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Industrial Processes and Product Use (IPPU) Emissions

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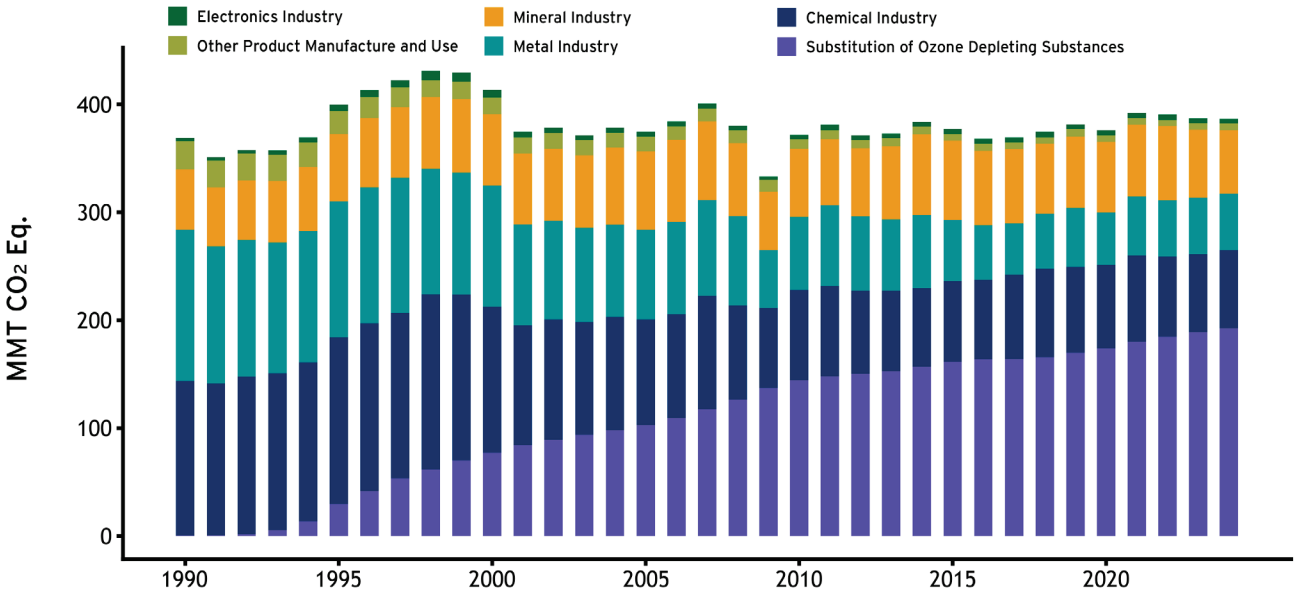
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Chapter 4. Industrial Processes and Product Use (IPPU)

The industrial processes and product use (IPPU) sector includes greenhouse gas (GHG) emissions from industrial processes that chemically or physically transform raw materials, as well as emissions released during the use of products. Industrial activities that emit GHGs include mineral production, metal production, chemical production, and product use applications. The primary GHGs emitted from IPPU activities include hydrofluorocarbons (HFCs), carbon dioxide (CO_2), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), and perfluorocarbons (PFCs). Small amounts of methane (CH_4) and nitrogen trifluoride (NF_3) are also emitted.

In 2024, emissions from this sector were 386.6 million metric tons of carbon dioxide equivalents (MMT CO_2 Eq.), accounting for approximately 6.2 percent of total U.S. GHG emissions. While overall sector emissions have increased by 4.7 percent since 1990, some sources have experienced significant increases and decreases over the time series (see Figure 4-1). Emissions have been influenced by a combination of long-term structural changes and short-term fluctuations in industrial activity. In recent years, trends in IPPU emissions have been driven primarily by changes in industrial production levels, including cement, steel, and chemical manufacturing, as well as evolving demand for fluorinated gases used in refrigeration, electronics, and other applications.

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



Emissions from the IPPU sector by source category and gas are presented in Table 4-1.

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

Gas/Source	1990	2005	2020	2021	2022	2023	2024
CO_2	**214.0**	**195.9**	**161.7**	**172.7**	**169.9**	**166.8**	**163.0**
Iron and Steel Production & Metallurgical Coke Production	104.7	70.1	41.1	47.9	45.7	46.8	46.7
Iron and Steel Production	*99.1*	*66.2*	*38.8*	*44.7*	*42.7*	*43.8*	*43.8*
Metallurgical Coke Production	*5.6*	*3.9*	*2.3*	*3.2*	*3.0*	*3.0*	*2.9*
Cement Production	33.5	46.2	40.7	41.3	41.9	40.6	37.2
Petrochemical Production	20.3	26.9	27.9	30.7	28.8	30.5	28.9
Ammonia Production	14.4	10.2	12.3	11.5	11.9	12.2	14.4
Lime Production	11.7	14.6	11.3	11.9	12.2	11.5	10.8
Other Process Uses of Carbonates	7.1	8.5	9.0	8.6	10.4	7.1	7.1
Other Uses of Carbonates	*4.8*	*6.2*	*7.4*	*7.0*	*8.8*	*5.5*	*5.5*
Ceramics Production	*0.8*	*0.8*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*
Other Uses of Soda Ash	*1.4*	*1.3*	*1.0*	*1.0*	*1.0*	*0.9*	*1.0*
Non-Metallurgical Magnesia	*0.1*	*0.2*	*0.2*	*0.2*	*0.2*	*0.3*	*0.3*
Urea Consumption for Non-Agricultural Purposes	*3.9*	*3.6*	*6.2*	*7.3*	*5.8*	*6.3*	*5.9*
Non-EOR Carbon Dioxide Utilization	1.5	1.4	2.8	2.9	2.8	2.1	2.1
Soda Ash Production	1.4	1.7	1.5	1.7	1.7	1.7	1.9
Glass Production	2.3	2.4	1.9	2.0	2.0	1.8	1.8
Titanium Dioxide Production	1.2	1.8	1.3	1.5	1.5	1.2	1.3
Ferroalloy Production	2.2	1.4	1.4	1.4	1.3	1.2	1.2
Aluminum Production	6.8	4.1	1.7	1.5	1.4	1.2	1.2
Zinc Production	0.6	1.0	1.0	1.0	0.9	0.9	0.9
Phosphoric Acid Production	1.5	1.3	0.9	0.9	0.8	0.8	0.8
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Carbide Production and Consumption	0.2	0.2	0.2	0.2	0.2	0.2	0.2

(continued)

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

Gas/Source	1990	2005	2020	2021	2022	2023	2024
Substitution of Ozone Depleting Substances[a]	+	+	+	+	+	+	+
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**	**20.8**	**19.7**	**16.1**	**14.9**	**14.9**
Nitric Acid Production	10.8	10.1	8.3	7.9	8.6	8.3	8.3
N_2O from Product Uses	3.8	3.8	3.8	3.8	3.8	3.8	3.8
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.5	1.9	1.1	1.2	1.3	1.3	1.4
Adipic Acid Production	13.5	6.3	7.4	6.6	2.1	1.2	1.2
Electronics Industry	+	0.1	0.3	0.3	0.3	0.3	0.3
HFCs	**47.8**	**125.0**	**177.8**	**184.3**	**189.5**	**191.0**	**194.3**
Substitution of Ozone Depleting Substances[a]	0.3	102.7	173.7	179.9	184.8	189.0	192.4
Fluorochemical Production	47.3	22.2	3.8	4.0	4.3	1.7	1.7
Electronics Industry	0.2	0.2	0.3	0.4	0.3	0.3	0.3
Magnesium Production and Processing	0.0	0.0	0.1	+	+	+	+
Other Product Manufacture and Use[c]	0.0	0.0	+	0.0	0.0	0.0	0.0
PFCs	**39.7**	**10.3**	**6.6**	**6.3**	**6.5**	**5.8**	**5.7**
Fluorochemical Production	17.7	4.1	2.5	2.6	2.8	2.7	2.7
Electronics Industry	2.5	3.0	2.6	2.7	2.8	2.4	2.4
Aluminum Production	19.3	3.1	1.4	0.9	0.8	0.5	0.4
Other Product Manufacture and Use[c]	0.1	0.1	0.1	0.1	0.1	0.2	0.2

(continued)

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

Gas/Source	1990	2005	2020	2021	2022	2023	2024
Substitution of Ozone Depleting Substances	0.0	+	+	+	+	+	+
Electrical Equipment	+	+	+	+	+	0.0	0.0
SF_6	**37.9**	**20.2**	**7.7**	**8.0**	**7.2**	**7.7**	**7.7**
Electrical Equipment	24.6	11.8	5.5	5.5	4.9	5.1	5.1
Magnesium Production and Processing	5.6	3.0	0.9	1.2	1.1	1.1	1.1
Other Product Manufacture and Use[c]	1.3	1.3	0.5	0.4	0.5	0.8	0.8
Electronics Industry	0.5	0.8	0.8	0.9	0.8	0.7	0.7
Fluorochemical Production	5.8	3.3	+	+	+	+	+
NF_3	**0.2**	**1.0**	**1.3**	**1.1**	**1.1**	**0.8**	**0.8**
Electronics Industry	+	0.4	0.6	0.6	0.6	0.5	0.5
Fluorochemical Production	0.1	0.6	0.7	0.5	0.5	0.3	0.3
Other Product Manufacture and Use[c]	+	+	+	+	+	0.0	0.0
Total[b]	**369.2**	**374.7**	**376.1**	**392.2**	**390.4**	**387.0**	**386.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

[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 4.4.

[c] Emissions included in Section 4.6.2 of this chapter.

Notes: Totals may not sum due to independent rounding. Emissions of F-HTFs that are not HFCs, PFCs or SF_6 are not included in *GHGIA* totals and are included for informational purposes only in Section 4.4. Emissions presented for informational purposes include HFEs, PFPMIEs, perfluoroalkylmorpholines, and perfluorotrialkylamines.

Unless otherwise noted, all estimates in this chapter are provided in MMT CO_2 Eq. Consistent with GHG inventories from other countries, this report uses 100-year Global Warming Potential values from Table 8.A.1 in Appendix 8.A of the *IPCC Fifth Assessment Report* for calculating CO_2 Eq. emissions. Supplemental data tables published with this *Greenhouse Gas Inventory and Analysis for the United States (GHGIA)* for download include all the tables presented in this chapter as well as tables with unweighted units reported as kilotons (kt).

Methodological Framework

Emissions are estimated based on Volume 3 (IPPU) of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (Intergovernmental Panel on Climate Change [IPCC], 2006) and the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 2019), using country-specific data where available.

Unless otherwise noted, methods are consistent with those used in Inventory of *U.S. Greenhouse Gas Emissions and Sinks: 1990-2023* (U.S. Environmental Protection Agency [EPA],2025)(see Table 4-2). Consistent with IPCC good practices, this *GHGIA* applies higher tier methods for more significant sources (e.g., Tier 2 and Tier 3 methods, which include use of country-specific methods and models, emission factors and site-specific information) and as data allow for smaller sources.

Table 4-2: Summary of Methods in the IPPU Chapter

Category (CRT Code)[a]	Gases	IPCC Methodological Tier	Methodological Refinements Compared to 1990-2023 Inventory (EPA, 2025)
Cement Production (2A1)	CO_2	Tier 2	New data source for 2024 clinker production
Lime Production (2A2)	CO_2	Tier 2	Alternate data source for 2024 lime production
Glass Production (2A3)	CO_2	Tier 2	Updated Annual Average Glass Production Index for historical series
Other Process Uses of Carbonates (2A4)	CO_2	Tier 2	No change
Ammonia Production (2B1)	CO_2	Tier 3	Petroleum coke-based: alternate data source for 2024; Natural gas-based: Used production ratio from prior GHGRP data
Urea Consumption for Non-Agricultural Purposes (2B10)	CO_2	Tier 1, Tier 2	Incorporates new data source across time series (1990-2023) to adjust for agricultural uses of urea consistent with Chapter 5 - Agriculture
Nitric Acid Production (2B2)	N_2O	Tier 2, Tier 3	No change

(continued)

Table 4-2: Summary of Methods in the IPPU Chapter *(continued)*

Category (CRT Code)[a]	Gases	IPCC Methodological Tier	Methodological Refinements Compared to 1990-2023 Inventory (EPA, 2025)
Adipic Acid Production (2B3)	N_2O	Tier 3	No change
Caprolactam Production (2B4)	N_2O	Tier 1	No change
Carbide Production and Consumption (2B5, 2B10)	CO_2, CH_4	Tier 1	Updated production and consumption data for 2022 and 2023
Titanium Dioxide Production (2B6)	CO_2	Tier 1	No change
Soda Ash Production (2B7)	CO_2	Tier 1	No change
Petrochemical Production (2B8)	CO_2	Tier 1, Tier 3	Updated data source for petrochemical production and use of new implied emission factor; proxy for 2024 carbon black
HCFC-22 Production (2B9a)	HFC-23	Tier 3	No change
Production of Fluorochemicals Other than HCFC-22 (2B9b)	HFCs, PFCs, SF_6, NF_3	Tier 3	No change
Non-EOR Carbon Dioxide Utilization (2H2, 2H3)	CO_2	Tier 3	No change
Phosphoric Acid Production (2B10)	CO_2	Tier 2	No change
Iron and Steel Production and Metallurgical Coke Production (2C1)	CO_2, CH_4	Tier 1, Tier 3	No change
Ferroalloy Production (2C2)	CO_2, CH_4	Tier 1	No change

(continued)

Table 4-2: Summary of Methods in the IPPU Chapter *(continued)*

Category (CRT Code)[a]	Gases	IPCC Methodological Tier	Methodological Refinements Compared to 1990-2023 Inventory (EPA, 2025)
Aluminum Production (2C3)	CO_2	Tier 2	No change
Aluminum Production (2C3)	CF_4, C_2F_6	Tier 3	No change
Magnesium Production (2C4)	SF_6, HFCs, CO_2	Tier 2	No change
Lead Production (2C5)	CO_2	Tier 1	No change
Zinc Production (2C6)	CO_2	Tier 1	No change
Electronics Industry (2E)	PFCs, HFCs, SF_6, NF_3, N_2O	Tier 3	No change
Substitution of Ozone Depleting Substances (2F)	HFCs, PFCs, CO_2	Tier 2, Tier 3	No change
Electrical Equipment (2G1)	SF_6, CF_4	Tier 3	No change
SF_6 and PFCs from Other Product Use (2G2)	SF_6, PFCs	Tier 1, Tier 2	No change
Nitrous Oxide from Product Uses (2G3)	N_2O	Tier 1, Tier 2	No change

[a] Codes in parentheses represent common reporting table (CRT) codes. The CRT code is a classification system to organize quantitative reporting of detailed emission and removal data in standardized data tables (i.e., CRTs) to facilitate comparison of national inventory data and trends. The code reflects classification levels (e.g., sector, subsector, category, subcategory, etc.). Translating 2A1: 2 = IPPU sector, A = subsector for minerals, and the second number 1 = category for cement production.

Quality Assurance/Quality Control

To ensure the quality of the IPPU sector, GHG emission estimates, general and category-specific quality assurance/quality control (QA/QC) procedures were implemented. These procedures involved checks focused on the activity data and methodology used for estimating each source of emissions from the IPPU sector. Emissions trends were investigated to determine whether any corrective actions were needed. Minor corrective actions were taken as necessary.

Uncertainty

The same uncertainty bounds reported in the 1990–2023 *Inventory* (EPA, 2025) were applied for each category and subcategory (as applicable); see Table 4-65. A qualitative description of the uncertainties and the total category uncertainty estimate is provided within each category. Future versions of this *GHGIA* will review and update the quantified uncertainty associated with activity data, emission factors, and other input parameters.

Future Areas of Improvement

Continuous improvement efforts are important for reflecting the latest science, reducing uncertainties in estimating emissions to the extent practicable from industrial processes, especially for significant categories such as CO_2 emissions from iron and steel production and metallurgical coke production, and HFC and PFC emissions from substitutes for ozone depleting substances.

For categories where the methodology has not changed in this *GHGIA* and remains consistent with previous analyses, any improvements identified in EPA (2025) will be reviewed. Any changes that have been incorporated into this *GHGIA* are discussed in the Methods and Recalculations sections of those respective categories.

For several categories, more significant methodological changes and/or refinements are anticipated, primarily due to challenges with data availability, particularly those categories that relied on data from EPA's Greenhouse Gas Reporting Program (GHGRP). In addition, a more thorough review of the discontinuity between GHGRP and alternative data sources will be conducted. Future versions of this report will specify more on scope, timing, and plans for phasing in improvements.

Box 4-1: Treatment of Non-Energy Uses of Fossil Fuels and Allocation Between Energy and IPPU Sectors

As noted in the Energy chapter of this *GHGIA*, fossil fuels that are consumed for non-energy purposes, such as lubricants, paraffin waxes, bitumen asphalt, and solvents, are addressed within the Energy chapter. Under the *2006 IPCC Guidelines*, these non-energy uses are to be reported in the IPPU sector rather than the Energy sector. However, because of national circumstances related to the organization of energy statistics and carbon balance data, the United States includes these non-energy uses in the Energy chapter of this *GHGIA*.

Although these emissions are presented in the Energy chapter, the estimation methods applied are consistent with the *2006 IPCC Guidelines,* scientifically grounded, and thoroughly documented. Reporting these emissions within the Energy chapter enhances transparency, supports a more comprehensive carbon balance, and helps prevent double counting.

For example, the IPPU sector requires reporting only emissions from the initial use of lubricants and waxes. In contrast, emissions associated with the use of lubricants in two-stroke engines, as well as emissions from secondary uses of lubricants and waxes in waste incineration with energy recovery, are reported in the Energy sector. Limiting IPPU reporting to first-use emissions would necessitate artificial modifications to the non-energy carbon balance and could create the risk of double counting. Similar adjustments would be required for asphalt and road oil, as well as for solvents (which are included within petrochemical feedstock emissions), and could likewise introduce the potential for double counting.

Finally, as described in the Energy chapter, portions of fuel consumption data for seven fuel categories are reassigned to the IPPU chapter when those fuels are used in industrial process activities. These fuel categories include coking coal, distillate fuel, industrial other coal, petroleum coke, natural gas, residual fuel oil, and other oil. Emissions resulting from the use of fossil fuels as feedstocks or reducing agents (for example, in petrochemical manufacturing, aluminum production, titanium dioxide production, and zinc production) are reported in the IPPU chapter, except where specific national circumstances warrant a different treatment. This reporting approach aligns with the *2006 IPCC Guidelines* and is supported by well-documented, scientifically sound methodologies. Assigning these emissions to the IPPU chapter improves transparency and avoids double counting between the energy and IPPU sectors. Additional details are also provided within each relevant IPPU emission source category.

