non-reporter TMLA for semiconductor manufacturing. Similarly, the uncertainty for the PV manufacture emission factors are assumed to be the same as the uncertainties in emission factors used for non-reporters in semiconductor manufacture.

Heat Transfer Fluids Emission Uncertainty

There is a lack of data related to the uncertainty of emission estimates of heat transfer fluids used for electronics manufacture. Therefore, per the *2006 IPCC Guidelines* (IPCC 2006, Volume 3, Chapter 6), uncertainty bounds of 20 percent were applied to estimate uncertainty associated with the various types of heat transfer fluids, including PFCs, HFC, and SF_6, at the national level.

The results of the Approach 2 quantitative uncertainty analysis for electronics manufacturing are summarized in Table 4-124. These results were obtained by convolving—using Monte Carlo simulation—the distributions of emissions for each reporting and non-reporting facility that manufactures semiconductors, MEMS, or PVs and use heat transfer fluids. The emissions estimate for total U.S. F-GHG, N_2O, and HTF emissions from electronics manufacturing were estimated to be between 4.44 and 5.02 MMT CO_2 Eq. at a 95 percent CI level. This range represents 6 percent below to 6 percent above the 2022 emission estimate of 4.73 MMT CO_2 Eq. for all emissions from electronics manufacture. This range and the associated percentages apply to the estimate of total emissions rather than those of individual gases. Uncertainties associated with individual gases will be somewhat higher than the aggregate but were not explicitly modeled.

Table 4-124: Approach 2 Quantitative Uncertainty Estimates for HFC, PFC, SF_6, NF_3 and N_2O Emissions from Electronics Manufacture (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound[b]	Upper Bound[b]	Lower Bound	Upper Bound
Electronics Industry	HFC, PFC, SF_6, NF_3, and N_2O	4.7	4.4	5.0	-6%	+6%

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

[b] Absolute lower and upper bounds were calculated using the corresponding lower and upper bounds in percentages.

QA/QC and Verification

For its GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[115] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter and Annex 8 for more details.

Recalculations Discussion

Any resubmitted emissions data reported to EPA's GHGRP from all prior years were updated in this *Inventory*. Additionally, EPA made the following changes:

- To estimate non-reporter F-GHG and N_2O emissions, EPA relies on data reported through Subpart I and the World Fab Forecast. This process requires EPA to map facilities that report through Subpart I and which are also represented in the World Fab Forecast. For this *Inventory* update, EPA identified and made

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[115] GHGRP Report Verification Factsheet. See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

corrections to a few instances of this mapping based on new information and additional reviews of the data. This had minimal effects on emission estimates.

- EPA re-ran regression analyses for years 2010 to 2021 to reflect updates to Subpart I and the World Fab Forecast. These changes had minor effects on the emission factors, standard error, and R^2 values for all years. This resulted in the recalculation of non-reporter's F-GHG and N_2O estimates for all years.
- EPA recalculated HTF emissions for years 1990 to 2021 using IPCC *Fifth Assessment Report* (AR5) GWP values (IPCC 2013). Emission estimates were incorrectly calculated using the IPCC *Fourth Assessment Report* (AR4) GWP values (IPCC 2007) in the previous *Inventory* (EPA 2023). Overall, the impact of these recalculations led to an average decrease of 0.009 MMT CO_2 Eq. (0.19 percent) across the time series (1990 through 2021).
- EPA recalculated fluorinated GHG consumption for 2014 to 2021 using the following methodology. Fluorinated GHG consumption estimates for unabated fabs were calculated using reported GHGRP emissions data and default emission factors for Subpart I. Because certain fluorinated GHGs are generated as by-products as well as used as input gases, both input gas emission factors and by-product gas emission factors were factored into this calculation. For abated fabs, a "consumption factor" was developed by dividing the reported emissions of each fluorinated GHG from unabated fabs by the estimated consumption of each fluorinated GHG for each wafter size. Fluorinated GHG consumption for 2021 was estimated based on GDP growth of the 2020 consumption estimate. The consumption estimate will be updated with reported 2021 GHGRP emissions data.
- EPA refined the non-reporting population for 2015 to 2022 by conducting an analysis into the criteria being used to determine which fabs should be included and excluded from this population. Overall, the impact of this refinement led to an average increase in semiconductor emissions by 0.02 MMT CO_2 Eq. (0.45 percent) for the time series 2015 to 2022.
- EPA recalculated non-reporter emissions for 2015 to 2022 by developing emission factors for individual gases and calculated on an MT basis. Overall, the impact of this refinement led to an average increase in semiconductor emissions by 0.04 MMT CO_2 Eq. (0.84 percent) for the time series 2014 to 2022.

Planned Improvements

The *Inventory* methodology uses data reported through the EPA Partnership (for earlier years) and EPA's GHGRP (for later years) to extrapolate the emissions of the non-reporting population. While these techniques are well developed, the accuracy of the emissions estimates for the non-reporting population could be further increased through EPA's further investigation of and improvement upon the accuracy of estimated activity in the form of TMLA.

The *Inventory* uses utilization from two different sources for various time periods–SEMI to develop PEVM and to estimate non-Partner emissions for the period 1995 to 2010 and U.S. Census Bureau for 2011 through 2022. SEMI reported global capacity utilization for manufacturers through 2011. U.S. Census Bureau capacity utilization include U.S. semiconductor manufacturers as well as assemblers. Further analysis on the impacts of using a new and different source of utilization data could prove to be useful in better understanding of industry trends and impacts of utilization data sources on historical emission estimates.

Estimates of semiconductor non-reporter and non-Partner emissions are based on EPA-developed emission factors for the time periods pre-2010, 2011 through 2012, and 2015 through 2022. Based on the data available for these time periods, the methods used to develop emission factors for non-reporters and non-Partners are slightly inconsistent for semiconductors (e.g., how data representing emissions and TMLA from the manufacture of various wafer sizes are aggregated or disaggregated for purposes of calculating emission factors). Further analyses to support potentially adjusting the methods for developing these emission factors could be done to better ensure consistency across the time series.

The methodology for estimating semiconductor emissions from non-reporters uses data from the International Technology Roadmap for Semiconductors (ITRS) on the number of layers associated with various technology node sizes. The ITRS has now been replaced by the International Roadmap for Devices and Systems (IRDS), which has published updated data on the number of layers used in each device type and node size (in nanometers). Incorporating this updated dataset will improve the accuracy of emissions estimates from non-reporting semiconductor fabs.

4.25 Substitution of Ozone Depleting Substances (CRT Source Category 2F)

This reporting category (2F) includes emissions from the substitution of ozone-depleting substance (ODS). Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and carbon dioxide (CO_2) are used as alternatives to several classes of ODS that are being phased out under the terms of the *Montreal Protocol* and the Clean Air Act Amendments of 1990.[116] Ozone-depleting substances—chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl chloroform, and hydrochlorofluorocarbons (HCFCs)—are used in a variety of industrial applications including refrigeration and air conditioning equipment, solvent cleaning, foam production, sterilization, fire extinguishing, and aerosols. Although HFCs and PFCs are not harmful to the stratospheric ozone layer, they are potent greenhouse gases. On December 27, 2020, the American Innovation and Manufacturing (AIM) Act was enacted by Congress and directs EPA to address HFCs by phasing down production and consumption (i.e., production plus import minus export), maximizing reclamation and minimizing releases from equipment, and facilitating the transition to next-generation technologies through sector-based restrictions. Emission estimates for HFCs, PFCs, and CO_2 used as substitutes for ODSs are provided in Table 4-125 and Table 4-126.[117]

Table 4-125: Emissions of HFCs, PFCs, and CO_2 from ODS Substitutes (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
HFC-23	0.0	+	+	+	+	+	+
HFC-32	0.0	0.3	6.1	6.9	7.8	9.4	10.5
HFC-125	+	8.2	48.8	53.1	57.8	66.3	72.0
HFC-134a	+	72.8	56.4	55.3	54.1	50.0	48.3
HFC-143a	+	10.0	29.7	29.9	29.9	30.0	29.8
HFC-236fa	0.0	1.0	0.8	0.7	0.7	0.6	0.6
CF_4	0.0	+	+	+	+	+	0.1
CO_2	+	+	+	+	+	+	+
Other Saturated HFCs[a]	0.3	6.9	15.9	16.0	15.9	16.3	16.8
Other PFCs and HFOs[b]	+	0.1	+	+	+	+	+
Total	**0.3**	**99.5**	**157.9**	**162.1**	**166.2**	**172.7**	**178.1**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Other Saturated HFCs represents an unspecified mix of saturated HFCs, which includes HFC-152a, HFC-227ea, HFC-245fa, HFC-365mfc, and HFC-43-10mee.

[b] Other PFCs and HFOs represents an unspecified mix of PFCs and HFOs, which includes 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

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[116] [42 U.S.C § 7671, CAA Title VI].

[117] Emissions of ODS are not included here consistent with UNFCCC reporting guidelines for national inventories noted in Box 4-1. See Annex 6.2 for more details on emissions of ODS. Emissions from CO_2 used in the food and beverage industry are separately reported in Chapter 4.16 Carbon Dioxide Consumption but does not include CO_2 in ODS substitute use sectors as a refrigerant, foam blowing agent, or fire extinguishing agent.

collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications. For estimating purposes, the GWP value used for PFC/PFPEs was based upon n-C_6F_{14}.

Note: Totals may not sum due to independent rounding.

Table 4-126: Emissions of HFCs, PFCs, and CO_2 from ODS Substitution (Metric Tons)

Gas	1990	2005	2018	2019	2020	2021	2022
HFC-23	0	1	2	2	2	2	3
HFC-32	0	397	9,008	10,156	11,461	13,958	15,582
HFC-125	+	2,580	15,406	16,761	18,240	20,909	22,704
HFC-134a	+	56,029	43,419	42,558	41,590	38,447	37,167
HFC-143a	+	2,093	6,188	6,230	6,234	6,240	6,203
HFC-236fa	0	127	99	91	84	78	72
CF_4	0	3	5	5	4	4	4
CO_2	14	1,325	3,093	3,303	3,516	3,734	3,969
Other Saturated HFCs[a]	M	M	M	M	M	M	M
Other PFCs and HFOs[b]	M	M	M	M	M	M	M

+ Does not exceed 0.5 MT.

M (Mixture of Gases).

[a] Other Saturated HFCs represents an unspecified mix of saturated HFCs, which includes HFC-152a, HFC-227ea, HFC-245fa, HFC-365mfc, and HFC-43-10mee.

[b] Other PFCs and HFOs represents an unspecified mix of PFCs and HFOs, which includes 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. For estimating purposes, the GWP value used for PFC/PFPEs was based upon n-C_6F_{14}.

In 1990 and 1991, the only significant emissions of HFCs and PFCs as substitutes to ODSs were relatively small amounts of HFC-152a—used as an aerosol propellant and also a component of the refrigerant blend R-500 used in chillers. Beginning in 1992, HFC-134a was used in growing amounts as a refrigerant in motor vehicle air-conditioners and in refrigerant blends such as R-404A.[118] In 1993, the use of HFCs in foam production began, and in 1994 ODS substitutes for halons entered widespread use in the United States as halon production was phased out. In 1995, these compounds also found applications as solvents. Non-fluorinated ODS substitutes, such as CO_2, have been used in place of ODS in certain foam production and fire extinguishing uses since the 1990s.

