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Greenhouse Gas Inventory and Analysis for the United States

1990-2024











Authors

Full report: Mausami Desai[1]*, Vincent Camobreco[1], Toby Hedger[1], William Irving[1], Kenna Rewcastle[1], John Steller[1], Lindsay Barbieri[2], Melissa Weitz[1], Tanvi Murumkar[1], Allen Fawcett[1], Jiehong Lou[1], Ryna Cui[1], Nate Hultman[1] (*corresponding author: desaim@umd.edu)

Executive Summary: Mausami Desai, Vincent Camobreco, Toby Hedger, William Irving, Kenna Rewcastle, John Steller, Lindsay Barbieri, Melissa Weitz, Tanvi Murumkar, Allen Fawcett, Jiehong Lou, Ryna Cui, Nate Hultman

Chapter 1. Introduction: Mausami Desai, William Irving, Allen Fawcett, Jiehong Lou, Ryna Cui, Nate Hultman

Chapter 2. Trends in Greenhouse Gas Emissions and Removals: Mausami Desai, William Irving

Chapter 3. Energy: Vincent Camobreco, Melissa Weitz

Chapter 4. Industrial Processes and Product Use: Toby Hedger, Vincent Camobreco, Mausami Desai, John Steller

Chapter 5. Agriculture: Kenna Rewcastle, John Steller

Chapter 6. Land Use, Land-Use Change and Forestry: John Steller, Kenna Rewcastle, Lindsay Barbieri

Chapter 7. Waste: Mausami Desai

Chapter 8. Other: Mausami Desai, Vincent Camobreco

Chapter 9. Recalculations and Improvements: Mausami Desai, Vincent Camobreco

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[1] Center for Global Sustainability, University of Maryland, College Park.
[2] Department of Geographical Sciences, University of Maryland, College Park

Foreword

There is scientific consensus that the planet is warming due to anthropogenic greenhouse gas (GHG) emissions. In response, a decades-long process linking scientific inquiry and policy decision-making has led to a set of shared processes and goals that can help inform strategies to reduce GHG emissions in diverse subnational and national policy contexts. Fundamental to these actions is transparency on basic information regarding greenhouse gas emissions, including on quantities of specific greenhouse gases being emitted and from what economic sectors. Such information provides the basis for understanding both what is happening across national economies and insight into policy strategies that may be valuable now and into the future. In this context, it is critical for scientific, policy, and civil society communities to have access to robust, transparent, consistent, and regularly reported data at both the national and subnational levels.

This report presents an annual inventory of greenhouse gas sources and sinks covering the geographical region of the United States of America. The data are for years 1990 through 2024, the most recent year data are available. The *Greenhouse Gas Inventory and Analysis for the United States (GHGIA)* has grounded the data collection, analysis, and presentation in practices that can enable comparability and continuity with past U.S. official inventories prepared by the U.S. Environmental Protection Agency. The *GHGIA* adheres to good practice as defined by the Intergovernmental Panel on Climate Change and adheres to international standards for transparency, accuracy, completeness, comparability, and consistency. We anticipate publishing annual reports following this approach in future years.

Some updates have been made in this *GHGIA* compared to previous, official reports. Nevertheless, there are many areas of opportunity for enhancement and improvement in the future. These include refining the specifics of this approach over time and working across the larger scientific community to improve inventory practice and integrate new methods and analytical approaches into these activities, both for this effort in the U.S. as well as for use by other countries and internationally. We look forward to continued partnership with others in the larger community in this effort.

The Center for Global Sustainability shares this *GHGIA* with the community with the hope that having open access to these data will support scientific and technical discussions, foster innovation and improvement in processes, and enhance learning across the global community. We are deeply grateful for the partnership from our research and scientific collaborators, from those who provided financial support to do this work, and from many in the larger U.S. and international communities who have provided support and feedback.

Nate Hultman
Director, Center for Global Sustainability
University of Maryland, College Park

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Executive Summary

ES.1 Background Information

The *Greenhouse Gas Inventory and Analysis for the United States (GHGIA)* presents a comprehensive picture of greenhouse gas (GHG) sources and sinks covering the geographical region of the United States. The data are presented for each year from 1990 through 2024, the latter being the most recent year comprehensive data are available for the entire economy.

Along with detailed results for single years and analyses of trends over time, this *GHGIA* presents methodological descriptions, data inputs, a characterization of uncertainties, recalculations, and improvements. The following gases are included: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). It also follows the five standard reporting sectors: energy; industrial processes and product use; agriculture; land use, land-use change and forestry (LULUCF); and waste.

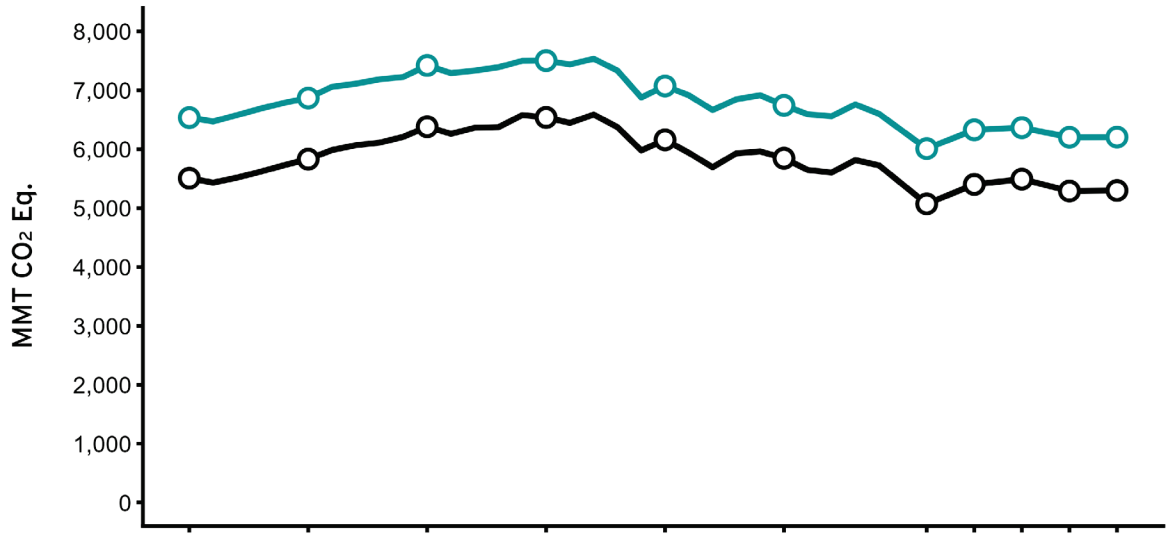
The *GHGIA* adheres to good practice as defined by the Intergovernmental Panel on Climate Change (IPCC) and to international standards for transparency, accuracy, completeness, comparability, and consistency. Users will find it possible to crosswalk the structure of this *GHGIA*, along with the results, with inventories from other countries. The use of established methodologies and data collection practices in this *GHGIA* can support its use by diverse scientific and policy communities. Moreover, this *GHGIA* has been developed in a manner that supports comparability and continuity with past official U.S. inventories prepared by the U.S. Environmental Protection Agency. The *GHGIA* is not an official national inventory produced on behalf of the United States, nor is it an official submission in the context of the United Nations Framework Convention on Climate Change (UNFCCC).

ES.2 Summary of Trends

Figure ES-1 shows the trend in both gross and net U.S. GHG emissions and removals since 1990. In 2024, total gross emissions were 6,205.3 million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.). This total is a 5.1 percent decrease from 1990 and a 0.04 percent annual increase from 2023. The decreasing trend from around 2005 is associated primarily with a decrease in CO_2 emissions from fossil fuel combustion. The factors influencing this change, including declining emissions from electricity production, are discussed in more detail in Chapter 2 (Trends) and in Chapter 3 (Energy).

In 2024, total net U.S. GHG emissions, including emissions and sinks from LULUCF, were 5,298.8 MMT CO_2 Eq. This total is a 3.8 percent decrease from 1990 and a 0.2 percent annual increase from 2023. Sequestration of CO_2 in the LULUCF sector offset the equivalent of 14.6 percent of total gross emissions in 2024 (906.5 MMT CO_2 Eq.).

Figure ES-1: U.S. Gross and Net Emissions



	1990	1995	2000	2005	2010	2015	2020	2021	2022	2023	2024	90-24
Gross Emissions	6,536	6,868	7,422	7,504	7,073	6,744	6,010	6,328	6,365	6,203	6,205	-5.1%
Net Emissions	5,507	5,831	6,381	6,539	6,159	5,846	5,071	5,402	5,491	5,290	5,299	-3.8%

ES.3 Overview of Source and Sink Categories

Figure ES-2 indicates the largest categories that contributed to overall GHG emissions in 2024, and Figure ES-3 shows categories that have experienced significant changes since 1990. Together, these categories are a subset of the inventory formally defined as "key categories" by the IPCC because they have the most significant impact on overall results.

Figure ES-2: Key Categories for 2024 and Their Emissions (Gross)

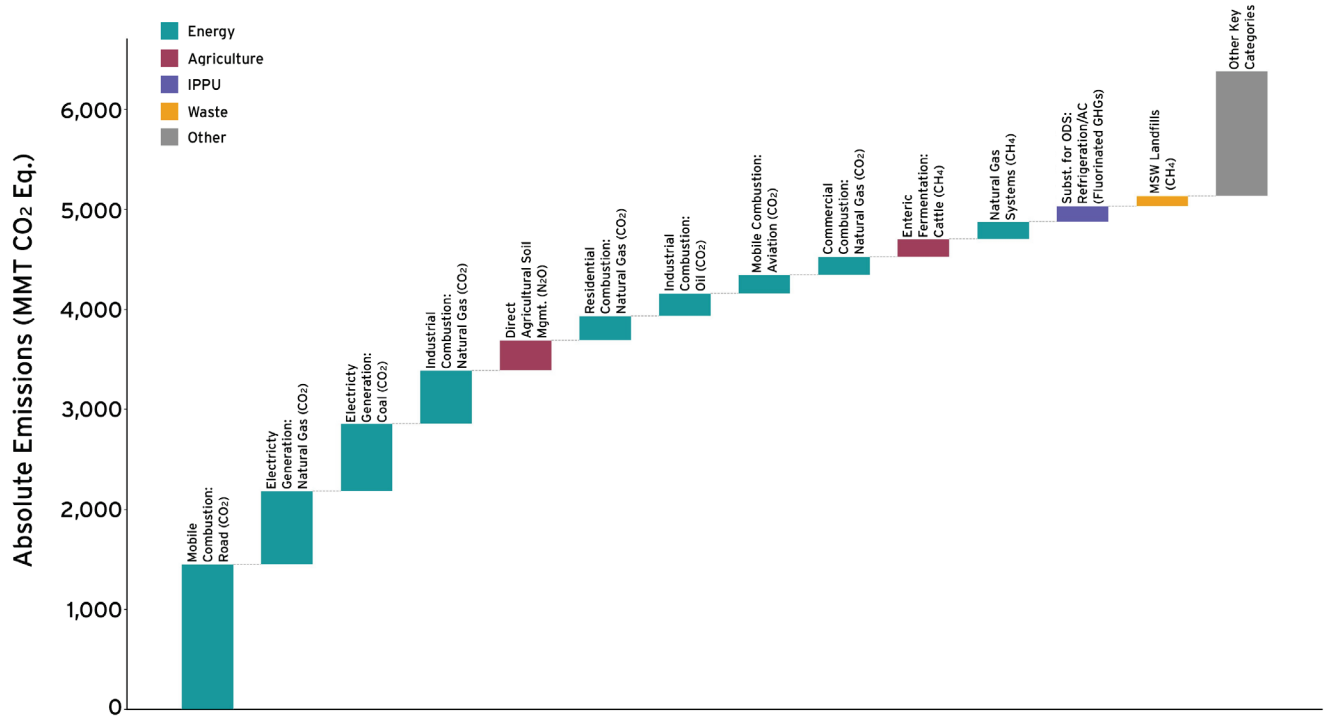
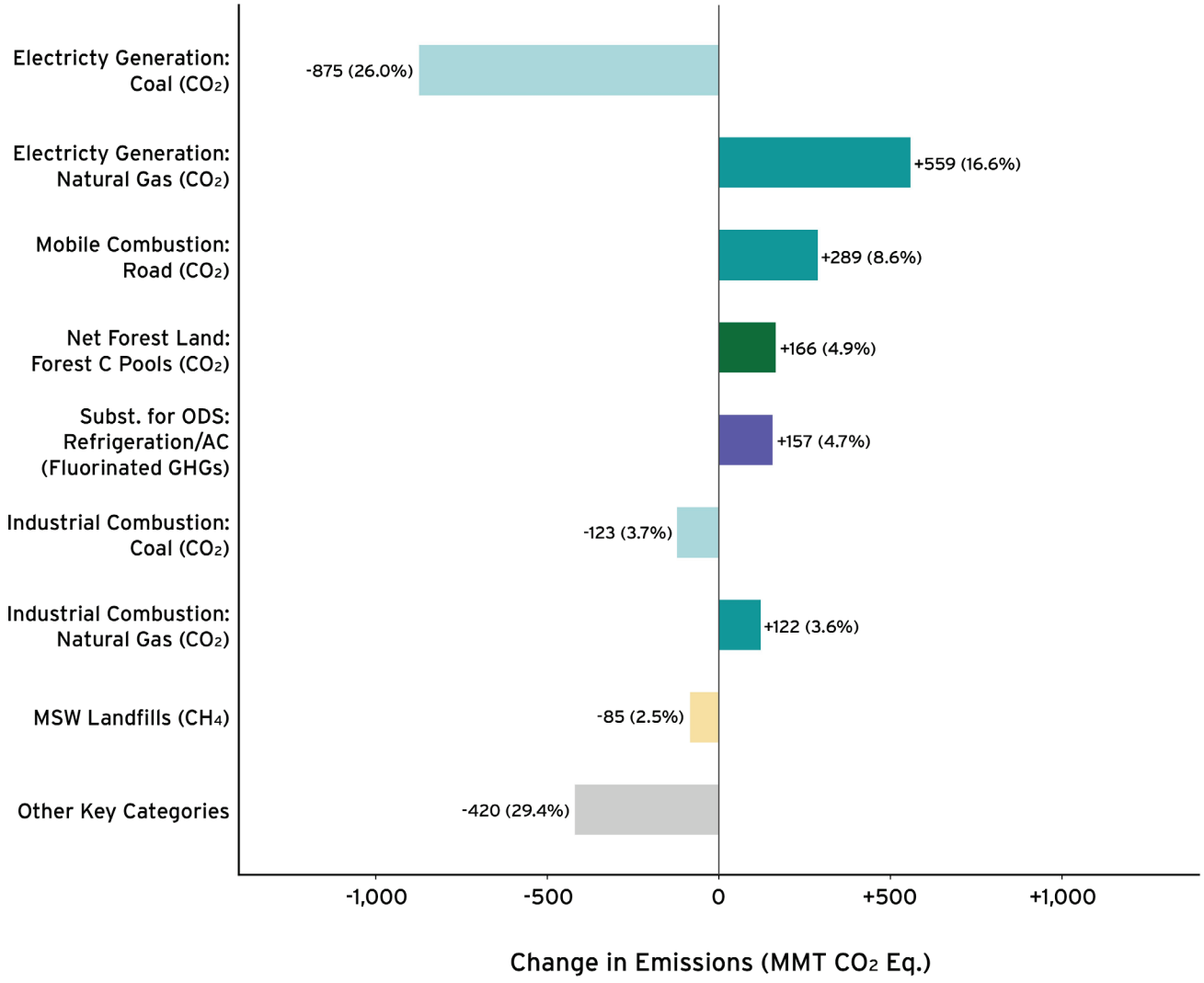


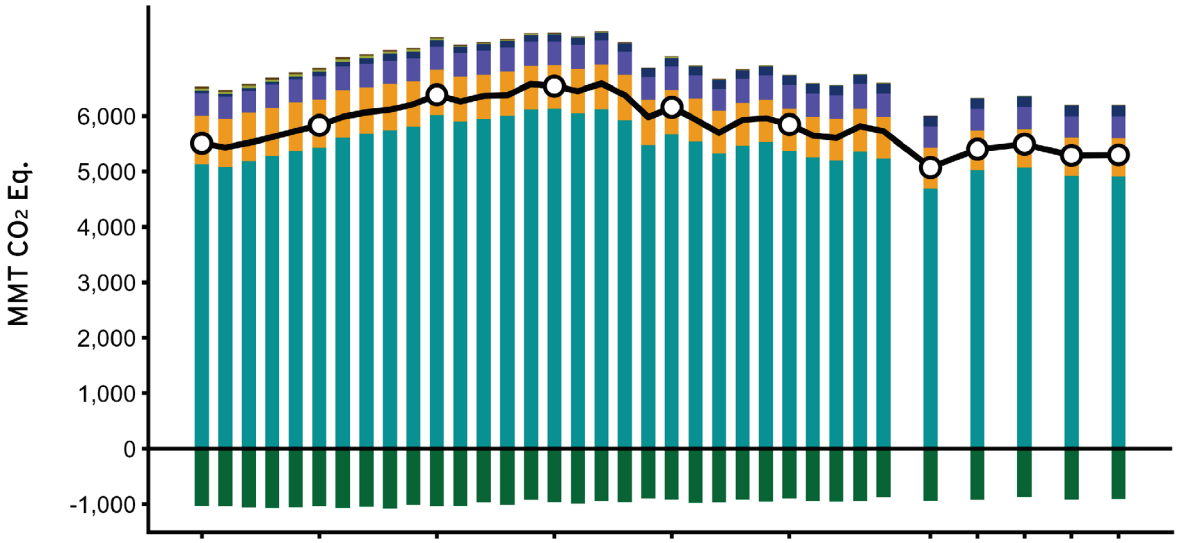
Figure ES-3: Key Categories with the Largest Changes Since 1990



ES.4 Emissions and Removals by Gas

Figure ES-4 shows the trend in emissions and removals since 1990 by GHG. CO_2 makes up the largest share of emissions in each year, and the 4.3 percent decline since 1990 is also the largest contributor to the overall reduction in emissions. On a percentage basis, CH_4, PFCs, and SF_6 also declined significantly since 1990, while HFCs experienced the largest growth. N_2O emissions did not change significantly in aggregate, but category level changes (e.g., in mobile combustion) are discussed more in Chapter 2 (Trends) and Chapter 3 (Energy).

Figure ES-4: Trends in Greenhouse Gas Emissions and Sinks by Gas

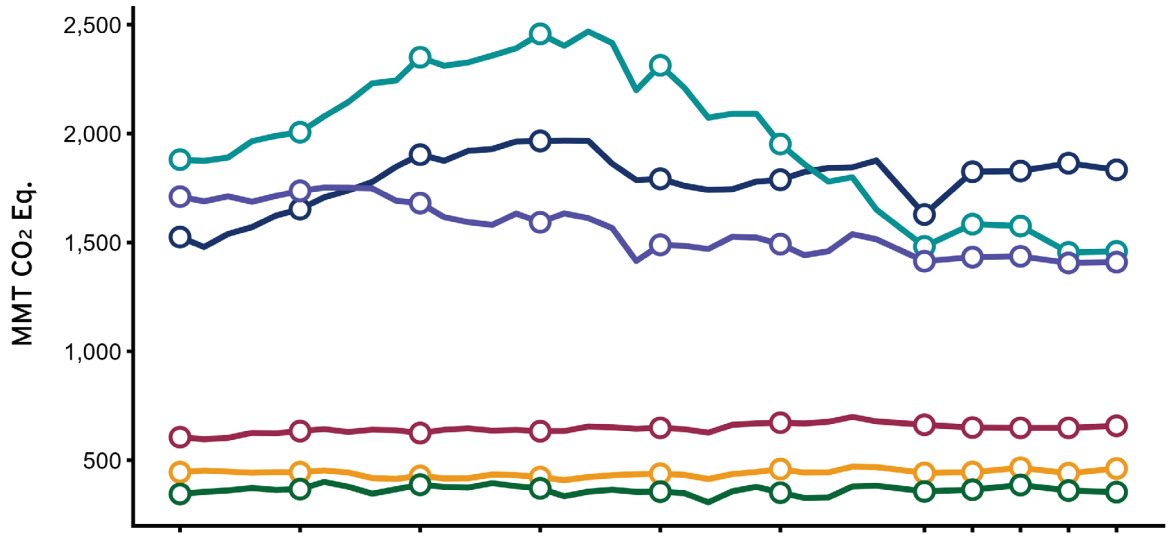


	1990	1995	2000	2005	2010	2015	2020	2021	2022	2023	2024	90-24
CO_2	5,130	5,431	6,019	6,125	5,664	5,366	4,694	5,018	5,066	4,924	4,912	-4.3%
CH_4	873	867	818	797	810	764	731	715	696	685	687	-21.3%
N_2O	408	423	413	425	421	429	391	396	399	388	398	-2.4%
HFCs	48	74	116	125	159	168	178	184	190	191	194	306.9%
SF_6	38	35	27	20	12	8	8	8	7	8	8	-79.6%
PFCs	40	37	29	10	7	7	7	6	7	6	6	-85.6%
NF_3	+	+	1	1	1	1	1	1	1	1	1	335.8%
LULUCF Net	(1,029)	(1,037)	(1,040)	(965)	(914)	(898)	(939)	(927)	(874)	(913)	(907)	11.9%
Net Emissions	**5,507**	**5,831**	**6,381**	**6,539**	**6,159**	**5,846**	**5,071**	**5,402**	**5,491**	**5,290**	**5,299**	**-3.8%**

ES.5 Emissions by Economic Sector

GHG emissions can also be categorized according to commonly used economic sectors. One of the benefits of this approach is that it shows how economic activities consume fossil fuels for energy, which is by far the largest category of emissions. Figure ES-5 shows the relative contribution of these sectors and their emission changes over time. Electric power was the largest economic sector in 1990 but was overtaken by transportation in 2017. Electric power emissions can be assigned to the economic sectors that consume electricity to provide an additional characterization of U.S. emissions. Please see Chapter 2 (Trends) and Chapter 3 (Energy) for more information.

Figure ES-5: Trends by Economic Sector



	1990	1995	2000	2005	2010	2015	2020	2021	2022	2023	2024	90-24
Transportation	1,525	1,653	1,903	1,966	1,792	1,788	1,628	1,825	1,828	1,864	1,833	20.2%
Electric Power	1,880	2,006	2,350	2,457	2,313	1,952	1,482	1,584	1,575	1,454	1,459	-22.4%
Industry	1,710	1,737	1,681	1,592	1,489	1,492	1,414	1,433	1,436	1,406	1,410	-17.6%
Agriculture	606	634	625	634	649	673	663	650	649	649	658	8.6%
Commercial	445	445	428	423	438	460	442	446	466	441	462	3.8%
Residential	346	368	388	371	356	351	357	365	387	361	354	2.5%
Total Gross Emissions	**6,513**	**6,843**	**7,375**	**7,444**	**7,038**	**6,716**	**5,986**	**6,302**	**6,341**	**6,175**	**6,177**	**-5.2%**

Note: Figure ES-5 excludes emissions from U.S. Territories and excludes emissions and removals from LULUCF sector.

ES.6 Improvements

This is the first *GHGIA* for the United States published by the Center for Global Sustainability. Future versions of the *GHGIA* will benefit from improvements consistent with IPCC good practice, including the refinement of existing methods, engagement with the larger scientific community to integrate new methods and analytical approaches, and innovations in data presentation and the online user experience.

Future versions may also reflect methodological evolution due in part to changes in availability of official data, such as facility-level GHG reporting and federal statistics, as well as opportunities to benefit from new nongovernmental initiatives.



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1

Introduction

Chapter 1. Introduction

1.1 Background

Overview

A greenhouse gas inventory (GHGI) is a fundamental component of an overall strategy to plan, manage, implement, and assess greenhouse gas (GHG) mitigation efforts. A national GHGI identifies the magnitude of individual sources and sinks within a country in a single year, and tracks changes over time, so that it is possible to compare source and sink strengths and trends.

This chapter provides an overview of the *Greenhouse Gas Inventory and Analysis for the United States (GHGIA)*, including descriptions of the institutional arrangements and methodological approaches used. Additional information on the methodological approach and results for individual categories of emissions is presented in subsequent chapters on a sector-by-sector basis (energy; industrial processes and product use; agriculture; land use, land-use change and forestry [LULUCF]; and waste). Supplementary information published with this *GHGIA* for download include all the tables presented across the *GHGIA* and its annexes.

Use of This Report

The U.S. government previously submitted a national GHGI to the United Nations Framework Convention on Climate Change (UNFCCC) annually following its ratification in 1992 until 2024. The annual inventory submission fulfilled an obligation under Article 4.1 of that Agreement, while also serving other important functions, including the following:

- Informing domestic policy development
- Facilitating international comparisons
- Supporting subnational inventory development
- Serving as a technical reference for methods, emission factors, and activity data.

This *GHGIA* is not an official national inventory nor is it an official inventory submission in the context of the UNFCCC. However, the information presented in this *GHGIA* has been grounded in standard inventory practices that enable continuity in comparing it to the previous U.S. official reports, and can support continued understanding of U.S. emissions for scientific and policy communities:

- It adheres to international standards for transparency, accuracy, completeness, comparability, and consistency.
- It is consistent with good practice as defined by the Intergovernmental Panel on Climate Change (IPCC).

- It builds from and improves upon recent versions of the U.S. Environmental Protection Agency's (EPA's) *Inventory of U.S. Greenhouse Gas Emissions and Sinks*.

1.2 Institutional Arrangements

Coordinating Organization

This *GHGIA* was coordinated and compiled by the Center for Global Sustainability (CGS) at the University of Maryland. CGS has overall responsibility for preparing emission and removal calculations, in addition to methodological choice, uncertainty assessment, quality assurance/quality control (QA/QC) processes, and improvement planning. CGS also serves as the official point of contact for data and report publication, communication, and partnerships.

Other organizations contributed to this first non-governmentally based *GHGIA* report as documented in the supplemental information. As part of an evolving institutional arrangement process, CGS will explore additional technical discussion and collaboration across the U.S. and international scientific communities for future development, particularly in areas where rapidly evolving technological and scientific tools are becoming available to improve GHG data quality (e.g., methane, agriculture, forestry, and other land use).

The report makes use of several publicly available datasets provided by the U.S. government, including information from the U.S. Department of Agriculture, the U.S. Forest Service, the Energy Information Administration, the National Oceanic and Atmospheric Administration (NOAA), the U.S. Geological Survey, the Federal Highway Administration, the Department of Transportation, the National Aeronautics and Space Administration (NASA), and the Department of Commerce.

For more information on the use of datasets from specific data providers and statistical compilers, see the individual category write-ups in the sectoral chapters.

Inventory Preparation Process

Following usual practice, this *GHGIA* presents inventory information following sequential steps, specifically: review of methods and the improvement plan, identification of priority improvements and updates (e.g., change and/or refine methods/data), compilation of source- and sink-level estimates, compilation of overall inventory database including uncertainty, and cross-cutting analytical work (e.g., trends, recalculations). The *GHGIA* then communicates the latest inventory findings at the cross-cutting, sector, and source levels. Consistent with IPCC good practice, CGS provides additional technical documentation to enhance transparency of methods and underlying data for more involved estimation methods.

Archiving

A cloud-based management system, maintained within by the *GHGIA* coordinator, provides a platform for facilitating (1) collaboration on inventory preparation during each compilation phase and (2) the efficient storage and archiving of electronic document and data files each annual cycle.

Consideration and Approval of the *GHGIA*

CGS is currently considering options for engaging experts and the scientific community, along with the broader public, as part of planning and publishing future versions of this report.

Methodologies and Data Sources

The methodologies used in this report are the same as those used to compile recent versions of the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* by EPA (EPA, 2025). The methodologies and data tables described in these recent EPA reports are generally transparent and, in most cases, it was possible to apply them in the same manner for this *GHGIA*. In specific cases identified in the sectoral chapters, the estimates for the most recent year (2024) were based on extrapolation techniques consistent with IPCC good practice, rather than full utilization of the previous EPA methodology.

Future versions of the *GHGIA* may reflect recalculated 2024 estimates using the full methodology where possible, and will explore alternative approaches where previous data and models used by EPA are no longer available or where there is no information on future availability (e.g., facility-level data through the Greenhouse Gas Reporting Program). Consistent with IPCC good practice, future versions of this *GHGIA* will also identify and implement methodological improvements to approaches previously used by EPA.

Key Categories

Key categories are those that individually, or as a group, are prioritized because their estimates have the greatest influence on the quality of a country's GHGI. Specifically, key categories are those that have the largest contribution to the absolute level, the trend, or overall uncertainty in the level or trend. Identifying key categories helps inventory teams to allocate time and resources efficiently to methodological and data improvements that matter the most.

This *GHGIA* uses the two quantitative approaches for identifying key categories as described by the IPCC. The IPCC also describes a qualitative approach, which was not used in this *GHGIA*. The three approaches are as follows:

- Quantitative Approach 1: Identifies key categories based on their contribution to the total level of emissions and to the overall trend of emissions. Emission and removal categories are ranked individually according to this impact and then summed. The key categories are those that cumulatively account for 95 percent of the total.

- Quantitative Approach 2: This approach is similar to Approach 1 but incorporates the evaluated statistical uncertainty of the results. Incorporating uncertainty can identify additional key categories that merit attention and resources from inventory compilers. Emission and removal categories are ranked individually according to their impact on the overall level and trend, weighted by their uncertainty estimates. Key categories are those that cumulatively account for 90 percent of total uncertainty. This approach has not been updated for this *GHGIA* but will be included in future annual reports.
- Qualitative Approach: The IPCC also provides inventory compilers with the flexibility to identify categories as key even if they do not meet Quantitative Approach 1 or 2 quantitative thresholds. An example would be a small category that is the subject of ambitious mitigation measures. Improving the methodology for the category would make it possible to reflect the results of mitigation more rigorously.

The basic Approach 1 "level" assessment identified 32 categories in this *GHGIA*, accounting for 95 percent of gross emissions, with four categories making up more than 50 percent. These four categories are as follow:

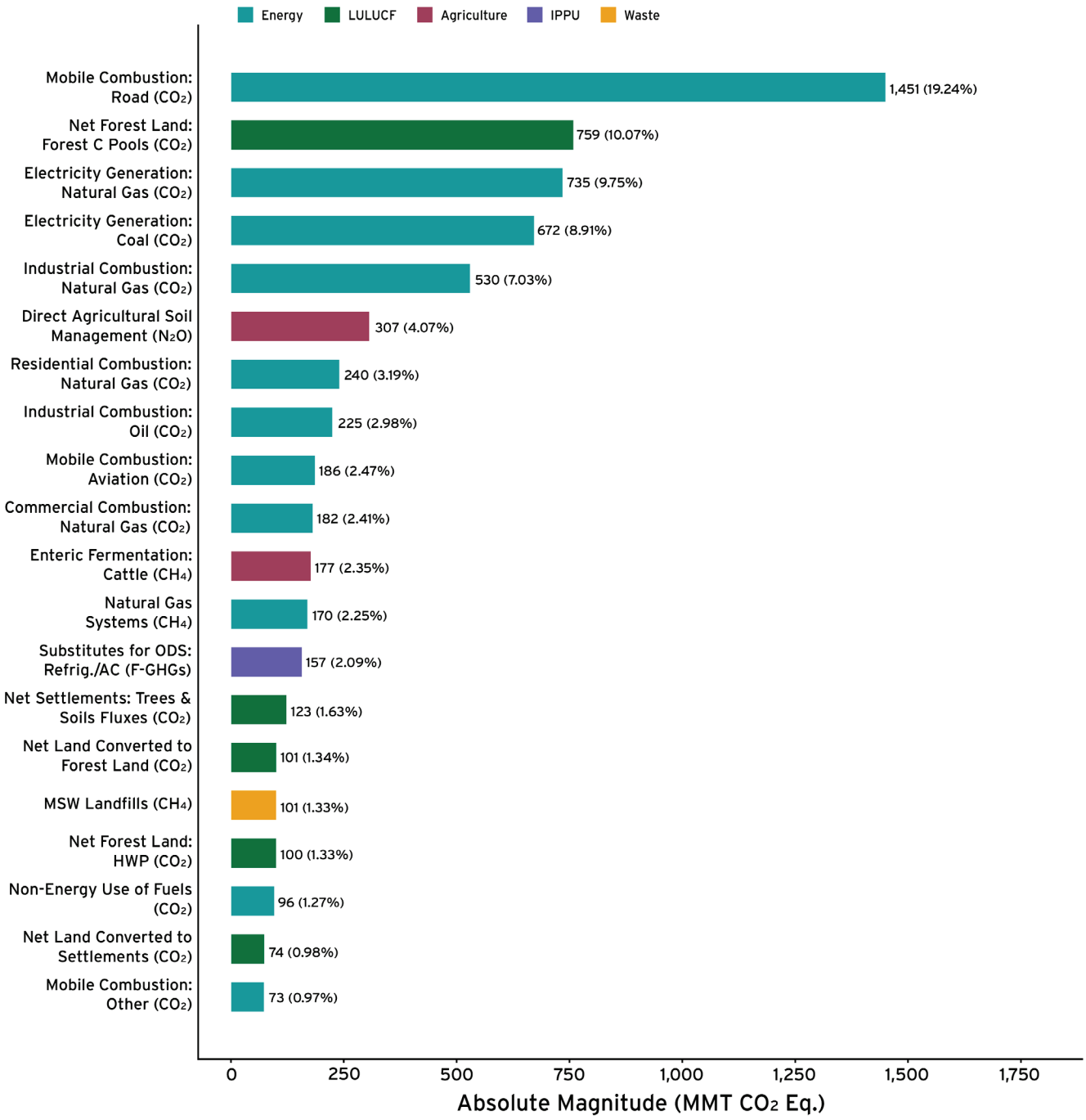
- Carbon dioxide (CO_2) emissions from mobile combustion (road)
- CO_2 emissions from stationary combustion of natural gas (electricity production)
- CO_2 emissions from stationary combustion of coal (electricity production)
- CO_2 emissions from stationary combustion of natural gas (industry)

Including LULUCF brought in an additional eight categories, including changes in the amount of carbon stored in existing forests ("forest land remaining forest land") and in urban and suburban areas ("settlements remaining settlements"). Figure 1-1 shows the 2024 key categories identified by the Approach 1 level assessment—including the LULUCF sector—in descending order of absolute magnitude.

The Approach 1 "trend" assessments, with and without LULUCF, identified additional categories: smaller sources that have trends that also contribute significantly to the overall trend, including fluorochemical production, stored carbon in croplands (e.g., soil carbon in "cropland remaining cropland"), and stored carbon in landfills (e.g., yard trimmings and food waste).

Please see Annex 1 to this *GHGIA* for more detailed technical information on the implementation of key category analysis.

Figure 1-1: Top 20 Key Categories Using Approach 1, Including LULUCF in 2024 (Absolute Magnitude, MMT CO_2 Eq.)



Note: MMT CO_2 Eq. = million metric tons of CO_2 equivalent.

Quality Assurance/Quality Control

General QA/QC checks were conducted that were consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* and its *2019 Refinement* (IPCC, 2006, 2019). CGS will explore development of a customized QA/QC plan for future reports.

Uncertainty Assessment

Conducting an uncertainty assessment provides invaluable information to inventory compilers on the quality of results. It can also inform the efficient use of time and resources by targeting them on those improvements with the biggest potential impacts.

The IPCC provides two quantitative approaches for combining the uncertainty of inputs and estimates. The first approach—error propagation—gives a good general indication of uncertainty but is not well-suited for handling strong correlations or non-normally distributed (e.g., skewed, bimodal) data. The second approach—Monte Carlo analysis—is more data- and computationally-intensive but also better able to accommodate correlations and non-normal datasets.

Although this version of the *GHGIA* does not include new Monte Carlo uncertainty analyses, future versions will incorporate this information on a rolling basis, beginning with key categories. Given that the methodologies and input data are largely consistent with previous EPA reports, the previous EPA-estimated Monte Carlo results reflect the best available uncertainty assessments and are presented in this *GHGIA*.