4.1 Mineral Industry

4.1.1 Cement Production (Source Category 2A1)

This source category includes the CO_2 emissions resulting from the calcination of carbonate materials during clinker production. Clinker is the intermediate product that is subsequently ground to produce finished Portland cement. Clinker is formed by heating a carefully proportioned mixture of raw materials—predominantly limestone (calcium carbonate) with materials containing silica, alumina, and iron oxides—in a high-temperature rotary kiln system. During the clinker production process, dust may be generated that is also partially calcined and referred to as cement kiln dust (CKD) The majority of direct CO_2 emissions from cement manufacturing are attributable to the thermal decomposition of limestone during the calcination process and directly proportional to the lime content in the clinker. A much smaller share of emissions come from the incomplete calcination of the associated CKD produced (EPA, 2025; IPCC, 2006).

Following clinker production, the material is cooled and ground with gypsum and, in some cases, other mineral additives to produce finished cement. These downstream finishing steps do not generate significant additional process-related CO_2 emissions (IPCC, 2006).

Energy-related CO_2 emissions result from the combustion of fossil fuels and alternative fuels in the kiln and associated preheater or precalciner systems to achieve temperatures typically on the order of 1,400–1,500°C. In accordance with IPCC methodological guidance, CO_2 emissions from fuels combusted for energy purposes at cement plants are reported in the Energy chapter under Industrial End-Use Sector fossil fuel combustion. Any adjustments related to non-energy uses of fossil fuels are addressed in Annex 5.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Construction trends over this period reflected differences between residential and nonresidential sectors, influencing cement demand and plant capacity utilization. In 2024, CO_2 emissions were estimated to be 37.2 MMT CO_2 Eq., an 11 percent increase since 1990 and an 8 percent decrease since 2023 (see Table 4-3).

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

Gas	1990	2005	2020	2021	2022	2023	2024
CO_2	33.5	46.2	40.7	41.3	41.9	40.6	37.2

Because cement is a primary input to concrete used in residential, commercial, and infrastructure applications, levels of public and private construction investment are primary drivers of domestic cement production. Cement production (and underlying clinker production) in the United States is closely associated with construction activity and macroeconomic conditions. Cement is produced at facilities located in 34 States and Puerto Rico, with Texas, Missouri, California, and Florida consistently accounting for approximately 43 to 44 percent of total domestic production in recent years (U.S. Geological Survey [USGS], 2025a). Domestic cement and clinker production declined

modestly from 2022 through 2024 (see Table 4-4), while imports of cement and clinker continued to represent a significant share of total U.S. consumption (USGS, 2025b).

Table 4-4: Clinker Production (kt)

Activity	1990	2005	2020	2021	2022	2023	2024
Clinker Production	64,355	88,783	78,200	79,400	80,500	78,100	71,527

Methods

The methodological approach for estimating cement production emissions is consistent with the approach described in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). Because 2024 GHGRP data were not available at the time of analysis, clinker production for 2024 was estimated using data published by the U.S. Geological Survey (USGS, 2025b).

Recalculations

No recalculations were implemented for 1990–2023 for this source category.

Uncertainty

Uncertainty in CO_2 emission estimates for cement production is primarily associated with activity data estimates of clinker production and the emission factors applied to estimate process-related emissions from carbonate decomposition, specifically uncertainties in the lime content of clinker and in the percentage of CKD recycled inside the cement kiln. Although emissions from calcination are directly proportional to the quantity of clinker produced and the carbon content of the carbonate materials, variability in raw material composition, kiln operating conditions, and clinker formulations across facilities may contribute to uncertainty in the national estimate. Because the methodology relies on established chemical relationships and nationally aggregated production data, the resulting emission estimates are considered robust within the constraints of available data.

For this *GHGIA*, the overall uncertainty associated national estimates of CO_2 from cement production is assumed to be similar to EPA (2025) given the use of the same basic methodology and data sources for most years, calculated using the *2006 IPCC Guidelines* Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). This confidence level indicates a range of approximately 4 percent below and 5 percent above the emission estimate in 2024. Uncertainty assessments for 1990 and 2024 are summarized at the end of this chapter in Table 4-65. Differences in reporting methodologies, coverage, and data aggregation between GHGRP and USGS sources may introduce additional uncertainty for the 2024 estimate and may affect consistency with prior years.

4.1.2 Lime Production (Source Category 2A2)

CO_2 emissions from lime production arise primarily from the calcination of carbonate materials by heating limestone (calcium carbonate) and, in some cases, dolomite (a calcium-magnesium carbonate) in high-temperature kilns. Trends in CO_2 emissions from lime production are directly proportional to trends in lime production. The principal lime products include quicklime and hydrated lime, which are used in a variety of industrial applications, including steel manufacturing, chemical production, environmental control systems, construction, and water treatment (EPA, 2025; IPCC, 2006).

Additional CO_2 emissions result from the combustion of fossil fuels and alternative fuels used to achieve kiln temperatures typically exceeding 900°C. Consistent with IPCC methodological guidance CO_2 emissions from fuels combusted for energy purposes at lime plants are reported in the Energy chapter under Industrial End-Use Sector fossil fuel combustion. Any adjustments related to non-energy uses of fossil fuels are addressed in Annex 5.1, *Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion* (IPCC, 2006).

Because lime is widely used in metallurgical processes and emissions control applications, production trends are influenced by conditions in heavy industry and manufacturing. In 2024, CO_2 emissions were estimated to be 10.8 MMT CO_2 Eq., an 8 percent decrease since 1990 and a 6 percent decrease since 2023 (see Table 4-5).

Table 4-5: Emissions from Lime Production (MMT CO_2 Eq.)

Gas	1990	2005	2020	2021	2022	2023	2024
CO_2	11.7	14.6	11.3	11.9	12.2	11.5	10.8

Overall production levels reflect changes in domestic industrial demand and operating conditions at lime manufacturing facilities. Lime production in the United States is closely associated with activity in the steel, construction, chemical, and environmental control sectors. Domestic production levels have fluctuated in recent years in response to changes in steel output, infrastructure spending, and broader industrial activity (see Table 4.6 and Table 4.7).

Table 4-6: Adjusted Lime Production (kt)

Activity	1990	2005	2020	2021	2022	2023	2024
High-Calcium	12,466	15,721	12,394	12,974	13,259	12,428	11,631
Dolomitic	2,800	3,522	2,766	3,071	3,011	2,927	2,739

Note: Minus water content of hydrated lime.

Table 4-7: High-Calcium- and Dolomitic-Quicklime, High-Calcium- and Dolomitic-Hydrated, and Dead-Burned-Dolomite Lime Production (kt)

Activity	1990	2005	2020	2021	2022	2023	2024
High-Calcium Quicklime	11,166	14,100	10,700	11,200	11,500	10,800	10,107
Dolomitic Quicklime	2,234	2,990	2,390	2,700	2,640	2,560	2,396
High-Calcium Hydrated	1,781	2,220	2,320	2,430	2,410	2,230	2,087
Dolomitic-Hydrated	319	474	252	244	244	238	223
Dead-Burned Dolomite	342	200	200	200	200	200	187

Methods

The methodological approach for estimating lime production emissions is consistent with the approach described in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). Lime production emissions are estimated based on total lime production and the application of emission factors reflecting the carbonate content of the raw materials.

Because the 2026 *Minerals Yearbook* (containing 2024 production data) was not available at the time of analysis, total lime production for 2024 was obtained from the *Mineral Commodity Summary: Lime* (USGS, 2026). Subtotals for quicklime and hydrated lime were estimated using the 2023 percentage distribution of total production for each product type. In addition, total CO_2 recovered (kilotons) was assumed to be equal to 2023 levels because 2024 GHGRP data were not available at the time of analysis.

Recalculations

No recalculations were implemented for 1990–2023 for this source category.

Uncertainty

Uncertainty in CO_2 emission estimates for lime production is primarily associated with activity data estimates of total lime production and the emission factors applied to estimate process-related emissions from carbonate decomposition.

Additional uncertainty arises from assumptions related to the carbonate content of limestone and dolomite used in lime manufacture, and the emission factors applied to estimate calcination-related CO_2 emissions. Variability in raw material composition, kiln operating conditions, and product mix across facilities may contribute to uncertainty in the national estimate. Because the methodology relies on established chemical relationships and nationally aggregated production

data, the resulting emission estimates are considered robust within the constraints of available data.

For this *GHGIA*, the overall uncertainty associated with national estimates of CO_2 from lime production is assumed to be similar to EPA (2025) given the use of the same basic methodology and data sources for most years, calculated using the *2006 IPCC Guidelines* Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). This confidence level indicates a range of approximately 2 percent below and 2 percent above the emission estimate in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 4-65. Since product-level production shares were derived from prior-year distributions, these data substitutions may introduce additional uncertainty for the 2024 estimates.

4.1.3 Glass Production (Source Category 2A3)

This source category includes emissions associated with glass production. CO_2 emissions from glass production occur from the decomposition of carbonate-based raw materials, usually a mixture of silica sand, soda ash (sodium carbonate), limestone (calcium carbonate), dolomite (calcium-magnesium carbonate), and other minor carbonate-containing constituents, when heated in furnaces to form molten glass (EPA, 2025; IPCC, 2006). The molten glass is then shaped and cooled into finished products, including container glass, flat glass, fiberglass, and specialty glass used in a range of industrial and consumer applications.

Additional CO_2 emissions are generated from the combustion of fossil fuels and alternative fuels used to achieve and maintain furnace temperatures. Consistent with IPCC methodological guidance emissions from fuels combusted for energy purposes at glass manufacturing facilities are reported in the Energy chapter under Industrial End-Use Sector fossil fuel combustion (IPCC, 2006).

In 2024, CO_2 emissions were estimated to be 1.8 MMT CO_2 Eq., a 22 percent decrease since 1990 and no change since 2023 (see Table 4-8).

Table 4-8: Emissions from Glass Production (MMT CO_2 Eq.)

Gas	1990	2005	2020	2021	2022	2023	2024
CO_2	2.3	2.4	1.9	2.0	2.0	1.8	1.8

Glass production in the United States is associated with activity in the construction, automotive, packaging, and consumer goods sectors. Production levels reflect demand for container glass, flat glass, and specialty glass used in industrial applications, and have varied in recent years with changes in durable goods manufacturing and overall industrial output. Trends in carbonate consumption and glass production indices are provided in Table 4-9.

Table 4-9: 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	2020	2021	2022	2023	2024
Limestone	1,409	1,690	1,334	1,397	1,370	1,252	1,252
Dolomite	714	857	824	893	925	824	824
Soda Ash	3,177	3,050	2,130	2,280	2,250	2,050	2,030
Other carbonates	2	3	2	2	2	2	2
Total	5,302	5,599	4,289	4,572	4,547	4,127	4,107
Production Index[a]	94.3	113.1	92.4	88.2	101.4	98.5	95.2

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

Note: Totals may not sum due to independent rounding.

Methods

The methodological approach for estimating glass production emissions is consistent with the approach described in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). Process-related CO_2 emissions are estimated based on carbonate consumption in glass manufacturing, with soda ash consumption serving as the primary activity indicator.

For 2024, complete GHGRP data were not available at the time of analysis. Therefore, activity data for glass production were assumed to be equal to 2023 levels, with the exception of total soda ash consumption for glass manufacturing, which was obtained from the U.S. Geological Survey (USGS, 2025).

In addition, the entire time series of the Annual Average Glass Production Index was updated using data from the Federal Reserve Economic Data (FRED) system (Board of Governors of the Federal Reserve System [US], 2026). Annual averages were calculated from monthly, not seasonally adjusted data for Industrial Production: Manufacturing: Durable Goods: Glass and Glass Product (NAICS 3272), based on the most recent publication available at the time of analysis. This updated index was applied consistently across the time series.

Recalculations

Minor recalculations were implemented for 1990–2023 to incorporate updated activity data. The update to the annual average glass production index resulted in minor adjustments to back-casted emissions for 1990–2009; however, these changes did not significantly impact the overall time series (<0.01 percent for 1990–2009).

Uncertainty

Uncertainty in CO_2 emission estimates for glass production is primarily associated with activity data estimates of carbonate consumption and the emission factors applied to estimate process-related emissions from carbonate decomposition. Soda ash consumption serves as the principal

activity driver, and variability in reported consumption data may contribute to uncertainty in annual estimates. Additional uncertainty arises from assumptions related to raw material composition, product mix, and the relationship between glass production and activity indicators used to estimate carbonate consumption. Because the methodology relies on established relationships between carbonate inputs and CO_2 emissions and nationally aggregated activity data, the resulting emission estimates are considered robust within the constraints of available data.

For this *GHGIA*, the overall uncertainty associated with national estimates of CO_2 from glass production is assumed to be similar to EPA (2025) given the use of the same basic methodology and data sources for most years, calculated using the *2006 IPCC Guidelines* Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). This confidence level indicates a range of approximately 3 percent below and 3 percent above the emission estimate in 2024. Uncertainty assessments for 1990 and 2024 are summarized at the end of this chapter in Table 4-65. For 2024, reliance on proxy activity data due to the unavailability of GHGRP data may introduce additional uncertainty for the most recent *GHGIA* year.

4.1.4 Other Process Uses of Carbonates (Source Category 2A4)

Emissions from this source category are driven primarily by industrial activity levels and the consumption of carbonate-containing materials used as raw materials or process inputs. Demand for these materials is driven by activity across several sectors, including chemical manufacturing, ceramics production, environmental control technologies, and other specialty industrial applications.

Other process uses of carbonates generate CO_2 emissions when carbonate minerals such as limestone, dolomite, soda ash, and magnesite are heated or chemically transformed in industrial processes that result in the decomposition of carbonate compounds (EPA, 2025). This source category includes emissions from several industrial uses of carbonates that are not captured under other industrial process categories in this *GHGIA*. These uses include the consumption of limestone and dolomite in industrial processes, carbonate use in ceramics manufacturing, soda ash consumption in applications other than glass manufacturing, and the use of carbonate materials in non-metallurgical magnesia production. CO_2 emissions associated with fossil fuel combustion used to generate process heat or electricity at these facilities are reported separately in the Energy chapter under industrial fuel combustion to avoid double counting (IPCC, 2006).

Other Uses of Carbonates (Limestone and Dolomite Consumption)

Limestone and dolomite uses in industrial applications outside of cement, lime, and glass manufacturing include flux stone in metallurgical processes, flue gas desulfurization systems for air pollution control, chemical processing applications, and others. When carbonate minerals are consumed in these processes, CO_2 is released because of carbonate decomposition during

chemical reactions or thermal treatment (IPCC, 2006). Consumption of limestone and dolomite for these applications is summarized in Table 4-10.

Table 4-10: Limestone and Dolomite Consumption from Other Uses of Carbonates (kt)

Activity	1990	2005	2020	2021	2022	2023	2024
Limestone	10,016	10,465	13,707	12,788	17,891	11,898	11,898
Dolomite	919	3,254	2,962	2,826	1,914	547	547
Total	**10,935**	**13,719**	**16,669**	**15,614**	**19,805**	**12,445**	**12,445**

Note: Totals may not sum due to independent rounding.

Ceramics Production

Carbonate minerals such as limestone and dolomite are used as raw materials in the manufacture of ceramic products including tiles, sanitary ware, and other ceramic materials. During firing of ceramic products in high-temperature kilns, carbonate minerals contained in the raw material mix decompose and release CO_2. Consumption of limestone and dolomite used in ceramics manufacturing is presented in Table 4-11.

Table 4-11: Limestone and Dolomite Consumption from Ceramics Production (kt)

Activity	1990	2005	2020	2021	2022	2023	2024
Limestone	1,444	1,569	758	764	776	766	766
Dolomite	255	277	134	135	137	135	135
Total	**1,699**	**1,846**	**892**	**899**	**913**	**901**	**901**

Note: Totals may not sum due to independent rounding.

Other Uses of Soda Ash

Soda ash (sodium carbonate) is used in a wide range of industrial applications beyond glass manufacturing. These applications include chemical manufacturing, detergents, water treatment, pulp and paper production, and other industrial processes. In certain applications, soda ash may undergo chemical reactions that release CO_2 as a byproduct (IPCC, 2006). Consumption of soda ash for applications other than glass manufacturing is summarized in Table 4-12.

Table 4-12: Other Uses of Soda Ash Consumption Not Associated with Glass Manufacturing (kt)

Activity	1990	2005	2020	2021	2022	2023	2024
Soda Ash[a]	3,351	3,144	2,310	2,364	2,391	2,189	2,321

[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 (EPA, 2025).

Non-Metallurgical Magnesia Production

Non-metallurgical magnesia is produced from carbonate minerals such as magnesite or magnesium-rich limestone through thermal processing, when magnesium carbonate decomposes at elevated temperatures to form magnesium oxide and CO_2. Non-metallurgical magnesia is used to produce refractory materials and other industrial products (IPCC, 2006). Consumption of magnesite and limestone used in non-metallurgical magnesia production is presented in Table 4-13.

Table 4-13: Magnesite and Limestone Consumption from Non-Metallurgical Magnesia Production (kt)

Activity	1990	2005	2020	2021	2022	2023	2024
Magnesite	214	363	410	439	388	513	513
Limestone	2	4	4	4	4	5	5
Total	**216**	**367**	**414**	**443**	**392**	**518**	**518**

Note: Totals may not sum due to independent rounding.

Other Process Uses of Carbonates

Limestone and dolomite consumption represents the largest share of activity within this source category, while ceramics production, soda ash consumption in non-glass applications, and non-metallurgical magnesia production contribute smaller but measurable quantities of carbonate use. Variations in industrial activity, technology use, and demand for these materials influence both carbonate consumption and associated emissions over time. CO_2 emissions from other process uses of carbonates are summarized in Table 4-14. In 2024, CO_2 emissions from other process uses of carbonates were 7.1 MMT CO_2 Eq., with no change since 1990 and no change since 2023.

Table 4-14: Emissions from Other Process Uses of Carbonates (MMT CO_2 Eq.)

Source	1990	2005	2020	2021	2022	2023	2024
CO_2	**7.1**	**8.5**	**9.0**	**8.6**	**10.4**	**7.1**	**7.1**
Other Uses of Carbonates	4.8	6.2	7.4	7.0	8.8	5.5	5.5
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	1.0	1.0	1.0	0.9	1.0
Non-Metallurgical Magnesia Production	0.1	0.2	0.2	0.2	0.2	0.3	0.3

[a] Soda ash consumption not associated with glass manufacturing.

Note: Totals may not sum due to independent rounding.