The use and subsequent emissions of HFCs, PFCs, and CO_2 as ODS substitutes has been increasing from small amounts in 1990 to 178.1 MMT CO_2 Eq. emitted in 2022. This increase was in large part the result of efforts to phase out CFCs, HCFCs, and other ODSs in the United States. Use and emissions of HFCs are expected to start decreasing in the next few years and continue downward as production and consumption of HFCs are phased down to 15 percent of their baseline levels by 2036 through an allowance allocation and trading program established by EPA. Improvements in recovery practices and the use of alternative gases and technologies, through voluntary actions and in response to existing and potential future regulations under the AIM Act, will also contribute to a reduction in HFC use and emissions.

Table 4-127 presents emissions of HFCs, PFCs, and CO_2 as ODS substitutes by end-use sector for 1990 through 2022. The refrigeration and air-conditioning sector is further broken down by sub-sector. The end-use sectors that contributed the most toward emissions of HFCs, PFCs, and CO_2 as ODS substitutes in 2022 include refrigeration and air-conditioning (144.6 MMT CO_2 Eq., or approximately 81 percent), aerosols (17.0 MMT CO_2 Eq., or approximately 10 percent), and foams (11.7 MMT CO_2 Eq., or approximately 7 percent). Within the refrigeration and air-conditioning end-use sector residential unitary AC, part of the Residential Stationary Air-conditioning subsector

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[118] R-404A contains HFC-125, HFC-143a, and HFC-134a.

shown below, was the highest emitting end-use (40.8 MMT CO_2 Eq.), followed by large retail food, which is part of the Commercial Refrigeration subsector. Each of the end-use sectors is described in more detail below.

Table 4-127: Emissions of HFCs, PFCs, and CO_2 from ODS Substitutes (MMT CO_2 Eq.) by Sector

Sector	1990	2005	2018	2019	2020	2021	2022
Refrigeration/Air Conditioning	**+**	**83.0**	**122.7**	**126.5**	**130.6**	**139.5**	**144.6**
Commercial Refrigeration	+	14.9	39.6	40.2	40.6	41.0	41.4
Domestic Refrigeration	+	0.2	1.2	1.2	1.2	1.1	1.0
Industrial Process Refrigeration	+	1.8	13.8	15.0	16.2	17.4	18.6
Transport Refrigeration	+	1.6	6.9	7.4	7.9	8.4	8.8
Mobile Air Conditioning	+	61.5	28.7	26.6	24.6	22.9	20.8
Residential Stationary Air Conditioning	+	1.2	26.2	29.4	33.2	41.5	46.4
Commercial Stationary Air Conditioning	+	1.7	6.2	6.6	6.9	7.3	7.6
Aerosols	**0.2**	**10.2**	**16.7**	**17.0**	**17.3**	**17.7**	**17.0**
Foams	**+**	**3.5**	**14.2**	**14.1**	**13.7**	**10.8**	**11.7**
Solvents	**+**	**1.6**	**2.0**	**2.0**	**2.0**	**2.1**	**2.1**
Fire Protection	**+**	**1.2**	**2.4**	**2.5**	**2.5**	**2.6**	**2.6**
Total	**0.3**	**99.5**	**157.9**	**162.1**	**166.2**	**172.7**	**178.1**

+ Does not exceed 0.05 MMT CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Refrigeration/Air Conditioning

The refrigeration and air-conditioning sector includes a wide variety of equipment types that have historically used CFCs or HCFCs. End-uses within this sector include motor vehicle air-conditioning, retail food refrigeration, refrigerated transport (e.g., ship holds, truck trailers, railway freight cars), household refrigeration, residential and small commercial air-conditioning and heat pumps, chillers (large comfort cooling), cold storage facilities, and industrial process refrigeration (e.g., systems used in food processing, chemical, petrochemical, pharmaceutical, oil and gas, metallurgical, and other industries). As the ODS phaseout has taken effect, most equipment has been retrofitted or replaced to use HFC-based substitutes. Common HFCs in use today in refrigeration/air-conditioning equipment are HFC-134a, R-410A,[119] R-404A, and R-507A.[120] Lower-GWP options such as hydrofluoroolefin (HFO)-1234yf in motor vehicle air-conditioning, R-717 (ammonia) in cold storage and industrial applications, and R-744 (carbon dioxide) and HFC/HFO blends in retail food refrigeration, are also being used. Manufacturers of residential and commercial air conditioning have announced their plans to use HFC-32 and R-454B[121] in the future, and at least one manufacturer has announced the availability of chillers operating on HFC-32 as of 2023 (Carrier, 2023). These refrigerants are emitted to the atmosphere during equipment operation (as a result of component failure, leaks, and purges), as well as at manufacturing (if charged at the factory), installation, servicing, and disposal events.

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[119] R-410A contains HFC-32 and HFC-125.

[120] R-507A, also called R-507, contains HFC-125 and HFC-143a.

[121] R-454B contains HFC-32 and HFO-1234yf.

Aerosols

Aerosol propellants are used in metered dose inhalers (MDIs) and a variety of personal care products and technical/specialty products (e.g., duster sprays and safety horns). Pharmaceutical companies that produce MDIs—a type of inhaled therapy used to treat asthma and chronic obstructive pulmonary disease—have replaced the use of CFCs with HFC-propellant alternatives. The earliest ozone-friendly MDIs were produced with HFC-134a, but the industry is using HFC-227ea as well. Conversely, since the use of CFC propellants in other types of aerosols was banned in the Unites States in 1978, most non-medical consumer aerosol products have not transitioned to HFCs, but to "not-in-kind" technologies, such as solid or roll-on deodorants and finger-pump sprays. The transition away from ODSs in specialty aerosol products has also led to the introduction of non-fluorocarbon alternatives (e.g., hydrocarbon propellants) in certain applications, in addition to HFC-134a or HFC-152a. Other low-GWP options such as HFO-1234ze(E) are being used as well. These propellants are released into the atmosphere as the aerosol products are used.

Foams

Chlorofluorocarbons and HCFCs have traditionally been used as foam blowing agents to produce polyurethane (PU), polystyrene, polyolefin, and phenolic foams, which are used in a wide variety of products and applications. Since the *Montreal Protocol*, flexible PU foams as well as other types of foam, such as polystyrene sheet, polyolefin, and phenolic foam, have transitioned almost completely away from fluorocompounds into alternatives such as CO_2 and hydrocarbons. The majority of rigid PU foams have transitioned to HFCs—primarily HFC-134a and HFC-245fa. Today, these HFCs are used to produce PU appliance, PU commercial refrigeration, PU spray, and PU panel foams—used in refrigerators, vending machines, roofing, wall insulation, garage doors, and cold storage applications. In addition, HFC-152a, HFC-134a, and CO_2 are used to produce polystyrene sheet/board foam, which is used in food packaging and building insulation. Low-GWP fluorinated foam blowing agents in use include HFO-1234ze(E) and HCFO-1233zd(E). Emissions of blowing agents occur when the foam is manufactured as well as during the foam lifetime and at foam disposal, depending on the particular foam type.

Solvents

Chlorofluorocarbons, methyl chloroform (1,1,1-trichloroethane or TCA), and to a lesser extent carbon tetrachloride (CCl_4) were historically used as solvents in a wide range of cleaning applications, including precision, electronics, and metal cleaning. Since their phaseout, metal cleaning end-use applications have primarily transitioned to non-fluorocarbon solvents and not-in-kind processes. The precision and electronics cleaning end-uses have transitioned in part to high-GWP gases, due to their high reliability, excellent compatibility, good stability, low toxicity, and selective solvency. These applications rely on HFC-43-10mee, HFC-365mfc, HFC-245fa, and to a lesser extent, PFCs. Electronics cleaning involves removing flux residue that remains after a soldering operation for printed circuit boards and other contamination-sensitive electronics applications. Precision cleaning may apply to either electronic components or to metal surfaces, and is characterized by products, such as disk drives, gyroscopes, and optical components, that require a high level of cleanliness and generally have complex shapes, small clearances, and other cleaning challenges. The use of these solvents yields fugitive emissions of these HFCs and PFCs.

Fire Protection

Fire protection applications include portable fire extinguishers ("streaming" applications) that originally used halon 1211, and total flooding applications that originally used halon 1301, as well as some halon 2402. Since the production and import of virgin halons were banned in the United States in 1994, the halon replacement agent of choice in the streaming sector has been dry chemical, although HFC-236fa is also used to a limited extent. In the total flooding sector, HFC-227ea has emerged as the primary replacement for halon 1301 in applications that require clean agents. Other HFCs, such as HFC-23 and HFC-125, are used in smaller amounts. The majority of HFC-227ea in total flooding systems is used to protect essential electronics, as well as in civil aviation, military mobile weapons systems, oil/gas/other process industries, and merchant shipping. Fluoroketone FK-5-1-12 is also used as a low-GWP option and 2-BTP is being use in niche applications. As fire protection equipment is tested or deployed, emissions of these fire protection agents occur.

Methodology and Time-Series Consistency

Using a Tier 2 method in accordance with the IPCC methodological decision tree, a detailed Vintaging Model of ODS-containing equipment and products was used to estimate the actual—versus potential—emissions of various ODS substitutes, including HFCs, PFCs, and CO_2. The name of the model refers to the fact that it tracks the use and emissions of various compounds for the annual "vintages" of new equipment that enter service in each end-use. The Vintaging Model predicts ODS and ODS substitute use in the United States based on modeled estimates of the quantity of equipment or products sold each year containing these chemicals and the amount of the chemical required to manufacture and/or maintain equipment and products over time. Emissions for each end-use were estimated by applying annual leak rates and release profiles, which account for the lag in emissions from equipment as they leak over time. By aggregating the data for 80 different end-uses, the model produces estimates of annual use and emissions of each compound. Further information on the Vintaging Model is contained in Annex 3.9.

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Uncertainty

Given that emissions of ODS substitutes occur from thousands of different kinds of equipment and from millions of point and mobile sources throughout the United States, emission estimates must be made using analytical tools such as the Vintaging Model or the methods outlined in IPCC (2006). Though the model is more comprehensive than the IPCC default methodology, significant uncertainties still exist with regard to the levels of equipment sales, equipment characteristics, and end-use emissions profiles that were used to estimate annual emissions for the various compounds.

The uncertainty analysis quantifies the level of uncertainty associated with the aggregate emissions across the 80 end-uses in the Vintaging Model. In order to calculate uncertainty, functional forms were developed to simplify some of the complex "vintaging" aspects of some end-use sectors, especially with respect to refrigeration and air-conditioning, and to a lesser degree, fire extinguishing. These sectors calculate emissions based on the entire lifetime of equipment, not just equipment put into commission in the current year, thereby necessitating simplifying equations. The functional forms used variables that included growth rates, emission factors, transition from ODSs, change in charge size as a result of the transition, disposal quantities, disposal emission rates, and either stock (e.g., number of air conditioning units in operation) for the current year or ODS consumption before transition to alternatives began (e.g., in 1985 for most end-uses). Uncertainty was estimated around each variable within the functional forms based on expert judgment, and a Monte Carlo analysis was performed.

Inputs to the ODS substitutes uncertainty model generally take on a normal distribution with a 90 to 95 percent confidence interval but do utilize other probability density functions such as a uniform or PERT BETA distribution. The uncertainty inputs are based on conversations with industry experts and how certain assumptions are developed in the Vintaging Model. For example, if the Vintaging Model estimates are specifically aligned with actual reported data, then the uncertainty is decreased. This can be seen with the unitary AC end-use where annual stock data is aligned with sales data published by the Air-Conditioning, Heating, and Refrigeration Institute (AHRI). The stock is assumed to be fairly accurate and therefore, uncertainty range for the stock of unitary AC is set to an upper and lower bound of only 2.5 percent. The most significant sources of uncertainty for the substitution of ODS source category include the total stock of refrigerant installed in industrial process refrigeration and cold storage equipment, as well as the charge size for technical aerosols using HFC-134a. For technical aerosols, a triangular distribution is utilized to apply an asymmetrical range to the inventory value. This is to account for the uncertainty that technical aerosols using HFC-134a might have higher market penetration than what the Vintaging Model currently estimates.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-128. Substitution of ozone depleting substances HFC and PFC emissions were estimated to be between 170.8 and 205.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 4.1 percent below to 15.1 percent above the emission estimate of 178.1 MMT CO_2 Eq.