The combined total uncertainty of net U.S. emissions is estimated to be 6 percent below to 5 percent above in 1990 and 5 percent below to 6 percent above in 2024. When the LULUCF sector is excluded from the analysis (i.e., gross emissions) the uncertainty of U.S. emissions is slightly lower, at 2 percent below to 4 percent above in 1990 and 2 percent below to 4 percent above in 2024.

Additionally, this *GHGIA* provides a qualitative discussion of the uncertainty for each category, along with assessments of areas of additional uncertainty introduced by using proxy data or drivers for the most recent year (2024) where historical datasets, facility-level data, or models were not available.

Completeness

This *GHGIA* is intended to be comprehensive and includes the vast majority of emissions and removals identified as anthropogenic. In general, sources or sink categories not accounted for in this *GHGIA* are excluded because they are not occurring in the United States, its territories, and tribal lands; because data are unavailable to develop an estimate; and/or because the categories were determined to be insignificant in terms of overall national emissions.

CGS will provide a list of sources and sink categories not included and more information on the significance of these categories following publication of this *GHGIA*.

Metrics

A global warming potential (GWP) estimates the globally averaged radiative forcing impacts of emissions of a particular GHG over time relative to a reference gas (i.e., the total radiative forcing over a specific time frame due to emitting 1 kilogram [kg] of the gas, relative to that of the reference gas CO_2) (IPCC, 2021). GWP-weighted emissions are measured in CO_2 equivalent (CO_2 eq.).[3] GWP values allow for a comparison of the impacts of emissions and reductions of different gases.

Consistent with GHGIs from other countries, this *GHGIA* uses 100-year GWP (GWP_{100}) values from Table 8.A.1 in Appendix 8.A of the *IPCC Fifth Assessment Report* (AR5) for calculating CO_2 eq. emissions (IPCC, 2013). Key GWP_{100} values include methane (CH_4; GWP_{100} = 28), nitrous oxide (N_2O; GWP_{100} = 265), and high-impact compounds such as sulfur hexafluoride (SF_6; GWP_{100} = 23,500) and nitrogen trifluoride (NF_3; GWP_{100} = 16,100). The values for the main GHGs are presented in Table 1-1 below. Detailed data and methodological notes can be found in AR5.

Table 1-1: 100-Year Global Warming Potentials for Greenhouse Gases

Greenhouse Gas	GWP_{100} (AR5)
Carbon dioxide (CO_2)	1
Methane (CH_4)	28
Nitrous oxide (N_2O)	265
HFC-23 (CHF_3)	12,400
HFC-32 (CH_2F_2)	677
HFC-134a (CH_2FCF_3)	1,300
Sulfur hexafluoride (SF_6)	23,500
Nitrogen trifluoride (NF_3)	16,100
Perfluoromethane (CF_4)	6,630
Perfluoroethane (C_2F_6)	11,100

Source: IPCC, 2013.

Future inventories may include estimates for short-lived gases with radiative forcing impacts such as carbon monoxide (CO), tropospheric ozone, ozone precursors (e.g., NO_x, and non-methane volatile organic compounds), and tropospheric aerosols (e.g., sulfur dioxide [SO_2] products and carbonaceous particles). Unlike well-mixed and relatively long-lived GHGs, it is difficult to quantify such gases' global radiative forcing impacts using GWP values.

[3] Carbon comprises 12/44^{ths} of carbon dioxide by weight.

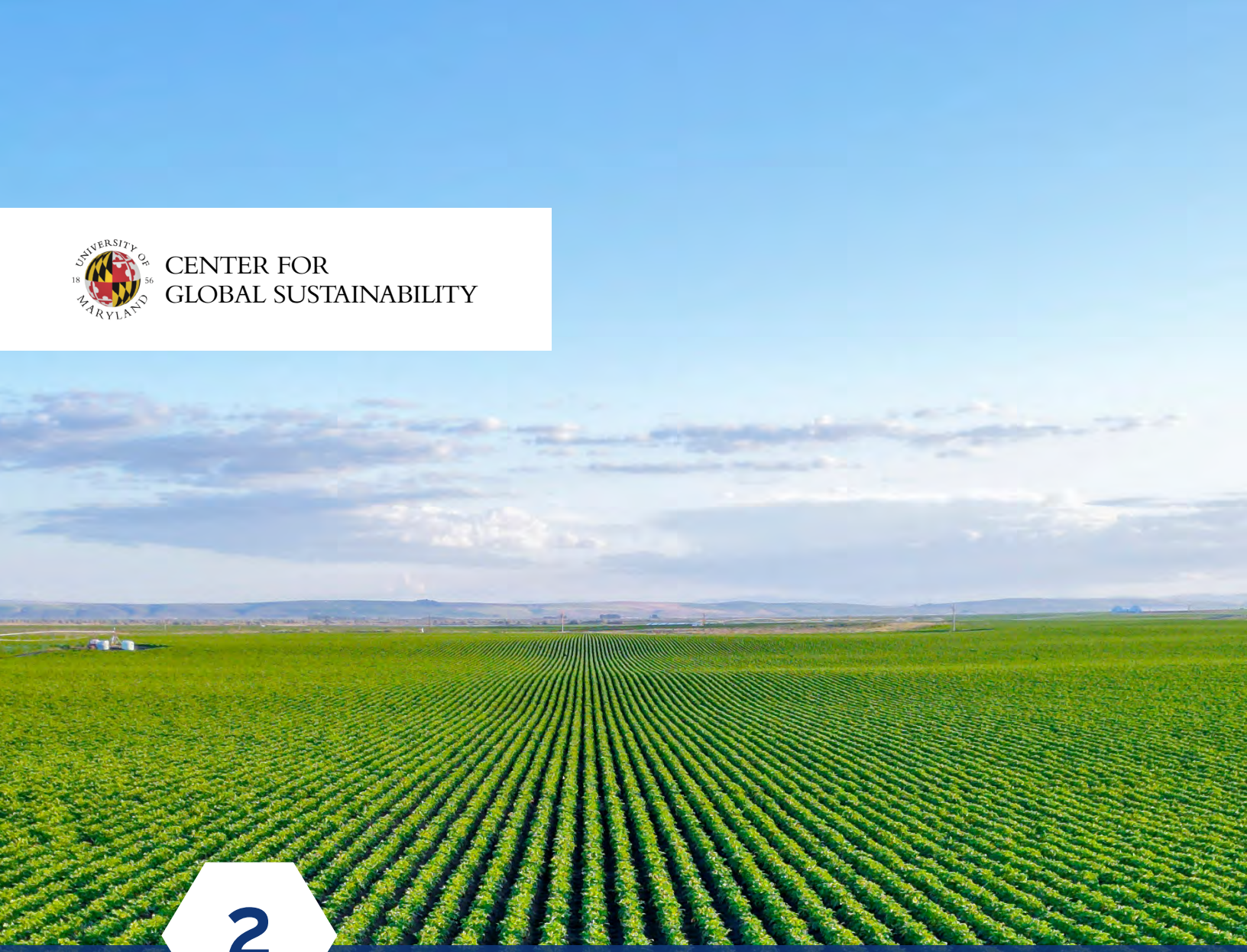
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2

Trends in Greenhouse Gas Emissions and Removals



Chapter 2. Trends in Greenhouse Gas Emissions and Removals

This chapter describes national greenhouse gas (GHG) emission trends by sector and by GHG. Emissions for non-carbon dioxide (CO_2) GHGs are presented as carbon dioxide equivalents (CO_2 Eq.) using the 100-year global warming potential (GWP) values contained in the *Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report* (IPCC, 2013). Converting emissions into CO_2 Eq. allows the radiative forcing effect of various gas emissions in the atmosphere to be compared.

Gross vs. Net Greenhouse Gas Emissions Totals

Gross emissions represent the total GHGs produced by human activities (e.g., from energy, industry, agriculture, waste activities) without considering anthropogenic (human-caused) CO_2 removals from the atmosphere through sinks (e.g., land use, land-use change, forestry), while net emissions account for all anthropogenic emissions and removals, including those through sinks.

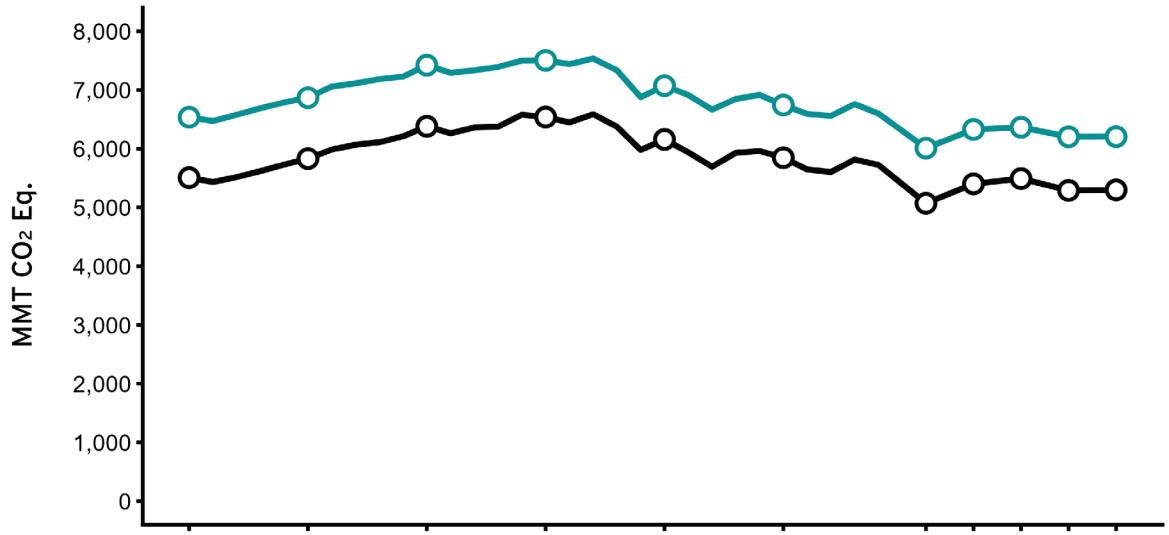
2.1 Aggregated Greenhouse Gas Emission and Removal Trends

Overall Trends

As shown in Figure 2-1, in 2024, total gross U.S. GHG emissions were 6,205.3 million metric tons of CO_2 Eq. (MMT CO_2 Eq.). This total is a 5.1 percent decrease from 1990 and a 0.04 percent annual increase from 2023. The decreasing trend since around 2005 is associated with a decrease in CO_2 emissions from fossil fuel combustion, which is discussed in more detail below and in Chapter 3 (Energy).

In 2024, total net U.S. GHG emissions, including emissions and sinks through land use, land-use change and forestry (LULUCF), were 5,298.8 MMT CO_2 Eq. This total is a 3.8 percent decrease from 1990 and a 0.2 percent annual increase from 2023. Sequestration of CO_2 in the LULUCF sector offset the equivalent of 14.6 percent of total gross emissions in 2024 (906.5 MMT CO_2 Eq.).

Figure 2-1: U.S. Gross and Net Emissions

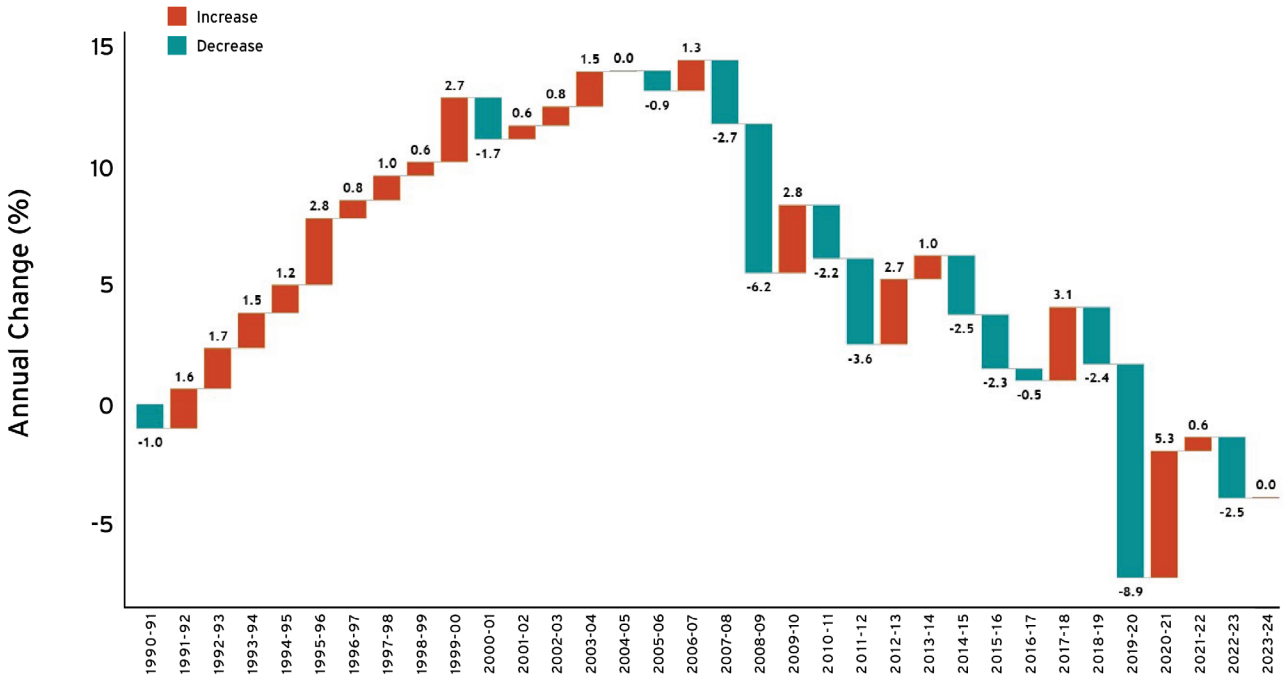


	1990	1995	2000	2005	2010	2015	2020	2021	2022	2023	2024	90-24
Gross Emissions	6,536	6,868	7,422	7,504	7,073	6,744	6,010	6,328	6,365	6,203	6,205	-5.1%
Net Emissions	5,507	5,831	6,381	6,539	6,159	5,846	5,071	5,402	5,491	5,290	5,299	-3.8%

Annual Changes in Emissions

Figure 2-2 shows the annual changes in gross emissions over the time series. Note that emissions dropped significantly in 2020–2021 due to the COVID-19 pandemic but have since partially rebounded.

Figure 2-2: Annual Percent Change in U.S. Gross Emissions

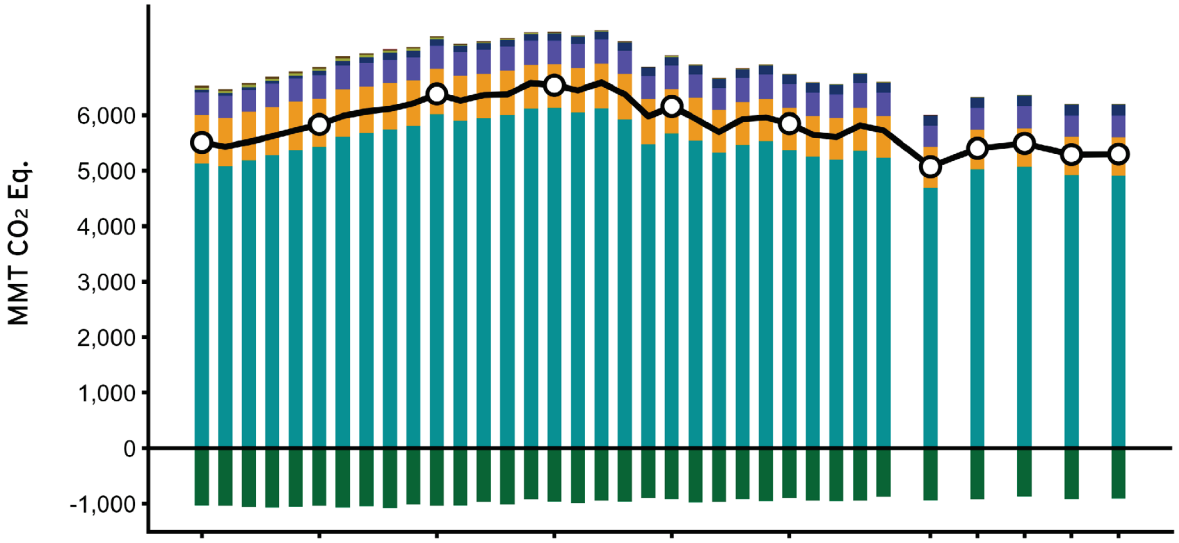


2.2 Emission and Removal Trends

Emissions and Removals by Gas

Figure 2-3 illustrates the trend in U.S. GHG emissions broken out by individual GHGs, in CO_2 Eq. (i.e., weighted by GWP).

Figure 2-3: Trends in Greenhouse Gas Emissions and Sinks by Gas



	1990	1995	2000	2005	2010	2015	2020	2021	2022	2023	2024	90-24
CO_2	5,130	5,431	6,019	6,125	5,664	5,366	4,694	5,018	5,066	4,924	4,912	-4.3%
CH_4	873	867	818	797	810	764	731	715	696	685	687	-21.3%
N_2O	408	423	413	425	421	429	391	396	399	388	398	-2.4%
HFCs	48	74	116	125	159	168	178	184	190	191	194	306.9%
SF_6	38	35	27	20	12	8	8	8	7	8	8	-79.6%
PFCs	40	37	29	10	7	7	7	6	7	6	6	-85.6%
NF_3	+	+	1	1	1	1	1	1	1	1	1	335.8%
LULUCF Net	(1,029)	(1,037)	(1,040)	(965)	(914)	(898)	(939)	(927)	(874)	(913)	(907)	11.9%
Net Emissions	**5,507**	**5,831**	**6,381**	**6,539**	**6,159**	**5,846**	**5,071**	**5,402**	**5,491**	**5,290**	**5,299**	**-3.8%**

CO_2 contributes the largest share to national GHG totals each year and has the greatest impact on both year-to-year changes and on the overall trend since 1990. Gross CO_2 emissions decreased by 4.3 percent from 1990 to 2024 and decreased by 0.3 percent from 2023 to 2024. Fossil fuel combustion for energy makes up the large majority (over 90 percent) of gross CO_2 emissions. For a more detailed discussion of fossil fuel-related trends, including contributions from electricity, transportation, residential and commercial buildings, see the Energy Sector and Trends in Focus sections, as well as Chapter 3. U.S. forests, croplands and other types of lands have resulted in a

net sink of CO_2 emissions each year since 1990, offsetting between the equivalent of approximately 12.3 percent to 16.1 percent of gross emissions each year.

Methane (CH_4) emissions make up the second largest share of total gross GHG emissions, ranging from 13 percent in 1990 to 11 percent in 2024. The long-term moderately declining trend of CH_4 emissions results from a variety of distinct contributing factors, including increases from some larger source categories (e.g., livestock manure management), decreases from other categories (e.g., landfills, coal mining), and categories where little has changed at an aggregate level (e.g., livestock enteric fermentation).

Nitrous oxide (N_2O) emissions have remained at comparable levels since 1990. A small overall decrease can be attributed to lower tailpipe emissions of N_2O from mobile combustion, as automobile catalytic converter technology targeting nitrogen oxides improved. By far the largest share of N_2O emissions comes from agricultural soil management (e.g., application of fertilizer and other management practices). The overall level of N_2O emissions from agriculture increased by approximately 7 percent since 1990, and its share of total N_2O emissions increased from approximately 70 percent in 1990 to 77 percent in 2024.

Fluorinated GHGs include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). HFCs make up by far the largest share of fluorinated GHG emissions, with their use as substitutes for ozone-depleting substances (ODS) increasing significantly since 1990 and then leveling off in recent years. PFC emissions have decreased overall due to reductions from fluorochemical production and primary aluminum production. SF_6 emissions have also declined from the two largest sources, electrical equipment and magnesium production.

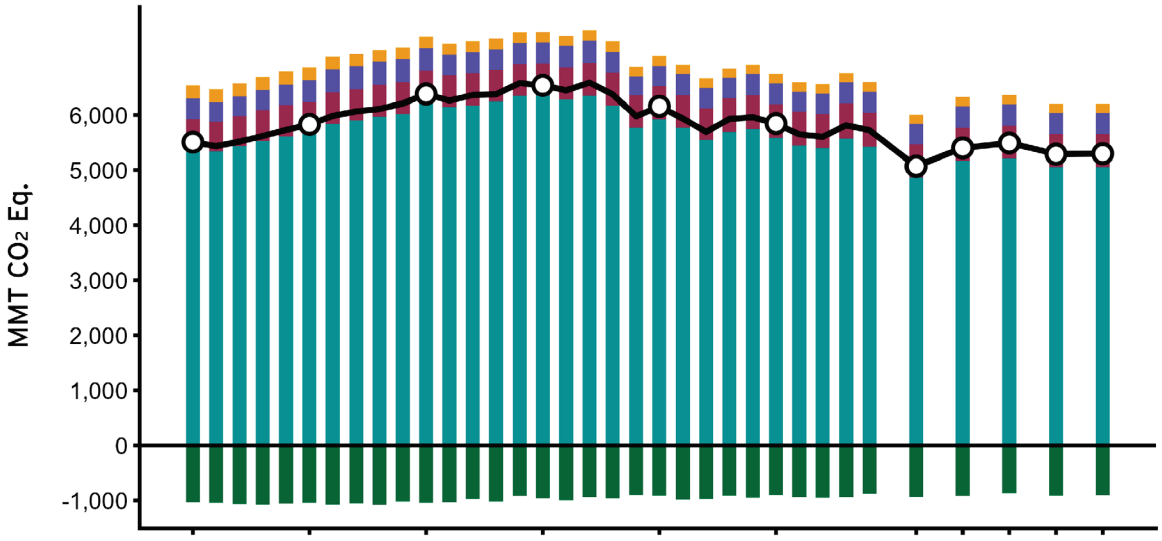
Emissions and Removals by Sector

Overview

Emissions and removals can also be categorized into the set of five sectors defined by the international inventory reporting guidelines and in the methodological framework provided by the Intergovernmental Panel on Climate Change (IPCC). Global adoption of this framework facilitates comparability across countries and provides additional insights into the economic drivers of national emissions and their changes over time.

Figure 2-4 shows total emissions since 1990 broken out by IPCC sector. The energy sector, which includes fossil fuel combustion, fugitive emissions, non-energy use of fossil fuels, and additional smaller categories, has the largest impact on the overall trend. Energy sector emissions peaked in 2005 at 18 percent above 1990 levels and subsequently declined to 6.1 percent above 1990 levels by 2024. For more information on the underlying factors influencing these trends, see the Energy Sector and Trends in Focus sections, which present information on transportation and electricity generation, and Chapter 3.

Figure 2-4: Trends in Greenhouse Gas Emissions and Sinks by Sector



	1990	1995	2000	2005	2010	2015	2020	2021	2022	2023	2024	90-24
Energy	5,380	5,661	6,241	6,354	5,918	5,580	4,864	5,169	5,207	5,055	5,051	-6.1%
Agriculture	551	574	567	583	600	616	600	601	603	595	602	9.3%
IPPU	369	400	414	375	372	377	376	392	390	387	387	4.7%
Waste	236	234	200	192	183	171	170	167	165	166	166	-29.6%
LULUCF Net	(1,029)	(1,037)	(1,040)	(965)	(914)	(898)	(939)	(927)	(874)	(913)	(907)	11.9%
Net Emissions	**5,507**	**5,831**	**6,381**	**6,539**	**6,159**	**5,846**	**5,071**	**5,402**	**5,491**	**5,290**	**5,299**	**-3.8%**

The industrial processes and product use (IPPU) and agriculture sectors have remained largely stable in terms of total emissions over the time series, while the share of overall emissions has increased marginally as emissions in the energy sector have decreased. For both the IPPU and agriculture sectors, there are more distinct changes at the category level, which are discussed in further detail below and in Chapters 4 and 5.

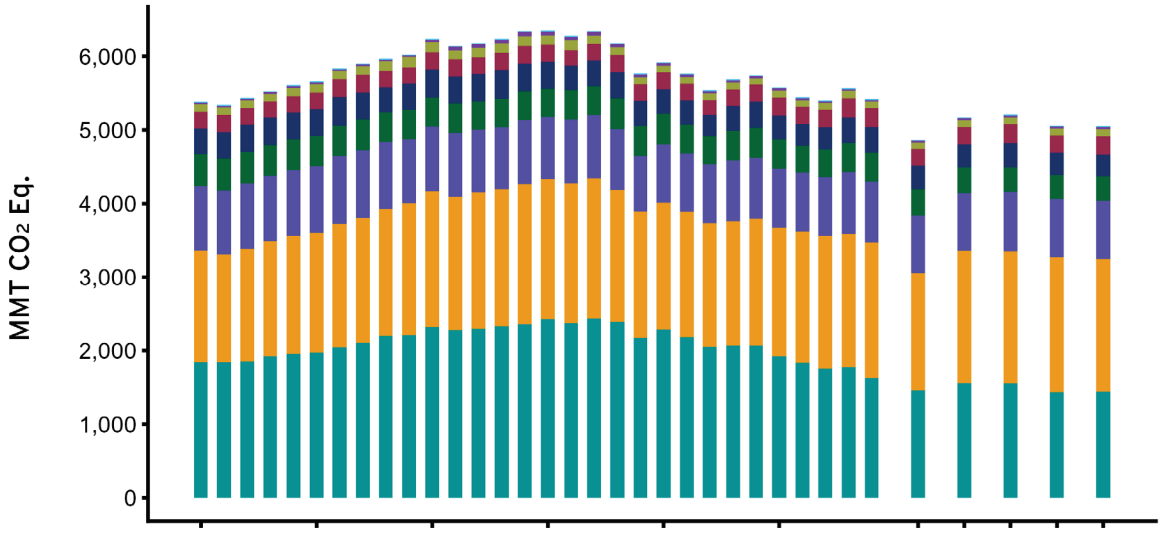
As discussed in the Emissions Removal by Gas section, the LULUCF sector, including forests, croplands and other types of lands, have been a large but slightly declining net sink of CO_2 emissions each year since 1990, with a total offset of gross emissions of 14.6 percent in 2024. The largest share of total net fluxes (sequestration) comes from existing forests, which are discussed in more detail in Chapter 6.

The waste sector is dominated by CH_4 emissions from municipal solid waste landfills, which have declined since 1990, with smaller contributions from wastewater, composting, and anaerobic digestion.

Energy Sector

Figure 2-5 shows the IPCC energy sector time series, broken out by a mix of categories and economic sectors where fossil fuel combustion occurs. Chapter 3 provides a detailed discussion of the emissions levels and trends for each energy category, along with detailed methodological information. Gases included in the IPCC energy sector are CO_2, CH_4, and N_2O. Note that under a different "Economic sector" classification scheme, a share of emissions of HFCs and SF_6 also attributed to energy-related sources (e.g., for mobile air conditioning or electricity transmission equipment).

Figure 2-5: Trends in Energy Sector Greenhouse Gas Sources



	1990	1995	2000	2005	2010	2015	2020	2021	2022	2023	2024	90-24
Transportation Fossil Fuel Combustion	1,518	1,629	1,845	1,900	1,726	1,741	1,594	1,792	1,797	1,837	1,808	19.1%
Electric Power Fossil Fuel Combustion	1,839	1,967	2,319	2,428	2,287	1,926	1,459	1,561	1,553	1,433	1,438	-21.8%
Industrial Fossil Fuel Combustion	875	911	880	848	794	807	782	790	811	795	793	-9.4%
Fugitive Emissions	440	413	396	387	405	396	360	342	328	324	327	-25.6%
Residential Fossil Fuel Combustion	345	360	378	364	342	324	318	318	335	305	295	-14.6%
Commercial Fossil Fuel Combustion	228	230	239	229	227	247	231	236	257	231	252	10.4%
Non-Energy Use of Fuels	101	114	133	132	91	96	84	90	89	90	96	-4.5%
U.S. Territories Fossil Fuel Combustion	20	22	37	52	34	28	23	26	24	27	28	39.4%
Incineration of Waste	13	15	13	14	13	15	13	13	13	13	12	-8.1%
CO_2 Transport, Injection & Storage	+	+	+	+	+	+	+	+	+	+	+	NA
Total Emissions	**5,380**	**5,661**	**6,241**	**6,354**	**5,918**	**5,580**	**4,864**	**5,169**	**5,207**	**5,055**	**5,051**	**-6.1%**

Fossil Fuel Combustion CO_2

Fossil fuel combustion of coal, petroleum, and natural gas is by far the most important contributor to the overall energy sector trend, with CO_2 being the primary gas. CO_2 from fossil fuel combustion has accounted for approximately 74 percent of CO_2 Eq. U.S. total gross emissions on average across the time series and accounted for 93 percent of total U.S. CO_2 emissions in 2024.

Fossil fuel combustion CO_2 emissions decreased by 3.8 percent (180.7 MMT CO_2 Eq.) from 1990 to 2024 and were responsible for most of the decrease in national emissions during this period. Similarly, CO_2 emissions from fossil fuel combustion have decreased by 20.3 percent (1,166.9 MMT CO_2 Eq.) since 2005. From 2023 to 2024, these emissions decreased by 0.3 percent (13.6 MMT CO_2 Eq.).

The main long-term (e.g., decadal) factors influencing fossil fuel combustion emissions include population and economic growth, technological changes, and the carbon intensity of energy fuel choices. Producing a unit of heat or electricity using natural gas instead of coal, for example, reduces CO_2 emissions because of the lower carbon content of natural gas. The shift from coal toward natural gas for electricity generation over time has been a main driver of emission reductions.

On a shorter-term time scale (e.g., year to year), the overall consumption and mix of fossil fuels in the United States fluctuates in response to changes in general economic conditions, overall energy prices, the relative price of different fuels, weather, and the availability of non-fossil alternatives. Significant unique events, such as the COVID-19 pandemic starting in 2020, can also have a major impact on annual changes.

As shown in Figure 2-5, fossil fuel combustion (as defined by the IPCC) can be further disaggregated into five general energy end-use sectors: transportation, electricity, industrial, commercial, and residential.[4] As noted below, the transportation and electricity sectors have the largest impact on overall emissions and the trend since 1990.

Transportation. The transportation sector has represented the largest source of CO_2 emissions from fossil fuel combustion (mainly petroleum) since 2017. Emissions increased by 21 percent since 1990 but decreased 2 percent from 2023 to 2024. The fuel economy of new light-duty vehicles declined between 1990 and 2004, coinciding with the increasing market share of light-duty trucks (from about 29.6 percent of new vehicle sales in 1990 to 48.0 percent in 2004). Starting in 2005, vehicle fuel economy began to improve, slowing the rate of increase of CO_2 emissions. For more detailed information on emissions trends related to transportation, see the Trend in Focus section below and Chapter 3 (Energy) of this *Greenhouse Gas Inventory and Analysis for the United States (GHGIA)*.

Electricity. In 1990, the electricity sector was the largest source of GHG emissions in the United States, representing one-third of the total (gross). Emissions peaked in the 2004-2006 period and then declined to 22 percent below 1990 levels in 2024. In 2024 the electricity sector represented

[4] This *GHGIA* uses the classification system from the Energy Information Administration to allocate fuel use and emissions across these energy consuming sectors (https://www.eia.gov/totalenergy/data/monthly/pdf/sec13.pdf).

24 percent of all U.S. GHG emissions (gross), second to transportation. The decline in emissions over the last two decades is due to a shift away from coal to less carbon-intensive natural gas and a smaller but growing share of renewable energy generation. The efficiency of electricity consumption has improved steadily throughout the time series, leading to lower emissions each year than would have otherwise occurred. For more detailed information on emissions trends related to electricity, see the Trends in Focus section below and Chapter 3 (Energy) of this *GHGIA*.

Industry. The Energy Information Administration (EIA) statistics for the industry sector include all facilities and equipment used for producing, processing, or assembling goods. From 1990 to 2024, direct energy emissions from the industrial sector decreased by 9.4 percent, as industrial output shifted in relative terms from energy-intensive manufacturing products (e.g., steel) to less energy-intensive products (e.g., computer equipment).

Residential. EIA's fuel consumption data for the residential sector consists of living quarters for private households, primarily oil and gas for heating and cooking needs. Although emissions have not changed significantly since 1990, the residential sector can fluctuate from year to year based on the severity of winters and summers and the associated demands on fuel use.

Commercial. EIA's fuel consumption data for the commercial sector consists of service-providing facilities and equipment from private and public organizations and businesses. As with the residential sector, commercial sector emissions have not changed significantly since 1990.

Other Energy Sector Categories

Non-energy use of fossil fuels. A small but important share of fossil fuels consumed each year in the United States is converted into short- and long-lived products (e.g., lubricants, plastics, asphalt). These products can release CO_2 over time during use and after disposal. Emissions from this category have increased slightly since 1990 but do not experience significant annual variations.

Fugitive emissions. Fugitive emissions include CO_2 and CH_4 and occur from the production, processing, transport, and distribution of coal, petroleum, and natural gas before the fuels are ultimately consumed. Although aggregate fugitive emissions have not changed significantly since 1990, emissions of some subcategories decreased significantly (e.g., CH_4 from coal mining), while others increased (e.g., CO_2 from petroleum systems). For more information on fugitive emissions, see Chapter 3 (Energy).

CO_2 emissions can also occur as the gas is transported, injected, and stored in geologic formations (i.e., for enhanced oil recovery or permanent storage in saline formations). This industry is a relatively small source of CO_2 emissions and does not impact the energy sector trend.

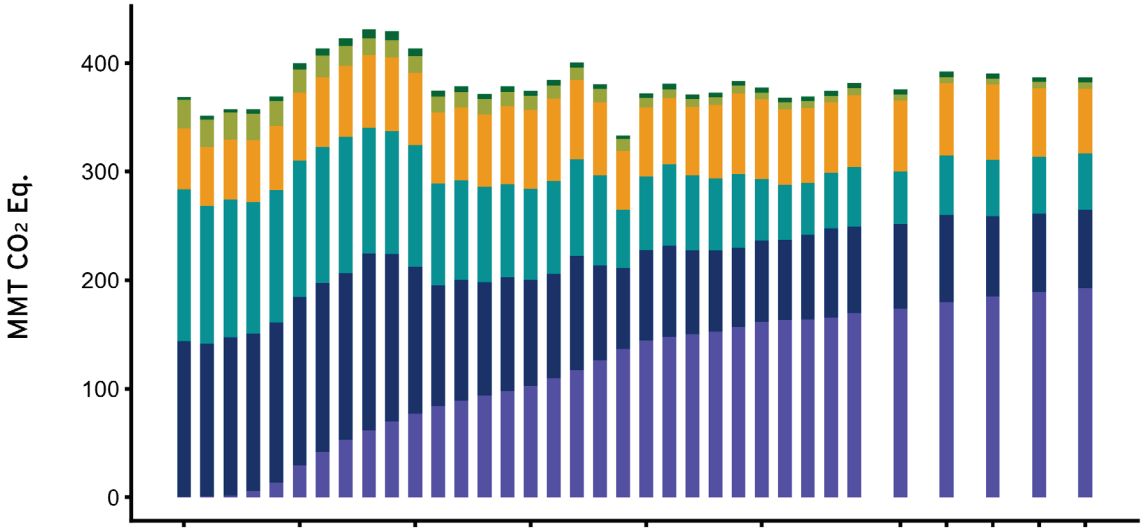
Energy emissions also include some categories that are not added to energy sector totals but are instead presented as memo items, including international bunker fuels and biomass emissions.

Industrial Processes and Product Use Sector

The IPCC IPPU sector includes the diversity of industry-related sources with the exclusion of fossil fuel use for energy at industrial facilities (captured in the IPCC energy sector). Figure 2-6 shows the IPPU trend from 1990 broken out by common groups of sources: minerals, metals, chemicals, use of substitutes for ODSs, electronics, and "other" sources.

Although the overall IPPU trend from 1990 is a modest 4.7 percent increase, and IPPU has a minor impact on the overall U.S. emissions trend, some IPPU categories with notable increases and decreases are described below. For a detailed description of IPPU data and methods, see Chapter 4.

Figure 2-6: Trends in Industrial Processes and Product Use Sector Greenhouse Gas Sources (MMT CO_2 Eq.)