Methods

The methodological approach for estimating emissions from other process uses of carbonates is consistent with the approach described in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025).

For 2024, complete activity data were not available at the time of estimation. Accordingly, 2024 activity levels were held constant at 2023 values for all inputs except soda ash consumption. Soda ash consumption was updated using data from the U.S. Geological Survey (USGS, 2025); the 2024 emissions estimate reflects this updated soda ash input while other activity data remained consistent with 2023 levels.

Recalculations

Minor recalculations were implemented for 1990–2023 to incorporate updated activity data. Specifically, soda ash consumption values were updated. This update resulted in a revision to the 2023 emissions estimate for other process uses of carbonates, decreasing emissions from 1.0 to 0.9 MMT CO_2 Eq. (10 percent).

Although the update affected the most recent year of the time series, it did not significantly alter overall emissions trends.

Uncertainty

Uncertainty in the emission estimates for other process uses of carbonates arises from variability in both activity data and emission factors. Activity data uncertainty reflects the reliability and completeness of reported carbonate consumption data across industrial applications. Emission factor uncertainty reflects variability in carbonate composition and the fraction of carbon released during use.

For this *GHGIA*, the overall uncertainty associated with national estimates of CO_2 from other process uses of carbonates is assumed to be similar to EPA (2025) given the use of the same basic methodology and data sources for most years. The 95 percent confidence interval for CO_2 emissions from other process uses of carbonates in 2023 ranges from 11 percent below to 15 percent above the reported emission estimate. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 4-65. Overall uncertainty is driven primarily by uncertainty in carbonate consumption quantities rather than emission factors, consistent with other carbonate-based process emission categories in this chapter.

4.2 Chemical Industry

4.2.1 Ammonia Production (Source Category 2B1)

This source category covers emissions from ammonia production. Emissions of CO_2 occur during the production of synthetic ammonia (NH_3), primarily through the use of natural gas or petroleum coke as feedstock to produce CO_2 and hydrogen (H_2), the latter of which is used in the production of ammonia. Not all the CO_2 produced during the production of ammonia is emitted directly to the atmosphere and only the CO_2 emitted directly to the atmosphere is accounted for in the emissions from ammonia production (EPA, 2025).[32]

In accordance with IPCC methodological guidance, emissions from fuels combusted 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. 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 (IPCC, 2006).

In 2024, total net emissions of CO_2 from ammonia production were 14.4 MMT CO_2 Eq., which is no change since 1990 and an 18 percent increase since 2023 (see Table 4-15).

Table 4-15: Emissions from Ammonia Production (MMT CO_2 Eq.)

Gas	1990	2005	2020	2021	2022	2023	2024
CO_2	14.4	10.2	12.3	11.5	11.9	12.2	14.4

Total ammonia production was 17,200 kilotons (see Table 4-16). Agriculture continues to drive demand for nitrogen fertilizers, accounting for approximately 88 percent of domestic ammonia consumption (USGS, 2026).

Table 4-16: Total Ammonia Production (kt)

Activity	1990	2005	2020	2021	2022	2023	2024
Ammonia Production	15,426	10,144	17,020	15,420	16,800	17,000	17,200

[32] Some CO_2 is captured during the ammonia production process and used to produce urea; some CO_2 from ammonia production is geologically sequestered.

Methods

The methodological approach for estimating ammonia production emissions is consistent with the approach described in the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025).

In the United States, ammonia is produced through two feedstocks, natural gas and petroleum coke. The methods for both previously relied on data from the EPA GHGRP. Because 2024 GHGRP data were not available at the time of analysis, emissions from petroleum coke-based ammonia production were based on data from CVR Energy, Inc. (CVR, 2025). The amount of petroleum coke feedstock used was converted to CO_2 based on the heat content and carbon content of petroleum coke.

No alternate data source was identified for the amount of natural gas used in ammonia production; therefore, natural gas-based ammonia production was estimated based on total ammonia produced (American Chemistry Council [ACC], 2025) subtracted by the amount of ammonia produced with petroleum coke. This value was then multiplied by the average ratio of quantity of natural gas feedstock per quantity of ammonia based on prior GHGRP data. The estimated amount of natural gas feedstock was then converted to CO_2 emissions based on the heat content and carbon content of natural gas.

The amount of CO_2 used in urea in 2024 was proxied to the 2023 value as 2024 GHGRP data were not available at the time of analysis. The amount of CO_2 captured and sequestered from ammonia production was also proxied to the 2023 value as the 2024 GHGRP data were not available at the time of analysis.

Recalculations

Recalculations were implemented to incorporate revised historical data for annual ammonia production as provided by ACC (2025). This impacted emission calculations for 1990–2008. The average annual change in emissions over that period was a decrease of 0.3 percent compared to previous estimates.

Uncertainty

The uncertainty associated with ammonia production emissions are primarily related to the accuracy of the emission factor used to represent average natural gas feedstock use across all ammonia plants. There is also uncertainty in the back-casting of natural gas feedstock used for 1990 based on recent GHGRP data, as well as associated with the assumptions around ammonia and subsequent urea production processes and that plants are co-located. Uncertainty is also associated with the petroleum coke-based ammonia process and the representativeness of the emission factor used. The uncertainty of the total urea production activity data is a function of the reliability of reported production data from the USGS source.

For this *GHGIA*, the overall uncertainty associated with national estimates of CO_2 from ammonia production is assumed to be similar to EPA (2025) given the use of the same basic methodology and data sources for most years, calculated using the *2006 IPCC Guidelines* Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). This confidence

level indicates a range of approximately 4 percent below and 4 percent above the emission estimate in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 4-65. Since different production estimates and derived emission factors were used for 2024, these data substitutions will likely introduce additional uncertainty for the 2024 estimates not reflected in the uncertainty ranges mentioned above.

4.2.2 Urea Consumption for Non-agricultural Purposes (Source Category 2B10)

This source category covers emissions from sources that do not fall within any other category, which includes emissions from urea consumption for non-agricultural purposes. Urea is manufactured from NH_3 and CO_2 as primary feedstocks. In the industrial sector, urea is used in adhesives, sealants, resins, catalysts, chemical intermediates, solvents, fragrances, deodorizers, flavoring agents, monomers, paint and coating additives, and surface treatment agents. It is also used to reduce nitrogen oxide emissions from coal-fired power plants and diesel engines (EPA, 2025; IPCC, 2006).

All urea produced in the United States is assumed to be produced at ammonia production facilities where both NH_3 and CO_2 are generated. Of total ammonia produced in the United States in 2024, urea was the largest derivative product (USGS, 2025a).

In 2024, CO_2 emissions from urea consumption for non-agricultural purposes were estimated to be 5.9 MMT CO_2 Eq, a 51 percent increase since 1990 and a decrease of 6 percent since 2023 (see Table 4-17).

Table 4-17: Emissions from Urea Consumption for Non-Agricultural Purposes (MMT CO_2 Eq.)

Gas	1990	2005	2020	2021	2022	2023	2024
CO_2	3.9	3.6	6.2	7.3	5.8	6.3	5.9

The amount of urea consumed for non-agricultural purposes was determined by summing urea production and urea imports and subtracting urea applied as fertilizer and urea exports (Table 4-18).

Table 4-18: Urea Production, Urea Applied as Fertilizer, Urea Imports, and Urea Exports (kt)

Activity	1990	2005	2020	2021	2022	2023	2024
Urea Production	7,450	5,270	11,500	10,521	11,272	11,306	11,306
Urea Applied as Fertilizer	3,113	4,861	6,471	6,148	6,609	6,400	6,894
Urea Imports	1,860	5,026	4,190	5,880	4,570	4,460	4,460

(continued)

Table 4-18: Urea Production, Urea Applied as Fertilizer, Urea Imports, and Urea Exports (kt) (*continued*)

Activity	1990	2005	2020	2021	2022	2023	2024
Urea Exports	854	536	777	270	1,320	820	820
Urea Consumed for Non-Agricultural Purposes	5,343	4,899	8,442	9,983	7,912	8,546	8,052

Methods

The methodological approach for estimating emissions from urea consumption for non-agricultural purposes is consistent with the approach described in the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). Because 2024 GHGRP data were not available at the time of analysis, data on urea production for 2024 was held constant with 2023 levels from GHGRP. Urea import and export data for 2023 were updated based on the latest available USGS nitrogen report (USGS, 2025b); the latest available year of values was 2023, so they were also held constant for 2024. Estimates of urea application for agricultural uses from 1990 through 2024 were updated based on data from the International Fertilizer Association (IFA, 2026) consistent with the agriculture sector.

Recalculations

Minor recalculations were implemented for 1990–2023 to incorporate updated USGS and IFA activity data. Compared to the previous *Inventory* analysis (EPA, 2025), CO_2 emissions from urea consumption for non-agricultural purposes changed between –6 percent (-0.3 MMT CO_2 Eq. in 2010) and 16 percent (0.8 MMT CO_2 Eq. in 2023), with an average recalculation over the time series of 1.3 percent (0.07 MMT CO_2 Eq.).

Uncertainty

Uncertainty in emission estimates for urea consumption from non-agricultural purposes is associated with many factors. As there is limited publicly available data on the quantities of urea produced and consumed for non-agricultural purposes, data on urea production, urea imports, urea exports, and the amount of urea used as fertilizer (consistent with urea fertilization data in the Agriculture chapter) are used to estimate the amount of urea used for non-agricultural purposes. The uncertainty ranges for these activity data are based on IPCC default ranges (IPCC, 2006). Given that activity data are derived from both USGS and EPA's GHGRP, there is additional uncertainty for portions of the time series reliant on GHGRP data. Finally, there is also uncertainty associated with the assumption that all the carbon in urea is released into the environment as CO_2 during use.

For this *GHGIA*, the overall uncertainty associated with national estimates of CO_2 from urea consumption for non-agricultural purposes is assumed to be similar to EPA (2025) given the use of the same basic methodology and data sources for most years, calculated using the *2006 IPCC Guidelines* Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC,

2006). This confidence level indicates a range of approximately 5 percent below and 4 percent above the emission estimate in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 4-65. Differences in reporting methodologies, coverage, and data aggregation between GHGRP and USGS sources may introduce additional uncertainty for the 2024 estimate and may affect consistency with prior years, in addition to the incorporation of new agricultural urea data into the time series.

4.2.3 Nitric Acid Production (Source Category 2B2)

This source category includes N_2O emissions generated during nitric acid production. Nitric acid is produced through the oxidation of ammonia over a platinum-based catalyst to form nitric oxide, which is subsequently oxidized and absorbed in water to produce nitric acid. N_2O is formed as a byproduct during the ammonia oxidation step and is emitted in the tail gas stream from nitric acid plants. The quantity of N_2O released depends on plant design, operating conditions, and the presence and performance of emission control technologies (EPA, 2025; IPCC, 2006).

CO_2 emissions associated with fossil fuel combustion used to generate process heat or electricity at nitric acid plants are reported separately in the Energy chapter to avoid double counting. Emissions associated with downstream fertilizer manufacturing processes are reported under their respective source categories elsewhere in this *GHGIA* (IPCC, 2006).

In 2024, N_2O emissions from nitric acid production were estimated to be 8.3 MMT CO_2 Eq., a 23 percent decrease since 1990 and no change since 2023 (see Table 4-19). Because nitric acid is an important intermediate input to fertilizer production, agricultural demand, fertilizer market conditions, and the implementation of N_2O abatement technologies remain key drivers of nitric acid production and associated emissions in the United States.

Table 4-19: Emissions from Nitric Acid Production (MMT CO_2 Eq.)

Gas	1990	2005	2020	2021	2022	2023	2024
N_2O	10.8	10.1	8.3	7.9	8.6	8.3	8.3

Nitric acid is produced at facilities across the country and is used primarily in the manufacture of ammonium nitrate and other nitrogen-based fertilizer products, as well as in certain industrial applications such as explosives and chemical intermediates (USGS, 2025). Domestic nitric acid production levels generally track fertilizer demand and agricultural market conditions, which influence plant utilization and output. Recent nitric acid production trends are presented in Table 4-20.

Table 4-20: Nitric Acid Production (kt)

Activity	1990	2005	2020	2021	2022	2023	2024
Nitric Acid Production	41	38	31	30	33	32	32

Methods

The methodological approach for estimating nitric acid production emissions is consistent with the approach described in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). For 2024, complete activity data were not available at the time of estimation. Accordingly, 2024 activity levels were held constant at 2023 values for all inputs.

Recalculations

No recalculations were implemented for 1990–2023 for this source category.

Uncertainty

Uncertainty in N_2O emission estimates for nitric acid production arises from uncertainty in activity data and emission factors. Activity data uncertainty is assumed to be low, reflecting the completeness and accuracy of reported nitric acid production, which is generally well characterized due to the availability of historical national-level production values and facility-level production values reported under EPA's GHGRP for more recent years.

Emission factor uncertainty reflects variability in N_2O generation rates across nitric acid plants and is influenced by process conditions such as operating pressure, catalyst performance, and plant configuration. Additional uncertainty is associated with the performance of N_2O abatement technologies, including variability in destruction efficiencies and operational conditions.

For this *GHGIA*, the overall uncertainty associated with national estimates of N_2O emission estimates for nitric acid production is assumed to be similar to EPA (2025) given the use of the same basic methodology and data sources for most years, calculated using the *2006 IPCC Guidelines* Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). This confidence level indicates a range of approximately 6 percent below and 6 percent above the emission estimate in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 4-65. Use of 2023 GHGRP data as a proxy for 2024 may introduce additional uncertainty to 2024 emission estimates, given the 2023 data may not reflect changes in operational practices, especially if new N_2O destruction technologies were added or existing abatement catalysts were replaced at individual facilities in 2024. Such changes would impact the implied average emission factor and estimated emissions.

4.2.4 Adipic Acid Production (Source Category 2B3)

This source category includes N_2O emissions generated during adipic acid production. Adipic acid is produced through a multi-step oxidation process in which cyclohexane is converted to a mixture of cyclohexanol and cyclohexanone, commonly referred to as KA oil, followed by oxidation with nitric acid to produce adipic acid. During this nitric acid oxidation step, N_2O is formed as a byproduct and released in the process off-gas stream (IPCC, 2006).

Emissions associated with fossil fuel combustion used to provide process heat or electricity at adipic acid facilities are reported separately in the Energy chapter under industrial fuel combustion. Nitric acid used as a reactant in the process is produced separately, and emissions

from nitric acid manufacturing are reported under the nitric acid production source category (EPA, 2025; IPCC, 2006).

Historically, adipic acid production was one of the largest industrial sources of N_2O emissions in the United States. However, emissions have declined substantially following the installation of N_2O abatement technologies at adipic acid plants. These emission control technologies significantly reduce N_2O emissions from the process and remain an important factor influencing emissions trends for this source category (IPCC, 2006).

In 2024, N_2O emissions from adipic acid production were estimated to be 1.2 MMT CO_2 Eq., a 91 percent decrease since 1990 and no change since 2023 (see Table 4-21). Because adipic acid is primarily used in nylon production, demand for nylon-based products and the continued operation of N_2O abatement technologies remain key drivers of emissions from this source category.

Table 4-21: Emissions from Adipic Acid Production (MMT CO_2 Eq.)

Gas	1990	2005	2020	2021	2022	2023	2024
N_2O	13.5	6.3	7.4	6.6	2.1	1.2	1.2

Adipic acid production in the United States is closely associated with demand for nylon-6,6 fibers and resins used in textiles, carpets, and engineering plastics. Smaller quantities of adipic acid are used in the manufacture of polyurethanes, plasticizers, and other specialty chemicals. Domestic adipic acid production levels therefore reflect broader manufacturing activity and demand for these downstream products. Trends in adipic acid production are presented in Table 4-22.

Table 4-22: Adipic Acid Production (kt)

Activity	1990	2005	2020	2021	2022	2023	2024
Adipic Acid Production	51	24	28	25	8	4	4

Methods

The methodological approach for estimating adipic acid production emissions is consistent with the approach described in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). For 2024, complete activity data were not available at the time of estimation. Accordingly, 2024 activity levels were held constant at 2023 values for all inputs.

Recalculations

No recalculations were implemented for 1990–2023 for this source category.

Uncertainty

Uncertainty in N_2O emission estimates for adipic acid production arises from uncertainty in emissions measurement methods and variations in site-specific emission factors.

Emission factor uncertainty reflects variability in N_2O generation rates during adipic acid production and is influenced by process conditions, plant configuration, and operating practices. Additional uncertainty is associated with the performance of N_2O abatement technologies, including variability in destruction efficiencies and operational conditions.

For this *GHGIA*, the overall uncertainty associated with national estimates of N_2O emission estimates for adipic acid production is assumed to be similar to EPA (2025) given the use of the same basic methodology and data sources for most years, calculated using the *2006 IPCC Guidelines* Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). This confidence level indicates a range of approximately 4 percent below and 4 percent above the emission estimate in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 4-65. Use of 2023 GHGRP data as a proxy for 2024 may introduce additional uncertainty within emission estimates, especially considering that one of the facilities has a history of highly variable year-to-year emissions, mostly due to the fluctuating use of N_2O destruction technologies.

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

This source category includes emissions from the production of three chemicals: caprolactam, glyoxal, and glyoxylic acid. Caprolactam is a colorless chemical building block (monomer) used to make nylon-6, which is widely used in fibers and plastics. A large share of nylon-6 is used in carpet manufacturing. Most caprolactam is produced from benzene; in the most common process, benzene is first converted to cyclohexane, which is then oxidized to form cyclohexanone, an intermediate compound that is further processed into caprolactam. N_2O is emitted during the ammonia oxidation step (EPA, 2025). Other air pollutants include CO_2, sulfur dioxide, and non-methane volatile organic compounds (NMVOCs); these are assumed to be non-significant in well-managed plants (e.g., CO_2 can be captured and recycled as part of the ammonium carbonate process). Conventional caprolactam production also generates large amounts of ammonium sulfate byproduct, so modified processes focus on reducing the volume of this byproduct (IPCC, 2006). As of 2024, there are only two facilities in the United States operated by AdvanSix and BASF.

The production of glyoxylic acid involves the nitric acid oxidation of glyoxal, a reaction that results in the formation of N_2O emissions as a byproduct (EPA, 2025; IPCC, 2006). Both chemicals are largely imported into the United States, with little domestic production. Therefore, estimates for this category do not currently include emissions from glyoxal and glyoxylic acid production.

Emissions from fuels burned to provide energy during their manufacture are reported in the Energy chapter (IPCC, 2006).

In 2024, N_2O emissions from caprolactam production were estimated to be 1.4 MMT CO_2 Eq., a 7 percent decrease since 1990 and an 8 percent increase since 2023 (see Table 4-23). Trends in caprolactam production are presented in Table 4-24.