Table 4-128: Approach 2 Quantitative Uncertainty Estimates for HFC and PFC Emissions from ODS Substitutes (MMT CO_2 Eq. and Percent)

Source	Gases	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Substitution of Ozone Depleting Substances	HFCs and PFCs	178.1	170.8	205.1	-4.1%	+15.1%

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

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter. Category specific QA/QC findings are described below.

The QA and verification process for individual gases and sources in the Vintaging Model includes review against up-to-date market information, including equipment stock estimates, leak rates, and sector transitions to new chemicals and technologies. In addition, comparisons against published emission and consumption sources by gas and by source are performed when available as described further below. 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. For the purposes of reporting emissions to protect Confidential Business Information (CBI), some HFCs and PFCs are grouped into two unspecified mixes of saturated HFCs and other PFCs and HFOs. The HFCs and PFCs within the unspecified mix of HFCs and PFCs are modelled and verified individually in the same process as all other gases and sources in the Vintaging Model.

Data from EPA's Greenhouse Gas Reporting Program (GHGRP)[122] and emissions of some fluorinated greenhouse gases estimated for the contiguous United States by scientists at the National Oceanic and Atmospheric Administration (NOAA) were used to perform additional quality control as specified in *2006 IPCC Guidelines for National Greenhouse Gas Inventories* and the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2019)*. These comparisons are detailed further in Annex 3.9.

Recalculations Discussion

For the current *Inventory*, updates to the Vintaging Model included updating 2022 growth rates for residential and commercial unitary air-conditioning to align with annual sales estimates published by AHRI. Projected growth rates

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[122] For the GHGRP data, EPA verifies annual facility-level and company-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015). Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data.

were updated for residential unitary air-conditioning to align with projected residential housing available from the Energy Information Administration (EIA) and commercial unitary air-conditioning growth rates were updated based on new commercial floorspace growth projections from EIA (EPA 2023a). Growth rates for window units were updated to align with sales data for Energy Star- and non-Energy Star-certified units (EPA 2023b).

The Vintaging Model was also updated to include the addition of two end-uses representing multi-split air-conditioning units: small ductless mini-split and multi-split air-conditioning and large ductless mini-split and multi-split air-conditioning. These end-uses were split from the existing residential unitary air-conditioning end-use. Stock for ductless mini-split and multi-split air-conditioning systems were estimated based on the EIA Residential Energy and Consumption Survey (RECS) and growth projected based on annual sales of split systems under 33,000 BTU/h (small mini/multi-splits) and split systems between 33,000 BTU/h and 65,000 BTU/h (large mini/multi-splits) published by AHRI (EPA 2023c).

In addition, the market size and growth rates of the streaming agents end-use in the Fire Suppression sector was updated, improving alignment of halon 1211 consumption with the 2022 Fire Suppression Technical Options Committee (FSTOC) estimates, the lifetime was adjusted to reflect internal inspection timelines, rather than physical extinguisher lifetimes, and refilling of leaks throughout the lifetime of extinguishers was modeled (EPA 2023d).

Together, these updates increased ODS substitute emissions on average by 0.06 MMT CO_2 Eq. (0.6 percent) between 1990 and 2021, compared to the previous (i.e., 2023) *Inventory* submission.

Planned Improvements

Future improvements to the Vintaging Model are planned for the Refrigeration and Air-conditioning, Fire Suppression, and Aerosols sectors. Specifically, refrigerated storage space estimates published biannually from the United States Department of Agriculture (USDA) are being compared to cold storage warehouse space currently estimated in the Vintaging Model. Flooding agent fire suppression market transitions are under review to align more closely with real world activities. In addition, further refinement of HFC consumption in MDIs is expected from review of data collected on HFC use for MDI production, imports, and exports in response to requests pursuant to AIM Act regulations for application-specific allowances for MDIs. EPA expects these revisions to be prepared for the 2025 *Inventory* submission.

As discussed above, future reporting under the AIM Act may provide useful information for verification purposes and possible improvements to the Vintaging Model, such as information on HFC stockpiling behaviors. EPA expects this reporting by late 2023 and incorporation into the 2025 or 2026 report. Should the data suggest structural changes to the model, such as the handling of stockpiles before use, EPA expects to introduce the revised model for the 2025 or 2026 *Inventory* submission.

Several potential improvements to the *Inventory* were identified in the 2022 *Inventory* submission based on the comparisons mentioned above and discussed in Annex 3.9—net supply values from the GHGRP and emission estimates derived from atmospheric measurements—and remain valid. To estimate HFC emissions for just the contiguous United States, matching the coverage by the atmospheric measurements, EPA will investigate the availability of data from Alaska, Hawaii, and U.S. territories. This is planned by the next (i.e., 2025) *Inventory* submission. To improve estimates of HFC-125 and HFC-143a, further research into the refrigeration market can be made. Research in this industry on the shift away from blends such as R-404A or success in lowering emission rates could be used to improve the *Inventory* estimate. This is planned for the 2025 *Inventory*. That said, for the years where both the atmospheric measurements and the model display a roughly constant emission of HFC-143a at similar levels, the new results suggest robust estimates for the refrigeration market. Uncertainty estimates by species would aid in comparisons to atmospheric data. EPA continues to explore the possibility of revising the Monte Carlo analysis to differentiate between species, starting with the higher-emitted HFCs identified above, in a future (i.e., 2025) *Inventory* submission. Reclamation reports and, when available, information gathered under the AIM Act, could be used to improve the understanding of how chemical moves through the economy and could resolve some of the temporal effects discussed in Annex 3.9. This would likely require revisions to the basic model structure and could be introduced for the 2026 or 2027 *Inventory* submission. The additional data from the atmospheric measurements suggests additional items to investigate. The faster uptick in HFC-32 and HFC-125 emissions suggests additional emissions of R-410A compared to the model's estimation. Further investigation into the average emission rate, the variability over time of the emission rate, stocks, lifetimes, and other factors will be investigated for the next (i.e., 2025) *Inventory* submission.

4.26 Electrical Equipment (CRT Source Category 2G1)

The largest use of sulfur hexafluoride (SF_6), both in the United States and internationally, is as an electrical insulator and interrupter in equipment that transmits and distributes electricity (RAND 2004). The gas has been employed by the electric power industry in the United States since the 1950s because of its dielectric strength and arc-quenching characteristics. It is used in gas-insulated substations, circuit breakers, and other switchgear. SF_6 has replaced flammable insulating oils in many applications and allows for more compact substations in dense urban areas. Another greenhouse gas emitted in much smaller amounts by the electric power industry is tetrafluoromethane (CF_4), which is mixed with SF_6 to avoid liquefaction at low temperatures (Middleton 2000). While mixed gas circuit breakers are more common in extremely cold climates in geographies outside of the United States, some U.S. manufacturers of electrical equipment are emitting CF_4 during the manufacturing of equipment designed to hold the SF_6/CF_4 gas mixture. However, no electrical equipment facilities in the United States have reported emissions of or equipment using CF_4. SF_6 emissions exceed PFC emissions from electric power systems on both a GWP-unweighted and GWP-weighted basis. This reporting category (2G1) includes emissions from electrical equipment.

Fugitive emissions of SF_6 and CF_4 can escape from gas-insulated substations and switchgear through seals, especially from older equipment. The gas can also be released during equipment manufacturing, installation, servicing, and disposal. Emissions of SF_6 and CF_4 from equipment manufacturing and from electrical equipment systems were estimated to be 5.1 MMT CO_2 Eq. (0.3 kt) in 2022. This quantity represents a 79 percent decrease from the estimate for 1990 (see Table 4-129 and Table 4-130). There are a few potential causes for this decrease: a sharp increase in the price of SF_6 during the 1990s and a growing awareness of the environmental impact of SF_6 emissions through programs such as EPA's voluntary SF_6 Emission Reduction Partnership for Electric Power Systems (Partnership) and EPA's GHGRP, regulatory drivers at the state and local levels, and research and development of alternative gases to SF_6 that can be used in gas-insulated substations. Utilities participating in the Partnership have lowered their emission factor from 13 percent in 1999 (kg SF_6 emitted per kg of nameplate capacity) to 0.9 percent in 2022. SF_6 emissions reported by electric power systems to EPA's GHGRP have decreased by 56 percent from 2011 to 2022,[123] with much of the reduction seen from utilities that are not participants in the Partnership. These utilities may be making relatively large reductions in emissions as they take advantage of relatively large and/or inexpensive emission reduction opportunities (i.e., "low hanging fruit," such as replacing major leaking circuit breakers) that Partners have already taken advantage of under the voluntary program

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[123] Analysis of emission trends from facilities reporting to EPA's GHGRP is imperfect due to an inconsistent group of reporters year to year. A facility that has reported total non-biogenic greenhouse gas emissions below 15,000 metric tons of carbon dioxide equivalent (MT CO_2 Eq.) for three consecutive years or below 25,000 MT CO_2 Eq. for five consecutive years to EPA's GHGRP can discontinue reporting for all direct emitter subparts. For this sector, most of the variability in the group of reporters is due to facilities exiting the GHGRP due to being below one of these thresholds; however, facilities must re-enter the program if their emissions at a later date are above 25,000 MT CO_2 Eq., which may occur for a variety of reasons, including changes in facility size and changes in emission rates.

(Ottinger et al. 2014). Total emissions from electrical equipment in 2022 were lower than 2021 emissions, decreasing by 15.3 percent.

Table 4-129: SF_6 and CF_4 Emissions from Electric Power Systems and Electrical Equipment Manufacturers (MMT CO_2 Eq.)

	1990	2005	2018	2019	2020	2021	2022
Electric Power Systems	24.3	11.2	4.7	5.7	5.3	5.6	4.8
Electrical Equipment Manufacturers	0.3	0.7	0.3	0.4	0.5	0.4	0.3
Total	24.7	11.9	5.0	6.1	5.9	6.0	5.1

Note: Totals may not sum due to independent rounding.

Table 4-130: SF_6 and CF_4 Emissions from Electric Power Systems and Electrical Equipment Manufacturers (kt)

	1990	2005	2018	2019	2020	2021	2022
SF_6 Emissions	1.0	0.5	0.2	0.3	0.3	0.3	0.2
CF_4 Emissions	+	+	NO	+	+	+	+

+ Does not exceed 0.5 kt.
NO (Not Occurring)

Methodology and Time-Series Consistency

The estimates of emissions from electrical equipment are comprised of emissions from electric power systems and emissions from the manufacture of electrical equipment. The methodologies for estimating both sets of emissions are described below.

1990 through 1998 Emissions from Electric Power Systems

Emissions from electric power systems from 1990 through 1998 were estimated based on (1) the emissions estimated for this source category in 1999, which, as discussed in the next section, were based on the emissions reported during the first year of EPA's SF_6 Emission Reduction Partnership for Electric Power Systems (Partnership), and (2) the RAND survey of global SF_6 emissions. Because most utilities participating in the Partnership reported emissions only for 1999 through 2011, modeling was used to estimate SF_6 emissions from electric power systems for the years 1990 through 1998. To perform this modeling, U.S. emissions were assumed to follow the same trajectory as global emissions from this source during the 1990 through 1999 period. To estimate global emissions, the RAND survey of global SF_6 sales was used, together with the following equation for estimating emissions, which is derived from the mass-balance equation for chemical emissions (Volume 3, Equation 7.3) in the *2006 IPCC Guidelines*.[124] (Although Equation 7.3 of the *2006 IPCC Guidelines* appears in the discussion of substitutes for ozone-depleting substances, it is applicable to emissions from any long-lived pressurized equipment that is periodically serviced during its lifetime.)