	1990	1995	2000	2005	2010	2015	2020	2021	2022	2023	2024	90-24
Substitution of Ozone Depleting Substances	0.3	29.6	77.2	102.7	144.6	161.5	173.7	179.9	184.9	189.0	192.4	76,013%
Chemical Industry	143.6	154.7	135.2	97.9	83.3	74.6	77.8	80.2	74.2	72.2	72.7	-49.4%
Mineral Industry	56.0	62.7	66.4	73.0	63.2	73.1	65.7	66.6	69.2	63.2	59.0	5.4%
Metal Industry	139.9	125.8	112.2	83.3	67.9	57.0	48.1	54.5	51.8	52.2	52.2	-62.7%
Other Product Manufacture and Use	26.1	21.3	15.5	13.3	9.2	6.5	6.2	6.0	5.5	6.1	6.1	-76.7%
Electronics Industry	3.3	5.7	7.1	4.5	3.9	4.6	4.5	4.9	4.8	4.2	4.2	27.2%
Total Emissions	**369.2**	**399.8**	**413.5**	**374.7**	**372.0**	**377.4**	**376.1**	**392.2**	**390.4**	**387.0**	**386.6**	**4.7%**

Substitutes for ODS. Emissions of HFCs started to increase dramatically in the 1990s as they were introduced to replace ozone-depleting chlorofluorocarbons (CFCs) and hydrofluorocarbons (HCFCs). In 2024, ODS substitute emissions made up 50 percent of total IPPU emissions.

Chemicals. Emissions decreased substantially from fluorochemical, adipic acid, and nitric acid production, contributing to an overall reduction from the chemical production industry since 1990. Petrochemical production emissions increased by 43 percent during this period.

Metals. Emissions from iron and steel production decreased significantly since 1990, with 2024 emissions at 55 percent below 1990 levels. This decrease corresponds with a more general decrease in output from the iron and steel industry, as well as shifts to more energy-efficient production approaches. Emissions of CO_2 and PFCs from aluminum production decreased by 94 percent during the same period due to a combination of aluminum recycling, reduced primary production, increasing use of clean energy, and technological and process improvements at production facilities.

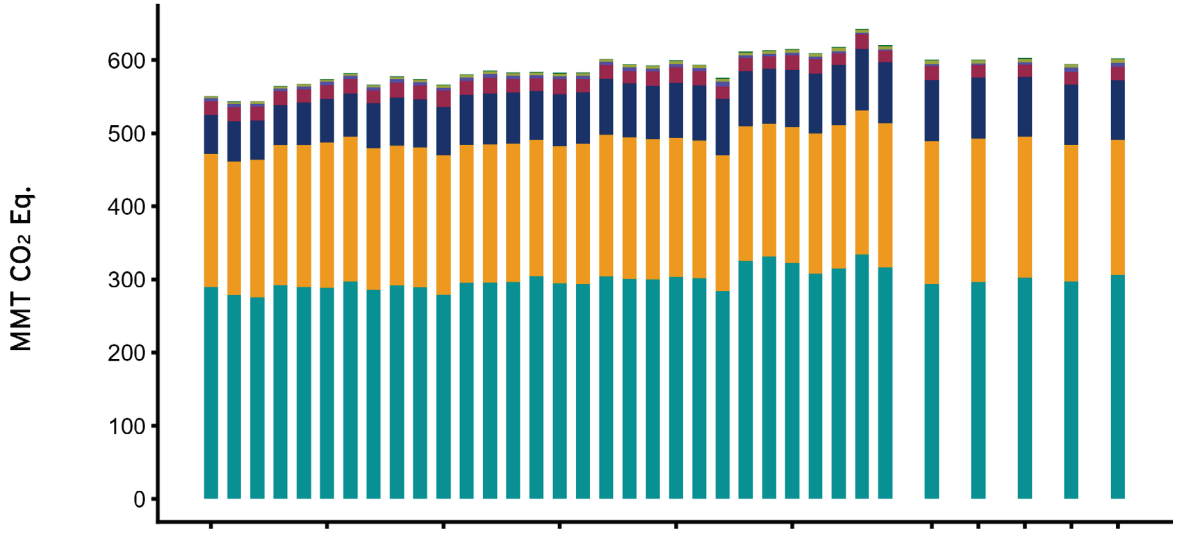
Other product manufacture and use. Emissions of SF_6 used in electrical equipment declined by 38 percent since 1990 as industry implemented efforts to reduce leakage.

Agriculture Sector

The IPCC agriculture sector includes emissions resulting from livestock management (e.g., enteric fermentation and manure management), rice cultivation, agricultural soil management, liming, urea fertilization, and field burning of agricultural residues. CH_4 and N_2O are the primary GHGs emitted by agricultural activities, with small amounts of CO_2 also emitted. Note that consistent with the *IPCC Guidelines*, carbon stock changes from agricultural lands are included in the LULUCF sector (see Chapter 5).

As shown in Figure 2-7, the overall trend in the agriculture sector from 1990 to 2024 is a 9.3 percent increase. Annual changes are also modest and typically reflect changes in weather patterns, fertilizer use, livestock populations, and crop production. Emissions from the largest agriculture category, N_2O from soil management, increased by 6 percent since 1990, whereas livestock enteric fermentation emissions did not change significantly. Livestock manure management is the exception, with a 55.8 percent increase in methane emissions from 1990 as livestock operations have become more concentrated in fewer, larger operations, resulting in a shift toward more liquid-based manure management practices (e.g., lagoons).

Figure 2-7: Trends in Agriculture Sector Emissions



	1990	1995	2000	2005	2010	2015	2020	2021	2022	2023	2024	90-24
Agricultural Soil Management	289.1	287.9	279.1	294.7	303.4	322.4	293.0	296.5	302.5	297.3	306.7	6.1%
Enteric Fermentation	182.8	199.2	190.2	188.2	190.8	185.9	196.3	196.5	192.6	187.2	184.1	0.7%
Manure Management	52.5	60.1	66.5	70.2	74.4	78.5	83.8	83.6	81.7	81.9	81.8	55.8%
Rice Cultivation	18.9	19.1	22.4	20.6	21.5	19.6	18.6	16.3	16.8	17.5	18.1	-4.3%
Liming	4.7	4.4	4.4	4.4	4.7	3.7	2.9	2.4	3.2	5.4	5.5	18.1%
Urea Fertilization	2.3	2.6	3.3	3.6	4.0	4.6	4.7	4.5	4.8	4.7	5.1	121.4%
Field Burning of Agricultural Residues	0.7	0.6	0.7	0.8	0.9	0.7	0.8	0.8	0.8	0.9	0.8	18.4%
Total Emissions	**551.0**	**573.9**	**566.7**	**582.5**	**599.9**	**615.5**	**600.2**	**600.6**	**602.5**	**594.9**	**602.1**	**9.3%**

Land Use, Land-Use Change, and Forestry Sector

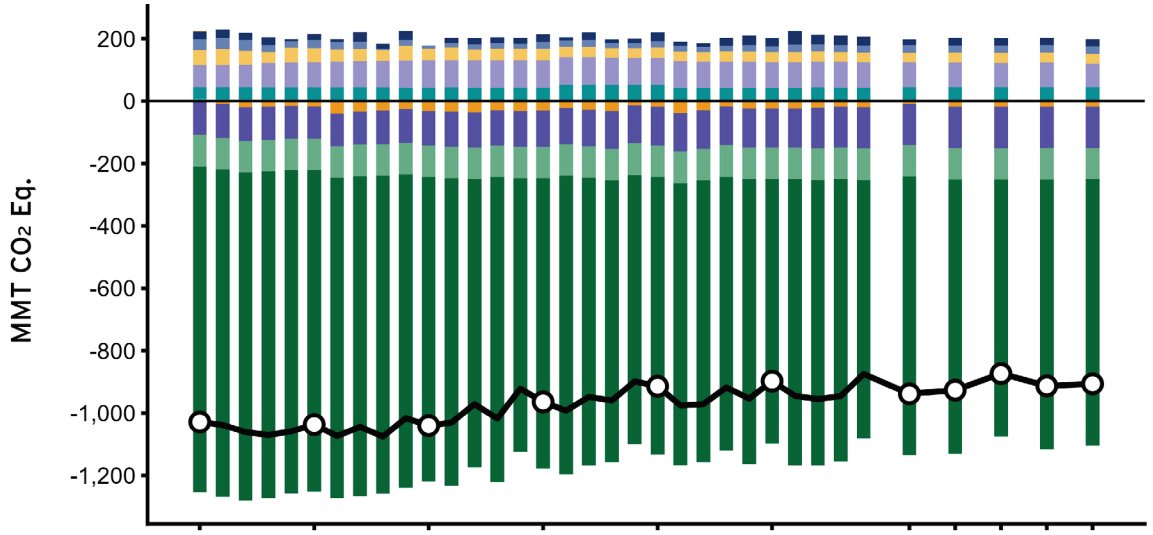
The LULUCF sector includes the entirety of anthropogenic impacts on fluxes of CO_2, CH_4, and N_2O from managed land.[5] Consistent with the IPCC Guidelines, this *GHGIA* presents GHG emissions and removals in the LULUCF sector by the six general managed land-use categories, as well as conversions between these categories: forest land, cropland, grassland, wetlands, settlements, and "other land."

Overall, including the net impact of both emissions and removals (from the atmosphere), the LULUCF sector has been a large net sink each year since 1990 (see Figure 2-8). Existing forests have made up by far the largest share of this net sink, offsetting the equivalent of 15.7 percent of total U.S. gross emissions in 1990 and decreasing slightly to a 14.6 percent offset equivalent in

[5] See Chapter 6 for more information on the definition of managed land area classifications in the United States.

2024. This decline in sequestration is the aggregate result of various underlying drivers, including aging forests, which sequester less carbon per year, and increased frequency and severity of forest disturbances (e.g., wildfire, weather, pest outbreaks, disease). Forest fires can also cause large annual changes in CH_4 and N_2O emissions, but to date these non-CO_2 gases have not had a major impact on annual GHG fluxes or the overall LULUCF trend.

Figure 2-8: Trends in LULUCF Sector Emissions and Removals



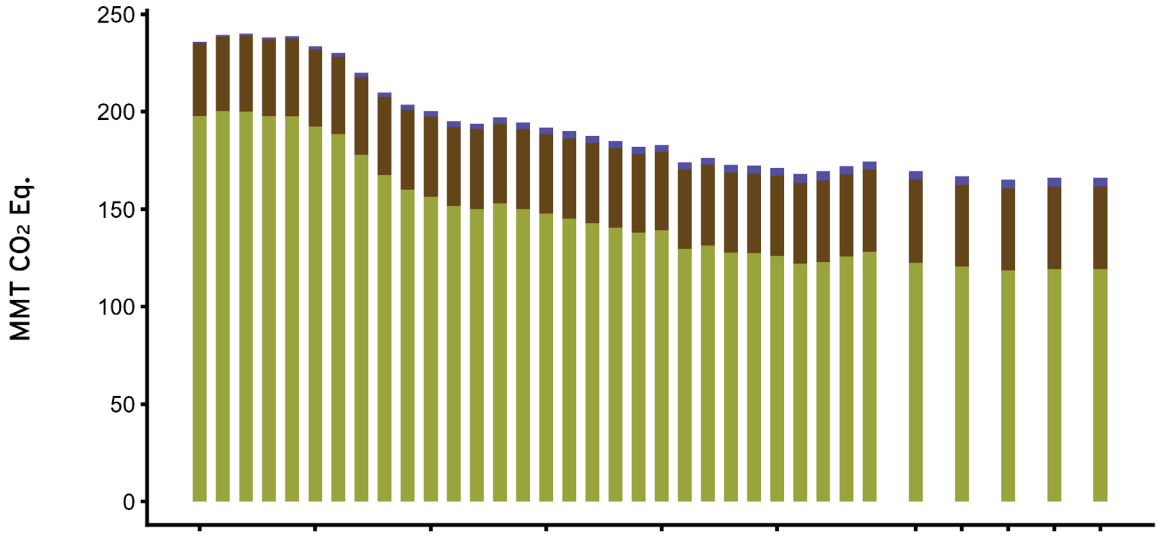
	1990	1995	2000	2005	2010	2015	2020	2021	2022	2023	2024	90-24
Forest Land Remaining Forest Land	(1,043.1)	(1,031.0)	(975.5)	(930.9)	(890.8)	(848.0)	(892.9)	(879.0)	(822.9)	(864.9)	(854.8)	18.1%
Land Converted to Forest Land	(100.8)	(100.9)	(101.0)	(101.2)	(101.3)	(101.5)	(100.9)	(100.9)	(100.8)	(100.8)	(100.9)	-0.1%
Cropland Remaining Cropland	1.0	(16.6)	(30.9)	(31.0)	(18.7)	(23.5)	(9.6)	(17.7)	(18.6)	(18.1)	(18.0)	-1,832%
Land Converted to Cropland	48.5	44.8	36.4	35.5	34.4	32.1	29.6	32.2	32.3	32.5	32.6	-32.9%
Grassland Remaining Grassland	24.2	19.1	(1.1)	24.5	27.4	25.3	17.0	24.7	23.2	23.2	22.9	-5.3%
Land Converted to Grassland	35.6	27.4	11.5	21.9	19.9	19.0	25.1	23.0	23.7	24.1	24.7	-30.6%
Wetlands Remaining Wetlands	38.5	39.2	40.1	40.9	50.3	39.8	44.0	43.9	44.0	43.9	44.0	14.4%
Land Converted to Wetlands	6.7	4.7	2.6	1.9	1.1	0.8	0.8	0.8	0.8	0.8	0.8	-88.1%
Settlements Remaining Settlements	(109.1)	(104.2)	(111.0)	(115.2)	(123.4)	(125.9)	(131.9)	(132.5)	(132.6)	(132.6)	(131.9)	-21.0%
Land Converted to Settlements	69.5	80.4	88.3	89.0	86.6	84.0	80.3	78.8	77.3	78.4	74.1	6.6%
LULUCF Sector Net Total	**(1,028.9)**	**(1,037.2)**	**(1,040.5)**	**(964.7)**	**(914.4)**	**(897.9)**	**(938.6)**	**(926.7)**	**(873.8)**	**(913.4)**	**(906.5)**	**11.9%**

Waste Sector

The IPCC waste sector consists of municipal solid waste landfills, domestic and industrial wastewater treatment, composting, and biogas facilities. Emissions of CH_4 result from the decomposition of organic matter in anaerobic conditions, and N_2O results from bacterial nitrification and denitrification processes.

As shown in Figure 2-9, landfills make up the majority of waste sector emissions through methane escaping from the surface and through on-site equipment. Landfill methane emissions declined by 40 percent from 1990 to 2024 from a variety of factors, including increased use of gas collection systems and increasing diversion of some decomposable materials (e.g., cardboard) to other treatment options (e.g., recycling).

Figure 2-9: Trends in Waste Sector Emissions



	1990	1995	2000	2005	2010	2015	2020	2021	2022	2023	2024	90-24
Landfills	197.8	192.3	156.4	147.7	139.0	126.0	122.6	120.7	118.6	119.4	119.4	-39.6%
Wastewater Treatment and Discharge	37.5	39.6	41.1	40.7	40.4	41.2	42.5	41.8	42.1	42.2	42.1	12.5%
Composting	0.7	1.7	2.9	3.6	3.5	4.1	4.4	4.4	4.4	4.4	4.5	513.6%
Anaerobic Digestion at Biogas Facilities	+	+	+	+	+	+	+	+	+	+	+	986.3%
Total Emissions	**235.9**	**233.6**	**200.3**	**192.0**	**182.9**	**171.3**	**169.5**	**166.8**	**165.2**	**166.0**	**166.0**	**-29.6%**

Emissions and Removals by Economic Sector

This section presents U.S. GHG emission according to more commonly used economic sectors. A main difference from the reporting sectoral classification is that fossil fuel combustion emissions are allocated to the U.S. economic sector in which they are consumed, rather than included solely in the energy sector. The result is similar to how fossil fuel combustion is subcategorized in the IPCC classification (e.g., electricity, transportation, industry), except for the inclusion of some combustion emissions under agriculture.

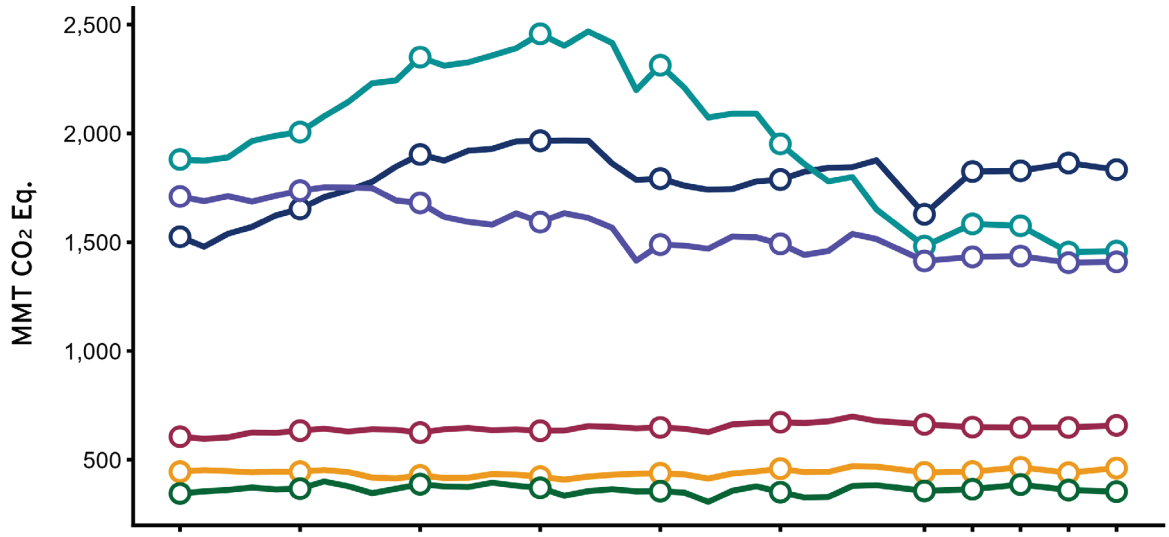
Industrial emissions now include both fossil fuel combustion and most IPPU emissions (e.g., process emissions from iron and steel, aluminum, chemical production).[6] As a result, the Industry economic sector makes up a much larger share of total U.S. emissions than the IPPU results. Figure 2-10 shows the trends by economic sector since 1990.

The overall trend highlights are largely the same in this classification as they are for the IPCC fossil fuel combustion results. Transportation is the largest sector, followed by electricity and then industry. All three experienced a significant drop in 2020 due to the onset of COVID-19.

The agriculture, commercial, and residential economic sectors all remained at roughly the same levels from 1990 to 2024, with some year-to-year changes related to weather and other factors.

[6] Some exceptions include SF_6 from electrical equipment, which is with electric power, and HFCs from mobile air conditioning systems, which are with transportation.

Figure 2-10: Trends by Economic Sector



	1990	1995	2000	2005	2010	2015	2020	2021	2022	2023	2024	90-24
Transportation	1,525	1,653	1,903	1,966	1,792	1,788	1,628	1,825	1,828	1,864	1,833	20.2%
Electric Power	1,880	2,006	2,350	2,457	2,313	1,952	1,482	1,584	1,575	1,454	1,459	-22.4%
Industry	1,710	1,737	1,681	1,592	1,489	1,492	1,414	1,433	1,436	1,406	1,410	-17.6%
Agriculture	606	634	625	634	649	673	663	650	649	649	658	8.6%
Commercial	445	445	428	423	438	460	442	446	466	441	462	3.8%
Residential	346	368	388	371	356	351	357	365	387	361	354	2.5%
Total Gross Emissions	**6,513**	**6,843**	**7,375**	**7,444**	**7,038**	**6,716**	**5,986**	**6,302**	**6,341**	**6,175**	**6,177**	**-5.2%**

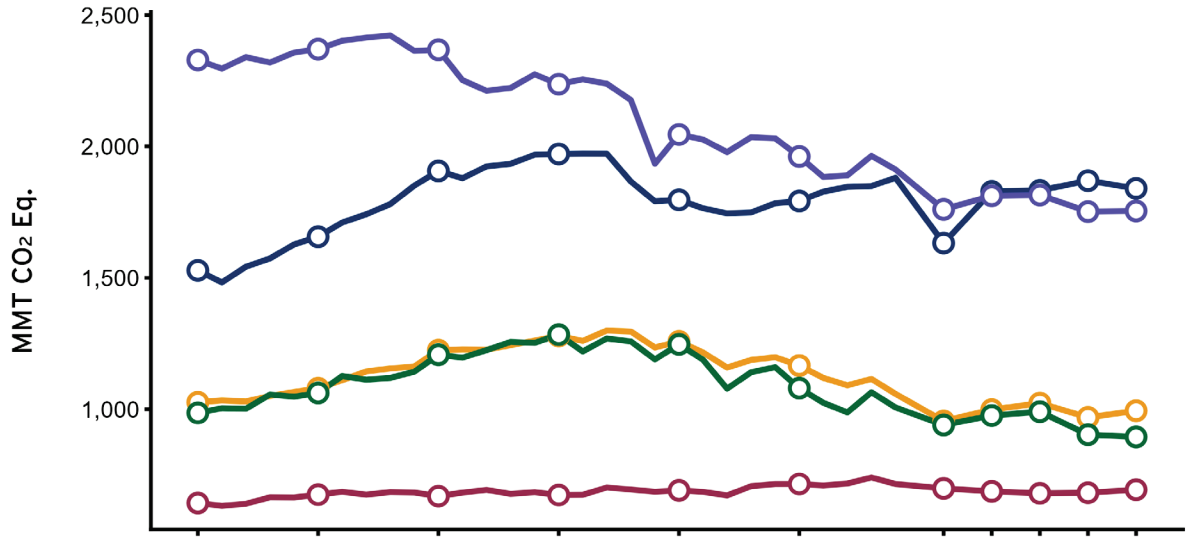
Note: Figure 2-10 excludes emissions from U.S. Territories and excludes emissions and removals from LULUCF sector.

Emissions and Removals by Economic Sector with Electricity Emission Distributed

When electricity emissions are allocated or distributed to the economic sector in which the electricity is ultimately consumed, the relative contribution to U.S. emissions and the trends show some significant differences.

As shown in Figure 2-11, industry consumes a significant amount of electricity to power processes and operate buildings and, as a result, is the largest economic sector for most of the time series. Electricity-related emissions attributable to industry decreased by 24.7 percent from 1990 to 2024, due to a shift away from energy-intensive industrial production, end-use efficiency improvements, and the overall drop in carbon intensity of electricity production in the United States.

Figure 2-11: Trends in Economic Sector Emissions with Electricity Distributed



	1990	1995	2000	2005	2010	2015	2020	2021	2022	2023	2024	90-24
Transportation	1,528	1,656	1,907	1,971	1,797	1,792	1,632	1,829	1,833	1,869	1,840	20.4%
Industry	2,329	2,370	2,368	2,237	2,045	1,962	1,760	1,812	1,815	1,752	1,754	-24.7%
Commercial	1,026	1,080	1,225	1,279	1,258	1,166	955	998	1,023	969	994	-3.1%
Residential	986	1,062	1,207	1,284	1,247	1,080	940	976	990	903	895	-9.3%
Agriculture	643	675	669	674	691	716	699	687	680	682	694	7.9%
Total Gross Emissions	**6,513**	**6,843**	**7,375**	**7,444**	**7,038**	**6,716**	**5,986**	**6,302**	**6,341**	**6,175**	**6,177**	**-5.1%**

Note: Figure 2-11 excludes emissions from U.S. Territories and excludes emissions and removals from LULUCF sector.

The overall trend in the transportation sector is basically the same as when electricity emissions are not included. Electricity use in transportation is increasing rapidly with the adoption of electric vehicles but is still a minor contributor to the total and trend.

As with industry, the level of electricity emissions attributable to the commercial and residential sectors is significant. In 2024, emissions from electricity distributed to the residential and commercial sectors made up 66 percent of the total direct and indirect emissions from those sectors. The relative importance of distributed electricity emissions has declined in recent years due to efficiency improvements and the lower carbon intensity of purchased electricity.

Trends in Focus

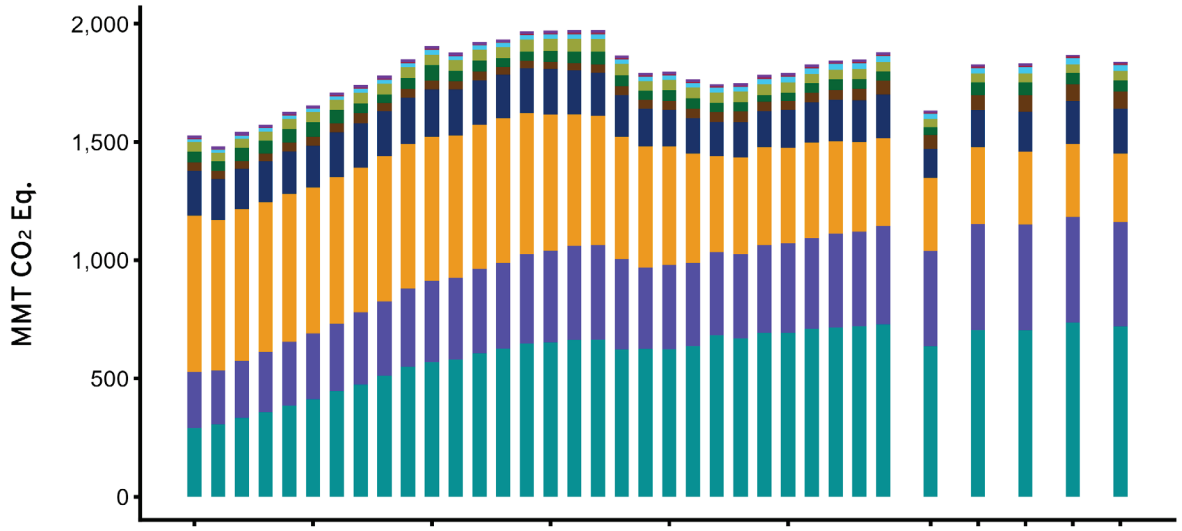
For this *GHGIA*, two key areas are discussed in more detail given their importance to understanding the long-term trend in total GHG emissions since 1990 and GHG emissions since 2005: transportation economic sector (all sources and all gases) and electricity sector (generation mix and fossil fuel CO_2 emissions).

Additionally, Box 2-1 presents trends in key economic and demographic indicators that can help illustrate how GHG emissions have changed in the context of other societal trends.

Transportation Economic Sector Emissions

Figure 2-12 shows emissions from the transportation economic sector, broken out by "mode" or vehicle type. In 1990, passenger cars made up by far the largest share of GHG emissions, but this share has declined almost every single year since then. In contrast, GHG emissions from light-duty trucks grew steadily over the period and now represent the largest share of emissions. This category includes some SUVs, pickup trucks, and minivans, which have grown significantly in popularity and typically have lower fuel economy than passenger cars due to their greater weight and engine size.

Figure 2-12: Trends in Transportation Sector by Mode



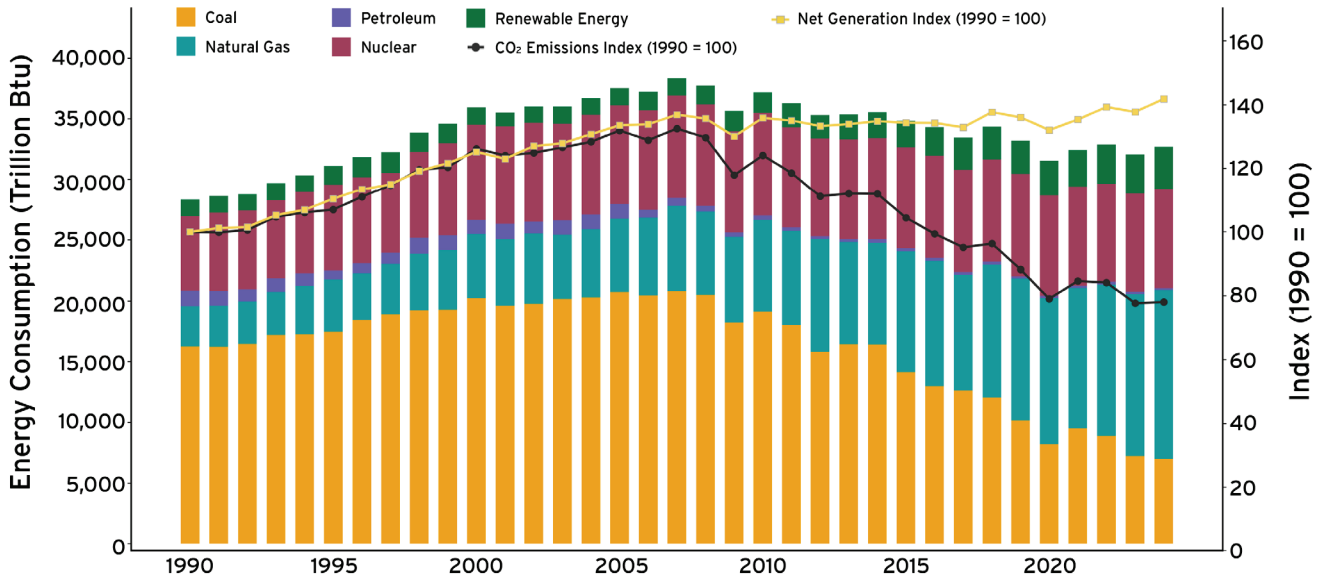
	1990	1995	2000	2005	2010	2015	2020	2021	2022	2023	2024	90-24
Light-Duty Trucks	291	411	570	651	624	693	636	705	705	736	721	147.7%
Medium- and Heavy-Duty Trucks	237	279	344	390	357	378	403	448	447	447	442	86.9%
Passenger Cars	661	619	610	574	501	406	310	326	308	308	289	-56.4%
Aircraft	189	176	199	193	155	160	123	155	168	182	189	-0.1%
Pipelines	36	38	35	33	38	39	58	65	72	71	73	103.7%
Ships and Boats	47	59	66	45	45	34	32	54	53	47	48	3.0%
Rail	39	43	46	51	44	44	35	37	37	37	38	-2.8%
Buses	13	15	19	18	17	22	20	23	25	26	25	94.2%
Motorcycles	3	4	4	5	6	7	6	7	8	9	9	163.2%
Lubricants	12	11	12	10	10	11	8	8	9	6	6	-48.7%
Total Emissions	**1,528**	**1,656**	**1,906**	**1,971**	**1,797**	**1,792**	**1,632**	**1,829**	**1,833**	**1,869**	**1,840**	**20.4%**

Electricity Sector—Generation Mix and Fossil Fuel CO_2 Emissions

Figure 2-13 shows the changing fuel mix for electricity generation in the United States since 1990, along with the overall trend in electricity sector generation and fossil fuel CO_2 emissions. The correlation between declining coal use and emission reductions is clear, particularly since the 2005–2007 period. In 1990, coal generation represented 54 percent of the total net electricity generation in the United States. By 2024, that share had declined to 16 percent. Natural gas generation, which has grown from 11 percent to 42 percent of the total over the same period, is typically 55 percent less carbon intensive per unit of energy than coal.

Renewable energy generation in 1990 was modest at 11 percent and included mostly hydroelectric power. Over the last decade or so, other forms of renewable electricity such as solar and wind have increased significantly, and the overall share of renewables climbed to 23 percent by 2024.

Figure 2-13: Trends in Electricity Sector by Fuel Type



Box 2-1: Key Economic and Demographic Indicator Trends

Gross GHG emissions can be compared to other indices to illuminate how underlying economic and societal changes compare to emission trends. Comparative indices included in this chapter include:

- Aggregate energy use (the largest driver of CO_2 emissions);
- Energy use per capita;
- Emissions per unit of total gross domestic product; and
- Emissions per capita.

Table 2-1 provides time series data for these indices, normalized to 1990, and Figure 2-14 presents this information in chart form. Gross U.S. GHG emissions in the United States decreased at an average annual rate of 0.1 percent. This growth rate is slightly slower than that for total energy use, overall gross domestic product (GDP) and national population.

Around the year 2005, GHG emissions, total energy use, and associated fossil fuel consumption began to peak. Since 2005, emissions have decreased at an average annual rate of 0.9 percent, while GDP and national population generally continued to increase. Energy use has decreased slightly, with 2020 being an exception due to the impact of the COVID-19 pandemic.

Indicator	1990	2005	2020	2021	2022	2023	2024	Avg. Annual % Change Since 1990[a]	Avg. Annual % Change Since 2005[a]
Greenhouse Gas Emissions[b]	100	115	92	97	97	95	95	–0.1%	–0.9%
Energy Use[c]	100	119	108	113	116	114	114	0.4%	–0.2%
GDP[d]	100	159	202	214	220	226	232	2.5%	2.0%
Population[e]	100	118	132	132	133	134	136	0.9%	0.7%

[a] Average annual growth rate.

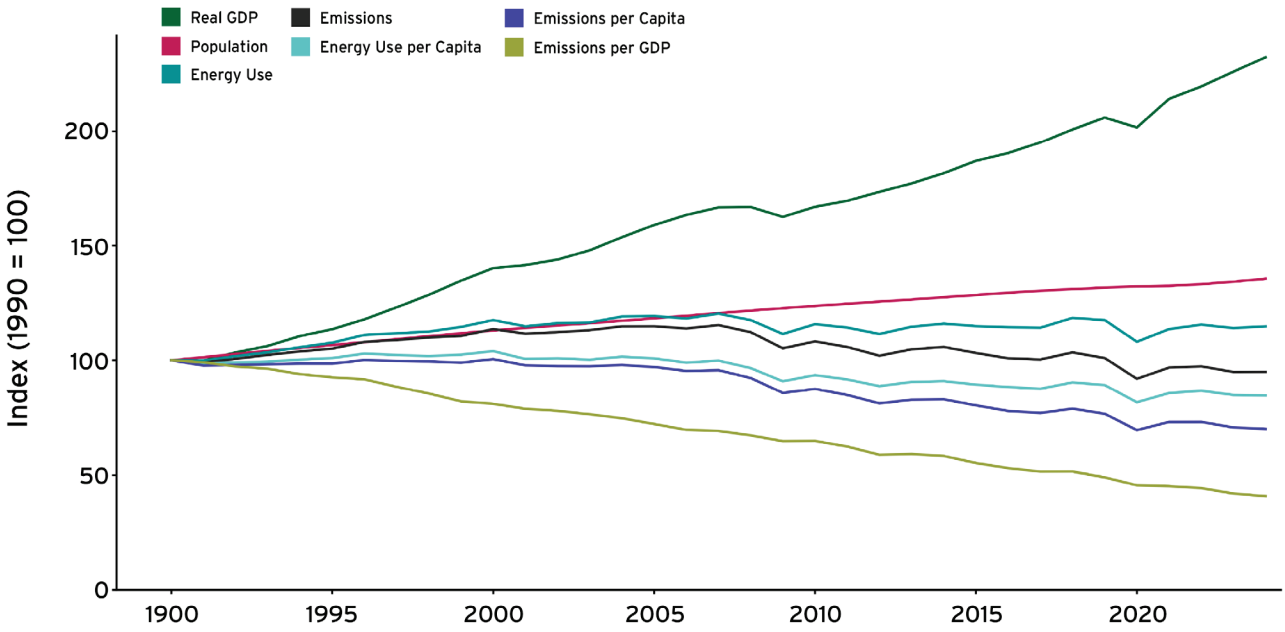
[b] Gross total GWP-weighted values.

[c] Energy-content-weighted values (EIA, 2026).

[d] GDP in chained 2017 dollars (BEA, 2026).

[e] U.S. Census Bureau (2024, 2025).

Figure 2-14: Key Economic and Demographic Indicator Trends



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3

Energy

Chapter 3. Energy

Emissions from the energy sector include greenhouse gases (GHGs) from fuel combustion and fugitive emissions associated with energy production, transmission, and use. The vast majority of energy-related emissions come from fossil fuel combustion, with carbon dioxide (CO_2) being the primary gas emitted, along with smaller amounts of methane (CH_4) and nitrous oxide (N_2O). Other energy-related activities, such as the production, transmission, storage, and distribution of coal, oil, and natural gas, also emit GHGs. These emissions are primarily fugitive CH_4 emissions from natural gas systems, coal mining, and petroleum systems. Additional non-combustion emissions from industrial production and product use sources are reported in Chapter 4. Industrial Process and Product Use. These energy-related activities are the primary sources of U.S. anthropogenic GHG emissions.