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

Gas	1990	2005	2020	2021	2022	2023	2024
N_2O	1.5	1.9	1.1	1.2	1.3	1.3	1.4

Table 4-24: Caprolactam Production (kt)

Activity	1990	2005	2020	2021	2022	2023	2024
Production	626	795	480	510	560	560	570

Methods

The methodological approach for estimating caprolactam, glyoxal, and glyoxylic acid production emissions is consistent with the approach described in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). National caprolactam production data sourced from the *Guide to the Business of Chemistry* (ACC, 2025) were multiplied by the IPCC default emissions factors to calculate N_2O emissions. CO_2 and CH_4 emissions may also occur from caprolactam production but currently the IPCC does not have methodologies for calculating these emissions.

Recalculations

No recalculations were implemented for 1990–2023 for this source category.

Uncertainty

The production of caprolactam and nitric acid involves ammonia oxidation, the source of N_2O emissions; therefore, the Tier 1 uncertainties associated with caprolactam production are consistent with those of nitric acid production. Generally, 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 (IPCC, 2006). For caprolactam production, default values have high uncertainty due to limited data availability.

For this *GHGIA*, the overall uncertainty associated with national estimates of N_2O from caprolactam production is assumed to be the same as EPA (2025) given the use of the same basic methodology and data sources, calculated using the *2006 IPCC Guidelines* Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). This confidence level indicates a range of approximately 31 percent below and 31 percent above the emission estimate in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 4-65.

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

This source category covers emissions from sources that do not fall within any other category, which includes emissions from carbide consumption. CO_2 and CH_4 are emitted during the production of silicon carbide (SiC), a hard, heat-resistant material used in industrial abrasives, metallurgical processes, and other specialized applications in the United States (EPA, 2025; IPCC, 2006). CO_2 is also emitted during the consumption of SiC; per IPCC guidance, emissions from the consumption of SiC should be reported where they occur but this analysis reports under one carbide production and consumption category due to lack of end-use data. In accordance with IPCC guidelines, emissions from fuels burned to provide energy during SiC production are reported in the Energy chapter (IPCC, 2006).

SiC is produced by reacting silica sand or quartz with carbon (C) in the form of petroleum coke. During this process, about 35 percent of the carbon in the petroleum coke remains in the final SiC product. The remaining carbon is emitted as CO_2, CH_4, and carbon monoxide (CO).

CO_2 and CH_4 are also emitted during the production of calcium carbide, a related chemical used to generate acetylene gas. The CO_2 from calcium carbide production is implicitly accounted for in the Energy chapter through the storage factor calculation for the non-energy use of petroleum coke (IPCC, 2006).

As of 2024, the United States had two SiC facilities, one in Illinois and another in Kentucky (USGS, 2025). In 2024, CO_2 and CH_4 emissions from SiC production and consumption were 0.2 MMT CO_2 Eq., with no change since 1990 and no change since 2023, as shown in Table 4-25. Production and consumption make up an equal share of total CO_2 emissions. CH_4 emissions from SiC production were 0.01 MMT CO_2 Eq. in 2024.

Table 4-25: Emissions from Silicon Carbide Production and Consumption (MMT CO_2 Eq.)

Source/Gas	1990	2005	2020	2021	2022	2023	2024
CO_2	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
SiC Production	0.2	0.1	0.1	0.1	0.1	0.1	0.1
SiC Consumption	0.1	0.1	0.1	0.1	0.1	0.1	0.1
CH_4	**+**	**+**	**+**	**+**	**+**	**+**	**+**
SiC Production	+	+	+	+	+	+	+
Total	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**

+ Does not exceed 0.05 MMT CO2 Eq.

Note: Totals may not sum due to independent rounding.

Overall demand for manufactured abrasives, including SiC, is closely tied to activity in U.S. aerospace, automotive, future, housing and steel manufacturing industries (USGS, 2026). According to the U.S. Geological Survey (2026), domestic production is limited due to foreign competition. Trends in silicon carbide production and consumption are presented in Table 4-26.

Table 4-26: Production and Consumption of Silicon Carbide (Metric Tons)

Activity	1990	2005	2020	2021	2022	2023	2024
SiC Production	65,000	35,000	35,000	35,000	40,000	45,000	40,000
SiC Consumption	132,448	219,949	113,756	146,312	191,126	147,569	142,150

Methods

The methodological approach for estimating carbide production and consumption emissions is consistent with the approach described in the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). SiC production and consumption activity data for 2024 were available from the USGS (2026), as well as updated values for 2022 and 2023 compared to prior analysis (EPA, 2025), as shown in Table 4-26. Silicon carbide crude and refined import and export data were updated from the Census Bureau (USITC, 2026).

Recalculations

Based on the updated activity data from USGS and USITC, recalculations were implemented, which resulted in changes to the years 2022 and 2023 compared to previous analysis (EPA, 2025). Recalculations for 2022 and 2023 increased by less than 0.02 MMT CO_2 Eq. (9 percent) compared to EPA (2025) in 2023 and had a negligible impact in 2025.

Uncertainty

Uncertainty stems from the SiC production data published by the USGS being rounded to avoid disclosure of company proprietary data. There is also uncertainty associated with the use of default emission factors, as noted by IPCC (2006). Finally, there is uncertainty associated with the USITC and the relative shares of total consumption attributed to metallurgical and other non-abrasive uses (EPA, 2025).

For this *GHGIA*, the overall uncertainty associated with national estimates of CO_2 and CH_4 from carbide production and consumption is assumed to be the same as EPA (2025) given the use of the same basic methodology and data sources, calculated using the *2006 IPCC Guidelines* Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). This confidence level indicates a range of approximately 10 percent below and 10 percent above the emission estimate in 2024 for CO_2, and 10 percent below and 11 percent above for CH_4. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 4-65.

4.2.7 Titanium Dioxide Production (Source Category 2B6)

Titanium dioxide production generates CO_2 emissions during the chemical processing of raw materials used to produce titanium dioxide, which is primarily used as a white pigment in paint, lacquers, varnishes, plastics, paper, and other products. Titanium dioxide is manufactured using one of two processes: the chloride process and the sulfate process. The chloride process uses petroleum coke and chlorine as feedstocks and emits process-related CO_2. In contrast, the sulfate process does not use petroleum coke or carbon-based feedstocks, and therefore, does not emit CO_2 (EPA, 2025; IPCC, 2006). 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 the Energy chapter.

In 2024, CO_2 emissions from titanium dioxide production were estimated to be 1.3 MMT CO_2 Eq., an increase of 8 percent since 1990 and an increase of 8 percent since 2023 (see Table 4-27).

In 2024, U.S. titanium dioxide production totaled 940,000 metric tons (USGS, 2026) (see Table 4-28). Five plants produced titanium dioxide in the United States in 2024 (USGS, 2025).

Table 4-27: Emissions from Titanium Dioxide Production (MMT CO_2 Eq.)

Gas	1990	2005	2020	2021	2022	2023	2024
CO_2	1.2	1.8	1.3	1.5	1.5	1.2	1.3

Table 4-28: Titanium Dioxide Production (kt)

Activity	1990	2005	2020	2021	2022	2023	2024
Production	979	1,310	1,000	1,150	1,150	910	940

Methods

The methodological approach for estimating titanium dioxide production emissions is consistent with the approach described in the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). Updated production data for 2023 and 2024 were obtained from the USGS *Minerals Commodity Summaries: Titanium and Titanium Dioxide* (USGS, 2026).

The petroleum coke portion of the total CO_2 process emissions from titanium dioxide 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 and Annex 5.1, *Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion*.

Recalculations

Recalculations were implemented to incorporate updated activity data from USGS for 2023 (USGS, 2026). The updates resulted in a 1.1 percent (0.01 MMT CO_2 Eq.) decrease in emissions for 2023 compared to previous analysis (EPA, 2025).

Uncertainty

Uncertainty in emissions from titanium dioxide production stems from the titanium industry data for titanium mineral and pigment production operations collected by the USGS. If titanium dioxide pigment plants do not respond, prior trends and production levels are used to estimate missing data points. Variability in response rates fluctuates from 67 to 100 percent of titanium dioxide pigment plants over the time series (EPA, 2025).

For this *GHGIA*, the overall uncertainty associated with national estimates of CO_2 from titanium production is assumed to be the same as EPA (2025) given the use of the same basic methodology and data sources, calculated using the *2006 IPCC Guidelines* Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). This confidence level indicates a range of approximately 13 percent below and 13 percent above the emission estimate in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 4-65.

4.2.8 Soda Ash Production (Source Category 2B7)

Soda ash production generates CO_2 emissions during the processing of naturally occurring sodium carbonate minerals and through chemical transformations involved in soda ash manufacturing (EPA, 2025; IPCC, 2006). Soda ash, also known as sodium carbonate, is an important industrial chemical used primarily in glass manufacturing, as well as in the production of detergents, chemicals, pulp and paper products, and water treatment compounds.

The United States is one of the world's leading producers and exporters of soda ash, with most domestic production derived from trona deposits located in the Green River Basin of Wyoming (USGS, 2025a). Domestic production is driven by demand from glass manufacturing, chemical production, and other industrial applications that rely on soda ash as a key raw material. In the United States, soda ash is produced primarily from trona ore, a naturally occurring mineral composed of sodium carbonate, sodium bicarbonate, and water. Trona ore is mined and processed to produce soda ash through refining and calcination steps that convert carbonate minerals into sodium carbonate. CO_2 emissions occur when carbonate materials decompose during these processing steps (IPCC, 2006).

Emissions associated with fossil fuel combustion used to generate heat or electricity at soda ash facilities are reported separately in the Energy chapter under industrial fuel combustion to avoid double counting (IPCC, 2006). Emissions associated with the downstream consumption of soda ash in industrial processes, including glass manufacturing and other uses of carbonates, are reported under their respective source categories elsewhere in this *GHGIA*.

CO_2 emissions from soda ash production are summarized in Table 4-29. These emissions reflect the processing of trona and other carbonate materials used in soda ash manufacturing. In 2024, CO_2 emissions from soda ash production were estimated to be 1.9 MMT CO_2 Eq., an increase of 36 percent since 1990 and an increase of 12 percent since 2023.

Table 4-29: Emissions from Soda Ash Production (MMT CO_2 Eq.)

Gas	1990	2005	2020	2021	2022	2023	2024
CO_2	1.4	1.7	1.5	1.7	1.7	1.7	1.9

Trona ore production is the primary activity driver for soda ash production in the United States. Trends in trona ore use are presented in Table 4-30.

Table 4-30: Trona Ore used in Soda Ash Production (kt)

Activity	1990	2005	2020	2021	2022	2023	2024
Trona Ore Use[a]	14,700	17,000	15,000	17,600	17,500	17,700	19,400

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

Methods

The methodological approach for estimating soda ash production emissions is consistent with the approach described in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). Trona production data for 2024 were available from the USGS (USGS, 2025).

Recalculations

No recalculations were implemented for 1990–2023 for this source category.

Uncertainty

Uncertainty in CO_2 emission estimates for soda ash production is associated with both activity data and emission factors, but is relatively low due to reliable and accurate data sources. Activity data uncertainty reflects the completeness and accuracy of reported trona ore production and soda ash processing, which are generally well characterized due to the limited number of facilities and availability of industry data. Emission factor uncertainty reflects variability in the carbonate content of trona and the fraction of carbon released during processing. Differences in ore composition and processing conditions contribute to uncertainty in the estimated emissions.

For this *GHGIA*, the overall uncertainty associated with national CO_2 emissions from soda ash production is assumed to be similar to EPA (2025) given the use of the same basic methodology and data sources for most years. Uncertainty is calculated using the *2006 IPCC Guidelines* Approach 2 methodology at the 95 percent confidence level, corresponding to a range of approximately 9 percent below and 8 percent above the emission estimate (IPCC, 2006). Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 4-65.

4.2.9 Petrochemical Production (Source Category 2B8)

Petrochemicals are chemicals isolated or derived from petroleum or natural gas. The production of some petrochemicals results in CO_2 and CH_4 emissions. This source 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 natural gas, coal, petroleum, or derivatives of these fuels for non-fuel purposes in the production of carbon black and other petrochemicals. Consistent with the IPCC methodological guidance, emissions from fuels and feedstocks combusted for energy purposes (e.g., indirect/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 (EPA, 2025; IPCC, 2006).

In 2024, emissions of CO_2 and CH_4 from petrochemical production were 28.9 MMT CO_2 Eq. and 0.005 MMT CO_2 Eq., respectively (see Table 4-31). CO_2 emissions from petrochemical production are driven primarily from ethylene production, while CH_4 emissions are only from acrylonitrile production. In 2024, CO_2 emissions increased by 43 percent since 1990 and decreased by 6 percent since 2023. In 2024, CH_4 emissions decreased by 23 percent since 1990 and decreased by 15 percent since 2023.

Table 4-31: Emissions from Petrochemical Production (MMT CO_2 Eq.)

Source	1990	2005	2020	2021	2022	2023	2024
CO_2	20.3	27.0	27.9	30.7	28.8	30.5	28.9
Carbon Black	3.4	4.3	2.6	3.0	3.1	2.6	2.6
Ethylene	13.1	19.0	20.7	22.8	20.7	22.6	22.3
Ethylene Dichloride	0.3	0.5	0.5	0.4	0.4	0.5	0.6
Methanol	1.2	0.4	1.6	1.7	2.0	2.1	2.2
Ethylene Oxide	1.1	1.5	1.7	1.9	1.7	1.7	0.3
Acrylonitrile	1.2	1.3	0.9	0.9	1.0	1.1	0.9
CH_4	+	+	+	+	+	+	+
Acrylonitrile	+	+	+	+	+	+	+
Total	20.3	27.0	27.9	30.7	28.8	30.5	28.9

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

The overall increase in CO_2 emissions since 1990 is primarily due to increased ethylene and methanol production over time, driven by increased natural gas production in the United States. The decrease in CO_2 emissions from 2023 is primarily driven by a decrease in emission estimates from ethylene oxide production. Changes in CH_4 emissions from acrylonitrile over time correspond with changes in the production levels of acrylonitrile. See Table 4-32 on production over time.

Table 4-32: Petrochemical Production (kt)

Activity	1990	2005	2020	2021	2022	2023	2024
Carbon Black	1,307	1,651	990	1,140	1,170	1,010	1,010
Ethylene	16,542	23,975	33,500	34,700	35,400	39,400	38,880
Ethylene Dichloride	6,283	11,260	11,900	11,500	12,100	11,500	15,220
Methanol	3,750	1,225	6,580	7,110	8,640	7,570	7,850
Acrylonitrile	1,214	1,325	850	850	950	1,070	930
Ethylene Oxide	2,429	3,220	4,680	4,860	5,310	5,430	2,580

Methods

The methodological approach for estimating petrochemical production emissions is consistent with the approach described in the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025).

EPA GHGRP data for 2024 were not available at the time of analysis; therefore, 2024 emission estimates were based on petrochemical production data multiplied by an implied emission factor for each petrochemical. The implied emission factor was developed based on the 2023 GHGRP emissions data divided by the 2023 production data from GHGRP. Petrochemical production data for 2024 was based on ACC (2025). Production data for carbon black was not available at the time of this analysis, so the 2024 value was proxied to equal the 2023 value.

It should be noted that the use of the production data from ACC in 2024 to estimate emissions does result in a time series inconsistency with prior results. This is particularly true for the ethylene oxide data where it is unclear if the production of ethylene oxide as an intermediate product is reflected in the ACC production values. This is an area of research to be addressed in future reports.

Recalculations

Recalculations were implemented to incorporate revised historical production data for petrochemicals based on the latest time series data from ACC (2025). The revisions impacted emission calculations for methanol for years 1990 through 2014. The average annual change in emissions over that time period was an increase of 0.6 percent compared to previous estimates.

Uncertainty

The uncertainty associated with CO_2 and CH_4 emissions from petrochemical production varies by the estimation methodologies used for the different petrochemicals. Emissions from acrylonitrile production are based on default or average factors, which are based on a limited number of studies and the uncertainty around estimates is fairly high. The recent year emissions for the other petrochemicals are based on reported GHGRP data and have a lower uncertainty range.

For this *GHGIA*, the overall uncertainty associated national estimates of CO_2 and CH_4 from petrochemical production is assumed to be similar to EPA (2025) given the use of the same basic methodology for most years, calculated using the *2006 IPCC Guidelines* Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). This confidence level indicates a range of approximately 4 percent below and 4 percent above the CO_2 emission estimate and 14 percent below and 14 percent above the CH_4 emission estimate in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 4-65. Since product-level production was derived from a different source (and has discontinuities with prior data especially for ethylene oxide), and derived emission factors were used in 2024, these data substitutions are likely to introduce additional uncertainty for the 2024 estimates.

4.2.10 HCFC-22 Production (Source Category 2B9a)

Hydrochlorofluorocarbon-22 (HCFC-22) production generates hydrofluorocarbon-23 (HFC-23) emissions as a byproduct from the chemical manufacturing processes (IPCC, 2006). HCFC-22 has historically been used as a refrigerant and as a feedstock in the production of fluoropolymers such as polytetrafluoroethylene (PTFE) and other fluorinated chemicals. During the production process, HFC-23 is formed as an unintended byproduct and may be emitted if not captured or destroyed.

HCFC-22 is produced through the fluorination of chloroform with hydrogen fluoride. During this reaction, a small portion of the material is converted to HFC-23. The quantity of HFC-23 generated can be significantly reduced through thermal oxidation or other destruction technologies (EPA, 2025; IPCC, 2006).

This source category includes emissions of HFC-23 generated during HCFC-22 production. Emissions associated with the downstream use of HCFC-22 as a refrigerant are reported under the ozone depleting substitutes source category elsewhere in this *GHGIA*. Emissions associated with fossil fuel combustion used to provide process heat or electricity at HCFC-22 production facilities are reported separately in the Energy chapter under industrial fuel combustion to avoid double counting.

Emissions from this source category have changed substantially over time due to regulatory requirements and technological changes affecting HCFC-22 production and byproduct destruction. Implementation of HFC-23 destruction technologies at HCFC-22 production facilities has significantly reduced emissions relative to earlier production practices.

In 2024, HFC-23 emissions from HCFC-22 production were estimated to be 0.4 MMT CO_2 Eq., a decrease of 99 percent since 1990 and a decrease of 0 percent since 2023 (see Table 4-33).

Because HCFC-22 is used primarily as a feedstock for fluoropolymer manufacturing, demand for fluorinated materials and the operation of HFC-23 destruction technologies remain key drivers of emissions from this source category.