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[124] Ideally, sales to utilities in the United States between 1990 and 1999 would be used as a model. However, this information was not available. There were only two U.S. manufacturers of SF_6 during this time period, so it would not have been possible to conceal sensitive sales information by aggregation.

Equation 4-24: Estimation for SF_6 Emissions from Electric Power Systems

Emissions (kilograms SF_6) = SF_6 purchased to refill existing equipment (kilograms) + nameplate capacity of retiring equipment (kilograms) [125]

Note that the above equation holds whether the gas from retiring equipment is released or recaptured; if the gas is recaptured, it is used to refill existing equipment, thereby lowering the amount of SF_6 purchased by utilities for this purpose.

Gas purchases by utilities and equipment manufacturers from 1961 through 2003 are available from the RAND (2004) survey. To estimate the quantity of SF_6 released or recovered from retiring equipment, the nameplate capacity of retiring equipment in a given year was assumed to equal 81.2 percent of the amount of gas purchased by electrical equipment manufacturers 40 years previous (e.g., in 2000, the nameplate capacity of retiring equipment was assumed to equal 81.2 percent of the gas purchased in 1960). The remaining 18.8 percent was assumed to have been emitted at the time of manufacture. The 18.8 percent emission factor is an average of IPCC default SF_6 emission rates for Europe and Japan for 1995 (IPCC 2006). The 40-year lifetime for electrical equipment is also based on IPCC (2006). The results of the two components of the above equation were then summed to yield estimates of global SF_6 emissions from 1990 through 1999.

U.S. emissions between 1990 and 1999 are assumed to follow the same trajectory as global emissions during this period. To estimate U.S. emissions, global emissions for each year from 1990 through 1998 were divided by the estimated global emissions from 1999. The result was a time series of factors that express each year's global emissions as a multiple of 1999 global emissions. Historical U.S. emissions were estimated by multiplying the factor for each respective year by the estimated U.S. emissions of SF_6 from electric power systems in 1999 (estimated to be MMT CO_2 Eq.).

Two factors may affect the relationship between the RAND sales trends and actual global emission trends. One is utilities' inventories of SF_6 in storage containers. When SF_6 prices rise, utilities are likely to deplete internal inventories before purchasing new SF_6 at the higher price, in which case SF_6 sales will fall more quickly than emissions. On the other hand, when SF_6 prices fall, utilities are likely to purchase more SF_6 to rebuild inventories, in which case sales will rise more quickly than emissions. This effect was accounted for by applying 3-year smoothing to utility SF_6 sales data. The other factor that may affect the relationship between the RAND sales trends and actual global emissions is the level of imports from and exports to Russia and China. SF_6 production in these countries is not included in the RAND survey and is not accounted for in any another manner by RAND. However, atmospheric studies confirm that the downward trend in estimated global emissions between 1995 and 1998 was real (see the Uncertainty discussion below).

1999 through 2022 Emissions from Electric Power Systems

Emissions from electric power systems from 1999 to 2022 were estimated based on: (1) reporting from utilities participating in EPA's SF_6 Emission Reduction Partnership for Electric Power Systems (Partners), which began in 1999; (2) reporting from utilities covered by EPA's GHGRP, which began in 2012 for emissions occurring in 2011 (GHGRP-Only Reporters); (3) SF_6 emissions from California estimated by the California Air Resources Board (CARB) and (4) the relationship between utilities' reported emissions and their transmission miles as reported in the 2001, 2004, 2007, 2010, 2013, and 2016 Utility Data Institute (UDI) Directories of Electric Power Producers and Distributors (UDI 2001, 2004, 2007, 2010, 2013, and 2017), and 2019, 2020, and 2021 Homeland Infrastructure Foundation-Level Data (HIFLD) (HIFLD 2019, 2020, and 2021), which was applied to the electric power systems that do not report to EPA (Non-Reporters). Total U.S. transmission mileage was interpolated between 2016 and 2019 to estimate transmission mileage of electric power systems in 2017 and 2018. (Transmission miles are defined as the miles of lines carrying voltages above 34.5 kV).

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[125] Nameplate capacity is defined as the amount of SF_6 within fully charged electrical equipment.

Partners

Over the period from 1999 to 2022, Partner utilities, which for inventory purposes are defined as utilities that either currently are or previously have been part of the Partnership,[126] represented 49 percent, on average, of total U.S. transmission miles. Partner utilities estimated their emissions using a Tier 3 utility-level mass balance approach (IPCC 2006). If a Partner utility did not provide data for a particular year, emissions were interpolated between years for which data were available or extrapolated based on Partner-specific transmission mile growth rates. In 2012, many Partners began reporting their emissions (for 2011 and later years) through EPA's GHGRP (discussed further below) rather than through the Partnership. In 2022, less than 1 percent of the total emissions attributed to Partner utilities were reported through Partnership reports. Approximately 99.6 percent of the total emissions attributed to Partner utilities were reported and verified through EPA's GHGRP.[127] Overall, the emission rates reported by Partners have decreased significantly throughout the time series.

Non-Partners

Non-Partners consist of two groups: Utilities that have reported to the GHGRP beginning in 2012 (reporting 2011 emissions) or later years (GHGRP-only Reporters) and utilities that have never reported to the GHGRP (Non-Reporters). EPA's GHGRP requires users of SF_6 in electric power systems to report emissions if the facility has a total SF_6 nameplate capacity that exceeds 17,820 pounds. (This quantity is the nameplate capacity that would result in annual SF_6 emissions equal to 25,000 metric tons of CO_2 equivalent at the historical emission rate reported under the Partnership). As under the Partnership, electric power systems that report their SF_6 emissions under EPA's GHGRP are required to use the Tier 3 utility-level mass-balance approach. GHGRP-Only Reporters accounted for 16 percent of U.S. transmission miles and 14 percent of estimated U.S. emissions from electric power system in 2022.[128]

From 1999 through 2018, emissions from both GHGRP-only Reporters and Non-Reporters were estimated in the same way. From 1999 through 2008, emissions were estimated using the results of a regression analysis that correlated the 1999 emissions from Partner utilities with their 1999 transmission miles.[129] The 1999 regression coefficient (emission factor) was held constant through 2008 and multiplied by the transmission miles estimated for the non-Partners for each year.

The 1999 regression equation for Non-Partners was developed based on the emissions reported by a subset of Partner utilities who reported non-zero emissions and non-zero transmission miles (representing approximately 50 percent of total U.S. transmission miles). The regression equation for 1999 is displayed in the equation below.

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[126] Starting in the 1990 to 2015 *Inventory*, partners who had reported three years or less of data prior to 2006 were removed. Most of these Partners had been removed from the list of current Partners but remained in the Inventory due to the extrapolation methodology for non-reporting partners.

[127] Only data reported as of August 21, 2023 are used in the emission estimates for the prior year of reporting. Emissions for Partners that did not report to the Partnership or GHGRP are extrapolated for three years using a utility-specific transmission mile growth rate. After four consecutive years of non-reporting they are included in the 'non-reporting Partners' category. It should be noted that data reported through EPA's GHGRP must go through a verification process. For electric power systems, verification involved a series of electronic range, completeness, and algorithm checks for each report submitted.

[128] GHGRP-reported and Partner transmission miles from a number of facilities were equal to zero with non-zero emissions. These facilities emissions were added to the emissions totals for their respective parent companies when identifiable and not included in the regression equation when not identifiable or applicable. Other facilities reported non-zero transmission miles with zero emissions, or zero transmission miles and zero emissions. These facilities were not included in the development of the regression equations (discussed further below). These emissions are already implicitly accounted for in the relationship between transmission miles and emissions.

[129] In the United States, SF_6 is contained primarily in transmission equipment rated above 34.5 kV.

Equation 4-25: Regression Equation for Estimating SF_6 Emissions of Non-Reporting Facilities in 1999

$$\text{Emissions (kg)} = 0.771 \times \text{Transmission Miles}$$

The 1999 emission factor (0.77 SF_6 emissions/Transmission Miles) for the non-Partners was held constant to estimate non-Partner emissions from 2000-2008. Non-partner emissions were assumed to decrease beginning in 2009, trending toward the regression coefficient (emission factor) calculated for the GHGRP-only reporters based on their reported 2011 emissions and transmission miles. Emission factors for 2009 and 2010 were linearly interpolated between the 1999 and 2011 emission factors. For 2009, the emissions of non-Partners were estimated by multiplying their transmission miles by the interpolated 2009 emission factor (0.65 kg/transmission mile).

The 2011 regression equation was developed based on the emissions reported by GHGRP-Only Reporters who reported non-zero emissions and non-zero transmission miles (representing approximately 23 percent of total U.S. transmission miles). The regression equation for 2011 is displayed below.

Equation 4-26: Regression Equation for Estimating SF_6 Emissions of GHGRP-Only Reporters in 2011

$$\text{Emissions (kg)} = 0.397 \times \text{Transmission Miles}$$

For 2011 and later years, the emissions of GHGRP-only reporters were generally equated to their reported emissions, unless they did not report. The emissions of GHGRP-only reporters that have years of non-reporting between reporting years are gap filled by interpolating between reported values.

For 2010 and later years, the emissions of non-Reporters were estimated by multiplying their transmission miles by the estimated 2010 emission factor (0.52 kg/transmission mile), which was held constant from 2010 through 2022.

Off-ramping GHGRP Facilities

The GHGRP program has an “off-ramp” provision (40 CFR Part 98.2(i)) that exempts facilities from reporting under certain conditions. If reported total greenhouse gas emissions are below 15,000 metric tons of carbon dioxide equivalent (MT CO_2 Eq.) for three consecutive years or below 25,000 MT CO_2 Eq. for five consecutive years, the facility may elect to discontinue reporting. Emissions of GHGRP reporters that have off-ramped are extrapolated for three years of non-reporting using a utility-specific transmission mile growth rate, unless the utility has transmission mileage in California. After three consecutive years of non-reporting, emissions for facilities (except those in California) that off-ramped from GHGRP were estimated using an emissions rate derived from the reported emissions and transmission miles of GHGRP-only reporters in the respective year. For facilities in California, a California-specific emissions rate is used as described in the following section.

Table 4-131: GHGRP-only Average Emission Rate (kg per mile)

Year	2011	2018	2019	2020	2021	2022
Average emission rate	0.43	0.22	0.29	0.27	0.25	0.22

Table 4-132: Categorization of Utilities and Timeseries for Application of Corresponding Emission Estimation Methodologies

Categorization of Utilities	Timeseries
Partners	1999 - 2021
Non-Partners (GHGRP-Only)	2011 – 2021
Non-Partners (Remaining Non-Reporting Utilities)	1999 – 2021
Off-ramping GHGRP Facilities	2017 – 2021

California

CARB reports the total SF_6 emissions from electrical equipment within the state of California (CARB 2023). Because California utilities are required to report their SF_6 emissions to CARB even when they are not required to report to the GHGRP, CARB's estimates of California SF_6 emissions are expected to be more accurate for the California utilities that do not report to GHGRP than the methodology described above. As a result, the CARB SF_6 emissions estimates are used as California's contribution to the national total for 2011-2022, except in years where CARB's estimate is smaller than the California estimates reported to EPA or years for which CARB has not published estimates. Since CARB's emissions estimates include emissions from facilities that do not report to GHGRP, emissions for California GHGRP reporters that have off-ramped are not extrapolated. Specifically, CARB estimates are used for 2011, 2012, 2013, 2014, 2017, 2018, 2019, 2020, and 2021.