In 2024, emissions from this sector were 5,050.6 million metric tons (MMT) CO_2 equivalent (CO_2 Eq.), accounting for approximately 81.4 percent of total gross U.S. GHG emissions on a CO_2 Eq. basis. This included 96, 40, and 9 percent of the nation's CO_2, CH_4, and N_2O gross emissions, respectively. Figure 3-1 shows the energy sector emissions trends by category from 1990 to 2024.

Figure 3-1: Trends in Energy Sector Greenhouse Gas Sources

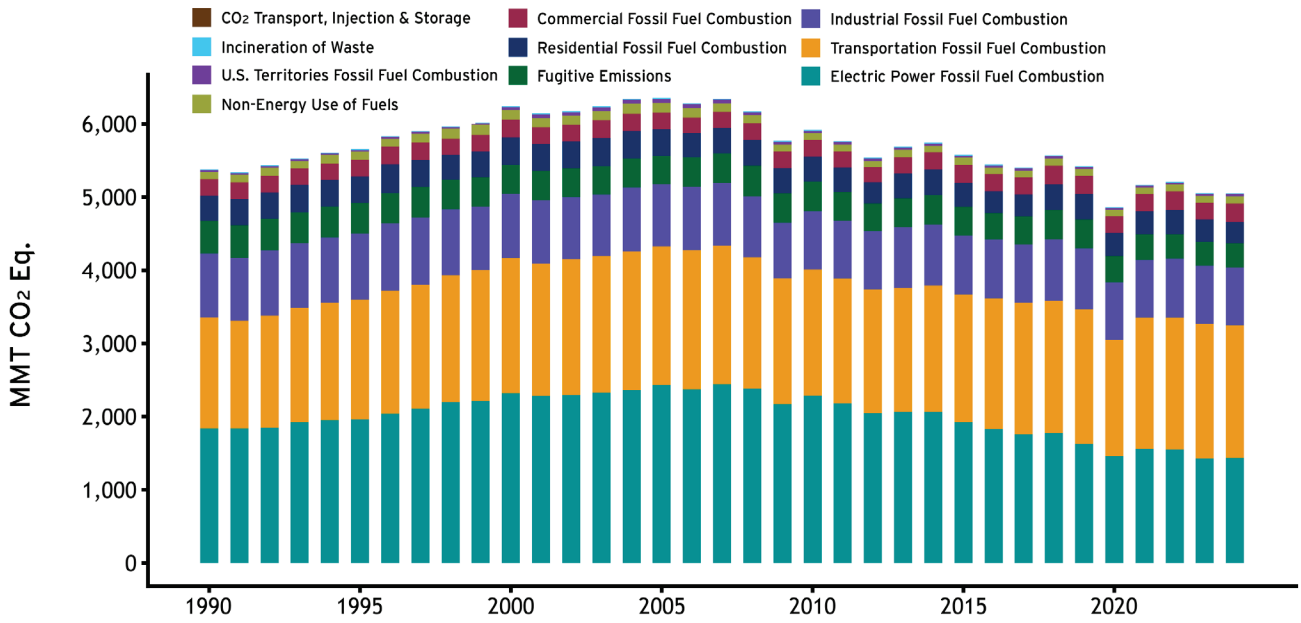


Table 3-1 has the energy sector emissions by category and gas for select years.

Table 3-1: CO_2, CH_4, and N_2O Emissions from Energy (MMT CO_2 Eq.)

Gas/Source	1990	2005	2020	2021	2022	2023	2024
CO_2	**4,909.0**	**5,921.3**	**4,524.5**	**4,838.4**	**4,888.0**	**4,747.3**	**4,738.0**
Fossil Fuel Combustion	4,748.8	5,735.0	4,360.0	4,673.7	4,725.0	4,581.7	4,568.1
Transportation	1,473.1	1,852.8	1,575.7	1,772.0	1,776.9	1,817.7	1,788.6
Electricity Generation	1,820.0	2,400.1	1,439.6	1,540.9	1,531.7	1,414.9	1,420.8
Industrial	870.4	843.3	778.3	786.8	807.5	791.7	789.7
Residential	338.6	359.1	314.0	313.4	329.4	300.7	290.6
Commercial	226.7	227.8	229.1	234.8	255.7	229.5	250.5
U.S. Territories	20.0	51.8	23.2	25.7	23.8	27.2	27.9
Non-Energy Use of Fuels	100.6	132.4	83.7	89.9	89.5	89.6	96.0
Natural Gas Systems	32.5	26.3	36.8	35.7	36.4	37.7	37.4
Petroleum Systems	9.6	10.2	28.9	24.1	22.1	23.3	22.3
Incineration of Waste	12.9	13.3	12.9	12.5	12.5	12.4	11.9
Coal Mining	4.6	4.2	2.2	2.5	2.5	2.4	2.3
CO_2 Transport, Injection, and Geological and Storage	0.0	0.0	+	0.1	0.1	0.1	0.1
Abandoned Oil and Gas Wells	+	+	+	+	+	+	+
Biomass-Wood[a]	215.2	206.9	189.5	192.8	207.1	190.6	185.7
International Bunker Fuels[b]	103.6	113.3	69.6	80.2	98.2	96.2	97.8
Biofuels-Ethanol[a]	4.2	22.9	71.8	79.1	79.6	80.7	80.9
Biofuels-Biodiesel[a]	0.0	0.9	17.7	16.1	15.6	18.2	18.2
Biomass-MSW[a]	18.5	14.7	15.6	15.3	14.9	13.9	13.9
CH_4	**410.4**	**360.1**	**302.3**	**290.9**	**279.0**	**271.4**	**276.2**
Natural Gas Systems	219.6	210.7	180.1	174.6	172.8	162.4	169.8
Coal Mining	108.0	71.4	46.1	45.7	43.6	45.4	44.3
Petroleum Systems	50.0	48.4	50.6	45.1	36.3	38.0	36.5
Abandoned Oil and Gas Wells	7.8	8.2	8.5	8.6	8.5	8.5	8.4
Stationary Combustion	9.6	8.8	7.9	8.0	9.0	8.2	8.1

(continued)

Table 3-1: CO_2, CH_4, and N_2O Emissions from Energy (MMT CO_2 Eq.) *(continued)*

Gas/Source	1990	2005	2020	2021	2022	2023	2024
Abandoned Underground Coal Mines	8.1	7.4	6.5	6.2	6.1	6.1	6.4
Mobile Combustion	7.2	5.2	2.6	2.7	2.7	2.7	2.7
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	0.2	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	**60.50**	**72.85**	**37.03**	**39.40**	**39.88**	**36.4**	**36.3**
Stationary Combustion	22.3	30.5	20.5	22.0	22.7	19.5	19.0
Mobile Combustion	37.8	42.0	16.1	17.0	16.9	16.5	17.0
Incineration of Waste	0.4	0.3	0.3	0.4	0.3	0.3	0.3
Petroleum Systems	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Natural Gas Systems	0.0	0.0	0.0	0.0	0.0	0.0	0.0
International Bunker Fuels[b]	0.8	0.9	0.5	0.6	0.8	0.8	0.8
Total	**5,379.8**	**6,354.3**	**4,863.8**	**5,168.7**	**5,206.9**	**5,055.0**	**5,050.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Emissions from biomass and biofuel consumption are not included specifically in summing energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for Land Use, Land-Use Change and Forestry (LULUCF).

[b] Emissions from international bunker fuels are not included in totals. These values are presented for informational purposes only, in line with the 2006 Intergovernmental Panel on Climate Change Guidelines.

Note: Totals may not sum due to independent rounding.

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 2 (Energy) 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 Inventories* (IPCC, 2019), using country-specific data where available. Unless otherwise noted (see Table 3-2), methods are consistent with those used in *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2023* (Environmental Protection Agency [EPA], 2025). Consistent with IPCC good practices, the *GHGIA* applies higher tier methods for more significant sources (e.g., Tier 2 and Tier 3 methods that

include use of country-specific methods and models, emission factors and site-specific information) and where feasible for smaller sources.

Table 3-2: Energy Sector Methods Summary

Category (CRT Code)[a]	Gas(s)	IPCC Methodological Tier	Methodological Refinements Compared to 1990–2023 (EPA, 2025)
Source Category: Fossil Fuel Combustion (1A)			
Electricity Sector	CO_2	Tier 2	No change
Electricity Sector	CH_4	Tier 2	No change
Electricity Sector	N_2O	Tier 2	No change
Transportation Sector	CO_2	Tier 2, Tier 3	No change
Transportation Sector	CH_4	Tier 2, Tier 3	No change
Transportation Sector	N_2O	Tier 2, Tier 3	No change
Industrial Sector	CO_2	Tier 2	No change
Industrial Sector	CH_4	Tier 1	No change
Industrial Sector	N_2O	Tier 1	No change
Residential Sector	CO_2	Tier 2	No change
Residential Sector	CH_4	Tier 1	No change
Residential Sector	N_2O	Tier 1	No change
Commercial Sector	CO_2	Tier 2	No change
Commercial Sector	CH_4	Tier 1	No change
Commercial Sector	N_2O	Tier 1	No change
Territories	CO_2	Country Specific, Tier 2	No change
Territories	CH_4	Tier 1	No change
Territories	N_2O	Tier 1	No change
Source Category: Carbon Emitted from Non-Energy Use (1A)			
Non-Energy Use of Fossil Fuels	CO_2	Country Specific, Tier 2	No change

(continued)

Table 3-2: Energy Sector Methods Summary *(continued)*

Category (CRT Code)[a]	Gas(s)	IPCC Methodological Tier	Methodological Refinements Compared to 1990-2023 (EPA, 2025)
Source Category: Waste Incineration (1A)			
Biogenic Municipal Solid Waste (MSW)	CO_2	Country Specific, Tier 2	Yes, use of U.S. Energy Information Administration (EIA) data for MSW amount combusted
Biogenic Municipal Solid Waste	CH_4	Country Specific, Tier 2	Yes, use of EIA data for MSW amount combusted
Biogenic Municipal Solid Waste	N_2O	Country Specific, Tier 2	Yes, use of EIA data for MSW amount combusted
Non-biogenic Municipal Solid Waste	CO_2	Country Specific, Tier 2	Yes, use of EIA data for MSW amount combusted
Non-biogenic Municipal Solid Waste	CH_4	Country Specific, Tier 2	Yes, use of EIA data for MSW amount combusted
Non-biogenic Municipal Solid Waste	N_2O	Country Specific, Tier 2	Yes, use of EIA data for MSW amount combusted
Source Category: Coal Mining (1B1a)			
Underground Mines	CH_4	Tier 2, Tier 3	Yes, proxy based on 2023 for Greenhouse Gas Reporting Program (GHGRP) mine data
Surface Mines	CH_4	Tier 2, Tier 3	No change
Underground Mines	CO_2	Tier 1	Yes, proxy based on 2023 for GHGRP mine data
Surface Mines	CO_2	Tier 1	No change
Source Category: Abandoned Underground Coal Mines (1B1a)			
Abandoned Underground Mines	CH_4	Tier 2, Tier 3	No change
Source Category: Petroleum Systems (1B2a)			
Petroleum Systems	CH_4	Tier 2, Tier 3	No change
Petroleum Systems	CO_2	Tier 2, Tier 3	No change
Petroleum Systems	N_2O	Tier 2, Tier 3	No change
Source Category: Natural Gas Systems (1B2b)			
Natural Gas Systems	CH_4	Tier 2	No change
Natural Gas Systems	CO_2	Tier 2	No change
Natural Gas Systems	N_2O	Tier 2	No change

(continued)

Table 3-2: Energy Sector Methods Summary *(continued)*

Category (CRT Code)[a]	Gas(s)	IPCC Methodological Tier	Methodological Refinements Compared to 1990–2023 (EPA, 2025)
Source Category: Abandoned Oil and Gas Wells (1B2a and 1B2b)			
Abandoned wells	CH_4	Tier 2	No change
Abandoned wells	CO_2	Tier 2	No change
Source Category: CO_2 Transportation, Injection, and Geologic Storage (TIGS) (1C)			
Transport of CO_2	CO_2	Tier 1	No change
Injection and Storage	CO_2	Tier 3	Yes, proxy based on 2023 for GHGRP data
Other	CO_2	Tier 3	Yes, proxy based on 2023 for GHGRP data
Source Category: International Bunker Fuels (Memo Item)			
Memo Items: International Bunkers	CO_2	Tier 2	Yes, proxy missing military and commercial aviation data
Memo Items: International Bunkers	CH_4	Tier 1	Yes, proxy missing military and commercial aviation data
Memo Items: International Bunkers	N_2O	Tier 1	Yes, proxy missing military and commercial aviation data
Source Category: Biomass (1A)			
Memo Items: Biomass Combustion	CO_2	Tier 2	No change
Electricity Sector	CH_4	Tier 2	No change
Electricity Sector	N_2O	Tier 2	No change
Transportation Sector	CH_4	Tier 2	No change
Transportation Sector	N_2O	Tier 2	No change
Industrial Sector	CH_4	Tier 1	No change
Industrial Sector	N_2O	Tier 1	No change
Residential Sector	CH_4	Tier 1	No change
Residential Sector	N_2O	Tier 1	No change
Commercial Sector	CH_4	Tier 1	No change
Commercial Sector	N_2O	Tier 1	No change

[a] Codes in parentheses represent common reporting table (CRT) codes. The CRT codes are 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. Translating 1A: 1 = energy sector, A = subsector Fossil Fuel Combustion

This chapter presents the methodologies and estimates of emissions for the following sources, each presented in its own section:

- fossil fuel combustion (CO_2, CH_4, N_2O)
    - broken out by end-use sector
- carbon emitted from non-energy use (NEU) of fossil fuels (CO_2)
- incineration of waste (CO_2, CH_4, N_2O)
- coal mining (CO_2, CH_4)
- abandoned underground coal mines (CH_4)
- petroleum systems (CO_2, CH_4, N_2O)
- natural gas systems (CO_2, CH_4, N_2O)
- abandoned oil and gas wells (CO_2, CH_4)
- CO_2 transport injection and geologic storage (TIGS) (CO_2)
- memo item: International bunker fuels (CO_2, CH_4, N_2O)
- memo item: Wood biomass and biofuels consumption (CO_2)

Quality Assurance/Quality Control

To ensure the quality of the energy sector GHG emission estimates, general and category-specific quality assurance/quality control (QA/QC) procedures were implemented. The category-specific procedures that were implemented involved checks specifically focusing on the activity data and methodology used for estimating each source of emissions from the energy sector. Emission totals for the different sectors and fuels were compared, and trends were investigated to determine whether any corrective actions were needed. Minor corrective actions were taken as necessary.

Along with the QA/QC checks for fossil fuel combustion, a "top-down" reference approach for estimating CO_2 emissions from fossil fuel combustion was implemented in addition to the primary "bottom-up" sectoral methodology presented in this chapter, in line with IPCC guidelines. The reference approach (detailed in Annex 3) uses alternative methodologies and different data sources than those used for the sectoral approach. The reference approach estimates fossil fuel consumption by adjusting national aggregate fuel production data by imports, exports, and stock changes rather than relying on the end-user consumption surveys that are used for the sectoral approach. The reference approach assumes that once carbon-based fuels are brought into a national economy, they are either saved (e.g., stored in products, kept in fuel stocks, or left unoxidized in ash) or combusted, and therefore the carbon in them is oxidized and, if not captured and stored, released into the atmosphere. In the reference approach, accounting for actual consumption of fuels at the sectoral or sub-national level is not required. One difference between the two approaches is that emissions from carbon that is emitted during non-energy use (NEU) of fuels are subtracted from the sectoral approach and reported separately (see Section 3.2). These emissions, however, are included directly in the reference approach and not reported separately.

Future Areas for Improvement

Continuous improvement efforts are important for reflecting the latest science and reducing uncertainties to the extent practicable in estimating emissions from energy sector activities, especially for significant categories and those with higher uncertainty in results. For categories where the methodology has not changed in this *GHGIA* and remains consistent with previous analyses, any improvements identified in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025) will be reviewed. Any improvements that have been incorporated into this *GHGIA* are discussed in the Methods and Recalculations sections of those respective categories.

There are several categories where potentially more significant methodological changes and/or refinements are anticipated, primarily due to challenges with data availability or changes compared with previous analysis. These include the following categories:

- Transportation fossil fuel combustion: Data for on-road gasoline and diesel fuel use is based on information from the U.S. Department of Transportation, Federal Highway Administration (FHWA). For the 2024 data release, FHWA changed their off-road model, which results in a discontinuity with older data for gasoline and diesel fuel use. A planned improvement is to examine ways to ensure the time series consistency of the data. There were some data sources, as discussed in the methodology section for transportation fossil fuel combustion emissions, that were proxied for this analysis. A planned improvement is to investigate gathering alternative data for those sources going forward.
- Electric power fossil fuel combustion: A longer-term planned improvement is to investigate differences between electricity sector characterization across different sources, including how biomass use and non-CO_2 emissions are counted under different sources.
- Industry fossil fuel combustion: Previously, data from the U.S. Greenhouse Gas Reporting Program (GHGRP) was used to help better characterize the industrial sector's energy consumption in the United States and further classify total industrial sector fossil fuel combustion emissions by business establishments according to industrial economic activity type. Future planned improvements include considering other data sources and methods that could be used to disaggregate industrial sector energy use by subsectors.
- U.S. Territories fossil fuel combustion: For the most part, the same physical characteristics are assumed for fuels used in U.S. Territories as for those used in the continental United States. There may be differences in heating contents of fuels used in U.S. Territories that would impact the calculations of total energy use. A planned improvement is to investigate other data sources for heating content of fuels used in U.S. Territories.
- NEU: A longer-term improvement is to review the links between NEU, fossil fuel combustion, and Industrial Processes and Product Use (IPPU) approaches to ensure there is no double counting but also to streamline reporting to make it more in line with IPCC methods for reporting NEU emissions under IPPU.
- CO_2 TIGS and waste incineration: A near-term improvement is to investigate alternative data sources due to lack of GHGRP data.

- International bunker fuels: There were some data sources, as discussed in the methodology section for International Bunker Fuels emissions, that were proxied for this analysis. A planned improvement is to investigate gathering alternative data for those sources going forward. This includes looking into Federal Energy Management Program (FEMP) data for military emissions and Department of Transportation data on commercial flights.
- Petroleum and natural gas systems: The 2026 *GHGIA* will be updated with the latest activity data, including revised well and well completion counts, and production data. The estimates will be updated to use the latest Bureau of Ocean Energy Management Inventory for offshore sources. Any available 2024 GHGRP data will be reviewed for potential updates and recalculations. In 2024, EPA had considered but did not implement updates to make the inventory more consistent with GHGRP emission factor updates. Implementing those updates would result in increased emissions estimates, closer to estimates derived by atmospheric observations. We will engage with researchers and will review available data that could improve our emission factors and/or methods for quantifying emissions from petroleum and natural gas systems.
- Abandoned oil and gas wells: The 2026 *GHGIA* will be updated with revised abandoned oil and gas well counts and the latest information on well plugging. Available data that could improve our emission factors and/or methods for quantifying emissions from abandoned oil and gas wells will be reviewed.

Future versions of this *GHGIA* will specify more on scope, timing, and plans for phasing in improvements.

3.1 Fossil Fuel Combustion (Source Category 1A)

The combustion of fossil fuels produces energy for useful heat and work. The combustion process oxidizes the carbon stored in the fuels, which is emitted as carbon dioxide (CO_2) and smaller amounts of other gases, including CH_4, carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs). In the context of estimating GHGs associated with fossil fuel combustion, it is assumed that all the carbon from fossil fuel combustion is eventually converted to atmospheric CO_2 (IPCC, 2006).

The combustion of biomass and biofuels generates CO_2 as well as non-CO_2 emissions (CH_4 and N_2O). In accordance with IPCC inventory guidelines, CO_2 emissions from biomass and biofuel combustion are estimated separately from fossil fuel CO_2 emissions and are excluded from energy sector totals to avoid double counting. 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). Section 3.11 below has more detail on biomass and biofuel CO_2 emissions. Non-CO_2 emissions from biomass and biofuel combustion are included in energy sector totals and are reported in this section as part of stationary and mobile combustion source categories.

The GHGs CH_4 and N_2O are also produced during fossil fuel combustion. These emissions depend upon fuel and combustion device characteristics, along with pollution control equipment, ambient environmental conditions, and operation and maintenance practices. Nitrous oxide (N_2O) emissions are closely related to air-fuel mixes and combustion temperatures, as well as the characteristics of any pollution control equipment that is employed. N_2O from mobile sources, in particular, can be formed by the catalytic processes used to control NO_x, CO, and hydrocarbon emissions. Methane (CH_4) emissions are a function of the CH_4 content of the fuel and combustion efficiency. CH_4 emissions from motor vehicles are also impacted by any post-combustion control of hydrocarbon emissions (such as catalytic converters).

The approach for determining fossil fuel combustion emissions is based on multiplying emissions factors by activity data on fuel consumption. The activity data on fuel consumption is from energy balances prepared for EIA's *Monthly Energy Review* estimates (2026a). Fuel use is determined by fuel type because different types of fuels have different carbon contents and therefore different emissions factors. The amount of carbon in fuels varies significantly by fuel type. For example, coal contains the highest amount of carbon per unit of useful energy. Petroleum has roughly 75 percent of the carbon per unit of energy as coal, and natural gas has only about 55 percent.[7]

The fossil fuel combustion amounts are broken out by energy-consuming sectors of U.S. society to provide more detail and information on trends; the sectors included are transportation, electric power, industrial, residential, and commercial. Data from U.S. Territories are also included in the analysis and reported separately. Data obtained from EIA's *International Energy Statistics* (2026b) for U.S. Territories (including American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other outlying U.S. Pacific Islands) are only available at the aggregate level and cannot be broken out by end-use sector so are just reported as a total.

Several adjustments are made to the data to account for fuel use and emissions that are either excluded or reported (or implicitly included) in other parts of the national inventory, as shown in Figure 3-2 (EPA, 2024).

[7] Based on national aggregate carbon content of all coal, natural gas, and petroleum fuels combusted in the United States.

Figure 3-2: Adjustments to Energy Consumption for Emissions Estimates

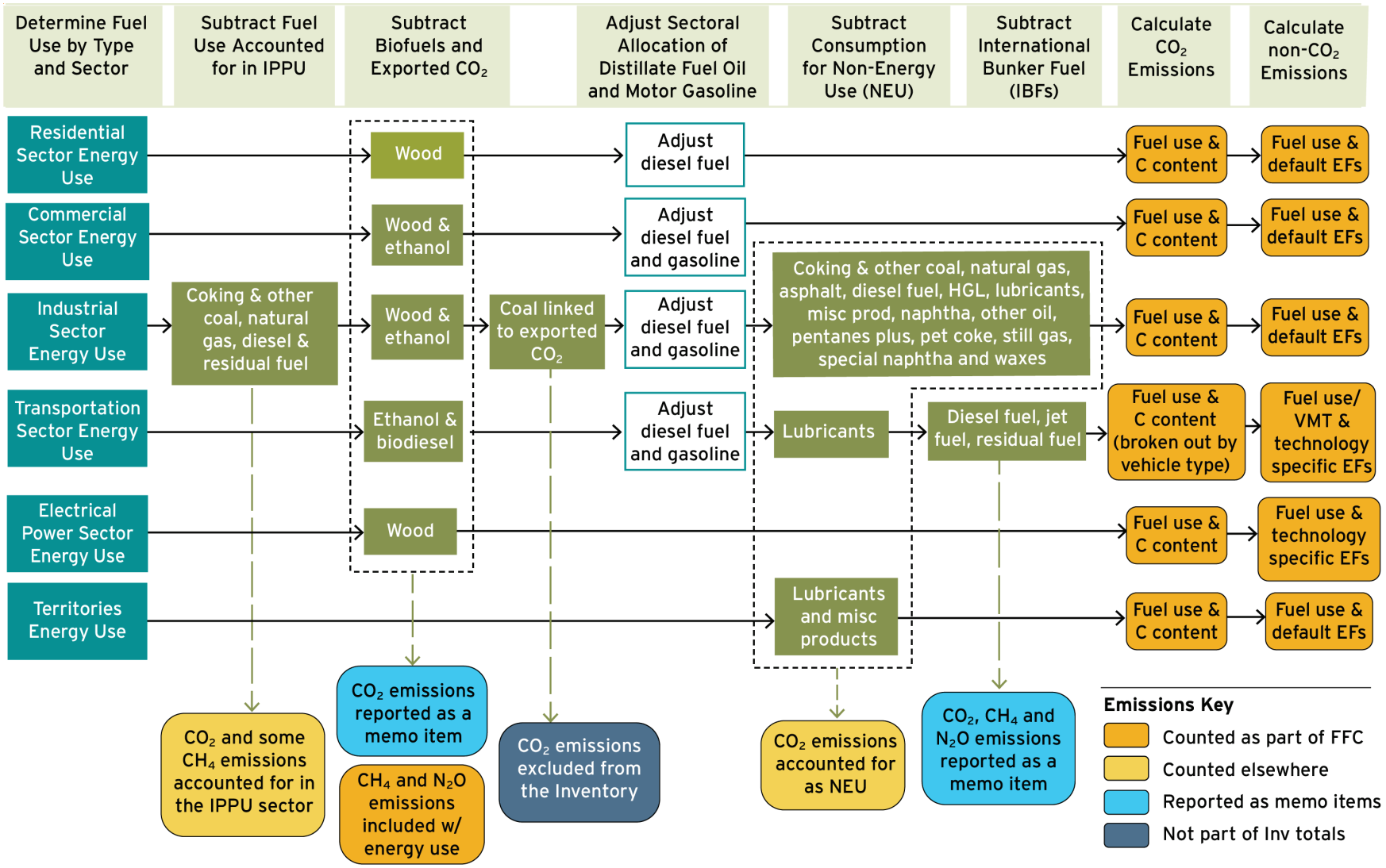


Table 3-3 provides an overview of the CO_2, CH_4, and N_2O emissions from fossil fuel combustion by sector and U.S. Territories.

Table 3-3: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion by Sector (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2020	2021	2022	2023	2024
Electric Power	**1,838.7**	**2,427.8**	**1,458.5**	**1,561.3**	**1,552.6**	**1,433.0**	**1,438.4**
CO_2	1,820.0	2,400.1	1,439.6	1,540.9	1,531.7	1,414.9	1,420.8
CH_4	0.5	1.0	1.4	1.4	1.5	1.5	1.5
N_2O	18.2	26.7	17.5	19.0	19.4	16.6	16.0
Transportation	**1,518.1**	**1,900.0**	**1,594.4**	**1,791.7**	**1,796.6**	**1,836.9**	**1,808.3**
CO_2	1,473.1	1,852.8	1,575.7	1,772.0	1,776.9	1,817.7	1,788.6
CH_4	7.2	5.2	2.6	2.7	2.7	2.7	2.7
N_2O	37.8	42.0	16.1	17.0	16.9	16.5	17.0
Industrial	**875.2**	**847.9**	**782.0**	**790.5**	**811.3**	**795.3**	**793.2**
CO_2	870.4	843.3	778.3	786.8	807.5	791.7	789.7
CH_4	2.1	1.9	1.6	1.6	1.7	1.6	1.6
N_2O	2.8	2.6	2.1	2.1	2.1	2.0	2.0
Residential	**345.4**	**364.5**	**318.2**	**317.8**	**334.6**	**305.2**	**294.9**
CO_2	338.6	359.1	314.0	313.4	329.4	300.7	290.6
CH_4	5.9	4.5	3.6	3.7	4.5	3.9	3.7
N_2O	0.9	0.8	0.6	0.6	0.7	0.6	0.6
Commercial	**228.2**	**229.3**	**230.7**	**236.4**	**257.3**	**231.0**	**252.1**
CO_2	226.7	227.8	229.1	234.8	255.7	229.5	250.5
CH_4	1.2	1.2	1.2	1.3	1.3	1.2	1.3
N_2O	0.3	0.3	0.3	0.3	0.3	0.3	0.3
U.S. Territories[a]	**20.1**	**52.1**	**23.3**	**25.8**	**23.8**	**27.3**	**28.0**
CO_2	20.0	51.8	23.2	25.7	23.8	27.2	27.9
CH_4	0.0	0.1	0.0	0.0	0.0	0.0	0.0
N_2O	0.0	0.1	0.1	0.1	0.1	0.1	0.1

(continued)

Table 3-3: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion by Sector (MMT CO_2 Eq.) *(continued)*

End-Use Sector	1990	2005	2020	2021	2022	2023	2024
Total	**4,825.8**	**5,821.5**	**4,407.1**	**4,723.5**	**4,776.3**	**4,628.7**	**4,614.9**
CO_2	4,748.8	5,735.0	4,360.0	4,673.7	4,725.0	4,581.7	4,568.1
CH_4	16.9	14.0	10.5	10.7	11.7	10.9	10.9
N_2O	60.1	72.5	36.7	39.0	39.5	36.1	36.0

[a] U.S. Territories are not apportioned by sector, and emissions shown in the table are total greenhouse gas emissions from all fuel combustion sources.

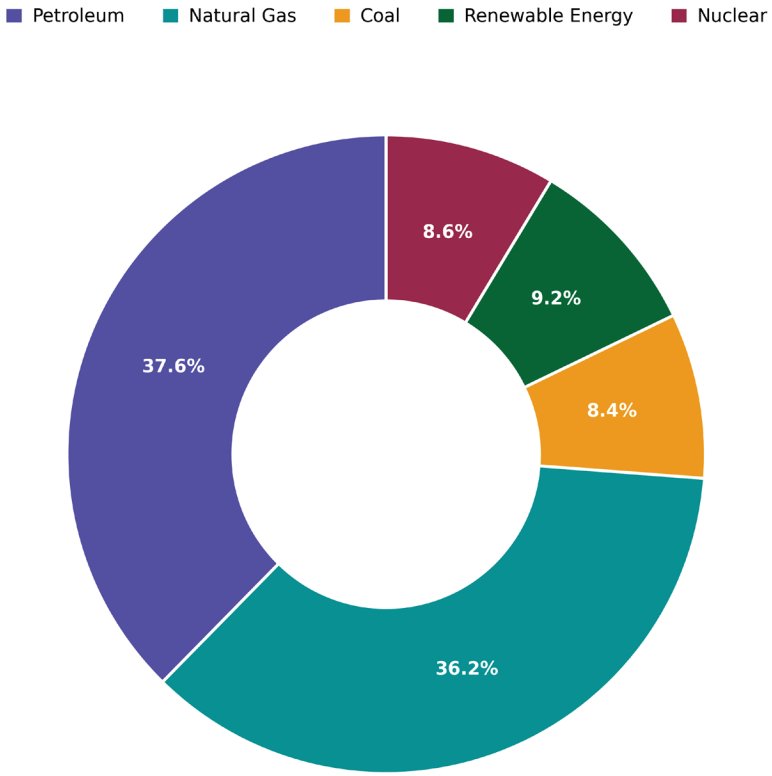
Note: Totals may not sum due to independent rounding.

CO_2 is the primary gas emitted from fossil fuel combustion and represents the largest share of U.S. total GHG emissions. In 2024, CO_2 emissions from fossil fuel combustion decreased by 0.3 percent relative to 2023 and were 3.8 percent below emissions in 1990. The change in CO_2 emissions from fossil fuel combustion is largely driven by changes in the total amount and type of fossil fuel energy used.

In the United States, 77.6 percent of the energy used in 2024 was produced through the combustion of fossil fuels such as petroleum, natural gas, and coal (see Figure 3-3 and Figure 3-4). Petroleum supplied the largest share of domestic energy demands, accounting for 37.7 percent of total U.S. energy used in 2024. Natural gas and coal followed in order of fossil fuel energy demand significance, accounting for approximately 36.2 percent and 8.4 percent of total U.S. energy used, respectively. Petroleum was consumed primarily in the transportation end-use sector, while the majority of coal was used in the electric power sector, and natural gas was broadly consumed in all end-use sectors except transportation (see Figure 3-5). The remaining portion of energy used in 2024 was supplied by nuclear electric power (8.7 percent) and by a variety of renewable energy sources (9.2 percent), primarily wind energy, hydroelectric power, solar, geothermal, and biomass (EIA, 2026a).[8]

[8] Renewable energy, as defined in EIA's energy statistics, includes the following energy sources: hydroelectric power, geothermal energy, biomass, solar energy, and wind energy.

Figure 3-3: 2024 U.S. Energy Use by Energy Source



Note: Totals may not sum due to independent rounding.