Table 4-33: Emissions from HCFC-22 Production (MMT CO_2 Eq.)

Gas	1990	2005	2020	2021	2022	2023	2024
HFC-23	38.6	16.8	1.8	2.2	1.8	0.4	0.4

HCFC-22 production in the United States is primarily associated with the manufacture of fluoropolymers and other fluorinated chemical products. Demand for these materials influences production levels and facility utilization. HCFC-22 production data are presented in Table 4-34.

Table 4-34: HCFC-22 Production (kt)

Activity	1990	2005	2020	2021	2022	2023	2024
Production	139	156	C	C	C	C	C

C (Confidential)

Note: HCFC-22 production in 2013 through 2023 is considered confidential business information (CBI) as there were only two producers of HCFC-22 in those years.

Methods

The methodological approach for estimating HCFC-22 production emissions is consistent with the approach described in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025).

For 2024, complete GHGRP data were not available at the time of analysis. Therefore, activity data for HCFC-22 production in 2024 were assumed to be equal to 2023 levels.

Recalculations

No recalculations were implemented for 1990–2023 for this source category.

Uncertainty

Uncertainty in HFC-23 emission estimates from HCFC-22 production arises from uncertainty in activity data and emission factors. Activity data uncertainty reflects the completeness and accuracy of reported HCFC-22 production, which is generally well characterized due to facility-level reporting and monitoring of production quantities. Emission factor uncertainty reflects variability in the generation rate of HFC-23 as a byproduct of HCFC-22 production and is influenced by process conditions, plant design, and operating practices. Additional uncertainty is associated with the performance of HFC-23 destruction technologies, including variability in destruction efficiencies and operational conditions.

For this *GHGIA*, the overall uncertainty associated with national HFC-23 emissions from HCFC-22 production is assumed to be similar to EPA (2025), given use of the same basic methodology and data sources for most years, calculated using the *2006 IPCC Guidelines* Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). This confidence level indicates a range of approximately 7 percent below and 10 percent above the emission estimate. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 4-65.

4.2.11 Production of Fluorochemicals Other than HCFC-22 (Source Category 2B9b)

Facilities in the United States generate emissions of fluorinated GHGs during the production and transformation of fluorinated gases other than HCFC-22. These emissions include HFCs, PFCs, SF_6, NF_3, and other fluorinated gases (that are not included in totals). Emissions may include the intentional manufactured chemical, reactants, or byproducts during chemical manufacturing processes (EPA, 2025; IPCC, 2006). Sources of fluorinated GHG emissions at fluorochemical production facilities include process vents, equipment leaks, and returned containers (venting to atmosphere, recovery for reuse, or routing to a treatment device for destruction). Fluorochemicals are used as feedstocks or intermediates in the production of refrigerants, foam blowing agents, solvents, propellants, fluoropolymers, and other specialty materials.

This source category includes emissions associated with the production and transformation of fluorochemicals other than HCFC-22. Emissions associated with HCFC-22 production are reported separately under the HCFC-22 production source category. Emissions associated with the downstream use of fluorinated gases in products such as refrigeration, air conditioning, foams, and aerosols are reported under the substitution of ozone-depleting substances source category in Section 4.5 of this *GHGIA*. Emissions associated with fossil fuel combustion used to generate heat or electricity at fluorochemical production facilities are reported separately in the Energy chapter under industrial fuel combustion to avoid double counting.

Production of fluorochemicals in the United States supports a range of industrial sectors including chemical manufacturing, electronics, refrigeration, and materials production. Emissions from this source category are influenced by production volumes, process technology, and the implementation of emission control technologies designed to reduce releases of fluorinated gases.

Emissions of HFCs, PFCs, SF_6, and NF_3

Production of fluorochemicals can result in emissions of several high global warming potential gases, including HFCs, PFCs, SF_6, and NF_3. The magnitude of emissions depends on production volumes, process chemistry, and emission control practices at manufacturing facilities. In 2024, emissions of HFCs, PFCs, SF_6, and NF_3 from production of fluorochemicals other than HCFC-22 were estimated to be 4.3 MMT CO_2 Eq., a 87 percent decrease since 1990 and no change since 2023 (see Table 4-35).

Table 4-35: Emissions from Production of Fluorochemicals Other Than HCFC-22 (MMT CO_2 Eq.)

Gas	1990	2005	2020	2021	2022	2023	2024
HFC-23	6.8	1.7	0.9	0.7	1.0	0.7	0.7
HFC-143a	0.2	0.8	0.3	0.3	0.3	0.2	0.2
HFC-134a	+	0.4	0.2	0.2	0.3	0.2	0.2
HFC-125	0.1	1.9	0.4	0.4	0.3	0.2	0.2
HFC-32	+	0.1	0.1	0.1	0.1	+	+
HFC-227ea	1.5	0.1	0.1	0.1	0.1	+	+
Other HFCs	0.1	0.3	0.1	0.1	0.5	+	+
Perfluorocyclobutane	11.3	0.7	1.1	1.2	1.2	1.3	1.3
PFC-14 (Perfluoromethane)	3.0	1.4	0.9	0.9	1.0	1.0	1.0
Other PFCs	3.5	2.0	0.4	0.4	0.6	0.5	0.5
NF_3	0.1	0.6	0.7	0.5	0.5	0.3	0.3
SF_6	5.8	3.3	+	+	+	+	+
Total	**32.4**	**13.3**	**5.2**	**4.8**	**5.8**	**4.3**	**4.3**

+ Does not exceed 0.05 MMT CO_2 Eq.

Emissions of Other Fluorinated Greenhouse Gases

In addition to the major fluorinated gases described above, other fluorinated GHGs are also emitted from fluorinated gas production and transformation processes. Although emissions of these gases are generally smaller than those of HFCs and PFCs, they may still contribute to overall GHG emissions from fluorochemical production.

In 2024, emissions of other fluorinated GHGs from production of fluorochemicals other than HCFC-22 were estimated to be 0.1 MMT CO_2 Eq., a 98 percent decrease since 1990 and no change since 2023 (see Table 4-36).

Table 4-36: Emissions of Other Fluorinated GHGs from Production of Fluorochemicals Other Than HCFC-22 (MMT CO_2 Eq.)

Gas	1990	2005	2020	2021	2022	2023	2024
1,1,1,2,2,3,3-Heptafluoro-3-(1,2,2,2-tetrafluoroethoxy)-propane	+	+	+	+	+	+	+
Hexafluoropropylene oxide	0.4	0.4	+	+	+	+	+
Octafluorotetrahydrofuran	1.0	1.9	+	+	+	+	+
Trifluoromethyl sulfur pentasulfide pentafluoride	0.5	0.9	+	+	+	+	+
HFE-449sl, (HFE-7100) Isomer blend	+	+	+	+	+	+	+
Others	3.1	0.5	0.1	+	+	+	+
Total other fluorinated GHGs	**4.9**	**3.7**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Production and Transformation of Fluorinated Greenhouse Gases

Production and transformation of F-GHGs represent the primary activity drivers for emissions from fluorochemical manufacturing processes. These activities include the production of fluorinated gases as final products as well as their transformation into other fluorochemicals used in industrial applications. Trends in the production and transformation of fluorinated GHGs in the United States are presented in Table 4-37.

Table 4-37: Production and Transformation of Fluorinated GHGs (kt)[a]

Set of Facilities	1990	2005	2020	2021	2022	2023	2024
Facilities reporting their F-GHG emissions, production, and transformation to GHGRP after 2010[b]	86	271	352	348	370	341	341
Facilities reporting only their F-GHG production and transformation to GHGRP after 2010	3.3	3.3	8.2	7.5	11	9.1	9.1
Total Production and Transformation	**89**	**274**	**360**	**356**	**381**	**350**	**350**

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

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

Note: Tables may not sum due to independent rounding

Methods

The methodological approach for estimating emissions from the production of fluorochemicals other than HCFC-22 is consistent with the approach described in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). For 2024, complete activity data from EPA's GHGRP were not available at the time of analysis. Accordingly, 2024 activity levels were held constant at 2023 values for all inputs.

Recalculations

No recalculations were implemented for 1990–2023 for this source category.

Uncertainty

Uncertainty in emission estimates from the production of fluorochemicals other than HCFC-22 arises from uncertainty regarding the identity of processes that emit particular fluorinated GHGs, process vent emission factors, equipment leak estimates, the quantities of residual gas vented from containers, level of control from destruction device operation, and emissions from facilities that produce fluorinated gases but do not report their emissions to the GHGRP. Emissions are based on facility-reported emissions data based on facility-specific emission factors, leak estimates, and recordkeeping of container venting and destruction; uncertainties for these data are low. For facilities that produce fluorinated gases but do not report their emissions to the GHGRP, the gases produced are reported (activity data), and uncertainties include which gases are emitted and the level of control at the facility.

For this *GHGIA*, the overall uncertainty associated with national emissions from the production of fluorochemicals other than HCFC-22 is assumed to be similar to EPA (2025), calculated using the *2006 IPCC Guidelines* Approach 1 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). This confidence level indicates a range of approximately 20 percent below and 20 percent above the emission estimate. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 4-65. Overall uncertainty is driven primarily by emission factor variability and process-specific differences rather than uncertainty in activity data.

4.2.12 Non-EOR Carbon Dioxide Utilization (Source Category 2H2 and 2H3)

CO_2 is produced from several sources, including naturally occurring CO_2 reservoirs, as a byproduct of energy and industrial production processes such as ammonia production, fossil fuel combustion, ethanol production, and during the production of crude oil and natural gas, which contain naturally occurring CO_2.

CO_2 is used in a wide range of applications, including food processing, chemical production, carbonated beverages, refrigeration, and enhanced oil recovery (EOR). As with prior estimates (EPA, 2025), for this analysis, CO_2 used in food and beverage and other non-EOR applications is assumed to be emitted to the atmosphere. Several ethanol plants capture biogenic CO_2 generated during fermentation as a source of CO_2 sequestration. This biogenic CO_2, absent capture, would not be included in this *GHGIA* as an emission source. These emissions are instead accounted for

within the land use, land use change, and forestry (LULUCF) sector through estimates of net carbon stock changes in biogenic carbon pools associated with forest and cropland systems (see Chapter 6). Where this CO_2 is captured by the ethanol plant before it can be released to the atmosphere and then sequestered, it is treated as an emission reduction. Because the biogenic CO_2 captured is likely a result of fermentation, the CO_2 captured for sequestration is subtracted from the food and beverage source category that includes ethanol facilities as opposed to from the fossil fuel combustion category. See Section 3.9 for more detail on CO_2 sequestration.

In 2024, the amount of CO_2 produced and captured for commercial applications was 3.0 MMT CO_2 Eq. The total CO_2 captured from ethanol production for sequestration in 2024 was 0.9 MMT CO_2 Eq. In 2024, total net CO_2 emissions (excluding sequestration) from non-EOR CO_2 utilization were 2.1 MMT CO_2 Eq., a 40 percent increase since 1990 and no change since 2023 (see Table 4-38).

Table 4-38: Net Emissions from Non-EOR CO_2 Utilization (MMT CO_2 Eq.)

Source	1990	2005	2020	2021	2022	2023	2024
Net CO_2 from Food and Beverage	IE	IE	1.8	1.9	1.8	1.1	1.1
CO_2 Emitted from Food and Beverage	IE	IE	2.4	2.4	2.4	2.0	2.0
CO_2 Sequestered from Food and Beverage	0.0	0.0	(0.5)	(0.4)	(0.6)	(0.9)	(0.9)
CO_2 Emitted from Other Non-EOR Applications	IE	IE	1.0	0.9	1.0	1.0	1.0
Total CO_2 Emitted	**1.5**	**1.4**	**2.8**	**2.9**	**2.8**	**2.1**	**2.1**

IE (Included elsewhere), meaning included in totals.

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

Methods

The methodological approach for estimating non-EOR CO_2 utilization emissions is consistent with the approach described in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). The approach is based on use of GHGRP data to determine capture, use and sequestration estimates. Because 2024 GHGRP data were not available at the time of analysis, the total CO_2 captured, used and sequestered was assumed to be equal to 2023 levels.

Recalculations

No recalculations were implemented for 1990–2023 for this source category.

Uncertainty

The uncertainty associated with emission estimates are mainly due to the uncertainty of the data reported through EPA's GHGRP. In addition, the amount of CO_2 transferred to all other end-use categories could be excluded. This latter category might include CO_2 quantities that are being used for non-EOR industrial applications such as firefighting. There is also uncertainty 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.

For this *GHGIA*, the overall uncertainty associated national estimates of CO_2 from non-EOR CO_2 utilization is assumed to be similar to EPA (2025) given the use of the same basic methodology and data sources for most years, calculated using the *2006 IPCC Guidelines* Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). This confidence level indicates a range of approximately 5 percent below and 5 percent above the emission estimate in 2024. Uncertainty assessments for 1990 and 2024 are summarized at the end of this chapter in Table 4-65. Since estimates were derived from prior-year values, these data substitutions are likely to introduce additional uncertainty for the 2024 estimates.

4.2.13 Phosphoric Acid Production (Source Category 2B10)

This source category covers emissions from sources that do not fall within any other category, which includes emissions from phosphoric acid production. Phosphoric acid production generates CO_2 emissions during the chemical processing of phosphate rock used to manufacture phosphoric acid (EPA, 2025). Phosphoric acid is produced primarily through the wet process, in which phosphate rock reacts with sulfuric acid to produce phosphoric acid and calcium sulfate. Carbonate impurities present in the phosphate rock react during this process and release CO_2 as a byproduct of the reaction.

The carbonate content of phosphate rock influences the amount of CO_2 released during phosphoric acid production. Because the composition of phosphate rock varies across deposits and production sources, the carbonate content used in emissions calculations reflects typical chemical composition values for the rock processed in the United States (EPA, 2025). The chemical composition of phosphate rock used in these estimates is presented in Table 4-39.

Table 4-39: Chemical Composition of Phosphate Rock (Percent by Weight)

Composition	Central Florida	North Florida	North Carolina (calcined)	Idaho (calcined)	Morocco	Peru
Total Carbon (as C)	1.6	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: EPA (2025)

CO_2 emissions from phosphoric acid production are estimated based on the quantity of phosphate rock processed and the carbonate content of the rock. Between 2021 and 2024, over 99 percent of imported phosphate was from Peru (USGS, 2026). In 2024, CO_2 emissions from phosphoric acid production were estimated to be 0.8 MMT CO_2 Eq., a 47 percent decrease since 1990 and no change since 2023 (see Table 4-40).

Table 4-40: Emissions from Phosphoric Acid Production (MMT CO_2 Eq.)

Gas	1990	2005	2020	2021	2022	2023	2024
CO_2	1.5	1.3	0.9	0.9	0.8	0.8	0.8

Phosphoric acid is used primarily in the manufacture of phosphate fertilizers as well as in a variety of industrial applications. Production levels are therefore closely linked to fertilizer demand and phosphate rock mining activity; domestic phosphate rock consumption is the primary activity driver for phosphoric acid production in the United States. Trends in domestic consumption, exports, and imports of phosphate rock are presented in Table 4-41 (USGS, 2026).

Table 4-41: Phosphate Rock Domestic Consumption, Exports, and Imports (kt)

Location	1990	2005	2020	2021	2022	2023	2024
U.S. Domestic Consumption	49,800	35,200	22,600	21,900	19,800	20,000	19,100
FL and NC	42,494	28,160	17,630	17,080	15,440	15,600	14,900
ID and UT	7,306	7,040	4,970	4,820	4,360	4,400	4,200
Exports—FL and NC	6,240	0	0	0	0	0	0
Imports	451	2,630	2,520	2,460	2,500	2,590	3,390
Total U.S. Consumption	**44,011**	**37,830**	**25,120**	**24,360**	**22,300**	**22,590**	**22,490**

Notes: Regional production data for 2021 through 2023 are estimates (USGS, 2022–2024). Totals may not sum due to independent rounding,

Methods

The methodological approach for estimating phosphoric acid production emissions is consistent with the approach described in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025).

Recalculations

No recalculations were implemented for 1990–2023 for this source category.

Uncertainty

Uncertainty in CO_2 emission estimates for phosphoric acid production arises from uncertainty in reported phosphate rock consumption and phosphoric acid production activity data. Emission

factor uncertainty reflects variability in the carbonate content of phosphate rock and the fraction of carbon released during processing. Because carbonate impurities vary across phosphate deposits and production sources, uncertainty in the chemical composition of phosphate rock contributes to variability in the estimated emissions. Activity data uncertainty is generally low, as total U.S. phosphate rock production, as well as export and import data, are reported by domestic producers to the USGS and the U.S. Census Bureau and are not considered significant sources of uncertainty. Some minor uncertainty exists in the degree to which regional production data represent actual production in those regions.

For this *GHGIA*, the overall uncertainty associated with national CO_2 emissions from phosphoric acid production is assumed to be similar to EPA (2025), given the use of the same basic methodology and data sources for most years. Uncertainty is calculated using the *2006 IPCC Guidelines* Approach 2 methodology at the 95 percent confidence level, corresponding to a range of approximately 18 percent below and 20 percent above the emission estimate (IPCC, 2006). Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 4-65.

4.3 Metal Industry

4.3.1 Iron and Steel Production (Source Category 2C1) and Metallurgical Coke Production

Iron and steel production generates CO_2 and CH_4 emissions from the use of carbon-containing raw materials and reducing agents in ironmaking and steelmaking processes. This source category includes emissions from metallurgical coke production, sinter production, pellet production, blast furnace ironmaking, basic oxygen furnace steelmaking, electric arc furnace steelmaking, and direct reduced iron production.

Emissions reported here reflect process-related emissions associated with carbon oxidation and carbonate use in these operations. Emissions from fuels combusted for energy purposes at iron and steel facilities are reported separately in the Energy chapter under Industrial Fuel Combustion to avoid double counting. Similarly, emissions associated with limestone and dolomite consumption for non-metallurgical purposes are reported under other process uses of carbonates where applicable.

Two primary production routes are used in the United States. Integrated mills produce iron from iron ore in blast furnaces using metallurgical coke as both a fuel and reducing agent, followed by conversion of pig iron to steel in basic oxygen furnaces. Electric arc furnace facilities primarily produce steel from scrap metal and may supplement scrap with direct reduced iron. Because these routes differ in their reliance on coke and primary iron reduction, their emissions profiles differ accordingly (EPA, 2025; IPCC, 2006).

Over time, structural changes in the U.S. steel industry have influenced emissions trends in this category. The shift away from integrated blast furnace and basic oxygen furnace production toward greater reliance on electric arc furnace production has reduced the use of coke and other carbon intensive inputs, contributing to long-term changes in emissions.