For each utility with transmission mileage in California, the GHGRP or voluntarily reported emissions attributed to California for that utility were determined using the percentage of that utility's transmission mileage within California based on data from HIFLD. These emissions across all California utilities were summed to find the California emissions that were reported through GHGRP or voluntarily to the EPA. Then, if CARB's emissions estimates for the reporting year were larger than the those from GHGRP and voluntary reporting, CARB's emissions replaced the California emissions from GHGRP and voluntary reporting.

If CARB's emissions estimates were lower than the California emissions from GHGRP and voluntary reporting, it is assumed there is likely an error, as this would imply negative emissions by GHGRP non-reporters. This was the case in 2015 and 2016. For these years, the GHGRP and voluntarily reported emissions from California are retained, and emissions from non-reporting utilities are estimated using a California-specific SF_6 emissions rate, which is based on CARB emission data. The California SF_6 emissions rate of 0.41 lbs SF_6 per transmission mile is found by taking the average of CARB emissions divided by the total California transmission mileage in years where CARB estimates are larger. Emissions from California non-reporting utilities are then found by multiplying the California SF_6 emissions rate by the California transmission mileage from non-reporting utilities. This methodology is also used if CARB has not published emissions estimates for a particular year. CARB has not yet published estimates for 2022.

Table 4-133: California GHGRP and Voluntarily Reported SF_6 Emissions Compared to CARB's SF_6 Emissions (MMT CO_2 Eq.)

	2011	2015	2016	2017	2018	2019	2020	2021	2022
CA GHGRP and Voluntary	0.19	0.16	0.24	0.12	0.11	0.14	0.20	0.14	0.15
CARB (CARB 2023)	0.24	0.14	0.10	0.18	0.14	0.17	0.24	0.24	NE
Final CA	0.24	0.21	0.29	0.18	0.14	0.17	0.24	0.24	0.20

NE (Not Estimated)

Total Industry Emissions

Total electric power system emissions from 1999 through 2022 were determined for each year by summing the Partner reported and estimated emissions (reported data was available through the EPA's SF_6 Emission Reduction Partnership for Electric Power Systems), the GHGRP-only reported emissions, off-ramping GHGRP Facilities (non-reporters), non-reporters who eventually report to GHGRP, and the non-reporting utilities' emissions (except California). Then, the California GHGRP and voluntarily reported emissions are subtracted from the total and replaced with CARB's emissions (or GHGRP and voluntarily reported emissions plus California non-reporting utilities' emissions).

Non-Partner Transmission Miles

Data on transmission miles for each Non-Reporter for the years 2000, 2003, 2006, and 2009, 2012, and 2016 were obtained from the 2001, 2004, 2007, 2010, 2013, and 2017 UDI Directories of Electric Power Producers and Distributors, respectively (UDI 2001, 2004, 2007, 2010, 2013, and 2017). For 2019 to 2022 non-reporter transmission mileage was derived by subtracting reported transmission mileage data from the total U.S.

transmission mileage from 2019 to 2022 HIFLD Data (HIFLD 2019, 2020, 2021, and 2022). The following trends in transmission miles have been observed over the time series:

- The U.S. transmission system grew by over 22,000 miles between 2000 and 2003 yet declined by almost 4,000 miles between 2003 and 2006. Given these fluctuations, periodic increases are assumed to occur gradually. Therefore, transmission mileage was assumed to increase at an annual rate of 1.2 percent between 2000 and 2003 and decrease by 0.20 percent between 2003 and 2006.
- The U.S. transmission system's annual growth rate grew to 1.7 percent from 2006 to 2009 as transmission miles increased by more than 33,000 miles.
- The annual growth rate for 2009 through 2012 was calculated to be 1.4 percent as transmission miles grew yet again by over 29,000 miles during this time period.
- The annual transmission mile growth rate for 2012 through 2016 was calculated to be 0.2 percent, as transmission miles increased by approximately 5,500 miles.
- The annual transmission mile growth rate for 2016 through 2020 was calculated to be 0.9 percent, as transmission miles increased by approximately 26,000 miles.
- The annual transmission mile growth rate for 2020 through 2021 was calculated to be 2.2 percent, as transmission miles increased by approximately 16,000 miles.
- The annual transmission mile growth rate for 2021 through 2022 was calculated to be 0.7 percent, as transmission miles increased by approximately 5,500 miles.

Transmission miles for each year for non-reporters were calculated by interpolating between UDI reported values obtained from the 2001, 2004, 2007, 2010, 2013 and 2017 UDI directories and HIFLD data for 2019 and subsequent years. In cases where a non-reporter previously reported the GHGRP or the Partnership, transmission miles were interpolated between the most recently reported value and the next available UDI value.

1990 through 2022 Emissions from Manufacture of Electrical Equipment

Three different methods were used to estimate 1990 to 2022 emissions from original electrical equipment manufacturers (OEMs).

- OEM SF_6 emissions from 1990 through 2000 were derived by assuming that manufacturing emissions equaled 10 percent of the quantity of SF_6 provided with new equipment. The 10 percent emission rate is the average of the "ideal" and "realistic" manufacturing emission rates (4 percent and 17 percent, respectively) identified in a paper prepared under the auspices of the International Council on Large Electric Systems (CIGRE) in February 2002 (O'Connell et al. 2002). The quantity of SF_6 provided with new equipment was estimated based on statistics compiled by the National Electrical Manufacturers Association (NEMA). These statistics were provided for 1990 to 2000.
- OEM SF_6 emissions from 2000 through 2010 were estimated by (1) interpolating between the emission rate estimated for 2000 (10 percent) and an emission rate estimated for 2011 based on reporting by OEMs through the GHGRP (5.7 percent), and (2) estimating the quantities of SF_6 provided with new equipment for 2001 to 2010. The quantities of SF_6 provided with new equipment were estimated using Partner reported data and the total industry SF_6 nameplate capacity estimate (156.5 MMT CO_2 Eq. in 2010). Specifically, the ratio of new nameplate capacity to total nameplate capacity of a subset of Partners for which new nameplate capacity data was available from 1999 to 2010 was calculated. These ratios were then multiplied by the total industry nameplate capacity estimate for each year to derive the amount of SF_6 provided with new equipment for the entire industry. Additionally, to obtain the 2011 emission rate (necessary for estimating 2001 through 2010 emissions), the estimated 2011 emissions (estimated using the third methodology listed below) were divided by the estimated total quantity of SF_6

provided with new equipment in 2011. The 2011 quantity of SF_6 provided with new equipment was estimated in the same way as the 2001 through 2010 quantities.

- OEM CF_4 emissions from 1991 through 2010 were estimated by using an average ratio of reported SF_6 and CF_4 emissions from 2011 through 2013. This ratio was applied to the estimated SF_6 emissions for 1991 through 2010 to arrive at CF_4 emissions. CF_4 emissions are estimated starting in 1991 and assumed zero prior to 1991 based on the entry of the CF_4/SF_6 gas mixture into the market (Middleton 2000).
- OEM emissions from 2011 through 2022 were estimated using the SF_6 and CF_4 emissions from OEMs reporting to the GHGRP, and an assumption that these reported emissions account for a conservatively low estimate of 50 percent of the total emissions from all U.S. OEMs (those that report and those that do not).
- OEM SF_6 emissions from facilities off-ramping from the GHGRP were determined by extrapolation. First, emission growth rates were calculated for each reporting year for each OEM reporting facility as well as an average emissions growth rate (2011 through 2022). Averages of reported emissions from last three consecutive reporting years were multiplied by the average growth rate for each off-ramping OEM to estimate emissions for the non-reporting year(s).

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Uncertainty

To estimate the uncertainty associated with emissions of SF_6 and CF_4 from electrical equipment, uncertainties associated with four quantities were estimated: (1) emissions from Partners, (2) emissions from GHGRP-Only Reporters, (3) emissions from Non-Reporters, and (4) emissions from manufacturers of electrical equipment. A Monte Carlo analysis was then applied to estimate the overall uncertainty of the emissions estimate.

Total emissions from the SF_6 Emission Reduction Partnership include emissions from both reporting (through the Partnership or EPA's GHGRP) and non-reporting Partners. For reporting Partners, individual Partner-reported SF_6 data was assumed to have an uncertainty of +/- 10 percent. Based on a Monte Carlo analysis, the cumulative uncertainty of all Partner-reported data was estimated to be 4.5 percent. The uncertainty associated with extrapolated or interpolated emissions from non-reporting Partners was assumed to be 20 percent.

For GHGRP-Only Reporters, reported SF_6 data was assumed to have an uncertainty of 10 percent. Based on a Monte Carlo analysis, the cumulative uncertainty of all GHGRP-Only reported data was estimated to be 7.4 percent.

As discussed below, EPA has substantially revised its method for estimating emissions from non-Reporters, assuming that the average emission rate of non-Reporters has declined much more slowly than the average emission rate of reporting facilities rather than declining at the same rate. This assumption brings the U.S. SF_6 emissions estimated in this *Inventory* into better agreement with the U.S. SF_6 emissions inferred from atmospheric observations. However, it must be emphasized that the actual emission rates of non-Reporters remain unknown. It is possible that they are lower or even higher than estimated here. One possibility is that SF_6 sources other than electric power systems are contributing to the emissions inferred from atmospheric observations, implying that the emissions from non-Reporters are lower than estimated here. Another is that the emissions inferred from atmospheric measurements are over- (or under-) estimated, implying that emissions from non-Reporters could be either lower or higher than estimated here. These uncertainties are difficult to quantify and are not reflected in the estimated uncertainty below. The estimated uncertainty below accounts only for the two sources of uncertainty associated with the regression equations used to estimate emissions in 2019 from Non-Reporters: (1) uncertainty in the coefficients (as defined by the regression standard error estimate), and (2) the uncertainty in total transmission miles for Non-Reporters. Uncertainties were also estimated regarding (1) estimates of SF_6 and CF_4 emissions from OEMs reporting to EPA's GHGRP, and (2) the assumption on the percent share of OEM emissions from OEMs reporting to EPA's GHGRP.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 1-57. electrical equipment emissions were estimated to be between 3.8 and 6.4 MMT CO_2 Eq. at the 95 percent confidence level, a range of approximately 25 percent below and 25 percent above the emission estimate of 5.1 MMT CO_2 Eq. CF_4 emissions were estimated to be between 0.000006 and 0.000009 MMT CO_2 Eq. at the 95 percent confidence level, a range of approximately 20 percent below and 20 percent above the emission estimate of 0.0000074 MMT CO_2 Eq.

Table 4-134: Approach 2 Quantitative Uncertainty Estimates for SF_6 and CF_4 Emissions from Electrical Equipment (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to 2022 Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Electrical Equipment	SF_6	5.1	3.8	6.4	-25%	+25%
Electrical Equipment	CF_4	0.0000074	0.000006	0.000009	-20%	+20%

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

In addition to the uncertainty quantified above for the 2022 estimate, there is uncertainty associated with the emission rates of GHGRP-only facilities before 2011 and of non-Reporters throughout the time series. As noted above in the discussion of the uncertainty of non-Reporters for 2022, these uncertainties are difficult to quantify.

There is also uncertainty associated with using global SF_6 sales data to estimate U.S. emission trends from 1990 through 1999. However, the trend in global emissions implied by sales of SF_6 appears to reflect the trend in global emissions implied by changing SF_6 concentrations in the atmosphere. That is, emissions based on global sales declined by 29 percent between 1995 and 1998 (RAND 2004), and emissions based on atmospheric measurements declined by 17 percent over the same period (Levin et al. 2010).