Figure 3-4: Annual U.S. Energy Use

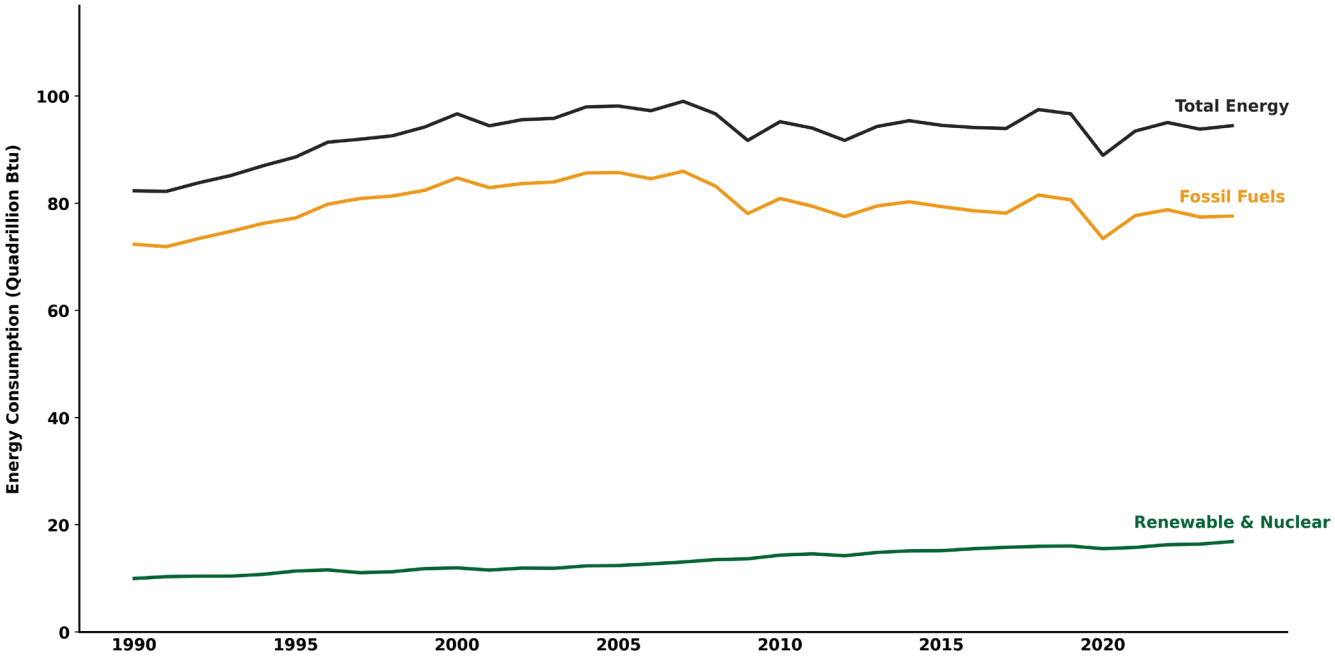
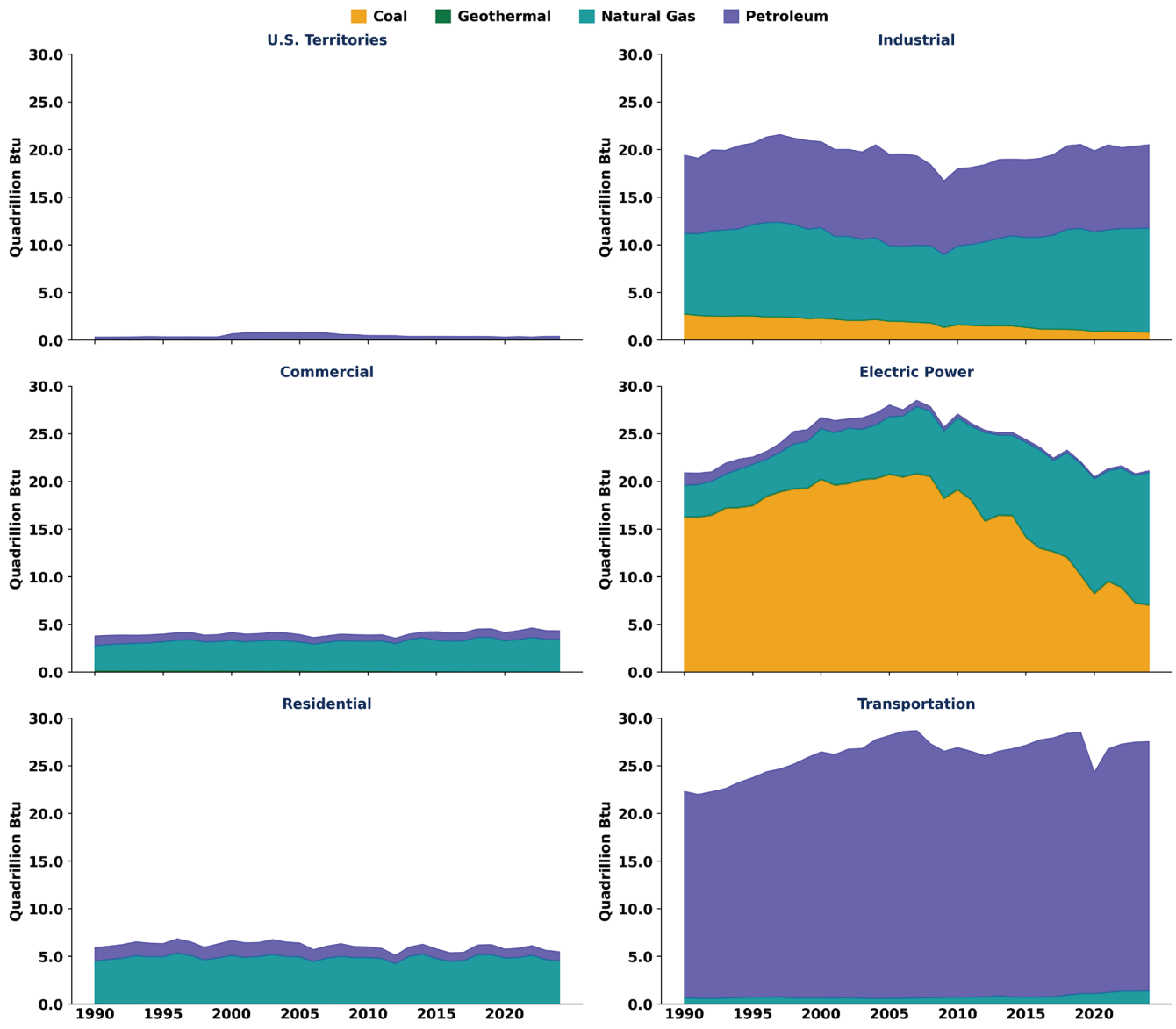


Figure 3-5: Fuel Use by End-Use Sector



CO_2 emissions from fossil fuel combustion are presented in Table 3-4 by sector and fuel type. The decrease in CO_2 emissions from fossil fuel combustion was a result of a change in types of fossil fuel energy use. See Annex 5 for data on energy use. CO_2 emissions from coal consumption decreased by 3.3 percent (24.1 MMT CO_2 Eq.) from 2023 to 2024, whereas CO_2 emissions from natural gas use increased by 1.4 percent (24.0 MMT CO_2 Eq.), and emissions from petroleum use decreased by 0.6 percent (13.6 MMT CO_2 Eq.) from 2023 to 2024. The increase in natural gas consumption and associated emissions in 2024 is observed mostly in the electric power sector; the decrease in petroleum use is mainly in the transportation sector offset by an increase in the commercial sector; and the coal decrease is mainly due to reduced use in the electric power sector. In 2024, CO_2 emissions from fossil fuel combustion were 4,568.1 MMT CO_2 Eq.

Table 3-4: CO_2 Emissions from Fossil Fuel Combustion by Fuel Type and Sector (MMT CO_2 Eq.)

Fuel/Sector	1990	2005	2020	2021	2022	2023	2024
Coal	**1,719.8**	**2,113.7**	**835.6**	**957.4**	**898.8**	**734.6**	**710.5**
Residential	3.0	0.8	0.0	0.0	0.0	0.0	0.0
Commercial	12.0	9.3	1.4	1.4	1.4	1.1	1.1
Industrial	157.8	117.8	43.0	43.0	43.0	36.4	34.9
Transportation	NO	NO	NO	NO	NO	NO	NO
Electric Power	1,546.5	1,982.8	788.2	910.1	851.5	694.6	672.0
U.S. Territories	0.5	3.0	3.1	2.9	2.9	2.5	2.5
Natural Gas	**998.6**	**1,166.6**	**1,630.1**	**1,636.3**	**1,724.0**	**1,741.1**	**1,765.1**
Residential	237.8	262.2	256.4	258.6	272.0	247.8	240.5
Commercial	142.0	162.9	173.5	180.4	192.3	182.4	181.8
Industrial	407.4	388.3	504.0	515.4	525.3	529.2	529.8
Transportation	36.0	33.1	58.8	65.2	72.3	71.9	73.7
Electric Power	175.4	318.9	634.8	612.8	659.3	705.3	734.8
U.S. Territories	NO	1.3	2.6	3.9	2.7	4.5	4.5
Petroleum	**2,029.9**	**2,454.2**	**1,893.9**	**2,079.6**	**2,101.8**	**2,105.6**	**2,092.1**
Residential	97.8	96.1	57.6	54.8	57.4	52.9	50.1
Commercial	72.7	55.6	54.3	53.0	62.0	46.0	67.6
Industrial	305.1	337.2	231.4	228.4	239.2	226.1	225.0
Transportation	1,437.1	1,819.7	1,516.9	1,706.8	1,704.6	1,745.8	1,714.8
Electric Power	97.5	98.0	16.2	17.7	20.5	14.7	13.7
U.S. Territories	19.5	47.5	17.5	18.9	18.1	20.1	20.9
Geothermal[a]	**0.5**	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**	**0.3**
Electric Power	0.5	0.5	0.4	0.4	0.4	0.4	0.3
Total	**4,748.8**	**5,735.0**	**4,360.0**	**4,673.7**	**4,725.0**	**4,581.7**	**4,568.1**

NO (Not Occurring)

[a] Although not technically a fossil fuel, geothermal energy-related CO_2 emissions are included for reporting purposes. The source of CO_2 is non-condensable gases in subterranean heated water.

Note: Totals may not sum due to independent rounding.

An alternative method of presenting combustion emissions is to allocate emissions associated with electric power to the sectors in which it is used. Four end-use sectors are defined: transportation, industrial, residential, and commercial. In Table 3-5 below, electric power emissions have been distributed to each end-use sector based upon the sector's share of national electricity use, with the exception of CH_4 and N_2O from transportation electricity use.[9] This method assumes that emissions from combustion sources are distributed across the four end-use sectors based on the ratio of electricity use in that sector.

Table 3-5: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion by End-Use Sector with Electricity Emissions Distributed (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2020	2021	2022	2023	2024
Transportation	**1,521.3**	**1,904.9**	**1,598.1**	**1,795.8**	**1,801.3**	**1,842.2**	**1,815.1**
CO_2	1,476.3	1,857.7	1,579.4	1,776.1	1,781.6	1,823.0	1,795.3
CH_4	7.2	5.2	2.6	2.7	2.7	2.7	2.7
N_2O	37.8	42.0	16.1	17.0	16.9	16.5	17.0
Industrial	**1,516.2**	**1,523.8**	**1,158.3**	**1,201.0**	**1,214.8**	**1,168.7**	**1,167.8**
CO_2	1,504.8	1,511.5	1,149.7	1,191.9	1,205.6	1,160.4	1,159.6
CH_4	2.2	2.2	2.0	2.0	2.0	2.0	2.0
N_2O	9.1	10.1	6.6	7.1	7.2	6.3	6.2
Residential	**971.8**	**1,265.8**	**891.9**	**919.9**	**929.5**	**839.1**	**827.7**
CO_2	958.6	1,250.2	880.2	907.6	916.3	827.8	816.9
CH_4	6.0	4.9	4.2	4.3	5.1	4.5	4.2
N_2O	7.2	10.7	7.5	8.0	8.2	6.8	6.6
Commercial	**796.5**	**1,074.9**	**735.5**	**781.1**	**806.8**	**751.4**	**776.3**
CO_2	789.1	1,063.7	727.4	772.4	797.8	743.3	768.3
CH_4	1.3	1.6	1.7	1.7	1.8	1.8	1.9
N_2O	6.0	9.6	6.4	6.9	7.2	6.3	6.2
Total	**4,805.7**	**5,769.4**	**4,383.8**	**4,697.7**	**4,752.4**	**4,601.4**	**4,586.9**

Notes: Totals may not sum due to independent rounding. Emissions from fossil fuel combustion by electric power are allocated based on aggregate national electricity use by each end-use sector.

[9] Separate calculations are performed for transportation and mobile source related CH_4 and N_2O emissions; see Section 3.1.2 for more details.

The following sections include a discussion of fossil fuel combustion emissions by energy—consuming sectors. A discussion of emissions in the electricity production sector is first, followed by discussions of the other electricity end-use sectors including transportation, industrial, and combined residential and commercial. Finally, there is a discussion of U.S. Territories combustion emissions.

3.1.1 Electric Power Sector

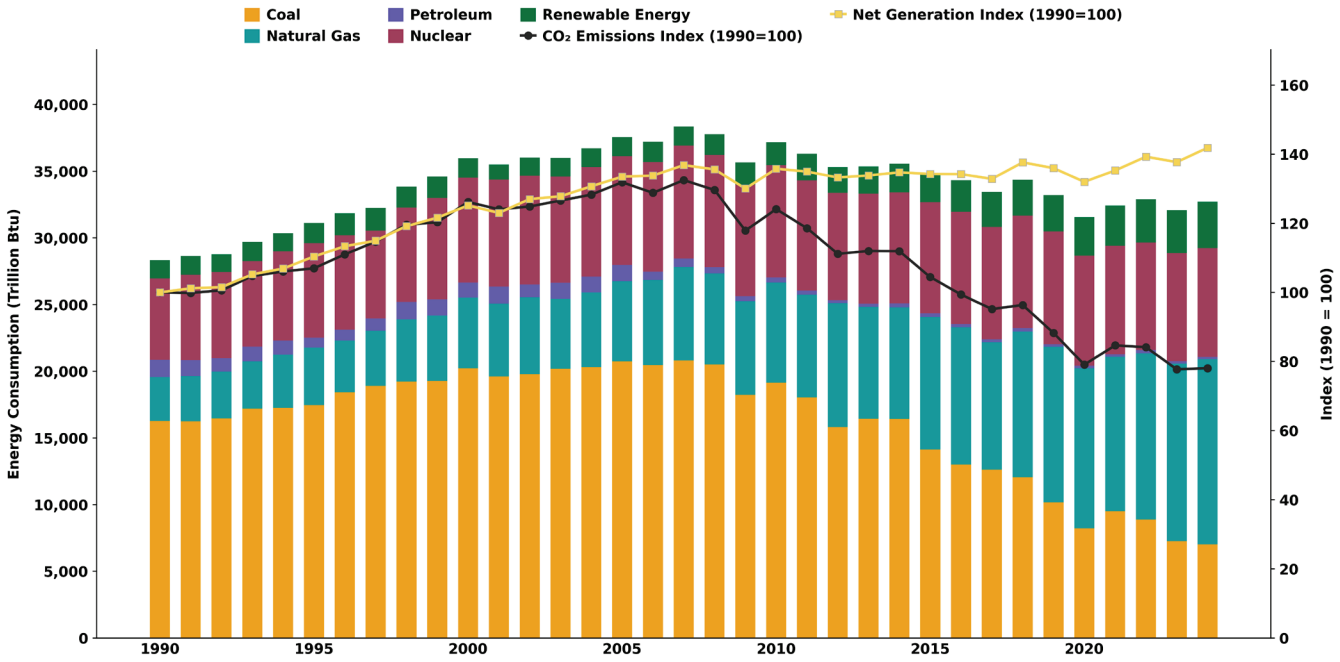
EIA places electric power generation into three functional categories: the electric power sector, the commercial sector, and the industrial sector. Energy use and emissions associated with electric generation in the commercial and industrial sectors (i.e., on-site generation of electricity at commercial facilities) are reported in those other sectors.[10]

The energy use and emissions associated with the electric power sector are included here. As defined by EIA, the electric power sector consists of electric utilities and independent power producers whose primary business is the production of electricity. This includes both regulated utilities and non-utilities (e.g., independent power producers, qualifying co-generators, and other small power producers) (EIA, 2026a).

Total GHG emissions from the electric power sector have decreased by 21.9 percent since 1990. Historical trends in electric power sector emissions are driven by electricity demand and the carbon intensity of electricity generated. The carbon intensity of electricity generated, in terms of CO_2 Eq. per kilowatt-hour (kWh), depends on the types of fuels and method used to generate electricity. Trends over time are shown in Figure 3-6. Generally, there has been a recent decoupling of emissions and electricity production indicating a decrease in the carbon intensity of electricity generation. This recent decarbonization of the electric power sector is a result of several key drivers.

[10] Where electricity generation occurs outside the EIA-defined electric power sector, it is typically for the entity's own use.

Figure 3-6: Fuels Used in Electric Power Generation and Total Electric Power Sector CO_2 Emissions



Coal-fired electric generation (in kWh) decreased from 54.1 percent of total generation in 1990 to 15.6 percent in 2024.[11] This corresponded with an increase in natural gas generation and renewable energy generation, largely from wind and solar energy. Natural gas generation (in kWh) represented 10.7 percent of electric power generation in 1990 and increased over the 35-year period to represent 42.4 percent of electric power sector generation in 2024 (see Table 3-6). Natural gas has a much lower carbon content than coal and is generated in power plants that are generally more efficient in terms of kWh produced per Btu of fuel combusted, which has led to lower emissions as natural gas replaces coal-powered electricity generation.

[11] Values represent electricity *net* generation from the electric power sector (EIA, 2026a).

Table 3-6: Electric Power Generation by Fuel Type (Percent)

Fuel Type	1990	2005	2020	2021	2022	2023	2024
Coal	54.1%	51.1%	19.9%	22.6%	20.3%	16.6%	15.6%
Natural Gas	10.7%	17.5%	39.5%	37.3%	38.8%	42.2%	42.4%
Nuclear	19.9%	20.0%	20.5%	19.7%	18.9%	19.2%	18.8%
Renewables	11.3%	8.3%	19.5%	19.8%	21.4%	21.5%	22.8%
Petroleum	4.1%	3.0%	0.4%	0.5%	0.5%	0.4%	0.3%
Other Gases[a]	0.0%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Net Electricity Generation (Billion kWh)[b]	2,905	3,902	3,852	3,955	4,076	4,031	4,161

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

[b] Represents net electricity generation from the electric power sector. Excludes net electricity generation from commercial and industrial combined-heat-and-power and electricity-only plants. Does not include electricity generation from purchased steam as the fuel used to generate the steam cannot be determined.

In 2024, CO_2 emissions from the electric power sector increased by 0.4 percent relative to 2023. This increase in CO_2 emissions was primarily driven by an increase in natural gas consumed to produce electricity in the electric power sector, offset by a decrease in coal consumption. Consumption of natural gas for electric power increased by 4.2 percent, whereas consumption of coal decreased 3.2 percent from 2023 to 2024, leading to a slight overall increase in emissions. Electricity generation from renewable sources increased by 5.9 percent from 2023 to 2024.

Emissions also include a small amount of CO_2 capture and sequestration, which have been netted out of the results for electric power sector coal CO_2 emissions. More information on CO_2 transport, injection, and geologic sequestration can be found in Section 3.9. Table 3-7 presents the GHG emissions from fossil fuel combustion in the electric power sector.

Table 3-7: GHG Emissions from Fossil Fuel Combustion in the Electric Power Sector (MMT CO_2 Eq.)

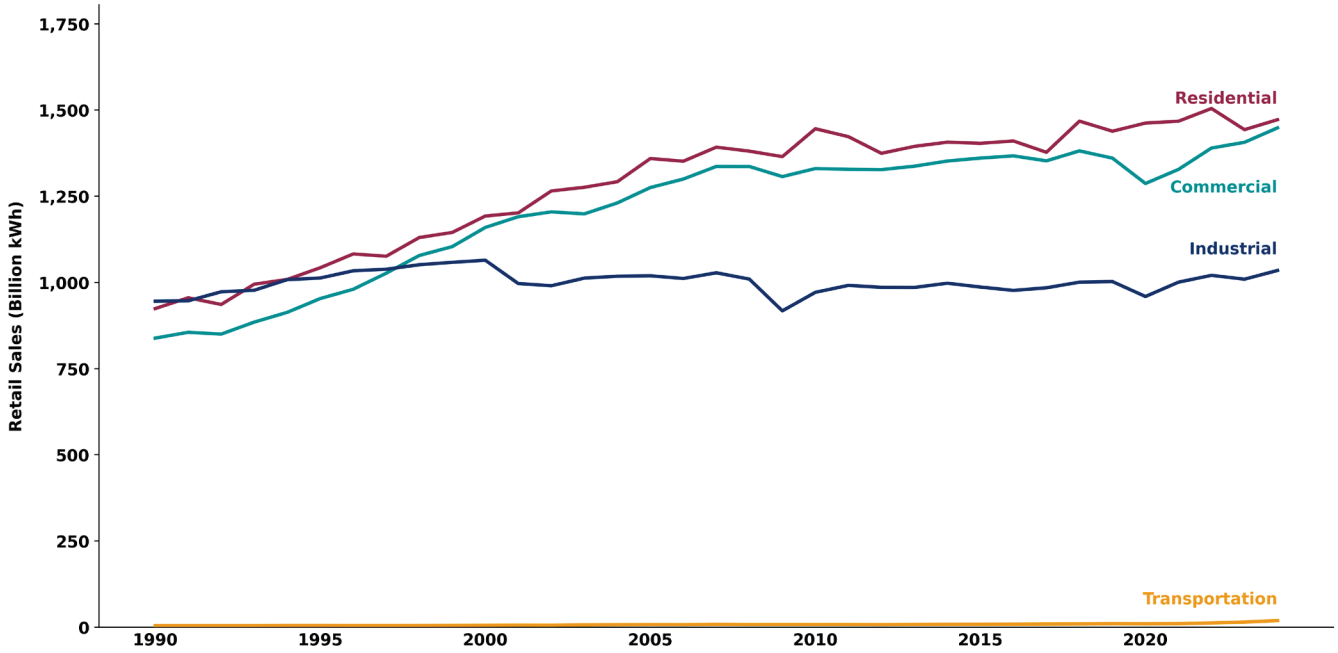
Fuel Type	1990	2005	2020	2021	2022	2023	2024
CO_2	**1,820.0**	**2,400.1**	**1,439.6**	**1,540.9**	**1,531.7**	**1,414.9**	**1,420.8**
Coal	1,546.5	1,982.8	788.2	910.1	851.5	694.6	672.0
Natural gas	175.4	318.9	634.8	612.8	659.3	705.3	734.8
Petroleum	97.5	98.0	16.2	17.7	20.5	14.7	13.7
Geothermal	0.5	0.5	0.4	0.4	0.4	0.4	0.3
CH_4	**0.5**	**1.0**	**1.4**	**1.4**	**1.5**	**1.5**	**1.5**
Coal	0.4	0.4	0.2	0.2	0.2	0.2	0.2
Petroleum	+	+	+	+	+	+	+
Natural gas	0.1	0.5	1.2	1.2	1.3	1.3	1.4
Wood	+	+	+	+	+	+	+
N_2O	**18.2**	**26.7**	**17.5**	**19.0**	**19.4**	**16.6**	**16.0**
Coal	17.9	24.9	13.5	15.1	15.2	12.1	11.4
Petroleum	0.1	0.1	+	+	+	+	+
Natural gas	0.3	1.7	4.0	3.9	4.2	4.4	4.6
Wood	+	+	+	+	+	+	+
Total	1,838.7	2,427.8	1,458.5	1,561.3	1,552.6	1,433.0	1,438.4

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Electricity was used primarily in the residential, commercial, and industrial end-use sectors for lighting, heating, electric motors, appliances, electronics, and air conditioning (see Figure 3-7). Use of electricity in the transportation sector has historically been used in rail but has grown recently due to use of electric vehicles. Section 3.1.2 Transportation Sector and Mobile Combustion provides a break-out of CO_2 emissions from electricity use in the transportation end-use sector.

Figure 3-7: Electric Power Retail Sales by End-Use Sector



In 2024, electricity sales to the residential and commercial end-use sectors increased by 2.0 percent and 3.0 percent relative to 2023, respectively. Electricity sales to the industrial sector in 2024 increased by 2.5 percent relative to 2023. The sections below describe end-use sector energy use in more detail. Overall, in 2024, the amount of electricity retail sales (in kWh) increased by 2.6 percent relative to 2023.

Methods

CO_2 emissions from fossil fuel combustion are largely dependent on fuel type and carbon content, whereas CH_4 and N_2O emissions also depend on combustion technologies and other factors. Therefore, methodologies for estimating CO_2 emissions from fossil fuel combustion differ from the estimation of non-CO_2 (CH_4 and N_2O) emissions from stationary fossil fuel combustion.

For this *GHGIA*, the methods used to estimate CO_2 emissions and non-CO_2 emissions from the electric power sector are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* report (EPA, 2025).

Recalculations

Recalculations were implemented on historic estimates to incorporate updated data from EIA. EIA often updates historical data when new data becomes available, impacting the most recent years of data. Updates to historical data based on the latest EIA data used (2026a) resulted in a 0.1 percent increase in emissions from natural gas used in the electric power sector in 2023.

3.1.2 Transportation Sector and Mobile Combustion

The transportation sector includes all vehicles whose primary purpose is transporting people and/or goods from one physical location to another. Included are automobiles; trucks; buses; motorcycles; trains, subways, and other rail vehicles; aircraft; and ships, barges, and other waterborne vehicles (EIA, 2026a). CO_2 emissions from other mobile source vehicles whose primary purpose is not transportation (e.g., construction cranes and bulldozers, farming vehicles, and warehouse tractors and forklifts) are generally reported in the end-use sector where they occur, e.g., in the industrial and commercial sectors. However, some non-CO_2 emissions from these non-transportation mobile sources are included in this section. This is because CO_2 emissions are estimated based on fuel use (allocated across end use sectors) while the methodology involved in estimating non-CO_2 emissions is based on the combustion source which is similar for all these vehicles.

Annex 5 presents the total emissions from all transportation and mobile sources, including CO_2, N_2O, CH_4, and hydrofluorocarbons (HFCs).

Petroleum-based products provide most of the energy consumed for transportation, with the majority being gasoline consumption in highway vehicles. Diesel fuel for freight trucks and jet fuel for aircraft accounted for most of the remaining consumption. CO_2 from fossil fuel combustion is the largest source of emissions from the transportation sector, with other non-CO_2 gases contributing a smaller amount.

The primary energy statistics used to calculate emissions from the transportation sector include consumption of fossil fuels that are ultimately used for international bunkers. Bunker fuel consumption is not included in nationally reported emissions and is instead reported separately as a memo item.[12] Therefore, the amount of each fuel type used for international bunkers was subtracted from fuel consumption data when determining fuel combustion emissions. Official estimates exclude emissions from the combustion of both aviation and marine international bunker fuels; however, estimates of international bunker fuel-related emissions are presented in the tables below for informational purposes. Section 3.10 has a further discussion of international bunker fuel related emissions.

In 2024 light-duty vehicles (including passenger cars and light-duty trucks) represented 54.9 percent of CO_2 emissions; medium- and heavy-duty trucks and buses represented 24.0 percent; aircraft represented 10.4 percent; and other sources represented 10.7 percent. In 2024, domestic transportation CO_2 emissions decreased by 1.5 percent (27.7 MMT CO_2 Eq.) compared to 2023 but still increased overall by 21.6 percent (318.9 MMT CO_2 Eq.) compared to 1990. See Table 3-8 for a detailed breakdown of transportation CO_2 emissions by mode and fuel type.

[12] As per IPCC and United Nations Framework Convention on Climate Change inventory reporting guidelines. There are other international organizations, including the International Civil Aviation Organization and the International Maritime Organization, that consider global action from these sectors.

Table 3-8: CO_2 Emissions from Fossil Fuel Combustion in Transportation End-Use Sector (MMT CO_2 Eq.)

Fuel/Vehicle Type	1990	2005	2020	2021	2022	2023	2024
Gasoline	**963.2**	**1,145.0**	**936.1**	**1,027.9**	**1,013.7**	**1,049.3**	**1,015.0**
Passenger Cars	625.5	522.7	297.5	313.8	296.4	297.5	278.2
Light-Duty Trucks	272.9	573.5	590.1	658.4	658.7	691.4	677.2
Medium- and Heavy-Duty Trucks[a]	42.0	28.7	29.5	34.7	35.8	36.7	36.0
Buses	5.2	1.8	3.1	3.5	3.9	4.2	4.2
Motorcycles	3.3	4.7	6.1	6.9	8.2	8.7	8.6
Recreational Boats	14.3	13.7	9.9	10.6	10.8	10.8	10.8
Diesel Fuel	**274.5**	**471.4**	**458.7**	**507.3**	**508.1**	**505.7**	**501.0**
Passenger Cars	9.9	4.1	2.0	2.1	2.0	1.9	1.7
Light-Duty Trucks	8.2	30.1	26.6	28.8	29.1	28.9	28.0
Medium- and Heavy-Duty Trucks[a]	191.9	355.7	363.6	402.9	401.1	400.1	395.9
Buses	7.8	14.9	16.4	18.5	20.3	20.2	20.1
Rail	35.6	46.0	32.0	34.0	34.3	33.9	34.9
Recreational Boats	2.7	2.8	2.6	2.9	3.1	3.1	3.3
Ships and Non-Recreational Boats	6.7	8.4	7.7	10.7	11.0	10.6	10.2
International Bunker Fuels	11.7	9.5	7.8	7.4	7.2	7.0	6.9
Jet Fuel	**222.3**	**249.5**	**160.4**	**203.5**	**231.5**	**245.5**	**251.7**
Commercial Aircraft[b]	109.9	132.7	91.3	119.0	129.7	129.7	129.7
Military Aircraft	35.7	19.8	11.7	12.5	12.4	11.5	10.5
General Aviation Aircraft	38.5	36.8	17.6	21.1	22.7	37.7	45.2
International Bunker Fuels	38.2	60.2	39.8	50.8	66.6	66.5	66.3
Aviation Gasoline	**3.1**	**2.4**	**1.4**	**1.5**	**1.5**	**1.5**	**1.6**
General Aviation Aircraft	3.1	2.4	1.4	1.5	1.5	1.5	1.6
Residual Fuel Oil	**76.3**	**62.9**	**29.4**	**46.2**	**47.3**	**39.3**	**42.5**
Ships and Non-Recreational Boats	22.6	19.3	7.3	24.2	22.9	16.6	18.0
International Bunker Fuels	53.7	43.6	22.1	21.9	24.4	22.7	24.5

(continued)

Table 3-8: CO_2 Emissions from Fossil Fuel Combustion in Transportation End-Use Sector (MMT CO_2 Eq.) *(continued)*

Fuel/Vehicle Type	1990	2005	2020	2021	2022	2023	2024
Natural Gas	**36.0**	**33.1**	**58.8**	**65.2**	**72.3**	**71.9**	**73.7**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks[a]	+	+	0.1	0.1	0.1	0.1	0.1
Buses	+	0.2	0.2	0.2	0.2	0.3	0.3
Pipeline[c]	36.0	32.8	58.5	64.9	72.0	71.5	73.3
Liquified Petroleum Gas (LPG)	**1.4**	**1.8**	**0.5**	**0.6**	**0.7**	**0.7**	**0.8**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	0.1	0.1	+	+	0.1	0.1	0.1
Medium- and Heavy-Duty Trucks[a]	1.3	0.9	0.5	0.5	0.5	0.5	0.6
Buses	+	0.7	0.1	0.1	0.1	0.1	0.1
Electricity	**3.0**	**4.7**	**3.6**	**3.9**	**4.5**	**5.2**	**6.6**
Passenger Cars	+	+	0.9	1.0	1.2	1.5	2.0
Light-Duty Trucks	+	+	0.2	0.4	0.8	1.2	2.0
Buses	+	+	+	0.1	0.1	0.1	0.1
Rail	3.0	4.7	2.4	2.5	2.5	2.4	2.4
Total (excludes bunkers)	**1,476.2**	**1,857.5**	**1,579.3**	**1,775.9**	**1,781.5**	**1,822.8**	**1,795.1**
International Bunker Fuels	**103.6**	**113.3**	**69.6**	**80.2**	**98.2**	**96.2**	**97.8**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Includes medium- and heavy-duty trucks over 8,500 lb.

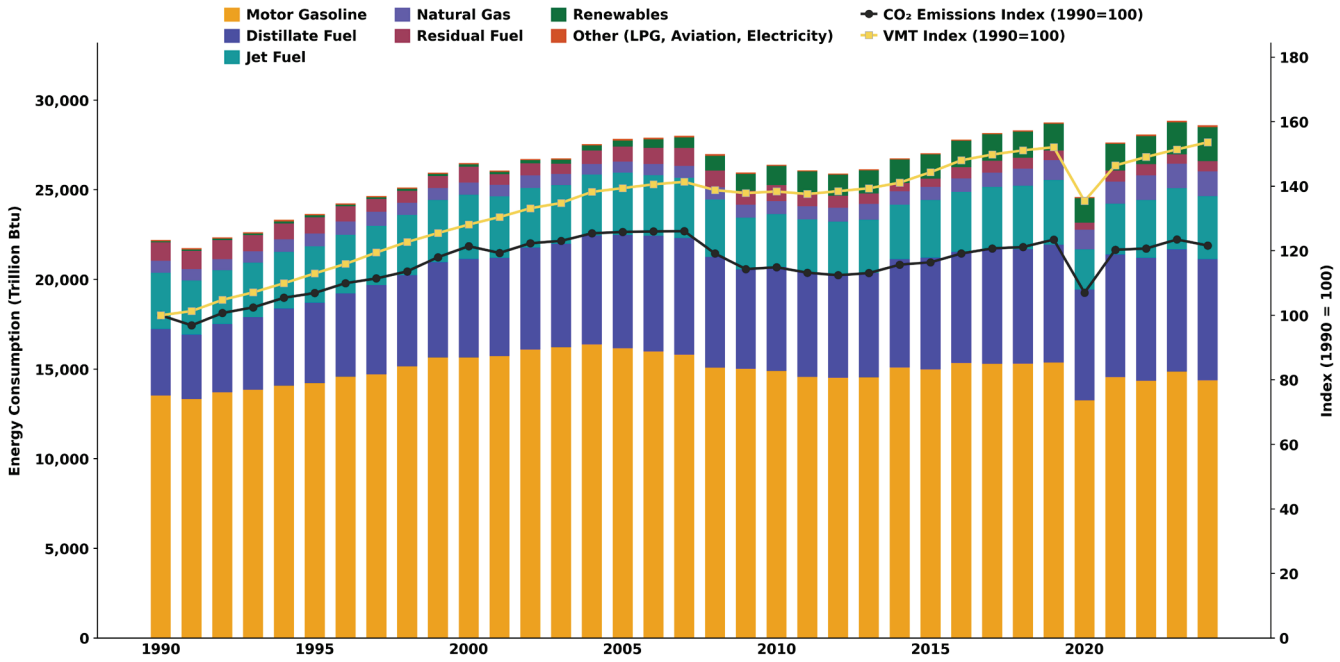
[b] Commercial aircraft, as modeled in Federal Aviation Administration's Aviation Environmental Design Tool, consists of passenger aircraft, cargo, and other chartered flights.

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

Notes: This table does not include emissions from non-transportation mobile sources, such as agricultural equipment and construction/mining equipment. It also does not include emissions associated with electricity consumption by pipelines or lubricants used in transportation. In addition, this table does not include CO_2 emissions from U.S. Territories, since these are covered in a separate chapter of the *GHGIA*. Totals may not sum due to independent rounding.

The increase in transportation emissions from fossil fuel combustion from 1990 to 2024 was, in large part, due to increased demand for travel (see Figure 3-8) along with changes in fuel efficiency as discussed below. The number of on-road vehicle miles traveled increased 53.6 percent, while on-road fleet fuel efficiency increased by 14.8 percent from 1990 to 2024.

Figure 3-8: Fuels Used in Transportation Sector, On-road VMT, and Total Sector CO_2 Emissions

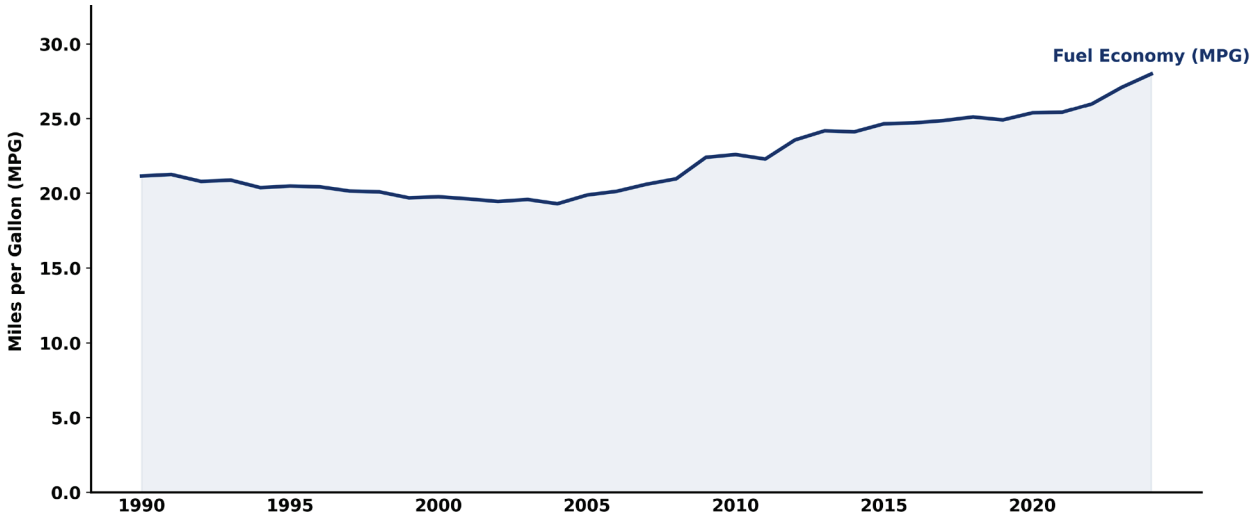


Notes: Distillate fuel, residual fuel, and jet fuel include adjustments for international bunker fuels. Distillate fuel and motor gasoline include adjustments for the sectoral allocation of these fuels.

CO_2 emissions from passenger cars and light-duty trucks totaled 989.2 MMT CO_2 in 2024, an increase of 7.9 percent from 1990. In particular, the change in CO_2 emissions from passenger cars and light-duty trucks is, in large part, due to a change in demand for travel (as shown in Figure 3-8) and fleet-wide light-duty vehicle fuel economy. The change in new light-duty vehicle fuel economy (see Figure 3-9) reflects improved fuel economy and changes in market share of light-duty trucks versus light-duty cars (see Figure 3-10).