Metallurgical Coke Production

Metallurgical coke is produced by heating coking coal in coke ovens in the absence of oxygen to remove volatile compounds and produce a carbon-rich material suitable for use in blast furnaces. This carbonization process generates CO_2 emissions and small quantities of fugitive CH_4 associated with volatile matter release, handling, and combustion of byproduct gases. The approach used to estimate emissions from coke production relies on a mass and carbon balance. All the carbon is assumed to be emitted in the form of CO_2 and therefore CH_4 emissions from coke production are not estimated directly but assumed to be included as part of the CO_2 estimates.

This source category includes process-related emissions from coke oven operations. Emissions from fuel combustion used to heat coke ovens are reported in the Energy chapter. Coke produced domestically is primarily consumed by integrated iron and steel facilities, and therefore trends in coke production generally follow changes in blast furnace activity.

In 2024, CO_2 emissions from metallurgical coke production were 2.9 MMT CO_2 Eq., a decrease of 48 percent since 1990 and a decrease of 3 percent since 2023 (see Table 4-42).

Table 4-42: Emissions from Metallurgical Coke Production (MMT CO_2 Eq.)

Gas	1990	2005	2020	2021	2022	2023	2024
CO_2	5.6	3.9	2.3	3.2	3.0	3.0	2.9

Coke production in 2024 was about 2.3 percent lower than in 2023 (EIA, 2025). See Table 4-43 and Table 4-44 for the inputs and outputs to coke production used in the emission estimates.

Table 4-43: Production and Consumption Data for the Calculation of CO_2 Emissions from Metallurgical Coke Production (Thousand Metric Tons)

Activity	1990	2005	2020	2021	2022	2023	2024
Coking Coal Consumption at Coke Plants	35,269	21,259	13,076	15,957	14,523	14,378	14,062
Coke Production at Coke Plants	25,054	15,167	9,392	11,381	10,337	10,193	9,958
Coke Breeze Production	2,645	1,594	981	1,197	1,089	1,078	1,055
Coal Tar Production	1,058	638	392	479	436	431	422

Table 4-44: Production and Consumption Data for the Calculation of CO_2 Emissions from Metallurgical Coke Production (Million ft^3)

Activity	1990	2005	2020	2021	2022	2023	2024
Coke Oven Gas Production	250,767	114,213	66,492	74,206	69,829	72,054	72,054
Natural Gas Consumption	599	2,996	1,873	2,091	1,967	2,030	2,030
Blast Furnace Gas Consumption	24,602	4,460	3,350	3,738	3,518	3,630	3,630

Iron and Steel Production

Iron and steel production emissions are generated during multiple stages of ironmaking and steelmaking. In integrated facilities, iron ore is processed into sinter or pellets and reduced to molten iron in blast furnaces using coke and other carbon-containing materials. The molten iron is subsequently refined into steel in basic oxygen furnaces, where additional carbon oxidation occurs. Direct reduced iron production, where applicable, also contributes to process emissions.

Electric arc furnace facilities produce steel primarily from recycled scrap metal and may use direct reduced iron as a supplemental input. Although electric arc furnace production avoids blast furnace ironmaking, process emissions occur from the use of carbon electrodes, injected carbon, and flux materials.

This section includes process-related emissions from these activities. Emissions from electricity consumption and on-site fuel combustion are reported in the Energy chapter. Emissions associated with downstream manufacturing activities are reported under their respective source categories elsewhere in this *GHGIA*.

Emissions from iron and steel production are driven by total steel output, production technology mix, direct reduced iron use, and raw material consumption patterns. Changes in the relative share of integrated and electric arc furnace production continue to influence both short-term variability and long-term trends.

In 2024, CO_2 emissions from iron and steel production were estimated to be 43.8 MMT CO_2 Eq., a decrease of 56 percent since 1990, and no change since 2023 (see Table 4-45). CH_4 emissions from iron and steel production do not contribute significantly to overall GHG emissions from the sector (see Table 4-45).

Table 4-45: Emissions from Iron and Steel Production (MMT CO_2 Eq.)

Gas/Source	1990	2005	2020	2021	2022	2023	2024
CO_2	**99.1**	**66.2**	**38.8**	**44.7**	**42.7**	**43.8**	**43.8**
Sinter Production	2.4	1.7	0.7	0.8	0.8	0.8	0.8
Iron Production	45.7	17.7	10.5	12.9	12.8	12.9	12.9
Pellet Production	1.8	1.5	0.8	0.8	0.8	0.8	0.8
Steel Production	8.0	9.4	7.0	8.0	7.5	7.8	7.8
Other Activities[a]	41.2	35.9	19.8	22.1	20.8	21.5	21.5
CH_4	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Sinter Production	+	+	+	+	+	+	+
Total	**99.2**	**66.2**	**38.8**	**44.7**	**42.8**	**43.8**	**43.8**

+ Does not exceed 0.05 MMT CO_2 Eq.

[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.

See Table 4-46 and Table 4-47 for the inputs and outputs to iron and steel used in the emission estimates.

Table 4-46: Production and Consumption Data for the Calculation of CO_2 and CH_4 Emissions from Iron and Steel Production (Thousand Metric Tons)

Activity	1990	2005	2020	2021	2022	2023	2024
Sinter Production	12,239	8,315	3,747	4,182	3,935	4,060	4,060
Direct Reduced Iron Production	517	1,303	C	C	C	C	C
Pellet Production	60,563	50,096	25,044	27,949	26,300	27,139	27,139
Pig Iron Production							
Coke Consumption	24,946	13,832	6,240	6,964	6,553	6,762	6,762
Pig Iron Production	49,669	37,222	18,320	22,246	19,791	21,000	20,600
Direct Injection Coal Consumption	1,485	2,573	2,110	2,354	2,216	2,286	2,286
EAF Steel Production							
EAF Anode and Charge Carbon Consumption	67	1,127	1,118	1,130	1,123	1,126	1,126
Scrap Steel Consumption	42,691	46,600	C	C	C	C	C
Flux Consumption	319	695	998	998	998	1,030	1,030
EAF Steel Production	33,511	52,194	51,349	57,307	53,926	55,645	55,645
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	311	347	326	337	337
BOF Steel Production	43,973	42,705	21,384	23,865	22,457	23,172	23,172

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Table 4-47: Production and Consumption Data for the Calculation of CO_2 Emissions from Iron and Steel Production (million ft^3 unless otherwise specified)

Activity	1990	2005	2020	2021	2022	2023	2024
Pig Iron Production							
Natural Gas Consumption	56,273	59,844	32,465	36,232	34,095	35,181	35,181
Fuel Oil Consumption (thousand gallons)	163,397	16,170	1,986	2,217	2,086	2,153	2,153
Coke Oven Gas Consumption	22,033	16,557	11,063	12,346	11,618	11,988	11,988
Blast Furnace Gas Production	1,439,380	1,299,980	715,509	798,522	751,418	775,364	775,364
EAF Steel Production							
Natural Gas Consumption	15,905	19,985	7,801	8,706	8,192	8,454	8,454
BOF Steel Production							
Coke Oven Gas Consumption	3,851	524	333	372	350	361	361
Other Activities							
Coke Oven Gas Consumption	224,883	97,132	55,096	61,489	57,861	59,705	59,705
Blast Furnace Gas Consumption	1,414,778	1,295,520	712,159	794,783	747,900	771,734	771,734

Methods

The methodological approach for estimating coke production and iron and steel production emissions is consistent with the approach described in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2023* (EPA, 2025). Emissions are estimated primarily based on a mass and carbon balance while some sources were estimated based on the application of emission factors to production data. In recent years the approach has relied on EPA's GHGRP data to proxy activity data that were no longer available from industry sources.

Because 2024 GHGRP data were not available at the time of analysis, many of the 2024 activity data points used in the analysis were estimated using the 2023 values as proxy (see Tables 4-47 and 4-48).

Recalculations

The data for direct reduced iron production for 2019–2023 was updated to reflect data on direct reduced iron consumption from USGS data (USGS, 2025). This recalculation resulted in an average annual increase in emissions for direct reduced iron of 1.3 percent from 2019–2023.

Uncertainty

The estimates of CO_2 emissions from metallurgical coke production are based on assessing material production and consumption data and average carbon contents. There is uncertainty in the underlying mass balances based on uncertainty in the underlying data. There are also uncertainties associated with carbon contents assumed for the different inputs and outputs.

For the most part, estimates of CO_2 emissions from iron and steel production are also based on material production and consumption data and average carbon contents. As with coke production estimates, there are uncertainties associated with mass inputs and outputs based on the underlying data sources as well as uncertainties associated with the carbon contents assumed for the different inputs and outputs.

Some categories of emissions (pellet, direct reduced iron and sinter production) are estimated based on production data and an IPCC default emission factor. There is uncertainty associated with the production data for those sources as well as uncertainty with the representativeness of the associated IPCC default emission factors.

For this *GHGIA*, the overall uncertainty associated national estimates of emissions from coke and iron and steel production is assumed to be similar to EPA (2025) given the use of the same basic methodology and data sources for most years, calculated using the *2006 IPCC Guidelines* Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). This confidence level indicates a range of approximately 16 percent below and 16 percent above the CO_2 emission estimate and a range of approximately 20 percent below and 21 percent above the CH_4 emission estimate in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 4-65. Since much of the process data used in the analysis was proxied based on prior-year data, there could be additional uncertainty associated with the 2024 estimates.

4.3.2 Ferroalloy Production (Source Category 2C2)

This source category includes emissions of CO_2 and CH_4 from the production of several ferroalloys. Ferroalloys are composites of iron (Fe) and other elements such as silicon (Si), manganese (Mn), and chromium (Cr). Ferroalloys are often produced at co-located facilities with the iron and steel industry and are used to alter the material properties of the steel. Production trends follow that of the iron and steel industry.

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) are included. 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. Additionally, production of ferrochromium in the United States ceased in 2009 (EPA 2025).

Emissions of CO_2 occur when metallurgical coke is oxidized during a high-temperature reaction with iron and the selected alloying element. 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 which is dependent on furnace efficiency, operation technique, and control technology.

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 (IPCC, 2006).

In 2024, CO_2 emissions from ferroalloy production were 1.2 MMT CO_2 Eq., a 41 percent reduction since 1990 and an 8 percent increase since 2023 (see Table 4-48). In 2024, CH_4 emissions from ferroalloy production were 0.01 MMT CO_2 Eq., a 49 percent decrease since 1990 and no change since 2023.

Table 4-48: Emissions from Ferroalloy Production (MMT CO_2 Eq.)

Gas	1990	2005	2020	2021	2022	2023	2024
CO_2	2.2	1.4	1.4	1.4	1.3	1.2	1.2
CH_4	+	+	+	+	+	+	+
Total	**2.2**	**1.4**	**1.4**	**1.4**	**1.3**	**1.2**	**1.3**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Changes in emissions over time are largely dependent on changes in production quantity of different ferroalloy product types over time. See Table 4-49 for production values used in this analysis.

Table 4-49: Production of Ferroalloys (Metric Tons)

Activity	1990	2005	2020	2021	2022	2023	2024
Ferrosilicon 25%–55%	321,385	123,000	126,681	131,280	122,119	114,581	114,581
Ferrosilicon 56%–95%	109,566	86,100	111,778	115,835	107,752	101,101	101,101
Silicon Metal	145,744	148,000	122,541	126,989	118,128	110,837	110,837
Misc. Alloys 32–65%	72,442	NA	NA	NA	NA	NA	NA

NA (Not applicable)

Methods

The methodological approach for estimating ferroalloy production emissions is consistent with the approach described in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). Emissions are estimated primarily based on production data and emissions factors. In recent years the approach has relied on EPA's GHGRP data to proxy data from sources that were no longer available.

Because 2024 GHGRP data were not available at the time of analysis, many of the factors used in the analysis were estimated using the 2023 values as proxy (see Table 4-49).

Recalculations

No updates were available for the data sources used. Therefore, no recalculations were implemented for 1990–2023 for this source category.

Uncertainty

The approach for calculating emissions from ferroalloy production relies on production data times emission factors. There is uncertainty in the production data. Particularly, starting with the 2011 data, ferroalloy production data are only available as total silicon materials production. The total production quantity is then allocated across the three categories based on the 2010 production share.

There is also uncertainty associated with the emission factors used and how representative they are for U.S. production processes. In particular, emissions of CH_4 from ferroalloy production vary depending on furnace specifics, such as type, operation technique, and control technology.

For this *GHGIA*, the overall uncertainty associated national estimates of emissions from ferroalloy production are assumed to be similar to EPA (2025) given the use of the same basic methodology and data sources for most years, calculated using the *2006 IPCC Guidelines* Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). This confidence level indicates a range of approximately 13 percent below and 13 percent above the CO_2 emission estimate and a range of approximately 12 percent below and 13 percent above the CH_4 emission estimate in 2024. Uncertainty assessments for 1990 and 2024 are summarized at the end of this chapter in Table 4-65. Since production data were proxied based on 2023 values, there could be additional uncertainty associated with the 2024 estimates.

4.3.3 Aluminum Production (Source Category 2C3)

Aluminum production generates CO_2 and PFC emissions during the electrolytic reduction process used to produce primary aluminum (IPCC, 2006; International Aluminium Institute [IAI], 2023). Aluminum is widely used in transportation, construction, packaging, and electrical applications due to its strength, low density, and corrosion resistance.

Emissions reported here include process-related CO_2 and PFC emissions generated during aluminum production. Emissions associated with fossil fuel combustion used to generate

electricity or process heat at aluminum facilities are reported separately in the Energy chapter under industrial fuel combustion. Emissions associated with electricity generation used to power aluminum smelters are also reported in the energy sector to avoid double counting.

The United States aluminum industry includes both primary smelting and secondary production from recycled materials. Secondary production accounts for the majority of domestic aluminum output, while a smaller number of facilities produce primary aluminum through electrolytic smelting. Domestic aluminum production levels are influenced by global aluminum markets, energy costs, and demand from major end-use sectors such as transportation, construction, and packaging (USGS, 2025).

Emissions of CO_2 from aluminum production result primarily from the consumption of carbon anodes during the electrolytic reduction process, as well as from anode baking operations. These emissions are proportional to aluminum production levels and the carbon content of the anodes used in the process. Emissions of PFCs from aluminum production occur during anode effects, which arise when alumina concentrations in the electrolytic bath become too low. Under these conditions, tetrafluoromethane (CF_4) and hexafluoroethane (C_2F_6) are formed instead of aluminum. The frequency and duration of anode effects influence the quantity of PFC emissions generated during the process (IPCC, 2006; IAI, 2023).

Estimated CO_2 and PFC emissions from aluminum production are presented in Table 4-50. In 2024, CO_2 emissions from aluminum production were estimated to be 1.2 MMT CO_2 Eq., an 82 percent decrease since 1990 and no change since 2023. In 2024, PFC emissions from aluminum production were estimated to be 0.5 MMT CO_2 Eq., a decrease of 97 percent since 1990 and no change since 2023. The decline in CO_2 and PFC emissions reflect both reduced domestic aluminum production and industry efforts to reduce anode effects through technological and operational improvements (EPA, 2025).

Table 4-50: Emissions from Aluminum Production (MMT CO_2 Eq.)

Gas	1990	2005	2020	2021	2022	2023	2024
CO_2	6.8	4.1	1.7	1.5	1.4	1.2	1.2
CF_4	16.1	2.6	1.2	0.8	0.7	0.4	0.4
C_2F_6	3.2	0.5	0.2	0.1	0.1	0.1	+
Total	**26.1**	**7.2**	**3.2**	**2.5**	**2.2**	**1.7**	**1.7**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Primary aluminum production in the United States decreased by 81 percent since 1990 (see Table 4-51).

Table 4-51: Production of Primary Aluminum (kt)

Year	1990	2005	2020	2021	2022	2023	2024
Production	4,048	2,482	1,012	889	861	750	750

Methods

The methodological approach for estimating aluminum production emissions is consistent with the approach described in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). For 2024, complete activity data were not available at the time of analysis. Accordingly, 2024 activity levels were held constant at 2023 values for all inputs.

Recalculations

No recalculations were implemented for 1990–2023 for this source category.

Uncertainty

Uncertainty in emission estimates for aluminum production is primarily associated with activity data estimates of primary aluminum production and the consumption of carbon anodes used in the electrolytic reduction process. Activity data uncertainty reflects the completeness and accuracy of reported aluminum production, which is generally well characterized due to national production statistics and facility-level reporting through EPA's GHGRP. Variability in production reporting and data aggregation may contribute to uncertainty in the national estimate.

Additional uncertainty arises from emission factors used to estimate both CO_2 and PFC emissions. CO_2 emission estimates depend on assumptions related to anode consumption rates and carbon content, while PFC emissions are influenced by the frequency and duration of anode effects and associated process conditions. Variability in plant operations, technology configurations, and process control practices across facilities may contribute to uncertainty in the estimated emissions. Because PFC emissions are highly sensitive to operational conditions, emission factor variability is a key source of uncertainty.

For this *GHGIA*, the overall uncertainty associated with national estimates of emissions from aluminum production is assumed to be similar to EPA (2025) given the use of the same basic methodology and data sources for most years, calculated using the *2006 IPCC Guidelines* Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). This confidence level indicates a range of approximately 3 percent below and 3 percent above the CO_2 emission estimate, 9 percent below and 11 percent above the CF_4 emission estimate, 9 percent below and 9 percent above the C_2F_6 emission estimate, and 8 percent below and 10 percent above the total PFC emission estimate in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 4-65.

4.3.4 Magnesium Production (Source Category 2C4)

Magnesium is a lightweight metal used primarily in aluminum alloys, automotive components, electronics, and other structural applications requiring high strength-to-weight ratios. Magnesium production generates emissions of fluorinated GHGs during casting and processing operations that use cover gases to prevent oxidation of molten magnesium (IPCC, 2006; International Magnesium Association [IMA], 2022).

During magnesium production and casting, molten magnesium reacts readily with oxygen and can ignite if not protected from the atmosphere. Historically, SF_6 was widely used as a protective cover gas, although alternatives such as HFCs (i.e., HFC-134a) and fluorinated ketones (i.e., FK 5-1-12) are increasingly used. Emissions occur when these gases are released during casting operations, equipment handling, and gas management processes. In addition, the processing of carbonate-based raw materials (e.g., dolomite) during magnesium production results in emissions of CO_2 (IPCC, 2006).

Emissions associated with fossil fuel combustion used to generate heat or electricity at magnesium facilities are reported separately in the Energy chapter under industrial fuel combustion. Emissions associated with downstream manufacturing processes that use magnesium alloys are reported under their respective source categories elsewhere in this *GHGIA*.