Several pieces of evidence indicate that U.S. SF_6 emissions were reduced as global emissions were reduced. First, the decreases in sales and emissions coincided with a sharp increase in the price of SF_6 that occurred in the mid-1990s and that affected the United States as well as the rest of the world. A representative from DILO, a major manufacturer of SF_6 recycling equipment, stated that most U.S. utilities began recycling rather than venting SF_6 within two years of the price rise. Finally, the emissions reported by the one U.S. utility that reported its emissions for all the years from 1990 through 1999 under the Partnership showed a downward trend beginning in the mid-1990s.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter and Annex 8 for more details. Category specific QC findings are described below.

For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[130] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

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[130] GHGRP Report Verification Factsheet. See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

Additionally, EPA provides additional quality control for the SF_6 emissions estimates using atmospheric derived estimates for comparison. The *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019) Volume 1: General Guidance and Reporting, Chapter 6: Quality Assurance, Quality Control and Verification notes that atmospheric concentration measurements can provide independent data sets as a basis for comparison with inventory estimates. Further, it identifies fluorinated gases as particularly suited for such comparisons. The *2019 Refinement* makes this conclusion for fluorinated gases based on their lack of significant natural sources,[131] their generally long atmospheric lifetimes, their well-known loss mechanisms, and the potential uncertainties in bottom-up inventory methods for some of their sources. Unlike non-fluorinated greenhouse gases (CO_2, CH_4, and N_2O), SF_6 has no significant natural sources; therefore, the SF_6 estimates derived from atmospheric measurements are driven overwhelmingly by anthropogenic emissions. The *2019 Refinement* provides guidance on conducting such comparisons (as summarized in Table 6.2 of IPCC (2019) Volume 1, Chapter 6) and provides guidance on using such comparisons to identify areas of improvement in national inventories (as summarized in Box 6.5 of IPCC (2019) Volume 1, Chapter 6). Emission estimates derived from atmospheric measurements of SF_6 made at NOAA and described in Hu et al. (2022) were used to perform a comparison to the inventory estimates. This comparison resulted in changes to historical emission estimates, as more thoroughly described in the previous *Inventory* cycle (EPA 2022). No further changes were made to the electrical equipment estimates for the current (i.e., 1990 through 2022) *Inventory* based on this comparison.

Recalculations Discussion

Several updates to activity data led to recalculations of previous *Inventory* results. The major updates are as follows:

- As discussed in the methodology above, CARB estimates of SF_6 emissions from electrical equipment in California were used as California's contribution to the national total starting in 2011, except in cases where CARB emissions were lower than GHGRP and voluntarily reported emissions from California, or in years where CARB has not published SF_6 emissions estimates.
- Updates were made to reporter emissions where facilities had resubmitted data.
- A correction was made to estimate 2021 nameplate capacities for two off-ramping utilities, which off-ramped in 2021; these estimations were inadvertently omitted in the previous *Inventory*.
- SF_6 emissions from electrical equipment manufacturing was corrected due to an erroneous data pull in the previous *Inventory*. This caused emissions to increase in years 2011 through 2019.
- Partner transmission mileage used for calculating average share of Partner utilities across the time series and for estimating nameplate capacity for non-reporting utilities was corrected. The calculation was previously referencing partner transmission mileage for the prior year for 2013 through 2021.

Planned Improvements

EPA plans to revisit the methodology for determining emissions from the manufacture of electrical equipment, in particular, the assumption that emissions reported by OEMs account for a conservatively low estimate of 50 percent of the total emissions from all U.S. OEMs. Additional market research will be required to confirm or modify the assumptions regarding the portion of industry not reporting to the GHGRP program.

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[131] See Harnisch and Eisenhauer (1998).

4.27 SF_6 and PFCs from Other Product Use (CRT Source Category 2G.2)

There are a variety of other products and processes that use fluorinated greenhouse gases. This section estimates emissions of sulphur hexafluoride (SF_6) and perfluorocarbons (PFCs) from other product use (CRT Source Category 2G.2), including military and scientific applications. Many of these applications utilize SF_6 or PFCs to exploit their unique chemical properties, such as the high dielectric strength of SF_6 and the stability of PFCs. Emission profiles from these processes may vary greatly, ranging from immediate and unavoidable release of all of the chemical to largely avoidable, delayed release from leak-tight products after decades of use.

Military applications employ SF_6 and PFCs in many processes, such as the use of SF_6 in the radar systems of military reconnaissance planes of the Boeing E-3A type, commonly known as Airborne Warning and Control Systems (AWACS). These systems use SF_6 to prevent electric flashovers in the hollow conductors of the antenna, where voltages can reach up to 135 kilovolts (kV). During ascent of the planes, SF_6 is automatically released from the AWACS to maintain appropriate pressure difference between the system and the outside air. During descent, the system is automatically charged with SF_6 from an SF_6 container on board. Most emissions occur during ascent but may also occur from system leakage during other phases of flight or during time on the ground. Emissions from AWACS are largely dependent on the number of active planes and sorties (take-offs) per year.

Other uses of SF_6 in military applications include the oxidation of lithium in navel torpedoes and infrared decoys. SF_6 has also been documented for use in the quieting of torpedo propellers, as well as a by-product of the processing of nuclear material for the production of fuel and nuclear warheads.

Military electronics are believed to be a key application for PFC heat transfer fluids, particularly in areas such as ground and airborne radar avionics, missile guidance systems, and sonar. PFCs may also be used to cool electric motors, especially for equipment where noise reduction is a priority (e.g., submarines). The specific PFCs used in military applications are similar to heat transfer fluids identified in the electronics industry (see Section 4.24). PFCs are typically contained in a closed system, so the emissions are most likely to occur during the manufacture, maintenance, and disposal of equipment.

SF_6 and PFCs are also employed in several scientific applications, such as for use in particle accelerators. Particle accelerators can be found in university and research settings, as well as in industrial and medical applications. SF_6 is typically used as an insulating gas and is operated in a vessel exceeding atmospheric pressure. The amount of SF_6 used in particle accelerators is largely dependent on the terminal voltage of the unit. Emissions of SF_6 typically occur when SF_6 is transferred to storage tanks while maintenance is occurring, when pressure relief valves are actuated, and through slow leaks. The emission and charge assumptions for industrial and medical particle accelerators differ from those of university and research accelerators, as discussed in the methodology below. PFCs (particularly PFC-14) may also be used in particle accelerators as particle detectors or counters (Workman 2022).

SF_6 may also be employed in other high-voltage scientific equipment, including lasers, x-rays, and electron microscopes. SF_6 emission estimates for this equipment were not disaggregated from particle accelerators for this *Inventory*.

There is a range of unidentified processes that also use SF_6 and PFCs, such as R&D activities. PFCs are likely used primarily as heat transfer fluids (HTFs). Emissions reported for these unknown activities group under “Other Scientific Applications”.

Emissions of SF_6 and PFCs from the applications outlined above are presented in Table 4-135.

Table 4-135: SF_6 and PFC Emissions from Other Product Use (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
SF_6	0.6	0.6	0.4	0.4	0.3	+	0.3
Total AWACs	**0.6**	**0.6**	**0.4**	**0.4**	**0.3**	**+**	**0.3**
SF_6	0.3	0.3	0.0	0.0	0.0	0.0	0.0
PFCs	0.1	0.1	0.2	0.2	0.2	0.1	0.2
Total Other Military Applications	**0.4**	**0.4**	**0.2**	**0.2**	**0.2**	**0.1**	**0.2**
SF_6	0.4	0.5	0.4	0.2	0.1	0.2	0.2
PFC-14	+	+	+	+	+	+	+
Total Particle Accelerators	**0.4**	**0.5**	**0.4**	**0.2**	**0.1**	**0.2**	**0.2**
SF_6	+	+	+	+	0.1	0.2	0.1
PFCs	+	+	+	+	+	+	+
Total Other Scientific Applications	**+**	**+**	**+**	**+**	**0.1**	**0.2**	**0.1**
Total Other Product Use	**1.4**	**1.5**	**0.9**	**0.8**	**0.7**	**0.5**	**0.8**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: PFC subtotals include estimates for HFEs. Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Emissions are based primarily on data reported through the Federal Energy Management Program (FEMP). However, the availability of data from FEMP differs across the 1990 through 2022 time series. Consequently, additional emission estimates were made through utilizing methodologies from the IPCC. Emissions from military applications and scientific applications were estimated separately, and the approaches are described immediately below.

Military Applications

1990 through 2007

FEMP data was not readily available for the 1990 to 2007 period as the first reporting year was in 2008. Thus for this period, estimated SF_6 emissions from AWACS were calculated based using the IPCC Tier 1 methodology (IPCC 2006). IPCC provided a default emissions factor of 740kg of SF_6 per plane per year. It was assumed that the U.S. AWAC fleet between 1990 through 2022 remained constant at 33 planes. The IPCC methodology was utilized for all years from 1990 to 2007.

Emissions for other military applications were estimated by taking the average of the emissions estimated for other applications as described in the next section for first five FEMP reporting years (i.e., 2008 through 2012) and held constant between 1990 through 2007. Emissions from AWACS were not specifically reported by FEMP; the estimates developed for AWACS using the IPCC methodology above were employed to determine emissions from remaining unidentified military applications.

2008 through 2021

For the period 2008 through 2021, the Department of Defense (DOD) reported emission data through FEMP which were used to develop estimates for SF_6 and PFCs from other military applications. SF_6 emission estimates developed for AWACS using the IPPC Tier 1 methodology (see 1990 through 2007) were compared against SF_6 emissions reported by DOD between 2008 and 2021. In years where SF_6 emissions reported by DOD was smaller than those estimated using the IPCC Tier 1 methodology, DOD-reported emissions were assumed to account for total AWAC emissions; in years where DOD emissions were greater than the calculated AWAC emissions, the remainder is assumed to be from other SF_6 applications.

Emissions from PFCs, HFEs, and other perfluoro compounds are directly reported by DOD. In years where there are data gaps from FEMP between two reporting years, expected emissions were interpolated.

2022

Estimates for emissions from AWACS and other military uses for 2022 were determined by taking an average of the previous five reporting years (i.e., 2017 through 2021).

Scientific Applications

1990 through 2007

For the period 1990 through 2007, where no reported data is available from the Department of Energy (DOE), estimates for emissions of SF_6 and PFCs from other product use at Department of Energy Laboratories were determined by taking an average of the first five reporting years (i.e., 2008 through 2012) and held constant from 1990 to 2007.

SF_6 emissions from other (non-DOE) research and industrial particle accelerators in the United States was calculated based on the IPCC Tier 1 methodology for estimating emissions from industrial and university/research particle accelerators. Default emission factors, charge sizes, and usage rates are provided by size and type of accelerator in the IPCC methodology. These default assumptions were multiplied against the number of particle accelerators estimated to be active in the United States by year. This methodology remained the same from 1990 to 2007.

2008 through 2021

For the period 2008 through 2021, SF_6 and PFC emissions from government particle accelerators and other scientific equipment were developed using DOE-reported emissions. SF_6 and PFC emissions from particle accelerators were directly reported by DOE. Other fugitive emissions reported by DOE for SF_6 were assumed to represent emissions from particle accelerators and other scientific equipment, as well as two DOE-managed power facilities (WAPA and BPA).[132] Emissions from these two facilities were subtracted out to present only SF_6 emissions from scientific equipment. Reported fugitive emissions for PFC-14 were assumed to wholly represent particle accelerator applications. SF_6 emissions from non-government particle accelerators were estimated using the IPPC Tier 1 methodology used for 1990 through 2007.