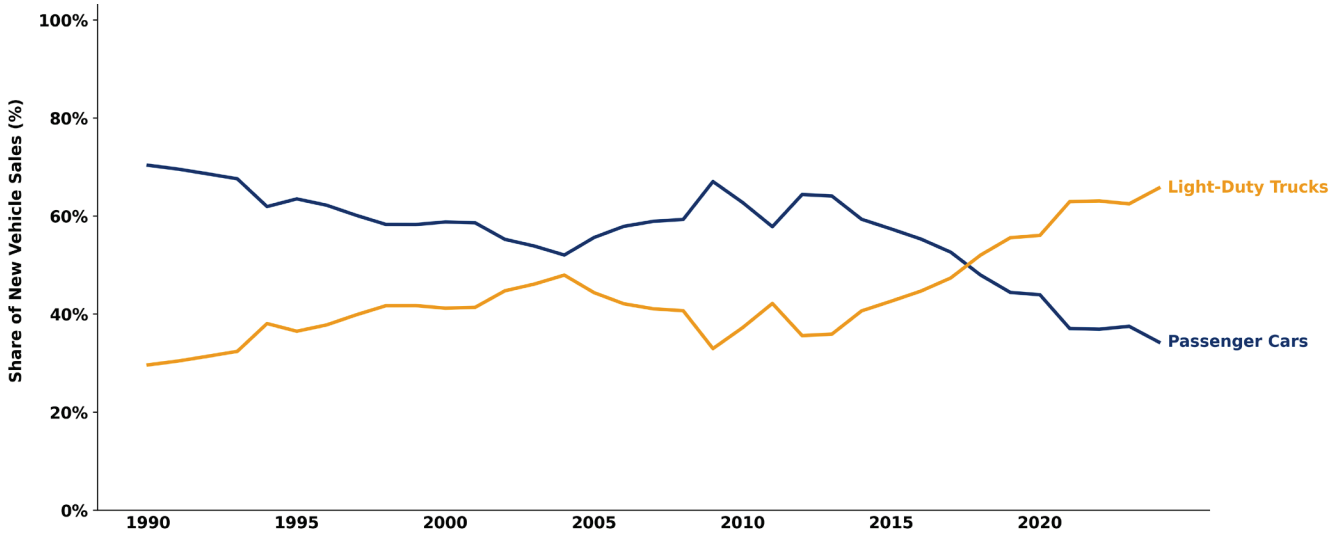
Average new vehicle fuel economy has improved almost every year since 2005, whereas the light-duty truck share of new vehicle sales has varied overtime. Since 2014, the light-duty truck share has steadily increased, reaching 66 percent of new vehicle sales in model year 2024.

Figure 3-9: Sales-Weighted Fuel Economy of New Passenger Cars and Light-Duty Trucks, 1990-2024



Source: EPA (2026).

Figure 3-10: Sales of New Passenger Cars and Light-Duty Trucks, 1990-2024



Source: EPA (2026).

Medium- and heavy-duty truck CO_2 emissions increased by 83.9 percent from 1990 to 2024. This increase was largely due to a substantial growth in medium- and heavy-duty truck vehicle miles traveled (VMT), which increased by 86.1 percent between 1990 and 2024.

Across all categories of aviation, excluding international bunkers, CO_2 emissions decreased by 0.1 percent between 1990 and 2024. Decreases in jet fuel emissions (excluding bunkers) started in 2007, in part due to improved operational efficiency that results in more direct flight routing, improvements in aircraft and engine technologies to reduce fuel burn and emissions, and the accelerated retirement of older, less fuel-efficient aircraft. However, the sharp decline in commercial aircraft emissions from 2019 to 2020 and their gradual recovery since is due to COVID-19 impacts on scheduled passenger air travel.

Table 3-9 and Table 3-10 provide fossil fuel CH_4 and N_2O emission estimates from mobile sources in MMT CO_2 Eq. Mobile combustion sources include emissions of CH_4 and N_2O from all transportation sources with the exception of pipelines and electric locomotives;[13] mobile sources also include non-transportation sources such as construction/mining equipment, agricultural equipment, vehicles used off-road, and other sources (e.g., snowmobiles, lawnmowers).

As described above, N_2O and CH_4 emissions are reported using different categories than CO_2. CO_2 emissions are reported by end-use sector (transportation, industrial, commercial, residential, U.S. Territories) and generally adhere to a fuel use and fuel emission factor approach to estimating emissions. CO_2 emissions from non-transportation mobile sources (e.g., lawn and garden equipment, farm equipment, construction equipment) are allocated to their respective end-use sector (i.e., construction equipment CO_2 emissions are included in the industrial end-use sector instead of the transportation end-use sector). CH_4 and N_2O emissions are reported using the "mobile combustion" category, which includes non-transportation mobile sources. CH_4 and N_2O emission estimates are technology-based estimates, based on total activity (fuel use, VMT) and emissions factors by source and technology type. These reporting schemes are in accordance with IPCC guidance. For informational purposes only, CO_2 emissions from non-transportation mobile sources are presented separately from their overall end-use sector in Annex 5, which also presents total emissions from all transportation and mobile sources, including CO_2, CH_4, N_2O, and HFCs.

From 1990 to 2024, mobile source CH_4 emissions declined, largely due to emissions control technologies employed in on-road vehicles since the mid-1990s to reduce CO, NOx, NMVOC, and CH_4 emissions. Earlier-generation control technologies initially resulted in elevated N_2O emissions. Improvements in later-generation emission control technologies have reduced N_2O output, resulting in an overall decrease in mobile source N_2O emissions from 1990 to 2024. Overall, CH_4 and N_2O emissions were predominantly from gasoline-fueled passenger cars, light-duty trucks, and non-highway sources.

[13] Emissions of CH_4 from natural gas systems are reported separately.

Table 3-9: CH_4 Emissions from Mobile Combustion (MMT CO_2 Eq.)

Fuel Type/Vehicle Type	1990	2005	2020[a]	2021	2022	2023	2024
Gasoline On-Road	**5.8**	**3.3**	**0.8**	**0.9**	**0.9**	**0.8**	**0.8**
Passenger Cars	3.8	1.8	0.2	0.2	0.2	0.2	0.2
Light-Duty Trucks	1.4	1.3	0.5	0.6	0.5	0.5	0.6
Medium- and Heavy-Duty Trucks and Buses	0.5	0.2	+	+	+	+	+
Motorcycles	+	+	+	+	+	+	+
Diesel On-Road	**+**	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks	+	+	0.1	0.1	0.1	0.1	0.1
Medium- and Heavy-Duty Buses	+	+	+	+	+	+	+
Alternative Fuel On-Road	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Non-Road[a]	**1.4**	**1.8**	**1.6**	**1.7**	**1.8**	**1.7**	**1.7**
Ships and Boats	0.4	0.5	0.4	0.5	0.5	0.5	0.5
Rail[b]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Aircraft	0.1	0.1	+	+	+	+	+
Agricultural Equipment[c]	0.2	0.2	0.1	0.1	0.1	0.1	0.1
Construction/Mining Equipment[d]	0.2	0.3	0.2	0.2	0.2	0.2	0.2
Other[e]	0.5	0.7	0.8	0.7	0.8	0.8	0.8
Total	**7.2**	**5.2**	**2.6**	**2.7**	**2.7**	**2.7**	**2.7**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Non-road fuel consumption estimates for 2020 are adjusted to account for the COVID-19 pandemic and associated restrictions. For agricultural equipment and airport equipment, sector-specific adjustment factors were applied to the 2019 data. For all other sectors, a 7.7 percent reduction factor is used, based on transportation diesel use trends in 2020 (EIA 2026a).

[b] Rail emissions do not include emissions from electric-powered locomotives. Class II and Class III diesel consumption data for 2014 to 2024 is estimated by applying the historical average fuel usage per carload factor to the annual number of carloads.

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

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

[e] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

Note: Totals may not sum due to independent rounding.

Table 3-10: N_2O Emissions from Mobile Combustion (MMT CO_2 Eq.)

Fuel Type/Vehicle Type	1990	2005	2020[a]	2021	2022	2023	2024
Gasoline On-Road	**31.4**	**33.4**	**6.4**	**6.2**	**5.6**	**5.0**	**5.2**
Passenger Cars	22.3	16.4	2.0	1.9	1.7	1.5	1.3
Light-Duty Trucks	8.2	15.8	4.2	4.1	3.7	3.3	3.6
Medium- and Heavy-Duty Trucks and Buses	0.9	1.2	0.2	0.2	0.2	0.2	0.2
Motorcycles	+	+	0.1	0.1	0.1	0.1	0.1
Diesel On-Road	**0.2**	**0.4**	**2.9**	**3.3**	**3.4**	**3.5**	**3.7**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	0.2	0.2	0.2	0.2	0.3
Medium- and Heavy-Duty Trucks	0.2	0.3	2.5	2.9	2.9	3.0	3.2
Medium- and Heavy-Duty Buses	+	+	0.2	0.2	0.2	0.2	0.3
Alternative Fuel On-Road	**+**	**+**	**+**	**0.1**	**0.1**	**0.1**	**0.1**
Non-Road[a]	**6.2**	**8.1**	**6.7**	**7.4**	**7.8**	**7.9**	**8.0**
Ships and Boats	0.2	0.2	0.1	0.3	0.3	0.2	0.2
Rail[b]	0.2	0.3	0.2	0.2	0.2	0.2	0.2
Aircraft	1.5	1.6	1.0	1.3	1.4	1.5	1.5
Agricultural Equipment[c]	1.2	1.4	1.1	1.1	1.1	1.1	1.1
Construction/Mining Equipment[d]	1.2	1.9	1.6	1.7	1.7	1.8	1.8
Other[e]	1.8	2.8	2.7	2.9	3.1	3.2	3.2
Total	**37.8**	**42.0**	**16.1**	**17.0**	**16.9**	**16.5**	**17.0**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Non-road fuel consumption estimates for 2020 are adjusted to account for the COVID-19 pandemic and associated restrictions. For agricultural equipment and airport equipment, sector-specific adjustment factors were applied to the 2019 data. For all other sectors, a 7.7 percent reduction factor is used, based on transportation diesel use (EIA, 2026a).

[b] Rail emissions do not include emissions from electric-powered locomotives. Class II and Class III diesel consumption data for 2014 through 2024 is estimated by applying the historical average fuel usage per carload factor to the annual number of carloads.

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

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

[e] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

Note: Totals may not sum due to independent rounding.

Methods

As discussed, CO_2 emissions from fossil fuel combustion are mainly based on fuel type and carbon content, whereas CH_4 and N_2O emissions also depend on combustion technologies and other factors. Therefore, methodologies for estimating CO_2 emissions from fossil fuel combustion differ from the estimation of non-CO_2 (CH_4 and N_2O) emissions from mobile fossil fuel combustion.

For CO_2 emission estimates, on-road fuel consumption data from FHWA were used to determine total on-road use of motor gasoline and diesel fuel (FHWA, 1996 through 2026). Ratios developed from the MOtor Vehicle Emission Simulator version 5 (MOVES5) output are used to apportion FHWA fuel consumption data to vehicle type and fuel type (see the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* [EPA, 2025] for more information about the MOVES5 model and how it was used).

For non-CO_2 emission estimates, gasoline and diesel fuel highway vehicle mileage estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA, 1996 through 2026). VMT estimates from FHWA are allocated to vehicle type using ratios of VMT per vehicle type to total VMT, derived from EPA's MOVES5 model.

For this *GHGIA,* the methods used to estimate CO_2 and non-CO_2 emissions from the transportation sector are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* report (EPA, 2025). However, there were a few areas where data was unavailable for 2024 and was proxied:

- Data for alternative fuel vehicles fuel use and emissions was proxied to 2023
- Data was proxied for vehicle control technologies; the same mix of technologies was assumed as for 2023
- Data on bunker fuel use was also largely proxied, as the data from multiple sources was not available (see Section 3.10 on International Bunker Fuels for more detail)

One change in data source used was that electricity use from light-duty battery electric vehicles and plug-in hybrid electric vehicles was taken directly from EIA data (2026c) for the years 2018 forward. This differed from a previous analysis that was based on research as outlined in Browning (2024).

Recalculations

There were some adjustments made to the historical data to reflect changes in data sources and updates to the existing data. The gasoline and diesel fuel allocation across sectors was updated to reflect totals from top-down estimates from EIA. This included updating the amounts of biofuels excluded from the analysis. Gasoline and diesel fuel use was also updated for 2023 based on updated FHWA data for 2023. The EIA Fuel Oil and Kerosine Sales (FOKS) data (EIA, 1991 through 2022) was discontinued in 2020. The FOKS data is used to allocate diesel fuel use to specific end-use categories, including maritime use. For this *GHGIA*, recent years of diesel fuel used in ships were extrapolated based on the historical percentages of total transportation sector diesel used in shipping. This was a change from using the 2020 data as a proxy for recent years. As a result of these updates, petroleum use emissions in the transportation sector increased by 2.4 percent in

2023 compared with previous estimates. The overall average annual change in emissions was 0.02 percent over the time series.

There was also a slight change in natural gas estimates in 2023 based on the latest data from EIA (EIA, 2025), resulting in less than a 0.2 percent change in 2023 natural gas estimates compared with the previous estimates.

3.1.3 Industrial Sector

The industrial end-use sector, per the underlying energy use data from EIA (2026a), includes activities such as manufacturing, construction, mining, and agriculture. The largest of these activities in terms of energy use is manufacturing, which represents the majority of energy use. This sector also includes generators that produce electricity and/or useful thermal output primarily to support the above-mentioned industrial activities.

Table 3-11 presents GHG emissions from fossil fuel combustion in the industrial sector including emissions from the electric power sector that are distributed to the industrial sector based on the amount of electricity used in the sector.

Table 3-11: GHG Emissions from Fossil Fuel Combustion in the Industrial Sector (MMT CO_2 Eq.)

GHG/Fuel Type	1990	2005	2020	2021	2022	2023	2024
CO_2	**1,504.8**	**1,511.5**	**1,149.7**	**1,191.9**	**1,205.6**	**1,160.4**	**1,159.6**
Coal	157.8	117.8	43.0	43.0	43.0	36.4	34.9
Natural gas	407.4	388.3	504.0	515.4	525.3	529.2	529.8
Petroleum	305.1	337.2	231.4	228.4	239.2	226.1	225.0
Electricity Distributed	634.4	668.1	371.4	405.1	398.1	368.7	369.9
CH_4	**2.2**	**2.2**	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**
Coal	0.5	0.3	0.1	0.1	0.1	0.1	0.1
Petroleum	0.2	0.2	0.1	0.1	0.1	0.1	0.1
Natural gas	0.2	0.2	0.3	0.3	0.3	0.3	0.3
Wood	1.2	1.2	1.1	1.1	1.1	1.1	1.1
Electricity Distributed	0.2	0.3	0.4	0.4	0.4	0.4	0.4
N_2O	**9.1**	**10.1**	**6.6**	**7.1**	**7.2**	**6.3**	**6.2**
Coal	0.7	0.5	0.2	0.2	0.2	0.2	0.1
Petroleum	0.5	0.5	0.3	0.3	0.3	0.2	0.2
Natural gas	0.2	0.2	0.2	0.2	0.2	0.2	0.3
Wood	1.5	1.5	1.4	1.4	1.4	1.3	1.3
Electricity Distributed	6.4	7.5	4.5	5.0	5.1	4.3	4.2
Total Direct Emissions	**875.2**	**847.9**	**782.0**	**790.5**	**811.3**	**795.3**	**793.2**
Total w/ Electricity Distributed	**1,516.2**	**1,523.8**	**1,158.3**	**1,201.0**	**1,214.8**	**1,168.7**	**1,167.8**

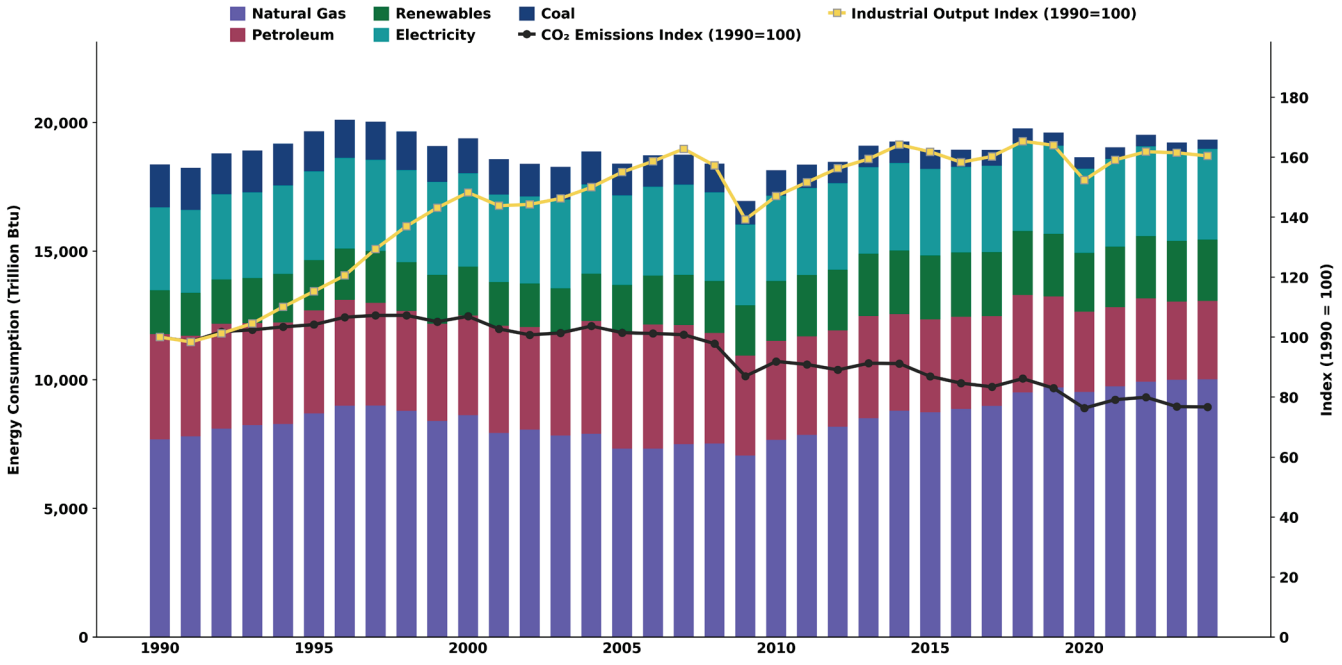
Note: Totals may not sum due to independent rounding.

In 2024, CO_2, CH_4, and N_2O emissions from fossil fuel combustion and electricity use within the industrial end-use sector totaled 1,167.8 MMT CO_2 Eq., a 0.1 percent decrease from 2023 emissions.

There are many dynamics that impact emissions from the industrial sector, including economic activity, changes in the make-up of the industrial sector, changes in the emissions intensity of industrial processes, and weather-related impacts on heating and cooling of industrial buildings.[14]

Despite the growth in industrial output (60.4 percent) from 1990 to 2024, direct emissions from fossil fuel combustion in the industrial sector decreased by 9.4 percent over the same time series (see Figure 3-11). Structural changes within the U.S. economy are to some extent responsible for the decoupling of industrial output growth from industrial GHG emissions, for example: (1) more rapid growth in output from less energy-intensive industries relative to traditional manufacturing industries (e.g., from steel to computer equipment), and (2) energy efficiency methods employed in energy-intensive industries such as increased use of electric arc furnaces.

Figure 3-11: Fuels and Electricity Used in Industrial Sector, Industrial Output, and Total Sector CO_2 Emissions (Including Electricity)



[14] Some large commercial customers pay an industrial price for natural gas and/or electricity and are grouped with the industrial end-use sector in U.S. energy statistics. This may cause the industrial end-use sector to appear to be sensitive to weather conditions due to the heating and cooling demands of the large commercial facilities.

Methods

As discussed, CO_2 emissions from fossil fuel combustion are mainly based on fuel type and carbon content, whereas CH_4 and N_2O emissions also depend on combustion technologies and other factors. Therefore, methodologies for estimating CO_2 emissions from fossil fuel combustion differ from the estimation of non-CO_2 (CH_4 and N_2O) emissions from stationary fuel combustion.

For this *GHGIA*, the methods used to estimate CO_2 emissions and non-CO_2 emissions from the industrial sector are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* report (EPA, 2025). However, there were some areas where data had to be proxied due to lack of 2024 data. As noted previously, adjustments were made to the industrial sector energy use data before calculating emissions. These mainly include adjusting for energy use that is transferred to the IPPU and NEU calculations. Many of the IPPU adjustments relied in part on data from the U.S. EPA Greenhouse Gas Reporting Program (GHGRP) including, for example, energy use for iron and steel and ammonia (see the IPPU Chapter 4 for more details). Due to lack of 2024 GHGRP data, these adjustments were, for the most part, proxied to 2023 values. The amount of energy use that was proxied represented 2.5 percent of unadjusted industrial sector energy use. So, while the proxy approach may lead to an under or over allocation of energy use between fossil fuel combustion and IPPU, the overall effect will be minor. More details on activity data are provided in Annex 5.

One other update to the prior approach was to revise the IPPU sector adjustment for carbon black. Previous estimates adjusted residual and other oil used in the industrial sector fossil fuel combustion emission calculations to account for the energy use and emissions that are included under IPPU. The previous estimates had more residual oil used in carbon black production than was reported to be used in the industrial sector, which resulted in undercounting some of the energy used in IPPU. The approach used in this *GHGIA* relies on the total industrial sector residual fuel oil use with the remaining amount needed assuming to come from other oils (which are adjusted under NEU).

Recalculations

Recalculations were implemented on historical estimates based on updates in the underlying data from EIA (2026a). EIA often updates historical data when new data becomes available, mostly impacting the most recent years of data. Updates to historical data based on the EIA data used resulted in a 0.3 percent decrease in coal use in 2023.

The biggest change in historical data resulted from an update to the amount of fuel used in NEU. This impacts the industrial sector fossil fuel combustion emissions, as energy used in NEU is subtracted from the industrial sector fossil fuel emission calculations and accounted for as part of NEU emissions. There was a decrease in the amount of natural gas used in NEU increasing the amount of natural gas use and emissions in the industrial sector fossil fuel combustion emissions. The change resulted in a 2.8 percent increase in natural gas emissions in 2023 compared with previous estimates and an average annual increase of 0.6 percent over the time series. The emissions from hydrocarbon gas liquids (HGLs) were also impacted due to updates in the amounts of HGLs used for NEU and the emission factors for HGLs, which were updated to reflect the mix of HGLs used for energy and NEU. The change resulted in a 6.3 percent decrease in industrial sector

fossil fuel combustion emissions in 2023 compared with previous estimates. The adjustment for gasoline and diesel used in the transportation sector also impacted other sectors, as they were adjusted to keep the totals the same. That resulted in an average annual decrease of 0.8 percent over the time series.

3.1.4 Residential and Commercial Sectors

According to EIA, the residential sector is an energy-consuming sector that consists of living quarters for private households. Common uses of energy associated with this sector include space heating, water heating, air conditioning, and lighting, refrigeration, cooking, and running a variety of other appliances. The residential sector excludes institutional living quarters (EIA, 2026a).

The commercial sector is an energy-consuming sector that consists of service-providing facilities and equipment of businesses; federal, state, and local governments; and other private and public organizations, such as religious, social, or fraternal groups. The commercial sector includes institutional living quarters. It also includes sewage treatment facilities. Common uses of energy associated with this sector include space heating, water heating, air conditioning, lighting, refrigeration, cooking, and running a wide variety of other equipment. This sector includes generators that produce electricity and/or useful thermal output primarily to support the activities of the above-mentioned commercial establishments (EIA, 2026a).

Table 3-12 presents GHG emissions from fossil fuel combustion in the residential and commercial sectors, including emissions from the electric power sector that are distributed to the residential and commercial sectors based on the amount of electricity used in those sectors.

Table 3-12: GHG Emissions from Fossil Fuel Combustion in the Residential and Commercial Sectors (MMT CO_2 Eq.)

GHG/Fuel Type	1990	2005	2020	2021	2022	2023	2024
CO_2	**1,747.7**	**2,314.0**	**1,607.6**	**1,680.0**	**1,714.0**	**1,571.1**	**1,585.2**
Coal	14.9	10.1	1.4	1.4	1.4	1.1	1.1
Natural gas	379.8	425.2	429.8	439.0	464.3	430.2	422.3
Petroleum	170.6	151.7	111.9	107.8	119.4	98.9	117.7
Electricity Distributed	1,182.4	1,727.0	1,064.5	1,131.8	1,128.9	1,040.9	1,044.1
CH_4	**7.4**	**6.5**	**5.9**	**6.0**	**6.9**	**6.2**	**6.1**
Coal	0.3	0.1	+	+	+	+	+
Petroleum	0.7	0.6	0.5	0.4	0.5	0.4	0.5
Natural gas	1.0	1.1	1.1	1.1	1.2	1.1	1.1
Wood	5.2	4.0	3.3	3.4	4.2	3.6	3.4
Electricity Distributed	0.3	0.7	1.0	1.0	1.1	1.1	1.1
N_2O	**13.1**	**20.4**	**13.9**	**14.9**	**15.4**	**13.2**	**12.8**
Coal	0.1	+	+	+	+	+	+
Petroleum	0.4	0.3	0.3	0.3	0.3	0.2	0.3
Natural gas	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Wood	0.6	0.5	0.4	0.4	0.5	0.5	0.4
Electricity Distributed	11.9	19.3	13.0	14.0	14.4	12.3	11.8
Total Direct Emissions	**573.7**	**593.8**	**548.9**	**554.1**	**592.0**	**536.2**	**547.0**
Total w/ Electricity Distributed	**1,768.2**	**2,340.8**	**1,627.4**	**1,700.9**	**1,736.3**	**1,590.5**	**1,604.1**

+ Does not exceed 0.05 MMT CO2 Eq.

Note: Totals may not sum due to independent rounding.

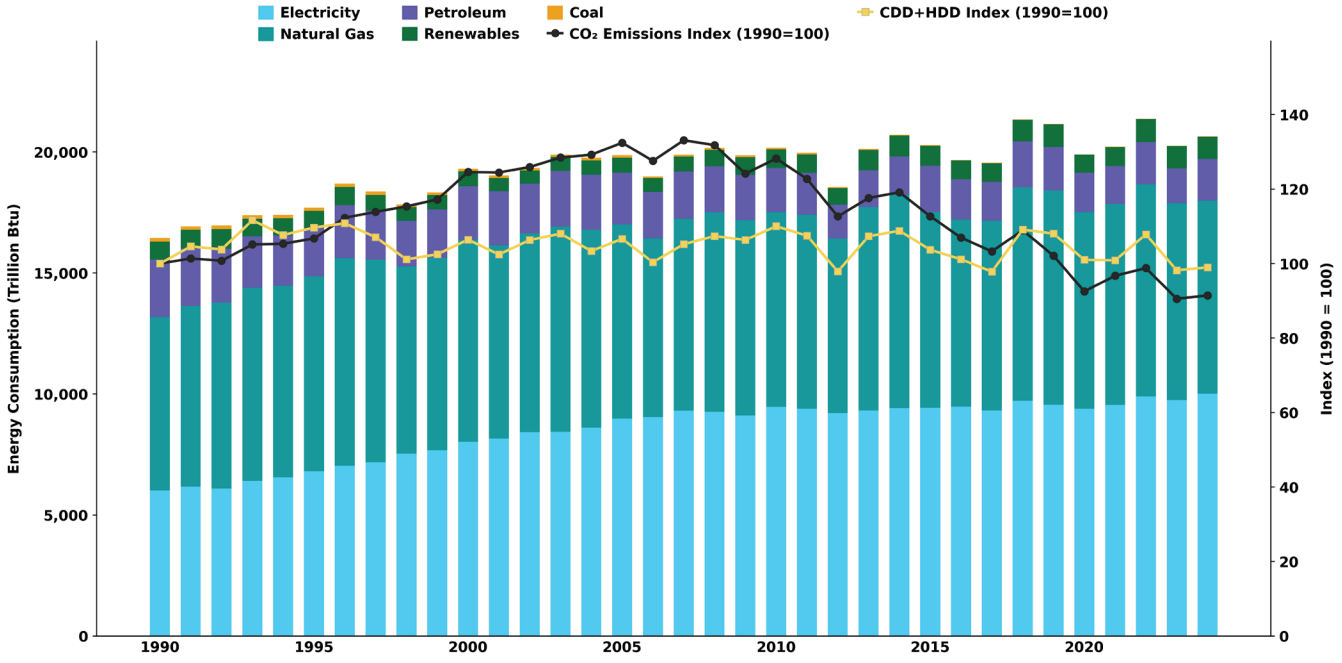
GHG emissions from the residential and commercial sectors increase substantially when emissions from electricity end-use are included, because the residential and commercial sectors use over 70 percent of the electricity generated in the United States (e.g., for building heating, ventilation, and air conditioning; lighting; and appliances) (National Renewable Energy Lab [NREL], 2023).

Short-term trends in the residential and commercial sectors are often correlated with seasonal weather conditions, which lead to fluctuations in energy use, rather than long-term economic conditions. Changes over time that tend to increase energy use include population growth and a trend toward larger houses. Other longer-term trends that tend to reduce energy use include population migration to warmer areas and improved energy efficiency and building insulation. The shift toward energy-efficient products and more stringent energy efficiency standards for household equipment has also contributed to a decrease in energy demand in households (EIA, 2023; Nadel et al., 2015).

In 2024, total emissions (CO_2, CH_4, and N_2O) from fossil fuel combustion and electricity use within the residential and commercial sectors 1,604.1 MMT CO_2 Eq. The trends in the residential and commercial sectors when electricity power sector distributed emissions are included are, in large part, dependent on the carbon intensity of the electric power sector. For example, starting around 2014, total energy use and emissions in the residential and commercial sectors began to decouple due to the decarbonization of the electric power sector (see Figure 3-12).

Direct CO_2, CH_4, and N_2O emissions from fossil fuel combustion within the residential and commercial end-use sectors increased by 2.0 percent from 2023 to 2024. This is partly due to a decrease in heating degree days (2.9 percent), combined with a larger increase in cooling degree days (10.3 percent) from 2023 to 2024. See Box 3.1 for more details on weather-related data. From 2023 to 2024, direct energy use of coal and natural gas in the residential and commercial sectors decreased by 6.1 percent and 1.8 percent, respectively. Petroleum use in the residential and commercial sectors increased by 18.8 percent from 2023 to 2024; however, this could largely be due to a discontinuity in the FHWA data used to allocate gasoline and diesel fuel across sectors.

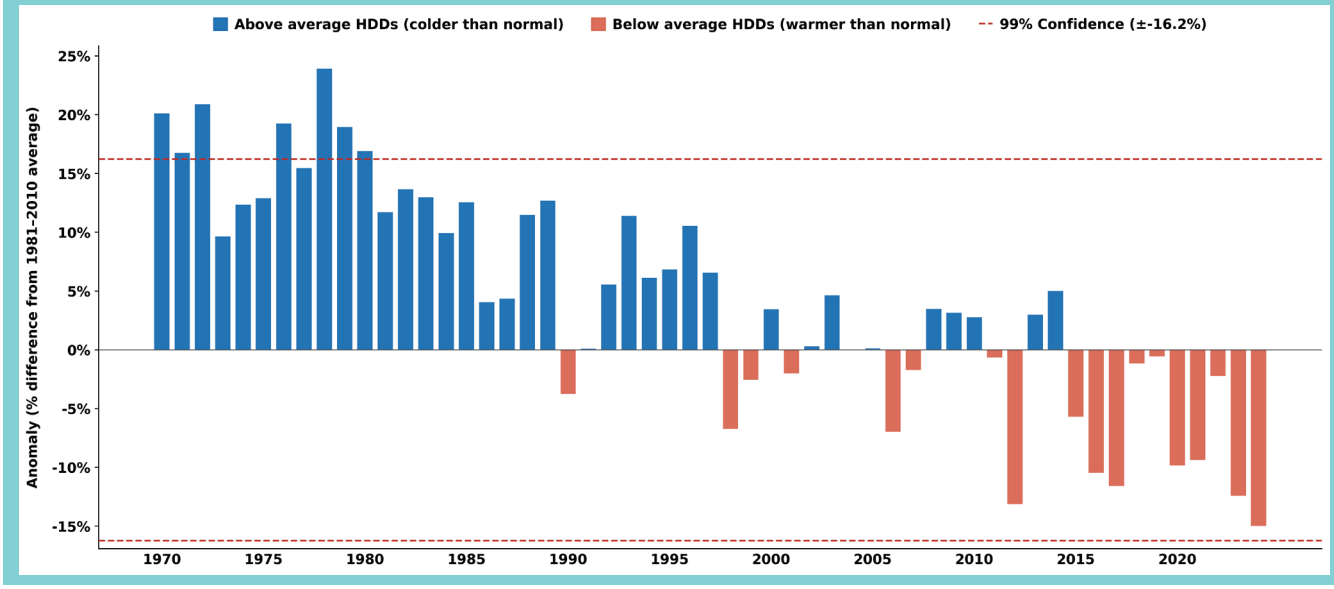
Figure 3-12: Fuels and Electricity Used in Residential and Commercial Sectors, Heating and Cooling Degree Days, and Total Sector CO_2 Emissions (Including Electricity)



Box 3-1: Weather and Non-Fossil Energy Effects on CO_2 Emissions from Fossil Fuel Combustion Trends

The United States in 2024 experienced a warmer winter overall compared to 2023, with a 2.9 percent decrease in heating degree days, and 2024 was warmer than normal with heating degree days 15.0 percent below normal[15] (see Figure 3-13). Along with a warmer winter, 2024 experienced a warmer summer than 2023, with cooling degree days 10.3 percent above 2023. Cooling degree days were 22.6 percent above normal (see Figure 3-14) (EIA, 2026a).[16] Warmer summers can lead to increased energy use, and associated emissions, to cool building spaces in the residential and commercial sectors, mostly from electricity use. Warmer winter conditions can lead to an overall decrease in direct energy use, and emissions from fossil fuel combustion, used for heating in the residential and commercial sectors.

Figure 3-13: Annual Deviations from Normal Heating Degree Days (HDDs) for the United States (1970–2023, Index Normal = 100)

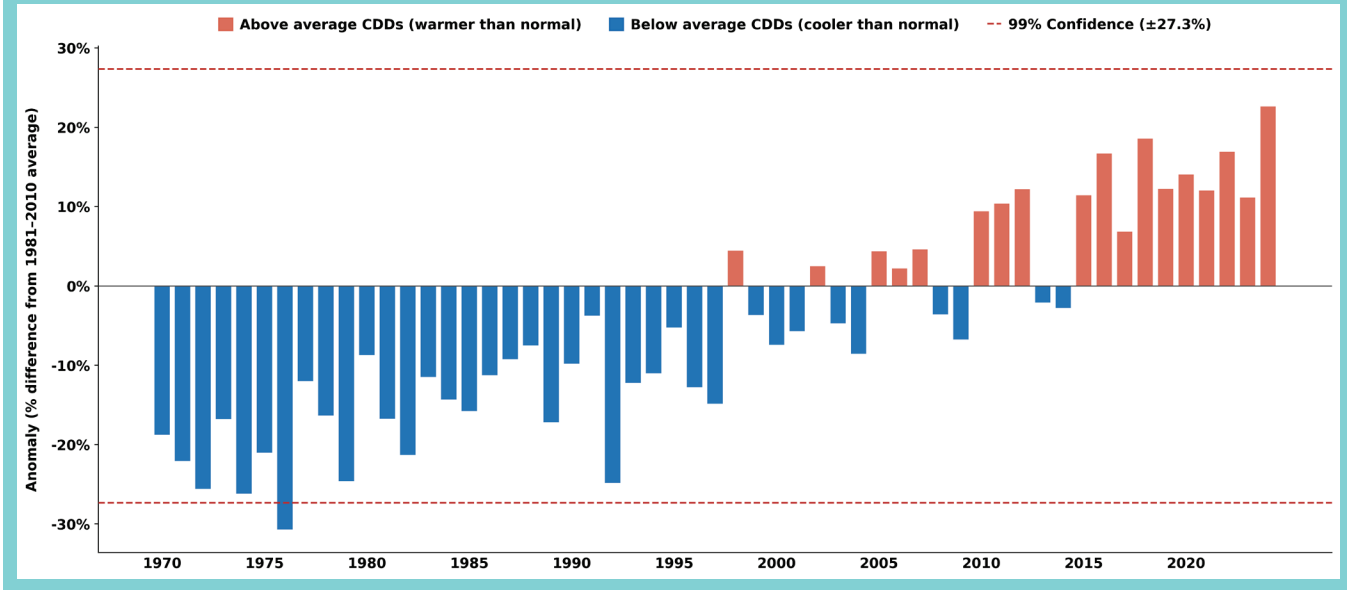


[15] The National Centers for Environmental Information of NOAA generates official U.S. climate normals every 10 years in keeping with the needs of the user community and the requirements of the World Meteorological Organization and National Weather Service. The 1991–2020 U.S. Climate Normals are the latest in a series of decadal normals first produced in the 1950s. See https://www.ncei.noaa.gov/products/land-based-station/us-climate-normals. The variation in these normals during this time period was ±16 percent and ±27 percent for heating and cooling degree days, respectively (99 percent confidence interval).