Emissions from magnesium production are driven by the quantity of magnesium produced and the type and amount of cover gases used during processing. Estimated emissions of SF_6, HFC-134a, FK 5-1-12, and CO_2 from magnesium production are presented in Table 4-52. In 2024, emissions from magnesium production were estimated to be 1.1 MMT CO_2 Eq., a decrease of 81 percent since 1990 and no change since 2023.

Table 4-52: Emissions from Magnesium Production (MMT CO_2 Eq.)

Gas	1990	2005	2020	2021	2022	2023	2024
SF_6	5.6	3.0	0.9	1.2	1.1	1.1	1.1
HFC-134[a]	0.0	0.0	0.1	0.0	0.0	+	+
CO_2	0.1	+	+	+	+	+	+
FK 5-1-12[a]	0.0	0.0	+	+	+	+	+
Total	**5.7**	**3.0**	**0.9**	**1.2**	**1.1**	**1.1**	**1.1**

+ 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.

Magnesium production in the United States includes both primary magnesium production and secondary production from recycled materials. Domestic production levels reflect demand from aluminum alloy manufacturing, automotive components, and other industrial applications that utilize lightweight metal materials (USGS, 2025).

Methods

The methodological approach for estimating magnesium production emissions is consistent with the approach described in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). For 2024, complete activity data were not available at the time of analysis. Accordingly, 2024 activity levels were held constant at 2023 values for all inputs.

Recalculations

No recalculations were implemented for 1990–2023 for this source category.

Uncertainty

Uncertainty in emission estimates for magnesium production is primarily associated with activity data estimates of magnesium production and the use of cover gases during casting and processing operations. Activity data uncertainty reflects the completeness and accuracy of reported magnesium production and cover gas usage, which are generally based on national production statistics and facility-level reporting through EPA's GHGRP. Variability in reporting practices, facility coverage, and estimation of gas usage may contribute to uncertainty in the national estimate.

Additional uncertainty arises from emission factors used to estimate releases of fluorinated GHGs during magnesium production. Emission estimates depend on assumptions related to cover gas usage rates, emission rates during casting operations, and gas handling practices. Variability in process conditions, equipment configurations, and the types of cover gases used across facilities may contribute to uncertainty in the estimated emissions. Because emissions are closely tied to gas usage and release during processing, variability in these parameters is a key source of uncertainty.

For this *GHGIA*, the overall uncertainty associated with national estimates of emissions from magnesium production is assumed to be similar to EPA (2025) given the use of the same basic methodology and data sources for most years, calculated using the *2006 IPCC Guidelines* Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). This confidence level indicates a range of approximately 8.2 percent below and 8.1 percent above the emission estimate in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 4-65.

4.3.5 Lead Production (Source Category 2C5)

Lead can be produced through either the primary or secondary processes which both emit CO_2. Primary production of lead through the direct smelting of lead concentrate reduces the concentrate in a furnace using metallurgical coke, producing CO_2 emissions (Sjardin, 2003). Primary lead production via direct smelting previously occurred at a single Missouri smelter, which closed at the end of 2013. A small amount of residual lead was processed during its demolition in 2014 (USGS, 2015). Since 2015, no primary lead production has occurred in the United States.

Secondary lead production primarily involves the recycling of lead acid batteries and other post-consumer scrap at secondary smelters. 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. CO_2 emissions from secondary production also occur through the treatment of secondary raw materials (Sjardin, 2003).

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.

In 2024, CO_2 emissions from lead production were 0.5 MMT CO_2 Eq., a 10 percent decrease since 1990 and a 2 percent increase since 2023 (see Table 4-53).

Table 4-53: Emissions from Lead Production (MMT CO_2 Eq.)

Gas	1990	2005	2020	2021	2022	2023	2024
CO_2	0.5	0.6	0.5	0.5	0.5	0.5	0.5

Changes in CO_2 emissions from lead production are primarily due to changes in lead production process over time (see Table 4-54). 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.

Table 4-54: Lead Production (Metric Tons)

Activity	1990	2005	2020	2021	2022	2023	2024
Primary	404,000	143,000	0	0	0	0	0
Secondary	922,000	1,150,000	1,090,000	1,050,000	1,010,000	1,010,000	1,030,000

Methods

The methodological approach for estimating lead production emissions is consistent with the approach described in the Inventory of *U.S. Greenhouse Gas Emissions and Sinks: 1990-2023* (EPA, 2025). Emissions are estimated based on total lead production and the application of emission factors reflecting the process used for production (USGS, 2026; IPCC, 2006). Activity data from 1990 through 2022 remained consistent with EPA (2025).

Recalculations

Recalculations were implemented for 2023 for this source category to incorporate slightly updated USGS (2026) data 2023 secondary lead production data value. The update resulted in a 1.0 percent increase in the 2023 production value.

Uncertainty

The uncertainty associated with lead production emission estimates relates to the emission factors and activity data used. The applicability of the default emission factors used for plants in the United States is uncertain. 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.

For this *GHGIA*, the overall uncertainty associated national estimates of CO_2 from lead production is assumed to be similar to EPA (2025) given the use of the same basic methodology and data sources for most years, calculated using the *2006 IPCC Guidelines* Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). This confidence level indicates a range of approximately 15 percent below and 15 percent above the emission estimate in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 4-65.

4.3.6 Zinc Production (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 CO_2 emissions (Viklund-White, 2000). 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 (IPCC, 2006).

In the electrothermic process, roasted zinc concentrate and secondary zinc products are fed into a sinter unit to remove impurities before entering an electric retort furnace. Under high temperatures, metallurgical coke reduces the zinc oxides, producing vaporized zinc that is captured in a vacuum condenser; this process also generates non-energy CO_2 emissions (EPA, 2025).

In the Waelz kiln process, electric arc furnace (EAF) dust from galvanized steel recycling enters a kiln along with a reducing agent, typically carbon-containing metallurgical coke, and heated to approximately 1,100 to 1,200°C. Zinc fumes are produced and combusted with air entering the kiln to form zinc oxide, which is collected in a baghouse or electrostatic precipitator and leached to remove chloride and fluoride. The process results in non-energy CO_2 emissions (EPA, 2025).

In 2024, CO_2 emissions from zinc production were estimated to be 0.9 MMT CO_2 Eq., an increase of 46 percent since 1990 and no change since 2023 (see Table 4-55). 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.

Table 4-55: Emissions from Zinc Production (MMT CO_2 Eq.)

Source	1990	2005	2020	2021	2022	2023	2024
CO_2	0.6	1.0	1.0	1.0	0.9	0.9	0.9

In 2024, United States primary and secondary refined zinc production were estimated to total 220,000 metric tons (USGS, 2026) (see Table 4-56), remaining at approximately the same production level as in 2021.

Table 4-56: Zinc Production (Metric Tons)

Activity	1990	2005	2020	2021	2022	2023	2024
Primary	262,704	191,120	110,000	110,000	110,000	110,000	110,000
Secondary	95,708	156,000	70,000	110,000	110,000	110,000	110,000
Total	**358,412**	**347,120**	**180,000**	**220,000**	**220,000**	**220,000**	**220,000**

Note: Totals may not sum due to independent rounding.

Methods

The methodological approach for estimating zinc production emissions is consistent with the approach described in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). Emissions are estimated based on activity data for zinc production and the application of emission factors reflecting the process used to produce zinc (IPCC 2006).

The activity data for zinc production comes from two main sources. One, U.S. primary and secondary zinc production is based on data from USGS, which was available for 2024 (USGS, 2026). Activity data are also gathered from industry sources on the amount of EAF dust used, which were not available at the time of this analysis. Therefore, the EAF dust data were proxied based on 2023 data.

Recalculations

No recalculations were implemented for 1990–2023 for this source category.

Uncertainty

There is uncertainty in the estimated amount of EAF dust consumed in the United States for secondary zinc production using emission-intensive Waelz kilns. The national estimate combines EAF dust consumption data from the Waelz kins currently operated by Befesa (formerly operated by AZR or Horsehead Corporation) with consumption data from those kilns operated by SDR.

Uncertainty also stems from the emission factors used to estimate CO_2 emissions from secondary zinc production. The Waelz kiln emission factors are based on materials balances for metallurgical coke and EAF dust consumed as provided by Viklund-White (2000); therefore, their accuracy depends upon the accuracy of these underlying materials balances. Because data limitations prevented the development of emission factors for the electrothermic process, Waelz kiln process emission factors were applied to both electrothermic and Waelz kiln production processes.

For this *GHGIA*, the overall uncertainty associated national estimates of CO_2 from zinc production is assumed to be similar to EPA (2025) given the use of the same basic methodology and data

sources for most years, calculated using the *2006 IPCC Guidelines* Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). This confidence level indicates a range of approximately 19 percent below and 21 percent above the emission estimate in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 4-65. Since some of the activity data were proxied for 2024, this may introduce additional uncertainty for the 2024 estimates.

4.4 Electronics Industry (Source Category 2E)

The electronic industry generates emissions of PFCs, HFCs, NF_3, SF_6, and N_2O that serve as process gases in plasma etching, chamber cleaning, and chemical vapor deposition operations during the manufacture of semiconductor devices, flat panel displays, photovoltaic cells, and other electronic components. During these operations, a portion of the process gases may be released to the atmosphere if not captured or destroyed through emission control systems (IPCC, 2006).

The electronics manufacturing sector in the United States produces integrated circuits, semiconductor devices, and other advanced electronic components used in computing, telecommunications, and consumer electronics. Production trends are influenced by global demand for electronic devices, technological advances in semiconductor fabrication, and industry efforts to reduce emissions from fluorinated process gases (Semiconductor Industry Association [SIA], 2024).

This source category includes emissions of fluorinated GHGs and N_2O generated during semiconductor manufacturing, flat panel display production, photovoltaic manufacturing, and other electronic device fabrication processes. Emissions associated with fossil fuel combustion used to generate heat or electricity at electronics manufacturing facilities are reported separately in the Energy chapter under industrial fuel combustion to avoid double counting. Emissions associated with the downstream use of electronic products are not included in this source category.

Emissions from the electronic industry are driven by the consumption of fluorinated process gases and the effectiveness of emission control technologies used during manufacturing. Estimated emissions of PFCs, HFCs, SF_6, NF_3, and N_2O from the electronic industry are presented in Table 4-57. In 2024, emissions from this source category were estimated to be 4.2 MMT CO_2 Eq., a 42 percent increase since 1990 and no change since 2023.

Table 4-57: Emissions from Electronics Industry (MMT CO_2 Eq.)

Gas/Source	1990	2005	2020	2021	2022	2023	2024
CF_4	0.8	1.0	1.5	1.6	1.7	1.5	1.5
C_2F_6	1.8	1.8	0.8	0.9	0.9	0.7	0.7
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	+	+
HFC-23	0.2	0.2	0.3	0.4	0.3	0.3	0.3
SF_6	0.5	0.8	0.8	0.9	0.8	0.7	0.7
NF_3	+	0.4	0.6	0.6	0.6	0.5	0.5

(continued)

Table 4-57: Emissions from Electronics Industry (MMT CO_2 Eq.) (*continued*)

Gas/Source	1990	2005	2020	2021	2022	2023	2024
C_4F_6	+	+	+	+	+	+	+
C_5F_8	+	+	+	+	+	+	+
CH_2F_2	+	+	+	+	+	+	+
CH_3F	+	+	+	+	+	+	+
CH_2FCF_3	+	+	+	+	0.0	+	+
Total Semiconductors	**3.3**	**4.3**	**4.2**	**4.5**	**4.4**	**3.9**	**3.9**
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	0.3	0.3	0.3	0.3	0.3
N_2O (MEMS)	0.0	+	+	+	+	+	+
N_2O (PV)	0.0	+	+	+	+	+	+
Total N_2O	**+**	**0.1**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
HFC, PFC and SF_6 F-HTFs	0.0	+	0.1	0.1	0.1	0.1	0.1
Total Electronics Manufacture	**3.3**	**4.5**	**4.5**	**4.9**	**4.8**	**4.2**	**4.2**

+ Does not exceed 0.05 MMT CO_2 Eq.

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

Fluorinated heat transfer fluids (F-HTFs) are also used in electronics manufacturing and may contribute to emissions from this source category. Emissions of F-HTFs by compound group are presented in Table 4-58.

Table 4-58: Emissions from Electronics Manufacture by Compound Group (kt CO_2 Eq.)

Gas	1990	2005	2020	2021	2022	2023	2024
HFCs	0.0	1	1	2	2	4	4
PFCs	0.0	37	54	63	53	58	58
SF_6	0.0	6	13	9	4	3	3
HFEs	0.0	4	6	3	17	3	3
PFPMIEs	0.0	105	146	144	146	137	137
Perfluoroalkylmorpholines	0.0	60	56	50	18	9	9
Perfluorotrialkylamines	0.0	154	300	275	164	186	186
Total F-HTFs	**0.0**	**367**	**577**	**547**	**404**	**401**	**401**

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

Methods

The methodological approach for estimating electronics industry emissions is consistent with the approach described in the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023 (EPA, 2025). For 2024, complete activity data were not available at the time of analysis. Accordingly, 2024 activity levels were held constant at 2023 values for all inputs.

Recalculations

No recalculations were implemented for 1990–2023 for this source category.

Uncertainty

Uncertainty in emissions estimates for the electronic industry is primarily associated with activity data estimates of fluorinated GHG consumption and use during semiconductor manufacturing and related electronic production processes. Activity data uncertainty reflects the completeness and accuracy of reported gas consumption, production levels, and abatement system operation, which are generally well characterized due to facility-level reporting through EPA's GHGRP. However, differences in reporting practices, data aggregation, and estimation of gas usage across facilities may contribute to uncertainty in the national estimate.

Additional uncertainty arises from emission factors used to estimate releases of fluorinated GHGs during plasma etching and chamber cleaning processes. Emission estimates depend on

assumptions related to gas utilization rates, byproduct formation, and the effectiveness of emission control technologies. Variability in process conditions, technology configurations, and abatement system performance across facilities may contribute to uncertainty in the estimated emissions. Because emissions are influenced by both process-specific factors and control technologies, variability in these parameters is a key source of uncertainty.

For this *GHGIA*, the overall uncertainty associated with national estimates of emissions from the electronic industry is assumed to be similar to EPA (2025) given the use of the same basic methodology and data sources for most years, calculated using the *2006 IPCC Guidelines* Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). This confidence level indicates a range of approximately 6 percent below and 6 percent above the emission estimate in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 4-65.

4.5 Substitution of Ozone Depleting Substances (Source Category 2F)

The substitution of ozone-depleting substances generates emissions of HFCs, PFCs, and other fluorinated GHGs used as alternatives to ozone-depleting substances (ODS) in a variety of industrial and consumer applications (IPCC, 2006), including refrigeration and air conditioning, foam blowing, aerosols, fire suppression, and solvents. The transition away from ODS was driven primarily by international agreements under the Montreal Protocol on Substances that Deplete the Ozone Layer, which established a global framework for phasing out ODS production and consumption (UNEP, 2023). As ODS were phased out, industries adopted alternative chemicals and technologies that do not harm the stratospheric ozone layer, but many of these substitutes are potent GHGs and can contribute to climate change if released to the atmosphere. In 2020, the U.S. Environmental Protection Agency (EPA) was directed by Congress to address HFCs through the American Innovation and Manufacturing (AIM) Act by implementing a phase down of the production and consumption of HFCs, managing use and reuse, and facilitating the transition to next-generation technologies.

Emissions from this source category occur during the manufacture, use, servicing, and disposal of products and equipment that contain HFCs, PFCs, and other fluorinated substitutes for ODS.[33] The magnitude of emissions depends on stock, equipment lifetimes, leakage rates during operation, servicing practices, and the recovery or destruction of refrigerants at the end of equipment life (IPCC, 2006). Demand for refrigeration, air conditioning, insulating foams, and other applications that use fluorinated substitutes has increased over time, influencing emissions trends in this category. At the same time, regulatory measures, technological improvements, and industry initiatives have promoted the adoption of lower-global-warming-potential alternatives and improved management of refrigerants.

Estimated emissions of HFCs, PFCs and CO_2 from ODS substitutes are presented in Table 4-59. In 2024, emissions from this source category were estimated to be 192.4 MMT CO_2 Eq., an increase of 64,000 percent since 1990 and an increase of 2 percent since 2023.

[33] Emissions from the production of fluorinated gases themselves are reported under fluorochemical production source categories elsewhere in this *GHGIA*. CO_2 emissions associated with fossil fuel combustion used to manufacture equipment or operate facilities are reported separately in the Energy chapter under industrial fuel combustion.

Table 4-59: Emissions from ODS Substitutes (MMT CO_2 Eq.)

Gas	1990	2005	2020	2021	2022	2023	2024
HFC-23	0.0	+	+	+	+	+	+
HFC-32	0.0	0.3	7.7	9.4	10.5	11.4	12.2
HFC-125	+	9.4	60.5	68.9	74.4	78.9	83.0
HFC-134a	+	72.9	54.1	50.0	48.3	47.2	46.0
HFC-143a	+	12.1	34.7	34.6	34.2	33.6	33.0
HFC-236fa	0.0	1.0	0.7	0.6	0.6	0.5	0.5
CF_4	0.0	+	+	+	+	+	+
CO_2	+	+	+	+	+	+	+
Other Saturated HFCs[a]	0.3	6.9	15.9	16.3	16.9	17.3	17.7
Other PFCs and HFOs[b]	+	0.1	+	+	+	+	+
Total	**0.3**	**102.7**	**173.7**	**179.9**	**184.9**	**189.0**	**192.4**

+ 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), C4F10, 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 global warming potential (GWP) value used for PFC/PFPEs was based upon n-C_6F_{14}.

Note: Totals may not sum due to independent rounding.

Emissions from ODS substitutes are distributed across multiple end-use sectors, with refrigeration and air conditioning representing the largest share of emissions. Other contributing sectors include foam blowing agents, aerosols, fire protection systems, and solvent use. Emissions by sector are presented in Table 4-60.

Table 4-60: Emissions from ODS Substitutes by Sector (MMT CO_2 Eq.)