Process emissions from other applications for SF_6 and PFCs were reported by DOE for activities such as R&D, and these emissions were summed by gas. However, the estimates presented here do not include emissions reported for semiconductor research and manufacture, or from refrigeration and air conditioning. Emissions from additional PFCs, HFEs, and other perfluoro compounds are directly reported by DOE and are reported as "Other Applications." Emissions reported to FEMP were generally calculated based on consumption data. In a number of years, negative values for emissions were reported due to more gas being returned to supply than purchased in a given year. When negative values were reported, EPA took the average of that year and the proceeding and following year and applied that value to all three years. This 3-year average was assumed to be more representative of actual emissions.

In years where there are data gaps between two reporting years, emissions were interpolated.

2022

For emission estimates developed using DOE-reported emissions, estimates for 2022 were determined by taking an average of the previous five reporting years (i.e., 2017 through 2021). SF_6 emissions from non-government

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[132] DOE-reported fugitive emissions for SF_6 and PFCs includes emissions from high-voltage scientific equipment such as lasers, x-rays, and electron microscopes. Emissions from this equipment is included in the particle accelerators total.

particle accelerators were estimated using the same IPPC Tier 1 methodology used for 2008 through 2021.

Uncertainty

A quantitative uncertainty analysis of this source category was performed using the IPCC-recommended Approach 2 uncertainty estimation methodology, the Monte Carlo stochastic simulation technique. The Monte Carlo stochastic simulation was performed on the total emissions estimate from other product use, represented in equation form as:

Equation 4-27: Total Emissions from Other Product Use

$$\begin{aligned}\text{Total Emissions } (\mathrm{E}_T) \\ &= \text{Military Applications SF}_6 \text{ and PFC Emissions } (\mathrm{E}_{Military}) \\ &+ \text{Scientific Applications of SF}_6 \text{ and PFC Emissions } (\mathrm{E}_{Scientific})\end{aligned}$$

The uncertainty in the total emissions for other product use, presented in Table 4-124 below, results from the convolution of two distributions of emissions, namely from military applications and scientific applications. The approaches for estimating uncertainty in each of the sources are described below:

Military Applications Emission Uncertainty

The Monte Carlo stochastic simulation was performed on the emissions estimate from military applications, represented in equation form as:

Equation 4-28: Total Emissions from Military Applications

$$\begin{aligned}\text{Military Applications SF}_6 \text{ and PFC Emissions } (\mathrm{E}_{Military}) \\ &= \text{Military AWACS SF}_6 \text{ Emissions } (\mathrm{E}_{AWACS,SF_6,Military}) \\ &+ \text{Other Military Applications SF}_6 \text{ Emissions } (\mathrm{E}_{Other,SF_6,Military}) \\ &+ \text{Other Military Applications PFC Emissions } (\mathrm{E}_{Other,PFC,Military})\end{aligned}$$

The uncertainty in $E_{Military}$ results from the convolution of three distributions of emissions, $E_{AWACS,SF6,Military}$, $E_{Other,SF6,Military}$, and $E_{Other,PFC,Military}$. The approaches for estimating each distribution and combining them to arrive at the reported 95 percent confidence interval (CI) for $E_{Military}$ are described in the remainder of this section.

The uncertainty estimate of $E_{AWACS,SF6,Military}$, or SF_6 emissions from AWACS, is developed based on the number of AWACS in commission in the United States and the per-plane emission factor. The estimated number of active planes installed with AWACS is 33, although estimates range between 31 and 35. The IPCC provides a per-plane emission factor of 740 kg of SF_6 per plane annually and estimates the uncertainty to have bounds of ±14 percent.

The uncertainty in $E_{Other,SF6,Military}$ and $E_{Other,PFC,Military}$, or SF_6 and PFC emissions from other military applications, was obtained by determining the accuracy of government-reported emissions data and reviewing the methodology the Department of Defense uses for developing inventory estimates.

The next step in estimating the uncertainty in emissions from military AWACS and other military applications is convolving the distribution of reported emissions, emission factors, and number of AWACS using Monte Carlo simulation. For this Monte Carlo simulation, the distributions of the reported emissions and emission factors are assumed to be normally distributed, and the number of AWACS is assumed to have a uniform distribution since this is a discrete number of planes. The uncertainty bounds are assigned at 1.96 standard deviations around the estimated mean.

Scientific Applications Emission Uncertainty

The Monte Carlo stochastic simulation was performed on the emissions estimate from scientific applications, represented in equation form as:

Equation 4-29: Total Emissions from Scientific Applications

$$\begin{aligned}
&\text{Scientific Applications SF}_6\text{ and PFC Emissions } \left(\mathrm{E}_{Scientific}\right) \\
&\quad = \text{ Particle Accelerators SF}_6\text{ Emissions } \left(\mathrm{E}_{Accelerators,SF_6,Scientific}\right) \\
&\quad + \text{ Particle Accelerators PFC Emissions } \left(\mathrm{E}_{Accelerators,PFC,Military}\right) \\
&\quad + \text{ Other Scientific Applications SF}_6\text{ Emissions } \left(\mathrm{E}_{Other,SF_6,Scientific}\right) \\
&\quad + \text{ Other Scientific Applications PFC Emissions } \left(\mathrm{E}_{Other,PFC,Scientific}\right)
\end{aligned}$$

The uncertainty in $E_{Scientific}$ results from the convolution of four distributions of emissions, $E_{Accelerators,SF6,Scientific}$, $E_{Accelerators,PFC,Military}$, $E_{Other,SF6,Scientific,}$ and $E_{Other,PFC,Scientific}$. The approaches for estimating each distribution and combining them to arrive at the reported 95 percent confidence interval (CI) for $E_{Scientific}$ are described in the remainder of this section.

The uncertainty estimate of $E_{Accelerators,SF6,Scientific}$ and $E_{Accelerators,PFC,Scientific}$, or SF_6 and PFC emissions from particle accelerators, is developed based on fugitive and process emissions reported by the Department of Energy and emission estimates from the number active university and industrial particle accelerators in the United States. The number of active particle accelerators in the United States for the time series 1990 through 2022 was determined using expert judgment; default emission factors and charge sizes for particle accelerators of various sizes were provided by IPCC guidelines. Emissions of SF_6 from electrical transmission and distribution equipment were removed from total emissions estimates for this source category, as they are reported elsewhere in the *Inventory.*

The uncertainty in $E_{Other,SF6,Scientific}$ and $E_{Other,PFC,Scientific}$, or SF_6 and PFC emissions from other scientific applications, was obtained by determining the accuracy of government-reported emissions data and reviewing the methodology the Department of Energy uses for developing inventory estimates.

The next step in estimating the uncertainty in emissions from particle accelerators and other scientific applications is convolving the distribution of calculated emissions, emission factors, number of accelerators using Monte Carlo simulation. Similarly, the distributions of the reported emissions and emission factors for this Monte Carlo simulation are assumed to be normally distributed, and the number of particle accelerators and other scientific applications is assumed to have a uniform distribution since this is a discrete number of accelerators. The uncertainty bounds are assigned at 1.96 standard deviations around the estimated mean.

The emissions estimate for total U.S. SF_6 and PFC emissions from other product use were estimated to be between 0.5 and 1.1 MMT CO_2 Eq. at a 95 percent CI level. This range represents 36 percent below and 38 percent above the 2022 emission estimate of 0.8 MMT CO_2 Eq. for all emissions from others product use. This range and the associated percentages apply to the estimate of total emissions rather than those of individual gases. Uncertainties associated with individual gases will be somewhat higher than the aggregate but were not explicitly modeled.

Table 4-136: Approach 2 Quantitative Uncertainty Estimates for SF_6 and PFC Emissions from Other Product Use (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound[b]	Upper Bound[b]	Lower Bound	Upper Bound
Other Product Use	SF_6 and PFC	0.8	0.5	1.1	-36%	+38%

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

[b] Absolute lower and upper bounds were calculated using the corresponding lower and upper bounds in percentages.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter and Annex 8 for more details.

Recalculations Discussion

This is a new category included for the current (i.e., 1990 to 2022) *Inventory*, thus, no recalculations were performed.

4.28 Nitrous Oxide from Product Uses (CRT Source Category 2G3)

Nitrous oxide (N_2O) is a clear, colorless, oxidizing liquefied gas with a slightly sweet odor which is used in a wide variety of specialized product uses and applications. This reporting category (2G3) includes exhalation emissions of N_2O that arise from medical applications and evaporative emissions of N_2O from use as a propellant in aerosol products primarily in food industry. The amount of N_2O that is actually emitted depends upon the specific product use or application.

There are a total of three N_2O production facilities currently operating in the United States (Ottinger 2021). Nitrous oxide is primarily used in carrier gases with oxygen to administer more potent inhalation anesthetics for general anesthesia, and as an anesthetic in various dental and veterinary applications. The second main use of N_2O is as a propellant in pressure and aerosol products, the largest application being pressure-packaged whipped cream. Small quantities of N_2O also are used in the following applications:

- Oxidizing agent and etchant used in semiconductor manufacturing;
- Oxidizing agent used, with acetylene, in atomic absorption spectrometry;
- Production of sodium azide, which is used to inflate airbags;
- Fuel oxidant in auto racing; and
- Oxidizing agent in blowtorches used by jewelers and others (Heydorn 1997).

Production of N_2O in 2022 was approximately 15 kt (see Table 4-137).

Table 4-137: N_2O Production (kt)

Year	1990	2005	2018	2019	2020	2021	2022
Production (kt)	16	15	15	15	15	15	15

Nitrous oxide emissions were 3.8 MMT CO_2 Eq. (14 kt N_2O) in 2022 (see Table 4-138). Production of N_2O stabilized during the 1990s because medical markets had found other substitutes for anesthetics, and more medical procedures were being performed on an outpatient basis using local anesthetics that do not require N_2O. The use of N_2O as a propellant for whipped cream has also stabilized due to the increased popularity of cream products packaged in reusable plastic tubs (Heydorn 1997).

Table 4-138: N_2O Emissions from N_2O Product Usage (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
N_2O Product Usage	3.8	3.8	3.8	3.8	3.8	3.8	3.8

Table 4-139: N_2O Emissions from N_2O Product Usage (kt N_2O)

Year	1990	2005	2018	2019	2020	2021	2022
N_2O Product Usage	14	14	14	14	14	14	14

Methodology and Time-Series Consistency

Emissions from N_2O product uses are calculated using a country-specific methodology that is consistent with *2006 IPCC Guidelines* and based on available data. The *2006 IPCC Guidelines* do not define tier methodologies for this source category. Emissions of N_2O are estimated using the national N_2O production by subcategory use or application, the share of the subcategory, and the appropriate emission rate for each category. The following equation is adapted from Equation 8.24 of the *2006 IPCC Guidelines*:

Equation 4-30: N_2O Emissions from Product Use

$$E_{pu} = \sum_{a} (P \times S_a \times ER_a)$$

where,

E_{pu} = N_2O emissions from product uses, metric tons

P = Total U.S. production of N_2O, metric tons

a = specific application

S_a = Share of N_2O usage by application *a*

ER_a = Emission rate for application *a*, percent

The share of total quantity of N_2O usage by end-use represents the share of national N_2O produced that is used by the specific subcategory (e.g., anesthesia, food processing). In 2020, the medical/dental industry used an estimated 89.5 percent of total N_2O produced, followed by food processing propellants at 6.5 percent. All other subcategories, including semiconductor manufacturing, atomic absorption spectrometry, sodium azide production, auto racing, and blowtorches, used the remainder of the N_2O produced. This subcategory breakdown changed slightly in the mid-1990s. For instance, the small share of N_2O usage in the production of sodium azide declined significantly during the 1990s. Due to the lack of information on the specific time period of the phase-out in this market subcategory, most of the N_2O usage for sodium azide production is assumed to have ceased after 1996, with the majority of its small share of the market assigned to the larger medical/dental consumption subcategory (Heydorn 1997). For 1990 through 1996, N_2O usage was allocated across the following subcategories: medical applications, food processing propellant, and sodium azide production. A usage emissions rate was then applied for each subcategory to estimate the amount of N_2O emitted.