[16] Degree days are relative measurements of outdoor air temperature. Heating degree days are deviations of the mean daily temperature below 65 degrees Fahrenheit, whereas cooling degree days are deviations of the mean daily temperature above 65 degrees Fahrenheit. Heating degree days have a considerably greater effect on direct energy demand and related emissions than do cooling degree days. Excludes Alaska and Hawaii.

Box 3-1: Weather and Non-Fossil Energy Effects on CO_2 Emissions from Fossil Fuel Combustion Trends *(continued)*

Figure 3-14: Annual Deviations from Normal Cooling Degree Days (CDDs) for the United States (1970–2023, Index Normal = 100)



Methods

As discussed, CO_2 emissions from fossil fuel combustion are mainly based on fuel type and carbon content, whereas CH_4 and N_2O emissions also depend on combustion technologies and other factors. Therefore, methodologies for estimating CO_2 emissions from fossil fuel combustion differ from the estimation of non-CO_2 (CH_4 and N_2O) emissions from stationary fossil fuel combustion.

For this *GHGIA*, the methods used to estimate CO_2 emissions and non-CO_2 emissions from the residential and commercial sectors are consistent with prior estimates (EPA, 2025).

Recalculations

Recalculations were implemented on historical estimates based on updates in the underlying data from EIA (EIA 2026a). EIA often updates historical data when new data becomes available, mostly impacting the most recent years of data. Updates based on revised EIA data resulted in a slight increase (0.1 percent) in natural gas use in the residential sector and a slight decrease (0.2 percent) in natural gas use in the commercial sector in 2023 compared with previous estimates.

The adjustment to gasoline and diesel fuel used in the transportation sector also impacted the residential and commercial sectors. The updates resulted in a decrease in residential sector emissions of 11.2 percent and a 23.6 percent reduction in the commercial sector in 2023. The annual average change was a 0.2 percent decrease in residential sector and a 0.3 percent increase in the commercial sector over the time series compared with previous estimates.

3.1.5 Territories

U.S. Territories included in this analysis are American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other outlying U.S. Pacific Islands. As described previously, this data is collected separately and is not available at the sector level. Therefore, U.S. Territories fossil fuel combustion emissions are presented in total but not broken out at the end-use sector level. The emissions will occur across all end-use sectors including stationary and mobile sources.

Table 3-13 presents GHG emissions from fossil fuel combustion in U.S. Territories.

Table 3-13: GHG Emissions from Fossil Fuel Combustion in U.S. Territories (MMT CO_2 Eq.)

GHG/Fuel Type	1990	2005	2020	2021	2022	2023	2024
CO_2	**20.0**	**51.8**	**23.2**	**25.7**	**23.8**	**27.2**	**27.9**
Coal	0.5	3.0	3.1	2.9	2.9	2.5	2.5
Natural gas	NO	1.3	2.6	3.9	2.7	4.5	4.5
Petroleum	19.5	47.5	17.5	18.9	18.1	20.1	20.9
CH_4	**+**	**0.1**	**+**	**+**	**+**	**+**	**+**
Coal	+	+	+	+	+	+	+
Petroleum	+	0.1	+	+	+	+	+
Natural gas	NO	+	+	+	+	+	+
Wood	NE	NE	NE	NE	NE	NE	NE
N_2O	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Coal	+	+	+	+	+	+	+
Petroleum	+	0.1	+	+	+	+	+
Natural gas	NO	+	+	+	+	+	+
Wood	NE	NE	NE	NE	NE	NE	NE
Total	**20.1**	**52.1**	**23.3**	**25.8**	**23.8**	**27.3**	**28.0**

+ Does not exceed 0.05 MMT CO_2 Eq.
NO (Not Occurring)
NE (Not Estimated)
Note: Totals may not sum due to independent rounding.

The emissions from fossil fuel combustion in U.S. Territories have generally increased over time due to increased fuel use across all fuel types. The emissions peaked around 2004 and then have declined generally due to an increase and then decrease in petroleum fuel used over time. In 2024, CO_2 emissions from fossil fuel combustion were 28.0 MMT CO_2 Eq., a 2.7 percent increase from 2023 and a 39.5 percent increase from 1990. The CO_2 emissions from fossil fuel combustion in U.S. Territories in 2024 represented only 0.6 percent of the total U.S. fossil fuel combustion CO_2 emissions.

Methods

As discussed, CO_2 emissions from fossil fuel combustion are mainly based on fuel type and carbon content, whereas CH_4 and N_2O emissions also depend on combustion technologies and other factors. Therefore, methodologies for estimating CO_2 emissions from fossil fuel combustion differ from the estimation of non-CO_2 (CH_4 and N_2O) emissions from stationary and mobile fossil fuel combustion.

For this *GHGIA*, the methods used to estimate CO_2 emissions and non-CO_2 emissions from U.S. Territories are consistent with previous reports (EPA, 2025). Some of the energy use data for 2024 was not available at the time of this *GHGIA* so was proxied to 2023 values.

Recalculations

Recalculations were implemented on historical estimates based on updates in the underlying data from EIA. EIA often updates historical data when new data becomes available, this mostly impacts the most recent years of data. The recalculations mostly impacted recent years of petroleum consumption. The 2023 data increased by 12.8 percent based on the revised data. The values over time were also impacted with an annual average change of 0.7 percent over the 1990 to 2023 time period.

Fossil Fuel Combustion Uncertainty

Uncertainty in emission estimates for fossil fuel combustion is associated with a few factors. As noted above, estimates of CO_2 from fossil fuel combustion are directly related to the amount of fuel combusted, the fraction of the fuel that is oxidized, and the carbon content of the fuel.

National statistics on the total amount of fossil fuel energy consumption are relatively accurate. However, the allocation to individual end-use sectors (i.e., residential, commercial, industrial, and transportation) is less certain. Uncertainties also result from the data and assumptions used to allocate emissions from the transportation end-use sector to individual vehicle types and transport modes.

There are also uncertainties associated with the adjustments made to energy use before calculating emissions. The adjustments include the amount of fuel used in non-energy production processes, the amount of fuel used in industrial processes, and fuel used in international bunker fuels. These factors all contribute to the uncertainty in the CO_2 estimates.

Another source of uncertainty is fuel consumption by U.S. Territories. The United States does not collect energy statistics for its territories at the same level of detail as for the fifty states and the District of Columbia. Therefore, estimating both emissions and bunker fuel consumption by these territories is difficult.

Uncertainties around carbon content of fuels and carbon oxidation efficiencies also occur. Given the same primary fuel type (e.g., coal, petroleum, or natural gas), the amount of carbon contained in the fuel per unit of useful energy can vary. For the United States, however, the impact of these uncertainties on overall CO_2 emission estimates is believed to be relatively small.

Uncertainties also occur around non-CO_2 fossil fuel combustion emission estimates from both stationary and mobile sources. CH_4 emission estimates from stationary sources exhibit high uncertainty, primarily due to uncertainties in emission estimates from wood combustion. There is also uncertainty associated with the use of broad indicators of emissions (i.e., fuel use multiplied by an aggregate emission factor for different sectors), rather than specific emission processes (i.e., by combustion technology and type of emission control). Uncertainty in mobile source non-CO_2 emission estimates are impacted by uncertainties in vehicle and fuel type VMT data, emission factor data, control technology type, fuel consumption, and emission factor data.

For this current *GHGIA*, the overall uncertainty associated with national estimates of CO_2 and non-CO_2 emissions from fossil fuel combustion is assumed to be similar to prior estimates (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 4 percent above the CO_2 emission estimate, a range of approximately 34 percent below and 125 percent above the stationary CH_4 emission estimate, a range of approximately 23 percent below and 51 percent above the stationary N_2O emission estimate, a range of approximately 4 percent below and 30 percent above the mobile CH_4 emission estimate, and a range of approximately 7 percent below and 22 percent above the mobile N_2O emission estimate in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 3-43. Some differences in reporting methodologies, coverage, and data gaps may introduce additional uncertainty for the 2024 estimate and may affect consistency with previous years.

3.2 Carbon Emitted from Non-Energy Uses of Fossil Fuels (Source Category 1A)

In addition to being combusted for energy use, fossil fuels are also used for non-energy uses (NEUs). These uses are diverse and include feedstocks for manufacturing plastics, rubber, synthetic fibers, and other materials; reducing agents in the production of metals and inorganic products; and the creation of products such as lubricants, waxes, and asphalt. Fuels used for non-energy purposes are subtracted from total fuel consumption data to avoid double-counting with fossil fuel combustion emissions.

Carbon dioxide (CO_2) emissions from NEUs can occur through several pathways. Emissions may be released during manufacturing, as in the production of plastics or rubber from fuel-derived feedstocks. Emissions may also occur during a product's use phase, such as through solvent use.

Under IPCC Inventory guidelines, emissions from NEUs should be reported under IPPU (IPCC, 2006). However, due to national circumstances and the inability to fully separate these uses within the national energy balance, these emissions are reported within the energy sector.

Table 3-14 shows CO_2 emissions and the amount of carbon stored from NEU. In 2024, emissions from NEU of fossil fuels were 96.0 million metric tons (MMT) CO_2 Eq., which constituted approximately 2.1 percent of overall fossil fuel combustion emissions. NEU emissions in 2024 increased by 7.1 percent from 2023 and decreased by 4.5 percent from 1990.

Table 3-14: CO_2 Emissions from NEU Fossil Fuel Consumption (MMT CO_2 Eq. and Percent Carbon)

Year	1990	2005	2020	2021	2022	2023	2024
Potential Emissions	293.8	374.0	308.9	324.6	315.5	327.7	346.0
Carbon Stored	193.3	241.6	225.3	234.7	226.0	238.1	250.0
Emissions as a % of Potential	34%	35%	27%	28%	28%	27%	28%
Carbon Emitted	**100.6**	**132.4**	**83.7**	**89.9**	**89.5**	**89.6**	**96.0**

Totals may not sum due to independent rounding.

The changes in NEU emissions over time are driven by the amount of fuel used in various types of NEU and by the assumed storage factors applied to each fuel. The overall amount of carbon emitted as a percentage of total potential emissions is shown in Table 3-14 above. Table 3-15 shows the amount of fossil fuels assumed to be used in NEU. In 2024, the consumption of fuels for NEUs was 5,521.6 Trillion Btus (TBtu), a 5.8 percent increase over 2023.

Table 3-15: Adjusted Consumption of Fossil Fuels for NEUs (TBtu)

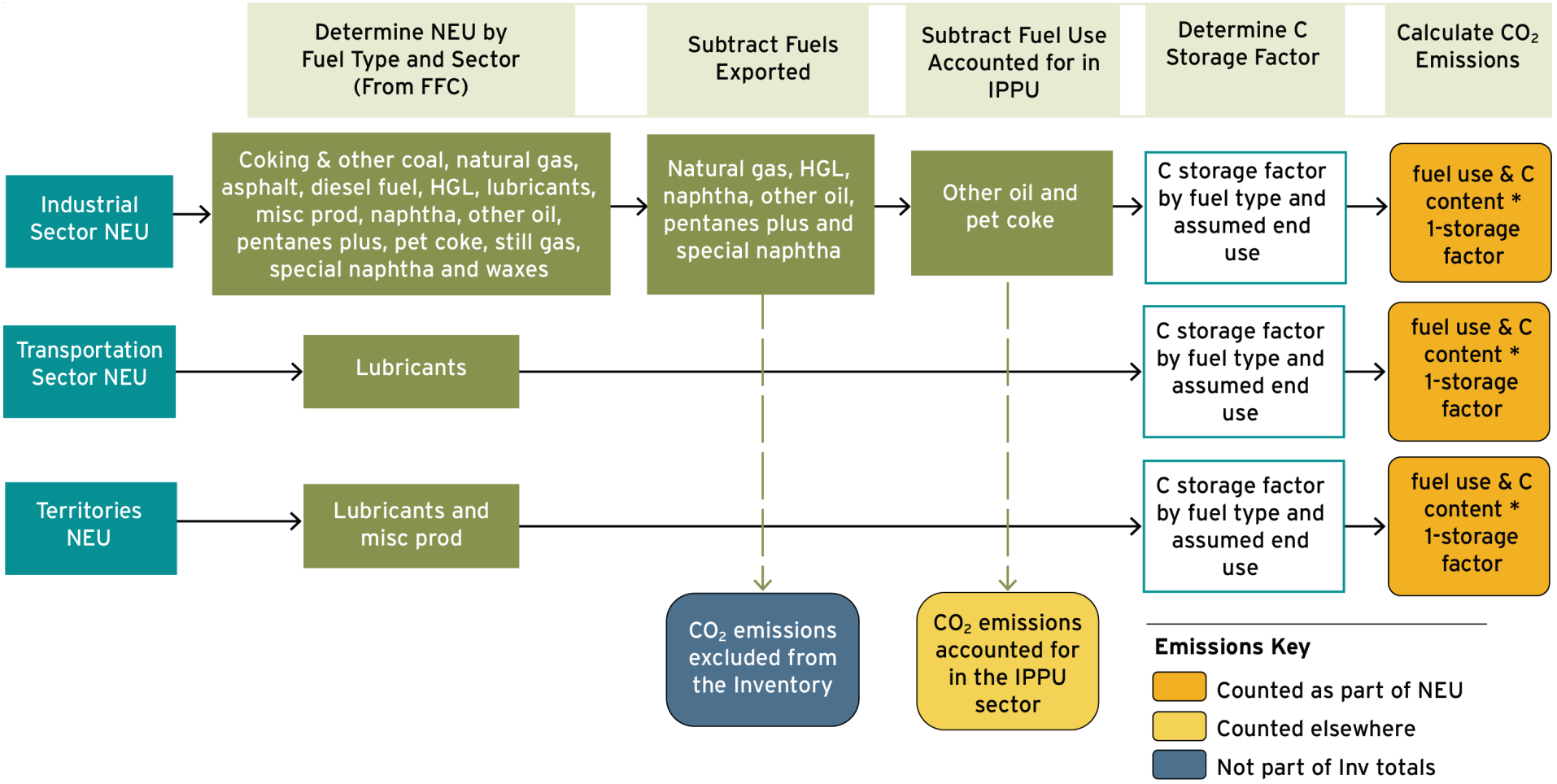
Year	1990	2005	2020	2021	2022	2023	2024
Industry	**4,138.8**	**5,172.6**	**4,763.2**	**4,987.5**	**4,890.3**	**5,121.6**	**5,426.2**
Industrial Coking Coal	0.0	80.4	79.4	77.5	46.4	65.4	57.9
Industrial Other Coal	7.6	11.0	9.5	9.5	9.5	9.5	9.4
Natural Gas to Chemical Plants	280.6	251.9	438.6	416.7	387.3	395.1	400.6
Asphalt & Road Oil	1,170.2	1,323.2	832.3	898.1	916.1	891.8	888.3
HGL	1,134.0	1,554.0	2,454.6	2,622.5	2,716.2	2,965.3	3,261.0
Lubricants	186.3	160.2	111.1	109.2	115.0	88.8	84.4
Naphtha (<401 °F)	325.4	679.1	326.2	327.5	242.5	251.7	238.5
Other Oil (>401 °F)	709.3	689.8	149.1	151.0	65.8	66.4	102.6
Still Gas	21.3	67.7	97.8	112.1	107.7	114.0	121.3
Petroleum Coke	25.2	138.0	0.0	0.0	0.0	0.0	0.0
Special Naphtha	100.6	60.9	80.0	75.3	81.9	83.0	73.2
Distillate Fuel Oil	7.1	12.2	4.9	5.5	5.5	5.4	5.2
Waxes	33.3	31.4	9.2	11.8	13.0	9.0	11.1
Miscellaneous Products	137.8	112.8	170.7	170.8	183.4	176.2	172.6
Transportation	**176.0**	**151.3**	**115.6**	**123.3**	**129.9**	**95.0**	**90.3**
Lubricants	176.0	151.3	115.6	123.3	129.9	95.0	90.3
U.S. Territories	**50.8**	**114.9**	**3.5**	**3.5**	**1.0**	**3.6**	**5.1**
Lubricants	0.7	4.6	1.0	1.0	1.0	1.0	1.0
Other Petroleum (Misc. Prod.)	50.1	110.3	2.5	2.5	0.0	2.5	4.0
Total	**4,365.7**	**5,438.8**	**4,882.4**	**5,114.3**	**5,021.3**	**5,220.2**	**5,521.6**

Note: Totals may not sum due to independent rounding.

Methods

Figure 3-15 outlines the method used to calculate NEU emissions (EPA, 2024). For this *GHGIA*, the methods used to estimate CO_2 emissions from NEU are consistent with prior estimates (EPA, 2025). Some of the data for 2024 were not available at the time of this *GHGIA*, so they were proxied to 2023 values—specifically, some of the data on product exports and some of the IPPU adjustments.

Figure 3-15: Approach for Calculating NEU Emission Estimates



Recalculations

Revisions were made across the time series based on several updates. The 2022 MECS (EIA, 2025b) data was available, which caused some adjustments in recent years regarding storage factors and assumptions about fuels used for NEU. The time series was also adjusted to better align with NEU fuel used listed by EIA (EIA, 2026a). In 2023, total NEU fuel use decreased by 5.9 percent compared with the value in prior analyses. The average annual change was a decrease of 1.1 percent over the 1990 to 2023 time period.

Uncertainty

The uncertainty in the NEU emission estimates is a function of uncertainty in both the quantity of fuel used for non-energy purposes and the storage factor associated with each fuel type. Several storage factors were based on U.S.-specific data, whereas others were based on IPCC defaults. There is uncertainty associated with the U.S.-specific data, as well as the applicability of the IPCC defaults to the U.S.-specific situation.

For this current *GHGIA*, the overall uncertainty associated with national estimates of CO_2 emissions from NEU is assumed to be similar to prior estimates (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 36 percent below and 62 percent above the CO_2 emission estimate in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 3.43. Some differences in reporting methodologies, coverage, and data gaps may introduce additional uncertainty for the 2024 estimate and may affect consistency with prior years.

3.3 Incineration of Waste (Source Category 1A)

Waste combustion in the United States includes all municipal solid waste (MSW), as well as scrap tires. Combustion of MSW generally occurs at waste-to-energy facilities or industrial facilities where useful energy is recovered. Similarly, scrap tires are mostly combusted for energy recovery at industrial sites. Therefore, emissions from waste combustion are accounted for in the Energy chapter.

Greenhouse gas (GHG) emissions from waste combustion result from conversion of the organic carbon containing inputs in the waste to carbon dioxide (CO_2) and from non-CO_2 (CH_4 and N_2O) emissions, which are dependent on waste combustion technologies used (De Soete, 1993; IPCC, 2006).

Organic materials in the waste stream come from biogenic and fossil origin. The emissions from waste combustion are calculated by estimating the quantity of waste combusted and the fraction of the waste that is carbon-derived from fossil sources and from biogenic sources. The CO_2 from biogenic origin is accounted for as a memo item in the *GHGIA*; see Section 3.11 for more details. The emissions from fossil-derived sources are accounted for here.

CO_2 emissions from combustion of waste in 2024 were 11.9 million metric tons (MMT) CO_2 Eq.—a decrease of 4.1 percent compared to 2023 and a 7.7 percent decrease since 1990. Emissions across the time series are shown in Table 3-16.

Waste combustion CH_4 and N_2O emissions are a relatively small amount of overall waste combustion emissions and have remained relatively constant over the time series. They are impacted by the total amount of waste combusted.

Table 3-16: CO_2, CH_4, and N_2O Emissions from the Combustion of Waste (MMT CO_2 Eq.)

Gas	1990	2005	2020	2021	2022	2023	2024
CO_2	12.9	13.3	12.9	12.5	12.5	12.4	11.9
CH_4	+	+	+	+	+	+	+
N_2O	0.4	0.3	0.3	0.4	0.3	0.3	0.3
Total	**13.3**	**13.6**	**13.3**	**12.8**	**12.8**	**12.8**	**12.2**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Data for the total amount of MSW combusted was derived from several sources including *BioCycle*, EPA Facts and Figures Report, Energy Recovery Council, EPA's Greenhouse Gas Reporting Program (GHGRP), and the U.S. Energy Information Administration (EIA). Multiple sources were used to ensure a complete, quality dataset, as each source encompasses a different timeframe (EPA, 2025). Tire combustion data comes from the U.S. Tire Manufacturers Association.

Table 3-17 provides the estimated tons of MSW combusted including and excluding tires.

Table 3-17: Municipal Solid Waste Combusted (Short Tons)

Activity	1990	2005	2020	2021	2022	2023	2024
Waste Combusted (excluding tires)	33,344,839	26,486,414	27,586,271	27,867,445	26,338,130	25,676,432	24,995,666
Waste Combusted (including tires)	33,766,239	28,631,054	29,106,686	29,261,445	27,808,130	27,222,432	26,541,666

Source: EPA (2025) for historical data

Methods

As with fossil fuel combustion estimates, different methods are used for estimating CO_2 and non-CO_2 emissions from waste combustion. Estimates of CO_2 emissions are based on the amount of waste combusted and carbon contents of the different components of the waste stream. For MSW, the amount of waste combusted comes from different sources over time (see Table 3.17). Most recently, MSW data was based on data from GHGRP. The carbon content of MSW is also based on data from the GHGRP and an implied emission factor is used for years where GHGRP data is not available. For tires, the amount combusted and composition is based on industry data. The carbon content of tires is based on carbon content of the different components. Non-CO_2 emissions are based on the total amount of waste and default emission factors (EPA, 2025).

The methods used here for CO_2 are consistent with those used in prior estimates (EPA, 2025). For 2024, GHGRP data is not available, so EIA data is used for the MSW combustion amount (EIA, 2025). Over time, the EIA MSW combustion data is fairly consistent with the data from GHGRP. Over the past 5 years of GHGRP data, the EIA MSW combustion data is within 2 percent of the GHGRP data. For 2024, an implied emission factor was applied for CO_2 estimates based on the last 5 years of GHGRP data. Data for 2024 on tires was not available so data was proxied to 2023. The CO_2 emission factors used in the analysis are shown in Table 3-18 and Table 3-19. The biogenic CO_2 factors shown in Table 3-19 are used to calculate biomass CO_2 emissions which are listed in Section 3.11.

Table 3-18: Calculated Fossil CO_2 Content per Ton Waste Combusted (kg CO_2/Short Ton Combusted)

Factor	1990	2005	2020	2021	2022	2023	2024
CO_2 Emission Factors	366	366	377	365	382	384	374

Table 3-19: Calculated Biogenic CO_2 Content per Ton Waste Combusted (kg CO_2/Short Ton Combusted)

Factor	1990	2005	2020	2021	2022	2023	2024
CO_2 Emission Factors	556	556	566	550	564	543	556

The non-CO_2 methods are consistent with those used in prior analysis (EPA, 2025). As described for CO_2 estimates, GHGRP data was not available for 2024, so EIA MSW amount was used instead.

Recalculations

Methods and activity data are consistent with prior analysis (EPA, 2025), and there were no updates to the underlying data sources used. Therefore, no recalculations were implemented for 1990–2023 for this source category.

Uncertainty

Uncertainties in waste combustion emission estimates are due to both the assumptions applied to the data and from the quality of the data. Key factors include reported MSW CO_2 emissions; N_2O and CH_4 emissions factors; and tire composition data. The highest levels of uncertainty surround the reported tonnage and emission estimates used in the analysis. Lower levels of uncertainty surround variables that were determined by quantitative measurements (e.g., combustion efficiency, carbon content of tire components).

For this *GHGIA*, the overall uncertainty associated with national estimates of CO_2 and non-CO_2 emissions from waste combustion are assumed to be similar to prior estimates (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 17 percent below and 20 percent above the CO_2 emission estimate, 102 percent below and 103 percent above the CH_4 emission estimate, and 53 percent below and 161 percent above the N_2O emission estimate in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 3-43. Some differences in reporting methodologies, coverage, and data gaps may introduce additional uncertainty for the 2024 estimate and may affect consistency with prior years.

3.4 Coal Mining (Source Category 1B1a)

Coal mining-related activities release both CH_4 and CO_2 to the atmosphere. Emissions can come from underground mining, surface mining, and post-mining (i.e., coal-handling) activities. CH_4 and CO_2 occur naturally in coal seams and can be released as the coal seam is exposed and mined. Underground mines can liberate gases from ventilation and degasification systems. The CH_4 generated can be recovered and used, reducing emissions to the atmosphere. Surface mines can generate emissions as the coal is exposed to the atmosphere during overburden removal. Post-mining activities can release trapped gases as the coal is processed, transported, and stored for use.

In 2024, 177 underground coal mines and 339 surface mines were operating in the United States (EIA, 2025). The amount of coal mined has generally declined since 1990 but does fluctuate from year to year (see Table 3-20). Total CH_4 emissions in 2024 were estimated to be 44.3 MMT CO_2 Eq., a decline of 2.5 percent relative to 2023 and a decline of 59.0 percent since 1990 (see Table 3-21).

Table 3-20: Coal Production (kt)

Year	1990	2005	2020	2021	2022	2023	2024
Underground							
Number of Mines	1,683	586	196	174	185	190	177
Production	384,244	334,399	177,380	200,122	201,525	217,929	206,167
Surface							
Number of Mines	1,656	789	350	332	354	362	339
Production	546,808	691,447	307,944	323,142	336,990	359,729	305,790
Total							
Number of Mines	3,339	1,398	546	506	539	552	516
Production	931,052	1,025,846	485,324	523,264	538,515	577,658	511,957

Note: Totals may not sum due to independent rounding.

Table 3-21: CH_4 Emissions from Coal Mining (MMT CO_2 Eq.)

Activity	1990	2005	2020	2021	2022	2023	2024
Underground (UG) Mining	**83.1**	**46.7**	**35.2**	**34.0**	**31.4**	**33.4**	**33.5**
Liberated	92.1	69.1	47.2	49.6	54.0	57.2	**57.3**
Recovered & Used	(9.1)	(22.4)	(12.1)	(15.6)	(22.6)	(23.8)	**(23.8)**
Surface Mining	**12.0**	**13.3**	**5.4**	**5.7**	**6.0**	**5.9**	**5.0**
Post-Mining (UG)	**10.3**	**8.6**	**4.3**	**4.8**	**4.8**	**4.8**	**4.7**
Post-Mining (Surface)	**2.6**	**2.9**	**1.2**	**1.2**	**1.3**	**1.3**	**1.1**
Total	**108.0**	**71.4**	**46.1**	**45.7**	**43.6**	**45.4**	**44.3**

Notes: Parentheses in above emissions tables indicate negative values. Totals may not sum due to independent rounding.

In 2024, total fugitive CO_2 emissions were estimated to be 2.3 MMT CO_2 Eq., a decline of 51.1 percent since 1990 and a decline of 6.5 percent since 2023 (see Table 3-22). Changes in emissions are due in part to changes in annual coal production but also depend on the number of underground mines and operating changes.

Table 3-22: CO_2 Emissions from Coal Mining (MMT CO_2 Eq.)

Activity	1990	2005	2020	2021	2022	2023	2024
Underground (UG) Mining	**4.2**	**3.6**	**2.0**	**2.2**	**2.2**	**2.1**	**2.0**
Liberated	4.2	3.6	1.9	2.2	2.2	2.1	2.0
Recovered & Used	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Flaring	NO	NO	+	+	+	+	+
Surface Mining	**0.4**	**0.6**	**0.2**	**0.3**	**0.3**	**0.3**	**0.2**
Total	**4.6**	**4.2**	**2.2**	**2.5**	**2.5**	**2.4**	**2.3**

+ Does not exceed 0.05 MMT CO_2 Eq.

NO (Not Occurring)

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

Methods

The methods used here are consistent with those used in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990–2023* (EPA, 2025). The approach for estimating emissions from underground coal mines relies heavily on net CH_4 emissions data reported by facilities under EPA's GHGRP. Data for 2024, as well as any updates to previously reported data, were not available at the time this *GHGIA* was prepared. The estimates also rely on data from the Mine Safety and Health Administration (MSHA), and state sales databases (EPA, 2025). Therefore, 2023 data was used as a proxy to estimate portions of underground coal mine GHG emissions for 2024 including for GHGRP and state sales data. MSHA data was available and updated for 2024 (MSHA, 2025).

Recalculations

Recalculations were implemented to account for the degasification volumes for four mines that include pre-mining wells. It was changed to attribute annual degasification volumes to the year in which they occur (i.e., reporting year) per IPCC guidance (IPCC, 2019). As a result of recalculations, CH_4 emissions decreased by an average of less than 0.1 percent across the time series, compared with previous estimates.

Uncertainty

Uncertainty associated with the estimates of CH_4 from underground coal mines are due to uncertainties in the measurement of ventilation systems data. There is also uncertainty associated with estimates of CH_4 liberated and recovered by degasification systems. There is considerably more uncertainty associated with surface mining and post-mining emissions than are associated with underground mines. This is because of the difficulty in developing accurate emission factors from field measurements. However, since underground coal mining constitutes the majority of estimated total coal mining emissions, the uncertainty associated with underground emissions is the primary factor that determines overall uncertainty.

For this current *GHGIA*, the overall uncertainty associated with national estimates of CO_2 and CH_4 emissions from coal mining are assumed to be similar to prior estimates (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 10 percent below and 21 percent above the CH_4 emission estimate and 68 percent below and 76 percent above the CO_2 emission estimate in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 3.43. Some differences in reporting methodologies, coverage, and data gaps may introduce additional uncertainty for the 2024 estimate and may affect consistency with prior years.

3.5 Abandoned Underground Coal Mines (Source Category 1B1a)

Coal mines can continue to release CH_4 after being closed and abandoned. Flooded mines might only produce CH_4 emissions for a short period of time, whereas other abandoned mines might produce CH_4 at a near-steady rate over a longer period of time. The CH_4 can migrate to the surface through vents used to prevent buildup or through overburden fractures, particularly if the mine was not sealed adequately. In addition, CH_4 can migrate to the surface through natural cracks and fissures in the strata overlying the coal mine. The following factors influence abandoned coal mine emissions:

- Time since abandonment
- Gas content and adsorption characteristics of coal
- CH_4 flow capacity of the mine
- Mine flooding
- Presence of vent holes
- Mine seals

In 2024, gross abandoned mine emissions were 9.4 million metric tons (MMT) CO_2 Eq. (see Table 3-23). The gross emissions are reduced by CH_4 recovered and used, resulting in net emissions of 6.4 MMT CO_2 Eq. in 2024.

Table 3-23: CH_4 Emissions from Abandoned Coal Mines (MMT CO_2 Eq.)

Activity	1990	2005	2020	2021	2022	2023	2024
Abandoned Underground Mines	8.1	9.3	9.4	9.2	9.1	9.0	9.4
Recovered & Used	NO	(2.0)	(2.9)	(3.0)	(3.0)	(2.9)	(3.0)
Total	**8.1**	**7.4**	**6.5**	**6.2**	**6.1**	**6.1**	**6.4**

NO (Not Occurring)

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

Changes in CH_4 emissions over time are mainly due to the number of mines closed and to the magnitude of the emissions from those mines when active. A mine is considered a "gassy" mine if it emits more than 100 thousand cubic feet of CH_4 per day (100 Mcfd).

Table 3-24 presents the count of mines by post-abandonment state in 2024.

Table 3-24: Number of Gassy Abandoned Mines Present in U.S. Basins in 2024, Grouped by Class According to Post-Abandonment State

Basin	Sealed	Vented	Flooded	Total Known	Unknown	Total Mines
Central Appl.	44	26	50	120	146	266
Illinois	35	3	14	52	31	83
Northern Appl.	50	23	15	88	38	126
Warrior Basin	0	0	16	16	0	16
Western Basins	30	4	2	36	10	46
Total	**159**	**56**	**97**	**312**	**225**	**537**

Methods

Methods are consistent with those used in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990–2023* (EPA, 2025).

Recalculations

Methods and activity data are consistent with prior analysis (EPA, 2025), and there were no updates to the underlying data used. Therefore, no recalculations were implemented for 1990–2023 for this source category.

Uncertainty

Uncertainty in emission estimates for abandoned mines is associated with a number of factors. There are uncertainties in the values of parameters that are estimated for each mine to predict its emissions. Because these parameters are not available for each mine, a methodological approach to estimating emissions was used that generates a probability distribution of potential outcomes based on the most likely value and the probable range of values for each parameter. This approach results in uncertainties in the parameters used to estimate emissions.

For this current *GHGIA*, the overall uncertainty associated with national estimates of CH_4 emissions from abandoned underground coal mines are assumed to be similar to prior estimates (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 24 percent above the CH_4 emission in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 3-43. Some differences in reporting methodologies, coverage, and data gaps may introduce additional uncertainty for the 2024 estimate and may affect consistency with prior years.

3.6 Petroleum Systems (Source Category 1B2a)

Methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O), emissions from leaks, venting, and flaring in petroleum systems are included in this category. The category covers petroleum exploration, production, transport, and refining segments. CH_4 emissions from petroleum systems are primarily associated with onshore and offshore crude oil exploration, production, transportation, and refining operations. CO_2 emissions from petroleum systems are primarily associated with onshore and offshore crude oil production and refining operations. CO_2 emissions in petroleum systems exclude all combustion emissions (e.g., engine combustion) except for flaring CO_2 emissions. All combustion CO_2 emissions (except for flaring) are accounted for in the fossil fuel combustion section above. Emissions of N_2O from petroleum systems are primarily associated with flaring.

Table 3-25: CH_4 Emissions from Petroleum Systems (MMT CO_2 Eq.)

Segment	1990	2005	2020	2021	2022	2023	2024
Exploration	3.0	5.3	0.3	0.2	0.1	0.1	0.1
Production	46.1	42.2	49.3	44.0	35.2	37.0	35.4
Transportation	0.2	0.1	0.2	0.2	0.2	0.3	0.2
Refineries	0.7	0.9	0.7	0.7	0.7	0.7	0.7
Total	**50.0**	**48.4**	**50.6**	**45.1**	**36.3**	**38.0**	**36.5**

Table 3-26: CO_2 Emissions from Petroleum Systems (MMT)

Segment	1990	2005	2020	2021	2022	2023	2024
Exploration	0.4	0.5	0.8	0.6	0.3	0.5	0.4
Production	6.0	6.2	25.2	20.5	18.9	19.9	19.1
Transportation	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Refineries	3.2	3.6	2.9	3.0	2.8	2.9	2.9
Total	**9.6**	**10.2**	**28.9**	**24.1**	**22.1**	**23.3**	**22.3**

Table 3-27: N_2O Emissions from Petroleum Systems (MMT CO_2 Eq.)

Segment	1990	2005	2020	2021	2022	2023	2024
Exploration	+	+	+	+	+	+	+
Production	+	+	+	+	+	+	+
Transportation	+	+	+	+	+	+	+
Refineries	+	+	+	+	+	+	+
Total	+	+	+	+	+	+	+

+Less than 0.05 MMT CO_2 Eq.

In 2024, CH_4 emissions were estimated to be 36.5 MMT CO_2 Eq. (see Table 3-25), 4 percent lower than in 2023, and CO_2 emissions were estimated to be 22.3 MMT (see Table 3-26), 4 percent lower than in 2023. N_2O emissions were estimated to be less than 0.05 MMT CO_2 Eq (see Table 3-27), 57 percent higher than in 2023. This results from the approach of averaging 2022 (which had a higher value of N_2O emissions from production in 2022 than 2023) and 2023 and applying it to 2024. See discussion in Methods below.

Methods

The methodological approach for estimating petroleum system emissions is generally consistent with the approach described in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). Emissions are estimated for activities in each segment (exploration, production, transport, and refining), summed for each segment and then summed for the total. Generally, emissions are estimated for each activity by multiplying emission factors (e.g., emission rate per equipment or per activity) by corresponding activity data (e.g., equipment count or frequency of activity). Certain sources within petroleum refineries are developed using an IPCC Tier 3 approach (i.e., all refineries in the nation report facility-level emissions data to the GHGRP, which are included directly in the national emissions estimates here). Other estimates are developed with a Tier 2 approach. Tier 1 approaches are not used.