Source	1990	2005	2020	2021	2022	2023	2024
Refrigeration/AC	+	86.2	138.1	146.7	151.3	154.7	157.4
Commercial Refrigeration	+	14.9	40.6	41.0	41.4	41.8	41.9
Domestic Refrigeration	+	0.2	1.2	1.1	1.0	0.9	0.9
Industrial Process Refrigeration	+	5.0	23.7	24.6	25.3	26.0	26.8
Transport Refrigeration	+	1.6	7.9	8.4	8.8	9.0	9.3
Mobile Air Conditioning	+	61.5	24.6	22.9	20.8	18.8	16.7
Residential Stationary Air Conditioning	+	1.2	33.2	41.5	46.4	50.3	53.4
Commercial Stationary Air Conditioning	+	1.7	6.9	7.3	7.6	7.9	8.4
Aerosols	0.2	10.2	17.3	17.7	17.0	17.4	17.7
Foams	+	3.5	13.7	10.8	11.7	12.1	12.3
Solvents	+	1.6	2.0	2.1	2.1	2.2	2.2
Fire Extinguishing	+	1.2	2.5	2.6	2.6	2.7	2.8
Total	0.3	102.7	173.7	179.9	184.9	189.0	192.4

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Methods

The methodological approach for estimating emissions from the substitution of ODS is consistent with the approach described in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). Emissions for 2024 were forecasted based on historical data.

Recalculations

No recalculations were implemented for 1990–2023 for this source category.

Uncertainty

Uncertainty in emission estimates for the substitution of ODS is primarily associated with activity data estimates of equipment stock, refrigerant consumption, and the use of fluorinated substitutes across multiple end-use applications. Activity data uncertainty reflects the completeness and accuracy of estimates of equipment populations, usage patterns, and refrigerant demand, which are derived from a combination of industry data, market statistics, and modeling assumptions. Variability in equipment lifetimes, usage rates, and market trends may contribute to uncertainty in the national estimate.

Additional uncertainty arises from emission factors used to estimate releases of fluorinated GHGs from equipment during operation, servicing, and disposal. Emission estimates depend on

assumptions related to leak rates, charge sizes, recovery efficiencies, and end-of-life practices. Variability in equipment design, maintenance practices, and technology adoption across sectors may contribute to uncertainty in the estimated emissions. Because emissions are distributed across multiple applications and occur over extended timeframes, uncertainty in these parameters is a key source of variability in the estimates.

For this *GHGIA*, the overall uncertainty associated with national estimates of emissions from the substitution of ODS is assumed to be similar to EPA (2025) given the use of the same basic methodology and data sources for most years, calculated using the *2006 IPCC Guidelines* Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). This confidence level indicates a range of approximately 3.1 percent below and 19.6 percent above the emission estimate in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 4-65. HFC use and emissions are anticipated to begin decreasing as the United States implements the phasedown of HFC production and consumption and sector-based transitions to lower-GWP alternatives under the AIM Act, which could introduce additional uncertainty to the projection of 2024 emissions based on historical estimates.

4.6 Other Product Manufacturing and Use

4.6.1 Electrical Equipment (Source Category 2G1)

Electrical equipment generates emissions of SF_6 and, to a lesser extent, carbon tetrafluoride (CF_4) from equipment used in the transmission and distribution of electricity (IPCC, 2006). SF_6 is widely used in gas-insulated switchgear, circuit breakers, and other high-voltage electrical equipment because of its excellent dielectric strength and arc-quenching properties, which allow SF_6-insulated equipment to operate safely and reliably at high voltages in compact installations. While emitted in much smaller quantities, CF_4 can be used in addition to SF_6 to prevent its liquefaction at low temperatures (Middleton, 2000).

Emissions occur when SF_6 and CF_4 escape from electrical equipment during normal operation, equipment servicing, installation, or equipment decommissioning, whether by leakage or intentional release during equipment maintenance or replacement. Because SF_6 has a very high global warming potential and a long atmospheric lifetime, even relatively small emissions can contribute significantly to GHG emissions (IPCC, 2006).

This source category includes emissions of SF_6 and CF_4 associated with the operation and maintenance of gas-insulated electrical equipment used in electricity transmission and distribution systems. Emissions associated with fossil fuel combustion used to generate electricity are reported separately in the Energy chapter. Emissions associated with the manufacture of SF_6 itself or other fluorinated gases are reported under fluorochemical production source categories elsewhere in this *GHGIA*.

SF_6-insulated equipment is used extensively by electric utilities and industrial power systems because of its reliability and space efficiency, particularly in high-voltage substations and densely populated areas where compact equipment designs are advantageous. Emissions from this source category are influenced by the quantity of installed SF_6-containing equipment, equipment maintenance practices, and the implementation of emission reduction programs within the electric power industry (International Electrotechnical Commission [IEC], 2018).

Estimated emissions of SF_6 and CF_4 from electric power systems and electrical equipment manufacturers are presented in Table 4-61. In 2024, emissions from this source category were estimated to be 5.1 MMT CO_2 Eq., a decrease of 79 percent since 1990 and no change since 2023.

Table 4-61: Emissions from Electric Power Systems and Electrical Equipment Manufacturers (MMT CO_2 Eq.)

Source/Gas	1990	2005	2020	2021	2022	2023	2024
SF_6	**24.6**	**11.8**	**5.5**	**5.5**	**4.9**	**5.1**	**5.1**
Electric Power Systems	24.3	11.1	5.0	5.1	47.6	4.9	4.9
Electrical Equipment Manufacture	0.3	0.7	0.5	0.4	0.3	0.2	0.2
CF_4	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Electric Power Systems	+	+	+	+	+	+	+
Electrical Equipment Manufacture	+	+	+	+	+	+	+
Total	**24.6**	**11.8**	**5.5**	**5.5**	**4.9**	**5.1**	**5.1**

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

Methods

The methodological approach for estimating electrical equipment emissions is consistent with the approach described in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). For 2024, complete activity data were not available at the time of analysis. Accordingly, 2024 activity levels were held constant at 2023 values for all inputs.

Recalculations

No recalculations were implemented for 1990–2023 for this source category.

Uncertainty

Uncertainty in emission estimates for electrical equipment is primarily associated with activity data estimates of SF_6 contained in transmission and distribution equipment and the quantities emitted during equipment operation and maintenance. Activity data uncertainty reflects the completeness and accuracy of reported equipment inventories, gas stocks, and emissions from electric utilities, which are generally well characterized due to facility-level reporting through EPA's GHGRP. However, differences in reporting practices, equipment coverage, and data aggregation across utilities may contribute to uncertainty in the national estimate.

Additional uncertainty arises from emission factors used to estimate releases of SF_6 from equipment. Emission estimates depend on assumptions related to leakage rates, equipment age, maintenance practices, and gas handling procedures. Variability in equipment types, operating conditions, and emission reduction practices across the electric power sector may contribute to uncertainty in the estimated emissions. Because emissions are influenced by both equipment characteristics and operational practices, variability in these parameters is a key source of uncertainty.

For this *GHGIA*, the overall uncertainty associated with national estimates of SF_6 emissions from electrical equipment is assumed to be similar to EPA (2025) given the use of the same basic methodology and data sources for most years, calculated using the *2006 IPCC Guidelines* Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). This confidence level indicates a range of approximately 20 percent below and 20 percent above the emission estimate in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 4-65.

Uncertainty associated with CF_4 emissions from electrical equipment is not estimated due to the small magnitude of emissions and limited data availability.

4.6.2 SF_6 and PFCs from Other Product Use (Source Category 2G2)

Emissions of SF_6 and PFCs from other product use arise from specialized applications that use these gases for scientific, technical, and industrial purposes (e.g., particle accelerators, tracer gas studies). These gases are valued for their chemical stability, electrical insulating properties, and thermal characteristics, which make them suitable for a range of niche industrial and scientific applications.

During these applications, emissions can occur through equipment leakage, venting during servicing, or losses during operation, and are influenced by the number of systems in use and gas management practices (IPCC, 2006). Because these gases have very high global warming potentials and long atmospheric lifetimes, even small releases contribute to GHG emissions (IPCC, 2006).

This source category includes emissions of SF_6 and PFCs associated with product uses not otherwise accounted for in other source categories within this *GHGIA*. Emissions associated with electrical transmission and distribution equipment are reported separately under the electrical equipment source category. Emissions associated with semiconductor manufacturing are reported under the electronic industry source category, and emissions from the production of fluorinated gases are reported under fluorochemical production source categories elsewhere in this *GHGIA*.

Applications covered under this category are generally specialized and relatively small compared to other fluorinated gas sources, but emissions can occur over extended periods due to the long service life of equipment and the persistence of these gases in the atmosphere. Trends in emissions are influenced by the number of systems in operation, technological changes in scientific equipment, and improved management practices for handling fluorinated gases.

Estimated emissions of SF_6 and PFCs from other product use are presented in Table 4-62. In 2024, emissions from this source category were estimated to be 1.0 MMT CO_2 Eq., a decrease of 33 percent since 1990 and no change since 2023.

Table 4-62: Emissions from Other Product Use (MMT CO_2 Eq.)

Gas/Source	1990	2005	2020	2021	2022	2023	2024
SF_6	0.6	0.6	0.3	+	0.2	0.5	0.5
Total Airborne Warning and Control Systems	**0.6**	**0.6**	**0.3**	**+**	**0.2**	**0.5**	**0.5**
SF_6	0.3	0.3	0.0	0.0	0.0	0.1	0.1
PFC	0.1	0.1	0.1	0.1	0.1	0.2	0.2
NF_3	0.0	0.0	0.0	0.0	+	0.0	0.0
Total Other Military Applications	**0.4**	**0.4**	**0.1**	**0.1**	**0.1**	**0.2**	**0.2**
SF_6	0.4	0.5	0.1	0.2	0.1	0.1	0.1
PFC-14	+	+	+	+	+	+	+
Total Particle Accelerators	**0.4**	**0.5**	**0.1**	**0.2**	**0.1**	**0.1**	**0.1**
SF_6	+	+	0.1	0.2	0.2	0.1	0.1
PFC	+	+	+	+	+	+	+
NF_3[b]	+	+	+	+	+	0.0	0.0
HFCs[a,b]	0.0	0.0	+	0.0	0.0	0.0	0.0
Total Other Scientific Applications	**+**	**+**	**0.1**	**0.2**	**0.2**	**0.1**	**0.1**
Total Other Product Use	**1.5**	**1.5**	**0.7**	**0.5**	**0.6**	**1.0**	**1.0**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] HFCs emissions not accounted for elsewhere in this *GHGIA*.

[b] Listed under "other product manufacture and use" in the summary tables.

Note: Totals may not sum due to independent rounding.

Methods

The methodological approach for estimating emissions of SF_6 and PFCs from other product use is consistent with the approach described in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). For 2024, complete activity data were not available at the time of analysis. Accordingly, 2024 activity levels were held constant at 2023 values for all inputs.

Recalculations

No recalculations were implemented for 1990–2023 for this source category.

Uncertainty

Uncertainty in emission estimates for SF_6 and PFCs from other product use is primarily associated with activity data estimates of the use of fluorinated gases in specialized applications, including scientific and technical uses. Activity data uncertainty reflects the completeness and accuracy of estimates of equipment populations, gas usage, and operational practices, which are derived from

a combination of limited reporting, industry information, and estimation methods. Variability in equipment usage and the lack of comprehensive data sources may contribute to uncertainty in the national estimate.

Additional uncertainty arises from emission factors used to estimate releases of SF_6 and PFCs during product use and servicing. Emission estimates depend on assumptions related to leakage rates, equipment operation, and gas handling practices. Variability in application types, operational conditions, and emission pathways across these specialized uses may contribute to uncertainty in the estimated emissions. Because emissions are associated with a diverse set of applications and are often estimated using limited data, uncertainty in these parameters is a key source of variability.

For this *GHGIA*, the overall uncertainty associated with national estimates of emissions from SF_6 and PFCs from other product use is assumed to be similar to EPA (2025) given the use of the same basic methodology and data sources for most years, calculated using the *2006 IPCC Guidelines* Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). This confidence level indicates a range of approximately 49 percent below and 51 percent above the emission estimate in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 4-65.

4.6.3 Nitrous Oxide from Product Uses (Source Category 2G3)

Certain commercial and industrial products use N_2O in ways that can result in GHG emissions during product use or disposal (IPCC, 2006). N_2O is valued for its chemical stability and physical properties and is used in applications such as medical anesthetics, food processing propellants (e.g., whipped cream dispensers), and other specialty applications (EPA, 2025). Other specialty applications included semiconductor manufacturing, atomic absorption spectrometry, sodium azide production, auto racing, and blowtorch use.

In applications for medical and food, N_2O is typically stored under pressure and released during normal product use. In these applications, the N_2O contained in these products is ultimately released to the atmosphere during use (EPA 2025; IPCC, 2006). For the other specialty applications, N_2O is consumed during use.

This source category includes emissions of N_2O associated with product uses not otherwise accounted for in other source categories within this *GHGIA*. Small quantities of N_2O are used as the oxidizing agent and etchant in semiconductor manufacturing, and emissions of N_2O from semiconductor manufacturing are described in Section 4.4.

Estimated emissions of N_2O from product use are presented in Table 4-63. In 2024, emissions from this source category were estimated to be 3.8 MMT CO_2 Eq., no change since 1990 and no change since 2023.

Table 4-63: Emissions from N_2O Product Usage (MMT CO_2 Eq.)

Year	1990	2005	2020	2021	2022	2023	2024
N_2O Product Uses	3.8	3.8	3.8	3.8	3.8	3.8	3.8

N_2O production is the primary activity driver for emissions from this source category (EPA, 2025). N_2O is produced for use in medical applications, food processing, and other specialty end uses/applications. Trends in N_2O production in the United States are presented in Table 4-64.

Table 4-64: N_2O Production (kt)

Year	1990	2005	2020	2021	2022	2023	2024
Production	16	15	15	15	15	15	15

Methods

The methodological approach for estimating emissions of N_2O from product use is consistent with the approach described in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025).

Recalculations

No recalculations were implemented for 1990-2023 for this source category.

Uncertainty

Uncertainty in emission estimates for N_2O from product uses is associated with the parameters used to estimate N_2O emissions, including production data (activity data), total market share of each end use/application, and the emission factors applied to each end use, respectively. Activity data uncertainty reflects the accuracy of N_2O annual nationwide production data and the completeness and accuracy of estimates of N_2O use (i.e., market share) in products such as medical applications, food processing, and other specialty uses, which are derived from a combination of industry data and estimation methods. Uncertainty from emission factors used to estimate releases of N_2O during product use is also considered. Emission estimates depend on assumptions related to the fraction of N_2O released during use, which is generally assumed to be high for medical and food use (100 percent emitted) and low for other application uses (0 percent emitted) where N_2O is consumed in the product use (IPCC, 2006; EPA, 2025).

For this *GHGIA*, the overall uncertainty associated with national estimates of emissions from N_2O product uses is assumed to be similar to EPA (2025) given the use of the same basic methodology and data sources for most years, calculated using the *2006 IPCC Guidelines* Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). This confidence level indicates a range of approximately 24 percent below and 24 percent above the emission estimate in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 4-65.

4.7 IPPU Uncertainty Summary

Table 4-65 shows the 2024 uncertainty summary for all IPPU sector sources. A discussion of the uncertainty ranges is included in each source category's respective chapter section.

Table 4-65: Quantitative Uncertainty Summary by IPPU Sector Source

Source	Gas	2024 Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cement Production	CO_2	37.2	35.7	39.1	-4%	5%
Lime Production	CO_2	10.8	10.6	11.0	-2%	2%
Glass Production	CO_2	1.8	1.7	1.8	-3%	3%
Other Process Uses of Carbonates	CO_2	7.1	6.3	8.2	-11%	15%
Ammonia Production	CO_2	14.4	13.8	15.0	-4%	4%
Urea Consumption for Non-Agricultural Purposes	CO_2	5.9	5.6	6.1	-5%	4%
Nitric Acid Production	N_2O	8.3	7.8	8.8	-6%	6%
Adipic Acid Production	N_2O	1.2	1.1	1.2	-4%	4%
Caprolactam Production	N_2O	1.4	0.9	1.8	-31%	31%
Carbide Production and Consumption	CO_2	0.2	0.2	0.2	-10%	10%
Carbide Production and Consumption	CH_4	+	0.0	0.0	-10%	11%
Titanium Dioxide Production	CO_2	1.3	1.1	1.4	-13%	13%
Soda Ash Production	CO_2	1.9	1.7	2.0	-9%	8%
Petrochemical Production	CO_2	28.9	27.7	30.1	-4%	4%
Petrochemical Production	CH_4	+	0.0	0.0	-14%	14%
HCFC-22 Production	HFC-23	0.4	0.4	0.4	-7%	10%

(continued)

Table 4-65: Quantitative Uncertainty Summary for All IPPU Sources *(continued)*

Source	Gas	2024 Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Production of Fluorochemicals Other than HCFC-22	HFCs, PFCs, SF_6, and NF_3	4.3	3.4	5.1	-20%	20%
Non-EOR Carbon Dioxide Utilization	CO_2	2.1	2.0	2.3	-5%	5%
Phosphoric Acid Production	CO_2	0.8	0.7	1.0	-18%	20%
Iron and Steel Production and Metallurgical Coke Production	CO_2	46.7	39.3	54.2	-16%	16%
Iron and Steel Production and Metallurgical Coke Production	CH_4	+	0.0	0.0	-20%	21%
Ferroalloy Production	CO_2	1.2	1.1	1.4	-13%	13%
Ferroalloy Production	CH_4	+	0.0	0.0	-12%	13%
Aluminum Production	CO_2	1.243	1.2	1.3	-3%	3%
Aluminum Production	CF_4	0.415	0.4	0.5	-9%	11%
Aluminum Production	C_2F_6	0.043	0.0	0.0	-9%	9%
Aluminum Production	PFCs	0.5	0.4	0.5	-8%	10%
Magnesium Production	SF_6, HFC-134a, CO_2	0.0	0.0	0.0	-8.2%	8.1%
Lead Production	CO_2	0.5	0.4	0.5	-15%	15%
Zinc Production	CO_2	0.9	0.7	1.1	-19%	21%
Electronics Industry	HFC, PFC, SF_6, NF_3, and N_2O	4.2	4.0	4.5	-6%	6%
Substitution of Ozone Depleting Substances	HFCs/ PFCs	192.4	186.4	230.1	-3.1%	19.6%

(continued)

Table 4-65: Quantitative Uncertainty Summary for All IPPU Sources *(continued)*

Source	Gas	2024 Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Electrical Equipment	SF_6	5.1	4.1	6.1	-20%	20%
	CF_4	NO	NE	NE	NE	NE
SF_6 and PFCs from Other Product Use	SF_6, PFC, HFC and NF_3	1.0	0.5	1.5	-49%	51%
N_2O from Product Uses	N_2O	3.8	2.9	4.7	-24%	24%

+ Does not exceed 0.05 MMT CO_2 Eq.

NO (Not occurring)

NE (Not estimated)

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Please see the Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023 (EPA, 2025) for additional references.

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