Only the medical/dental and food propellant subcategories were assumed to release emissions into the atmosphere that are not captured under another source category, and therefore these subcategories were the only usage subcategories with emission rates. Emissions of N_2O from semiconductor manufacturing are described in Section 4.24 and reported under CRT Source Category 2H3. For the medical/dental subcategory, due to the poor solubility of N_2O in blood and other tissues, none of the N_2O is assumed to be metabolized during anesthesia and quickly leaves the body in exhaled breath. Therefore, an emission factor of 100 percent was used for this subcategory (IPCC 2006). For N_2O used as a propellant in pressurized and aerosol food products, none of the N_2O is reacted during the process and all of the N_2O is emitted to the atmosphere, resulting in an emission factor of 100 percent for this subcategory (IPCC 2006). For the remaining subcategories, all of the N_2O is consumed or reacted during the process, and therefore the emission rate was considered to be zero percent (Tupman 2002).

The 1990 through 1992 N_2O production data were obtained from SRI Consulting's *Nitrous Oxide, North America* (Heydorn 1997). Nitrous oxide production data for 1993 through 1995 were not available. Production data for

1996 was specified as a range in two data sources (Heydorn 1997; Tupman 2002). In particular, for 1996, Heydorn (1997) estimates N_2O production to range between 13.6 and 18.1 thousand metric tons. Tupman (2002) provided a narrower range (15.9 to 18.1 thousand metric tons) for 1996 that falls within the production bounds described by Heydorn (1997). Tupman (2002) data are considered more industry-specific and current; therefore, the midpoint of the narrower production range was used to estimate N_2O emissions for years 1993 through 2001 (Tupman 2002). The 2002 and 2003 N_2O production data were obtained from the Compressed Gas Association Nitrous Oxide Fact Sheet and Nitrous Oxide Abuse Hotline (CGA 2002, 2003). These data were also provided as a range. For example, in 2003, CGA (2003) estimates N_2O production to range between 13.6 and 15.9 thousand metric tons. Due to the lack of publicly available data, production estimates for years 2004 through 2022 were held constant at the 2003 value.

The 1996 share of the total quantity of N_2O used by each subcategory was obtained from SRI Consulting's *Nitrous Oxide, North America* (Heydorn 1997). The 1990 through 1995 share of total quantity of N_2O used by each subcategory was kept the same as the 1996 number provided by SRI Consulting. The 1997 through 2001 share of total quantity of N_2O usage by sector was obtained from communication with a N_2O industry expert (Tupman 2002). The 2002 and 2003 share of total quantity of N_2O usage by sector was obtained from CGA (2002, 2003). Due to the lack of publicly available data, the share of total quantity of N_2O usage data for years 2004 through 2021 was assumed to equal the 2003 value. The emission factor for the food processing propellant industry was obtained from SRI Consulting's *Nitrous Oxide, North America* (Heydorn 1997) and confirmed by a N_2O industry expert (Tupman 2002). The emission factor for all other subcategories was obtained from communication with a N_2O industry expert (Tupman 2002). The emission factor for the medical/dental subcategory was obtained from the *2006 IPCC Guidelines*.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2022.

Uncertainty

The overall uncertainty associated with the 2022 N_2O emission estimate from N_2O product usage was calculated using the *2006 IPCC Guidelines* Approach 2 methodology. Uncertainty associated with the parameters used to estimate N_2O emissions include production data, total market share of each end use, and the emission factors applied to each end use, respectively. The uncertainty associated with N_2O production data is ±25 percent, and a uniform probability density function is assigned, based on expert judgment (RTI 2023). The uncertainty associated with the market share for the medical/dental subcategory is ±0.56 percent, and uncertainty for the market share of food propellant subcategory is ±25 percent, both based on expert judgment (RTI 2023). Uncertainty for emission factors was assumed to be zero, and using this suggested uncertainty provided in the *2006 IPCC Guidelines* is appropriate based on expert judgment (RTI 2023).

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-140. Nitrous oxide emissions from N_2O product usage were estimated to be between 2.9 and 4.6 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 24 percent below to 24 percent above the emission estimate of 3.8 MMT CO_2 Eq.

Table 4-140: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from N_2O Product Usage (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
N_2O from Product Uses	N_2O	3.8	2.9	4.6	-24%	+24%

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

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

No recalculations were performed for the 1990 to 2021 portion of the time series.

Planned Improvements

EPA recently initiated an evaluation of alternative production statistics for cross-verification and updating time-series activity data, emission factors, assumptions, etc., and a reassessment of N_2O product use subcategories that accurately represent trends. This evaluation includes conducting a literature review of publications and research that may provide additional details on the industry. This work remains ongoing, and thus far no additional sources of data have been found to update this category.

Pending additional resources and planned improvement prioritization, EPA may also evaluate production and use cycles, and the potential need to incorporate a time lag between production and ultimate product use and resulting release of N_2O. Additionally, planned improvements include considering imports and exports of N_2O for product uses.

Finally, for future Inventories, EPA will examine data from EPA's GHGRP to improve the emission estimates for the N_2O product use subcategory. Particular attention will be made to ensure aggregated information can be published without disclosing CBI and time-series consistency, as the facility-level reporting data from EPA's GHGRP are not available for all inventory years as required in this *Inventory*. This is a lower priority improvement, and EPA is still assessing the possibility of incorporating aggregated GHGRP CBI data to estimate emissions; therefore, this planned improvement is still in development and not incorporated in the current *Inventory* report.

4.29 Industrial Processes and Product Use Sources of Precursor Gases

In addition to the main greenhouse gases addressed above, many industrial processes can result in emissions of various greenhouse gas precursors. The reporting requirements of the Paris Agreement and the UNFCCC[133] request that information should be provided on precursor emissions, which include carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), and sulfur dioxide (SO_2). These gases are not direct greenhouse gases, but indirectly impact Earth's radiative balance by altering the concentrations of greenhouse gases (e.g., ozone) and atmospheric aerosol (e.g., particulate sulfate). Combustion byproducts such as CO and NO_x are emitted from industrial applications that employ thermal incineration as a control technology. NMVOCs, commonly referred to as "hydrocarbons," are the primary gases emitted from most processes employing organic or petroleum-based products, and can also result from the product storage and handling.

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[133] See paragraph 51 of Annex to 18/CMA.1 available online at: https://unfccc.int/sites/default/files/resource/CMA2018_03a02E.pdf.

Accidental releases of precursors associated with product use and handling can constitute major emissions in this category. In the United States, emissions from product use are primarily the result of solvent evaporation, whereby the lighter hydrocarbon molecules in the solvents escape into the atmosphere. The major categories of product uses include: degreasing, graphic arts, surface coating, other industrial uses of solvents (e.g., electronics), dry cleaning, and non-industrial uses (e.g., uses of paint thinner). Product usage in the United States also results in the emission of hydrofluorocarbons (HFCs) and small amounts of hydrofluoroethers (HFEs), which are included under Substitution of Ozone Depleting Substances and the Electronics Industry in this chapter.

Total emissions of NO_x, CO, NMVOCs, and SO_2 from non-energy industrial processes and product use from 1990 to 2022 are reported in Table 4-141.

Table 4-141: NO_x, CO, NMVOC, and SO_2 Emissions from Industrial Processes and Product Use (kt)

Gas/Source	1990	2005	2018	2019	2020	2021	2022
NO_x	**774**	**672**	**461**	**440**	**393**	**403**	**389**
Mineral Industry	160	200	118	114	101	99	95
Other Industrial Processes[a]	326	355	218	206	187	189	184
Metal Industry	96	58	63	60	52	60	56
Chemical Industry	192	80	61	59	54	55	53
CO	**4,099**	**1,701**	**1,022**	**1,011**	**855**	**902**	**897**
Metal Industry	2,261	707	447	448	340	355	335
Other Industrial Processes[a]	564	662	332	331	294	309	329
Mineral Industry	182	120	111	106	96	95	95
Chemical Industry	1,093	211	132	126	125	142	138
NMVOCs	**6,982**	**3,668**	**3,119**	**2,996**	**3,366**	**3,508**	**3,505**
Other Industrial Processes[a]	6,270	3,396	3,003	2,883	3,261	3,398	3,401
Chemical Industry	601	221	88	86	81	84	79
Mineral Industry	9	10	7	7	6	6	6
Metal Industry	102	40	21	20	17	19	19
SO_2	**1,488**	**776**	**335**	**309**	**266**	**274**	**261**
Other Industrial Processes[a]	474	256	145	134	120	126	119
Chemical Industry	283	242	106	97	83	83	75
Mineral Industry	166	138	25	25	26	28	28
Metal Industry	566	140	58	53	37	38	39

[a] Other Industrial Processes includes storage and transport, other industrial processes (manufacturing of agriculture, food, and kindred products; wood, pulp, paper, and publishing products; rubber and miscellaneous plastic products; machinery products; construction; transportation equipment; and textiles, leather, and apparel products), and miscellaneous sources (catastrophic/accidental release, other combustion (structural fires), health services, repair shops, and fugitive dust). It does not include agricultural fires or slash/prescribed burning, which are accounted for under the Field Burning of Agricultural Residues source.

Note: Totals by gas may not sum due to independent rounding.

Source: (EPA 2023a). Emission categories from EPA (2023a) are aggregated into sectors and categories reported under the Paris Agreement and the UNFCCC as shown in Table ES-3.

Methodology and Time-Series Consistency

Emission estimates for 1990 through 2020 were obtained from data published on the National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data website (EPA 2023a). For Table 4-141, NEI reported emissions of CO, NO_x, SO_2, and NMVOCs were recategorized from NEI Emissions Inventory System (EIS) sectors to source categories more closely aligned with reporting sectors and categories under the Paris Agreement and the UNFCCC based on discussions between the EPA GHG Inventory and NEI staff (see crosswalk documented in Annex 6.3).[134] EIS sectors mapped to the IPPU sector categories in this report include: chemical and allied product manufacturing, metals processing, storage and transport, solvent utilization, other industrial processes, and miscellaneous sources. As described in the NEI Technical Support Documentation (TSD) (EPA 2023c), NEI emissions are estimated through a combination of emissions data submitted directly to the EPA by state, local, and tribal air agencies, as well as additional information added by the Agency from EPA emissions programs, such as the emission trading program, Toxics Release Inventory (TRI), and data collected during rule development or compliance testing.

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2021, which are described in detail in the NEI's TSD and on EPA's Air Pollutant Emission Trends web site (EPA 2023a; EPA 2023c). A quantitative uncertainty analysis was not performed.

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[134] The NEI estimates and reports emissions from six criteria air pollutants (CAPs) and 187 hazardous air pollutants (HAPs) in support of National Ambient Air Quality Standards. EPA reported CAP emission trends are grouped into 60 sectors and 15 Tier 1 source categories, which broadly cover similar source categories to those presented in this chapter. For reporting precursor emissions in the common reporting tables (CRTs), EPA has mapped and regrouped emissions of greenhouse gas precursors (CO, NO_x, SO_2, and NMVOCs) from NEI's EIS sectors to better align with NIR source categories, and to ensure consistency and completeness to the extent possible. See Annex 6.3 for more information on this mapping.