Calculations for petroleum systems emissions rely heavily on data reported by facilities to the GHGRP. Data for year 2024 were unavailable to support the preparation of this *GHGIA*. It was not possible to develop updated estimates for individual activities (or to recalculate the time series with any corrected data) for this *GHGIA*.

Instead, emissions calculated in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025) were used for 1990–2023 without update, and emissions for 2024 were quantified for each segment by calculating the average emissions rates for CH_4, CO_2, and N_2O using emissions data for 2022 and 2023 for each segment and an activity dataset for which 2022, 2023, and 2024 data were available. The rates for 2022 and 2023 (EPA 2025 emissions divided by activity data for that year) were calculated and then averaged together and applied to the relevant activity data for 2024. Exploration and production segment emissions were

calculated using total oil wells as the activity data.[17] Transport and refining emissions were calculated using refinery input as the activity data.[18]

Recalculations

Methods and activity data are consistent with the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025); therefore, no recalculations were implemented for 1990–2023 for this source category.

Uncertainty

Uncertainty in emission estimates for petroleum systems is associated with a number of factors. The basic activity data that is used to scale up emissions estimates to the national level (e.g., oil well counts, petroleum production, petroleum refinery input) has very low uncertainty. Detailed refinery activity data (e.g., equipment counts) in general has low uncertainty as almost all refineries have reported data to GHGRP. For petroleum exploration and production, there is uncertainty associated with applying activity and emission factors developed from GHGRP to the non-GHGRP population. In all segments, there is uncertainty associated with emission factors.

In addition, using other methods (e.g., calculating emissions based on atmospheric methods), emissions have been estimated to be higher than those presented here.

For this *GHGIA*, the overall uncertainty associated with national estimates of emissions from petroleum systems is assumed to be similar to prior estimates (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). For the CH_4 emission estimate in 2024, this confidence level indicates a range of approximately 13 percent below and 24 percent above. For both the CO_2 and N_2O emission estimates in 2024, this confidence level indicates a range of approximately 18 percent below for and 22 percent above.

However, given the methods to quantify 2024 emissions, additional uncertainty arises from the use of 2022 and 2023 emissions rates to quantify 2024 emissions, which can lead to over- or underestimates as changes in practices and data are not captured. For the exploration and production segments, 2024 GHGRP data would include some optional use of new methods that would improve emissions and activity data. In addition, for these segments, 2024 was the first year for which emissions reductions were expected from EPA's 2023 New Source Performance Standards (NSPS) for the oil and natural gas sector. EPA calculated that the NSPS would reduce emissions across natural gas and petroleum systems by 6.4 MMT CO_2 Eq. in 2024.[19] Further, 2024 was the first year for which certain facilities in these segments would have been subject to a Waste Emissions Charge (delayed in July 2025 by Congress until 2034), which may have led to

[17] https://www.eia.gov/petroleum/wells/xls/WDR2025_Appendix%20C.xlsx. EIA definitions for oil and gas wells differ from definitions used in EPA 2025.

[18] https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=mttro_nus_1&f=a

[19] https://www.epa.gov/system/files/documents/2023-12/eo12866_oil-and-gas-nsps-eg-climate-review-2060-av16-ria-20231130.pdf

emissions reductions in 2024 in preparation for the charge.[20] EPA calculated that in 2024, the Waste Emissions Charge would lead to emissions reductions across natural gas and petroleum systems of 3.1 MMT CO2e.[21] Uncertainty assessments for 1990 and 2024 are summarized at the end of this chapter in Table 3-43.

[20] https://www.congress.gov/bill/119th-congress/house-bill/1/text

[21] https://www.epa.gov/system/files/documents/2024-11/wec-ria-final_11-2024.pdf

3.7 Natural Gas Systems (Source Category 1B2b)

Methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O), emissions from leaks, venting, and flaring in natural gas systems are included in this category. The category covers natural gas exploration, production (including gathering), processing, transmission and storage, distribution, and post-meter activities. CH_4 emissions from natural gas systems are primarily associated with production and transmission and storage. CO_2 emissions from natural gas systems are primarily associated with processing and production. CO_2 emissions in natural gas systems exclude all combustion emissions (e.g., engine combustion) except for flaring CO_2 emissions. All combustion CO_2 emissions (except for flaring) are accounted for in the fossil fuel combustion section above. Emissions of N_2O from natural gas systems are primarily associated with flaring.

Table 3-28: CH_4 Emissions from Natural Gas Systems (MMT CO_2 Eq.)

Segment	1990	2005	2020	2021	2022	2023	2024
Exploration	6.7	19.7	0.2	0.1	0.2	0.1	0.1
Production	65.9	93.7	96.3	92.1	89.7	80.8	86.2
Processing	23.9	13.0	14.0	14.2	14.8	15.2	15.2
Transmission and Storage	64.0	46.1	41.1	39.8	39.6	37.3	38.8
Distribution	50.9	28.5	15.5	15.3	15.2	15.2	15.5
Post-Meter	8.1	9.6	13.0	13.1	13.4	13.8	13.8
Total	**219.6**	**210.7**	**180.1**	**174.6**	**172.8**	**162.4**	**169.8**

Table 3-29: CO_2 Emissions from Natural Gas Systems (MMT)

Segment	1990	2005	2020	2021	2022	2023	2024
Exploration	0.6	2.7	0.1	0.0	0.0	0.0	0.0
Production	3.3	4.6	9.2	9.3	8.6	9.7	9.3
Processing	28.3	18.8	25.5	25.5	26.6	26.8	27.0
Transmission and Storage	0.2	0.2	2.0	0.9	1.1	1.2	1.2
Distribution	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Post-Meter	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	**32.5**	**26.3**	**36.8**	**35.7**	**36.4**	**37.7**	**37.4**

Table 3-30: N_2O Emissions from Natural Gas Systems (MMT CO_2 Eq.)

Segment	1990	2005	2020	2021	2022	2023	2024
Exploration	+	+	+	+	+	+	+
Production	+	+	+	+	+	+	+
Processing	+	+	+	+	+	+	+
Transmission and Storage	+	+	+	+	+	+	+
Distribution	+	+	+	+	+	+	+
Total	**+**	**+**	**+**	**+**	**+**	**+**	**+**

+Less than 0.05 MMT CO_2 Eq.

In 2024, CH_4 emissions were estimated to be 169.8 MMT CO_2 Eq. (see Table 3-28), 5 percent higher than in 2023, and CO_2 emissions were estimated to be 37.4 MMT (see Table 3-29), 1 percent lower than in 2023. N_2O emissions were estimated to be less than 0.05 MMT CO_2 Eq. (see Table 3-30) and 65 percent higher than in 2023. This results from the approach of averaging 2022 (which had a higher value of N_2O emissions from production and processing in 2022 than 2023) and 2023 and applying it to 2024. See discussion in Methods below.

Methods

The methodological approach for estimating natural gas system emissions is generally consistent with the approach described in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). Emissions are estimated for activities in each segment (exploration, production, processing, transmission and storage, distribution and post-meter), summed for each segment, and then summed for the total. Generally, emissions are estimated for each activity by multiplying emission factors (e.g., emission rate per equipment or per activity) by corresponding activity data (e.g., equipment count or frequency of activity). The estimates are developed with an IPCC Tier 2 approach; Tier 1 approaches are not used.

Calculations for natural gas systems emissions rely heavily on data reported by facilities to the GHGRP. Data for year 2024 were unavailable to support the preparation of this *GHGIA*. It was not possible to develop updated estimates for individual activities (or to recalculate the time series with any corrected data) for this *GHGIA*.

Instead, emissions calculated in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025) were used for 1990–2023 without update, and emissions for 2024 were quantified for each segment by calculating the average emissions rates for CH_4, CO_2, and N_2O using emissions data for 2022 and 2023 for each segment and an activity dataset for which 2022, 2023, and 2024 data were available. The rates for 2022 and 2023 (GHGI emissions divided by activity data for that year) were calculated and then averaged together and applied to the relevant activity data for 2024. Exploration segment emissions were calculated using total gas

wells as the activity data.[22] Production, processing, and transmission and storage emissions were calculated using total natural gas production as the activity data.[23] Distribution and post-meter emissions were calculated using total natural gas consumption as the activity data.[24]

Recalculations

Methods and activity data are consistent with the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025); therefore, no recalculations were implemented for 1990–2023 for this source category.

Uncertainty

Uncertainty in emission estimates for natural gas systems is associated with a number of factors. The basic activity data that is used to scale up emissions estimates to the national level (e.g., gas well counts, gas production, gas consumption, pipeline miles) has very low uncertainty. For natural gas exploration through distribution, there is uncertainty associated with applying activity and emission factors developed from GHGRP to the non-GHGRP population. In all segments, there is uncertainty associated with emission factors.

In addition, using other methods (e.g., calculating emissions based on atmospheric methods), emissions have been estimated to be higher than those presented here.

For this *GHGIA*, the overall uncertainty associated with national estimates of emissions from natural gas systems is assumed to be similar to prior estimates (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). For the CH_4 emission estimate in 2024, this confidence level indicates a range of approximately 10 percent below and 11 percent above. For both the CO_2 and N_2O emission estimates in 2024, this confidence level indicates a range of approximately 14 percent below and 17 percent above.

However, given the methods to quantify 2024 emissions, additional uncertainty arises from the use of 2022 and 2023 emissions rates to quantify 2024 emissions, which can lead to over or underestimates as changes in practices and data are not captured. For the exploration through distribution segments, 2024 GHGRP data would include some optional use of methods that would improve emissions and activity data. In addition, 2024 was the first year for which emissions reductions were expected from EPA's 2023 New Source Performance Standards (NSPS) for the oil and natural gas sector (impacting exploration through transmission and storage). EPA calculated that the NSPS would reduce emissions across natural gas and petroleum systems by 6.4 MMT CO_2 Eq. in 2024.[25] In addition, 2024 was the first year for which certain facilities in segments other than distribution and post-meter would have been subject to a Waste Emissions

[22] https://www.eia.gov/petroleum/wells/xls/WDR2025_Appendix%20C.xlsx

[23] https://www.eia.gov/petroleum/wells/xls/WDR2025_Appendix%20C.xlsx

[24] https://www.eia.gov/dnav/ng/hist/n9140us2a.htm

[25] https://www.epa.gov/system/files/documents/2023-12/eo12866_oil-and-gas-nsps-eg-climate-review-2060-av16-ria-20231130.pdf

Charge (delayed in July 2025 by Congress until 2034), which may have led to emissions reductions in 2024 in preparation for the charge, [26] EPA calculated that in 2024, the Waste Emissions Charge would lead to emissions reductions across natural gas and petroleum systems of 3.1 MMT CO2e.[27] Uncertainty assessments for 1990 and 2024 are summarized at the end of this chapter in Table 3-43.

[26] https://www.congress.gov/bill/119th-congress/house-bill/1/text

[27] https://www.epa.gov/system/files/documents/2024-11/wec-ria-final_11-2024.pdf

3.8 Abandoned Oil and Gas Wells (Source Categories 1B2a and 1B2b)

Methane (CH_4) and carbon dioxide (CO_2) emissions from wells with no recent production are included in this category. This includes wells with no owner (orphaned wells) and wells with owners with no recent production. It includes the emissions from wells that have not been plugged and wells that have been plugged, which have significantly lower emissions.

Although some wells that have been taken out of service are later brought back online, the total population of abandoned wells increases over time. Due to various efforts at national, state, and local levels the fraction of abandoned wells that is plugged increases over time.

Based on estimates developed for 2023 in *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025), the U.S. population of abandoned oil and gas wells is around 3.9 million (with around 3.0 million abandoned oil wells and 0.9 million abandoned gas wells), and around 43 percent of the abandoned well population in the United States is plugged.

Table 3-31: CH_4 Emissions from Abandoned Oil and Gas Wells (MMT CO_2 Eq.)

Activity	1990	2005	2020	2021	2022	2023	2024
Abandoned oil wells	6.4	6.6	6.6	6.6	6.6	6.6	6.5
Abandoned gas wells	1.4	1.6	1.9	1.9	1.9	1.9	1.9
Total	**7.8**	**8.2**	**8.5**	**8.6**	**8.5**	**8.5**	**8.4**

Table 3-32: CO_2 Emissions from Abandoned Oil and Gas Wells (MMT)

Activity	1990	2005	2020	2021	2022	2023	2024
Abandoned oil wells	+	+	+	+	+	+	+
Abandoned gas wells	+	+	+	+	+	+	+
Total	**+**	**+**	**+**	**+**	**+**	**+**	**+**

+ Less than 0.05

In 2024, CH_4 emissions were estimated to be 8.4 MMT CO_2 Eq. (see Table 3-31), 2 percent lower than in 2023, and CO_2 emissions were estimated to be less than 0.05 MMT (see Table 3-32) and 1 percent lower than in 2023.

Methods

The methodological approach for estimating abandoned oil and gas well emissions is generally consistent with the approach described in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023*. Emissions are estimated based on abandoned oil and gas well populations in Appalachia and outside of Appalachia. Within these populations, the percentage of wells plugged versus unplugged is determined and an emission factor for each group (region and plugging status) is applied.

It was not possible to develop updated estimates for abandoned oil and gas well populations or well plugging for 2024 (or to recalculate the time series with any corrected data) for this *GHGIA*. Instead, estimates from the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025) were used for 1990–2023 emissions. For 2024, emissions were quantified by calculating for abandoned oil wells and abandoned gas wells the average emissions rates for CH_4 and CO_2 using emissions calculated for 2022 and 2023 and total well oil well and total gas well populations using EIA data.[28] The rates for those 2 years were then averaged together and applied to the total populations for oil wells and of gas wells for year 2024.

Recalculations

Methods and activity data are consistent with the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025); therefore, no recalculations were implemented for 1990–2023 for this source category.

Uncertainty

Uncertainty in CH_4 and CO_2 emission estimates for abandoned wells is associated with activity data estimates of total abandoned wells, the population of abandoned wells that is plugged, and the emission factors applied.

For this *GHGIA*, the overall uncertainty associated with national estimates of emissions from abandoned oil and gas wells is assumed to be similar to prior estimates (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). For the CH_4 and CO_2 emission estimates in 2024, this confidence level indicates a range of approximately 83 percent below for all well types and 223 percent above for oil wells and 255 percent above for gas wells.

However, given the methods to quantify 2024 emissions, additional uncertainty arises from lack of updated estimates for total abandoned wells and well plugging in 2024. Generally, the population of total abandoned wells rises over time as does the percentage of wells that are plugged. It is likely that the percentage of wells plugged has increased faster in 2024 compared with previous years due to impacts of well plugging programs under the 2021 Infrastructure

[28] https://www.eia.gov/petroleum/wells/xls/WDR2025_Appendix%20C.xlsx. Note that EIA definitions for oil and gas wells differ from definitions used in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025).

Investment and Jobs Act (under which over 10,000 wells have been plugged as of June 2025).[29] Future *GHGIA* years will likely show further increases in plugging due to the Methane Emissions Reduction Program of the 2022 Inflation Reduction Act.[30] Uncertainty assessments for 1990 and 2024 are summarized at the end of this chapter in Table 3-43.

[29] https://www.doi.gov/sites/default/files/documents/2025-11/fy-2025-orphaned-wells-congressional-report.pdf

[30] https://www.epa.gov/inflation-reduction-act/financial-assistance-methane-emissions-reduction-program

3.9 CO_2 Transport, Injection, and Geological Storage (Source Category 1C)

Carbon dioxide (CO_2) capture and geological storage includes the capture and compression of CO_2, its transport to a storage location, and its long-term isolation from the atmosphere. Geological storage can take place in natural underground reservoirs such as oil and gas fields, coal seams, and saline water-bearing formations utilizing natural geological barriers to isolate the CO_2 from the atmosphere. Geological CO_2 storage may take place either at sites where the sole purpose is CO_2 storage, or in tandem with enhanced oil recovery, enhanced gas recovery or enhanced coalbed methane (CH_4) recovery operations (IPCC, 2005).

As per the IPCC Guidelines (IPCC, 2006), emissions and reductions from CO_2 capture and sequestration are reported under the sector in which the capture takes place. Any fugitive emissions from the systems used to transport captured CO_2, from activities and equipment at the injection site and those from the end containment of CO_2 storage are represented as part of CO_2 transport, injection, and geological storage (TIGS) reporting. Emissions from TIGS are shown in Table 3-33.

Table 3-33: Emission from TIGS (kt CO_2)

Category	1990	2005	2020	2021	2022	2023	2024
Transport	NO	NO	2	2	2	2	2
Injection	NO	NO	13	37	28	31	31
Geological Storage	NO	NO	23	26	23	64	64
Total	**NO**	**NO**	**39**	**65**	**53**	**98**	**98**

NO (Not Occurring)

Note: Totals may not sum due to independent rounding.

The amount of CO_2 sequestered is allocated back to the different possible capture source categories as shown in Table 3-34. The allocation is based on information from the EPA Greenhouse Gas Reporting Program (GHGRP), 40 CFR Part 98, Subpart PP, also referred to as "Subpart PP" (EPA, 2024).

Table 3-34: Allocation of Sequestered CO_2 for Sector Adjustment (kt CO_2)

Sector	1990	2005	2020	2021	2022	2023	2024
Adjustments Made							
Power Plants	NO	NO	-	-	-	360	360
Industrial Gas Plants	NO	NO	-	-	-	-	-
Chemical Plants	NO	NO	-	-	-	-	-
Synthetic Gas Production	NO	NO	-	-	-	-	-
Ammonia Plants	NO	NO	660	714	652	665	665
Ethanol Plants	NO	NO	522	444	603	903	903
Breweries	NO	NO	-	-	-	-	-
Distilleries	NO	NO	-	-	-	-	-
Paper Mills	NO	NO	-	-	-	-	-
Total Adjustments	**NO**	**NO**	**1,182**	**1,158**	**1,255**	**1,928**	**1,928**
Adjustments Not Made							
CO_2 Domes	NO	NO	4,156	3,960	4,624	10,420	10,420
Petroleum Refineries	NO	NO	-	-	-	-	-
Natural Gas Processing	NO	NO	1,465	1,835	2,174	3,951	3,951
Total (No Adjustments)	**NO**	**NO**	**5,621**	**5,794**	**6,798**	**14,370**	**14,370**

NO (Not Occurring)

Note: Totals may not sum due to independent rounding.

There is no adjustment needed for the CO_2 sequestered sourced from natural domes since it is considered a transfer from one sink to another. For the CO_2 from natural gas processing and petroleum refining, the captured and sequestered CO_2 emissions are already netted out in those emission source calculations.

Methods

Methods are consistent with those described in the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025).

All CO_2 transport is assumed to be through pipelines. To calculate emissions, a default factor was applied to pipeline miles, which are sourced from the Pipeline and Hazardous Materials Safety Administration (PHMSA, 2026). In 2024, 5,345 miles of CO_2 pipeline were in operation in the United States (see Table 3-35).

Table 3-35: Pipeline Mileage (Miles)

Measure	1990	2005	2020	2021	2022	2023	2024
Miles	NO	NO	5,150	5,339	5,354	5,331	5,345

NO (Not Occurring)

Fugitive emissions from injection and storage and total amount of CO_2 sequestered are based on information from the GHGRP. Those values were assumed to be equal to 2023 levels because 2024 GHGRP data were not available at the time of analysis.

Recalculations

Methods and activity data are consistent with the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025), and there were no changes to underlying data sources. Therefore, no recalculations were implemented for 1990–2023 for this source category.

Uncertainty

The uncertainties in pipeline emissions arise from the data used on length of pipelines and from accuracy of the default emissions factor used to determine pipeline fugitive emissions. There are also uncertainties associated with equipment leakage and surface leakage, mostly due to the accuracy of the reported data.

For this *GHGIA*, the overall uncertainty associated with national estimates of CO_2 emissions from TIGS are assumed to be similar to prior estimates (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 51 percent below and 51 percent above the CO_2 emission level in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 3-43. Some differences in reporting methodologies, coverage, and data gaps may introduce additional uncertainty for the 2024 estimate and may affect consistency with prior years.

3.10 International Bunker Fuels (Source Category 1: Memo Items)

According to IPCC methodological guidance, countries should report emissions from ships or aircraft that depart from their ports with fuel purchased within national boundaries and are engaged in international transport separately from national totals. Therefore, emissions resulting from the combustion of fuels used for international transport activities, termed international bunker fuels, are not included in national emission totals, but are reported separately based upon location of fuel sales (IPCC, 2006). Emissions from road vehicles and trains, even when crossing international borders, are allocated to the country where the fuel was purchased or loaded into the vehicle and are not considered bunker fuel emissions.

Two main modes of transport are addressed as part of international bunker fuel estimates: aviation and marine. Within each, fuel use and emissions can occur from civil (commercial and general) and military operations. The calculation of greenhouse gas (GHG) emissions from the combustion of international bunker fuels is the same as for other fossil fuels and includes CO_2, based on fuel carbon content, and non-CO_2 emissions (CH_4 and N_2O) based on combustion technologies.[31]

In 2024, emissions from the combustion of international bunker fuels from both aviation and marine activities were 98.6 MMT CO_2 Eq. (see Table 3-36). Aviation-related emissions decreased by 0.4 percent from 2023 but have increased by 73.5 percent from 1990. Marine emissions increased by 6.2 percent from 2023 but have decreased by 51.9 percent from 1990. The majority of emissions were in the form of CO_2.

[31] Data suggest that little or no CH_4 is emitted by modern aircraft engines so those emissions are reported as not occurring.

Table 3-36: CO_2, CH_4, and N_2O Emissions from International Bunker Fuels (MMT CO_2 Eq.)

Gas/Mode	1990	2005	2020	2021	2022	2023	2024
CO_2	**103.6**	**113.3**	**69.6**	**80.2**	**98.2**	**96.2**	**97.8**
Aviation	38.2	60.2	39.8	50.8	66.6	66.5	66.3
Commercial	*30.0*	*55.6*	*36.7*	*47.6*	*63.5*	*63.5*	*63.5*
Military	*8.2*	*4.6*	*3.1*	*3.2*	*3.1*	*3.0*	*2.8*
Marine	*65.4*	*53.1*	*29.9*	*29.4*	*31.6*	*29.6*	31.5
CH_4	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Aviation	NO	NO	NO	NO	NO	NO	0.0
Marine	0.2	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	**0.8**	**0.9**	**0.5**	**0.6**	**0.8**	**0.8**	**0.8**
Aviation	0.3	0.5	0.3	0.4	0.6	0.6	0.6
Marine	0.4	0.4	0.2	0.2	0.2	0.2	0.2
Total	**104.6**	**114.3**	**70.3**	**80.9**	**99.1**	**97.0**	**98.6**

NO (Not Occurring)

Notes: Totals may not sum due to independent rounding. Includes aircraft cruise altitude emissions.

Jet fuel consumption estimates used in the analysis are presented in Table 3-37.

Table 3-37: Aviation Jet Fuel Consumption for International Transport (TBtu)

Source	1990	2005	2020	2021	2022	2023	2024
U.S. and Foreign Carriers	426	791	521	677	902	902	902
U.S. Military	116	64	43	44	44	42	39
Total	**542**	**854**	**564**	**721**	**946**	**944**	**941**

Note: Totals may not sum due to independent rounding.

Marine fuel consumption estimates are presented in Table 3-38.

Table 3-38: Marine Fuel Consumption for International Transport (Million Gallons)

Fuel Type	1990	2005	2020	2021	2022	2023	2024
Residual Fuel Oil	4,781	3,881	1,964	1,953	2,172	2,016	2,182
Distillate Diesel Fuel & Other	617	444	461	437	435	423	410
U.S. Military Naval Fuels	522	471	296	285	263	255	265
Total	**5,920**	**4,796**	**2,721**	**2,674**	**2,870**	**2,694**	**2,857**

Note: Totals may not sum due to independent rounding.

Methods

Methods are consistent with those described in the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025).

Data on civilian marine bunkers has historically been available from the Foreign Trade Division of the U.S. Department of Commerce's Bureau of the Census. Because the same data was not available at the time of analysis, total civilian marine bunkers for 2024 were extrapolated based on recent year's ratio of bunkers to total marine diesel and residual fuel use.

Data on military use of domestic fuel and percent bunkers for aviation and marine use historically comes from Department of Defense's Defense Logistics Agency Energy. Because the same data was not available at the time of analysis, total military domestic fuel use in 2024 was estimated based on data from the Federal Energy Management Program (FEMP) (DOE, 2022). The FEMP data is available on total worldwide military transportation fuel use. It was assumed that domestic use changed at the same rate as international fuel use from 2023 to 2024 and that the percentage used in bunkers was the same as 2023.

Data on civilian aviation total and bunker fuel use has historically been available from the Federal Aviation Administration (FAA). The same data has not been available since 2022. Therefore, total civilian aviation bunkers for 2023 and 2024 were proxied to the 2022 value.

Recalculations

Methods and activity data are consistent with the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025) and no updates were available; therefore, no recalculations were implemented for 1990–2023 for this source category.

Uncertainty

Emission estimates related to the combustion of international bunker fuels are subject to the same uncertainties as those from domestic aviation and marine mobile combustion emissions. However, some additional uncertainties could result from the difficulty in accurately estimating the share of total fuel consumption activity data used for international transport activities (separate from domestic transport activities). This challenge occurs with both civilian and military fuel use.

There are also uncertainties in fuel end-uses by fuel type, emissions factors, fuel densities, diesel fuel sulfur content, aircraft and vessel engine characteristics, and fuel efficiencies, which could all impact emission estimates.

For this *GHGIA*, no uncertainties have been recalculated for international bunker fuels.

3.11 Biomass and Biofuel Consumption (Source Category 1A)

Combustion of biomass and biofuels generates CO_2 and non-CO_2 emissions (CH_4 and N_2O). In accordance with IPCC inventory guidelines, CO_2 emissions from biomass and biofuel combustion are estimated separately from fossil fuel CO_2 emissions and are excluded from energy sector totals to avoid double counting. 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).

Accordingly, CO_2 emissions from biomass and biofuel combustion are provided here for informational transparency regarding biomass and biofuel use. Non-CO_2 emissions (CH_4 and N_2O) from biomass and biofuel combustion are included in energy sector totals and are reported in Section 3.1 as part of stationary and mobile combustion source categories.

In 2024, total CO_2 emissions from the combustion of biomass and biofuels in all end-use sectors were approximately 298.7 MMT CO_2 Eq. (see Table 3-39).

Table 3-39: CO_2 Emissions from Biomass and Biofuel Consumption (MMT CO_2 Eq.)

Sector/Fuel Type	1990	2005	2020	2021	2022	2023	2024
Transportation	**4.1**	**22.5**	**85.8**	**91.5**	**90.6**	**95.7**	**92.9**
Ethanol	4.1	21.6	68.1	75.4	75.0	77.5	74.7
Biodiesel	0.0	0.9	17.7	16.1	15.6	18.2	18.2
Industrial	**135.5**	**137.4**	**128.9**	**129.7**	**134.6**	**127.2**	**127.3**
Ethanol	0.1	1.2	1.6	1.5	1.8	1.3	2.6
Wood	135.3	136.3	127.3	128.2	132.8	125.9	124.7
Commercial	**6.8**	**7.4**	**9.7**	**9.6**	**10.4**	**9.3**	**11.0**
Ethanol	0.1	0.2	2.2	2.1	2.8	1.9	3.6
Wood	6.8	7.2	7.5	7.5	7.5	7.4	7.4
Residential	**59.8**	**44.3**	**35.6**	**36.8**	**46.4**	**39.4**	**36.9**
Wood	59.8	44.3	35.6	36.8	46.4	39.4	36.9
Electric Power	**31.8**	**33.8**	**34.7**	**35.6**	**35.2**	**31.9**	**30.6**
Wood	13.3	19.1	19.1	20.3	20.4	17.9	16.7
MSW	18.5	14.7	15.6	15.3	14.9	13.9	13.9
Total	**237.9**	**245.4**	**294.7**	**303.3**	**317.2**	**303.5**	**298.7**

The CO_2 emission estimates for biomass and biofuels were calculated in a similar way to fossil fuel combustion estimates and are dependent on the amount of fuel combusted and its carbon content. For the biogenic component of MSW, CO_2 emissions were estimated based on the tons of waste combusted and a calculated carbon factor, see Section 3.3 Incineration of Waste for more details. Emissions for the other biomass and biofuel sources were based on the energy content of the fuels combusted.

Table 3-40 provides wood consumption in energy units for the industrial, residential, commercial, and electric power sectors. Table 3-41 provides ethanol consumption estimates for the industrial, commercial, and transportation sectors and Table 3-42 provides biodiesel consumption in energy units for the transportation sector.

Table 3-40: Woody Biomass Consumption by Sector (Trillion Btu)

End-Use Sector	1990	2005	2020	2021	2022	2023	2024
Industrial	1,441.9	1,451.7	1,356.2	1,365.9	1,415.0	1,341.1	1,328.2
Residential	580.0	430.0	345.1	356.8	449.5	382.1	358.2
Commercial	65.7	70.0	72.9	72.6	73.0	71.8	71.7
Electric Power	128.5	185.0	185.4	196.7	197.7	174.1	161.7
Total	**2,216.2**	**2,136.7**	**1,959.5**	**1,992.0**	**2,135.2**	**1,969.0**	**1,919.9**

Note: Totals may not sum due to independent rounding.

Table 3-41: Ethanol Consumption by Sector (Trillion Btu)

End-Use Sector	1990	2005	2020	2021	2022	2023	2024
Transportation	59.3	315.8	994.6	1,101.7	1,094.9	1,132.2	1,091.0
Industrial	1.5	17.2	23.1	22.0	26.2	19.5	37.7
Commercial	0.9	2.2	31.9	31.2	41.6	27.3	52.8
Total	**61.7**	**335.1**	**1,049.5**	**1,155.0**	**1,162.7**	**1,179.0**	**1,181.5**

Note: Totals may not sum due to independent rounding.

Table 3-42: Biodiesel Consumption by Sector (Trillion Btu)

End-Use Sector	1990	2005	2020	2021	2022	2023	2024
Transportation	NO	11.6	239.4	218.2	211.6	246.3	246.4

NO (Not Occurring)

Methods

Methods are consistent with those described in the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025).

Recalculations

There were updates to some of the data sources used, therefore recalculations were implemented for 1990–2023 for this source category. Updates included the historical data on wood combustion from EIA. The updated data resulted in an annual average change in wood CO_2 emissions of 1.1 percent over the 2016 to 2023 time period. The sector allocation of ethanol use in 2023 was also updated to reflect the updated fuel used data from FHWA for 2023.

Uncertainty

There are uncertainties in biofuel consumption data that impact the results of the biomass and biofuel emission estimates. There is also uncertainty in the composition of the fuels and the carbon content of fuels combusted.

For this *GHGIA*, the overall uncertainty associated with national estimates of CO_2 emissions from biomass and biofuel combustion are assumed to be similar to prior estimates (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 9 percent below and 12 percent above the CO_2 emissions in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 3-43. Some differences in reporting methodologies, coverage, and data gaps may introduce additional uncertainty for the 2024 estimate and may affect consistency with prior years.

3.12 Energy Uncertainty Summary

Table 3-43 shows the uncertainty summary for each energy sector source. A discussion of the uncertainty ranges is included in each source category's respective chapter section.

Table 3-43: Quantitative Uncertainty Summary by Energy 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
Fossil Fuel Combustion CO_2						
Coal	CO_2	710.5	689.2	774.4	-3%	9%
Residential	CO_2	NO	NO	NO	NO	NO
Commercial	CO_2	1.1	1.0	1.2	-5%	15%
Industrial	CO_2	34.9	33.2	40.5	-5%	16%
Transportation	CO_2	NO	NO	NO	NO	NO
Electric Power	CO_2	672.0	645.1	739.2	-4%	10%
U.S. Territories	CO_2	2.5	2.2	3.0	-12%	19%
Natural Gas	CO_2	**1,765.1**	1,747.5	1,853.4	-1%	5%
Residential	CO_2	240.5	233.3	257.3	-3%	7%
Commercial	CO_2	181.8	176.3	194.5	-3%	7%
Industrial	CO_2	529.8	513.9	566.9	-3%	7%
Transportation	CO_2	73.7	71.5	78.9	-3%	7%
Electric Power	CO_2	734.8	712.8	771.6	-3%	5%
U.S. Territories	CO_2	4.5	3.9	5.2	-12%	17%
Petroleum	CO_2	**2,092.1**	1,966.6	2,217.6	-6%	6%
Residential	CO_2	50.1	47.1	52.6	-6%	5%
Commercial	CO_2	67.6	64.2	71.0	-5%	5%
Industrial	CO_2	225.0	173.2	276.7	-23%	23%
Transportation	CO_2	1,714.8	1,611.9	1,817.7	-6%	6%

(continued)

Table 3-43 Quantitative Uncertainty Summary by Energy Sector Source *(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
Electric Power	CO_2	13.7	13.1	14.6	-4%	7%
U.S. Territories	CO_2	20.9	19.4	23.0	-7%	10%
Geothermal	CO_2	0.3	0.2	1.0	-46%	187%
Electric Power	CO_2	0.3	0.2	1.0	-46%	187%
Total	CO_2	4,568.1	4,476.7	4,750.8	-2%	4%
Fossil Fuel Combustion Non-CO_2						
Stationary Combustion	CH_4	8.1	5.4	18.3	-34%	125%
Stationary Combustion	N_2O	19.0	14.6	28.7	-23%	51%
Mobile Sources	CH_4	2.7	2.6	3.5	-4%	30%
Mobile Sources	N_2O	17.0	15.8	20.7	-7%	22%
Non-Energy Use of Fuels						
Feedstocks	CO_2	78.2	45.3	138.4	-42%	77%
Asphalt	CO_2	0.3	0.1	0.6	-58%	116%
Lubricants	CO_2	11.8	9.8	13.7	-17%	16%
Waxes	CO_2	0.3	0.3	0.7	-26%	103%
Other	CO_2	5.4	1.0	6.3	-81%	17%
Total	CO_2	96.0	61.4	155.5	-36%	62%
Waste Incineration						
Incineration of Waste	CO_2	11.9	9.9	14.3	-17%	20%
Incineration of Waste	CH_4	+	+	+	-102%	103%
Incineration of Waste	N_2O	0.3	0.1	0.8	-53%	161%
Coal Mining						
Coal Mining	CO_2	44.3	39.8	53.6	-10%	21%
Coal Mining	CH_4	2.3	0.7	4.0	-68%	76%

(continued)

Table 3-43 Quantitative Uncertainty Summary by Energy Sector Source *(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
Abandoned Underground Coal Mines						
Abandoned Underground Coal Mines	CH_4	6.4	5.2	8.0	-20%	24%
Petroleum Systems						
Petroleum Systems	CH_4	36.5	31.7	45.2	-13%	24%
Petroleum Systems	CO_2	22.3	18.3	27.3	-18%	22%
Petroleum Systems	N_2O	+	+	+	-18%	22%
Natural Gas Systems						
Natural Gas Systems	CH_4	169.8	152.8	188.5	-10%	11%
Natural Gas Systems	CO_2	37.4	32.2	43.8	-14%	17%
Natural Gas Systems	N_2O	+	+	+	-14%	17%
Abandoned Oil and Gas Wells						
Abandoned Oil Wells	CH_4	6.5	1.1	20.9	-83%	223%
Abandoned Gas Wells	CH_4	1.9	0.3	6.7	-83%	255%
Abandoned Oil Wells	CO_2	+	+	+	-83%	223%
Abandoned Gas Wells	CO_2	+	+	+	-83%	255%
CO_2 Transport, Injection, and Geological Storage						
Total Emissions from TIGS	CO_2	0.1	+	0.1	-51%	51%
International Bunker Fuels						
N/A	–	–	–	–	–	–
Biomass and Biofuel Combustion						
Biomass and Biofuel Combustion	CO_2	298.7	271.8	334.5	-9%	12%

+ Does not exceed 0.05 MMT CO_2 Eq.

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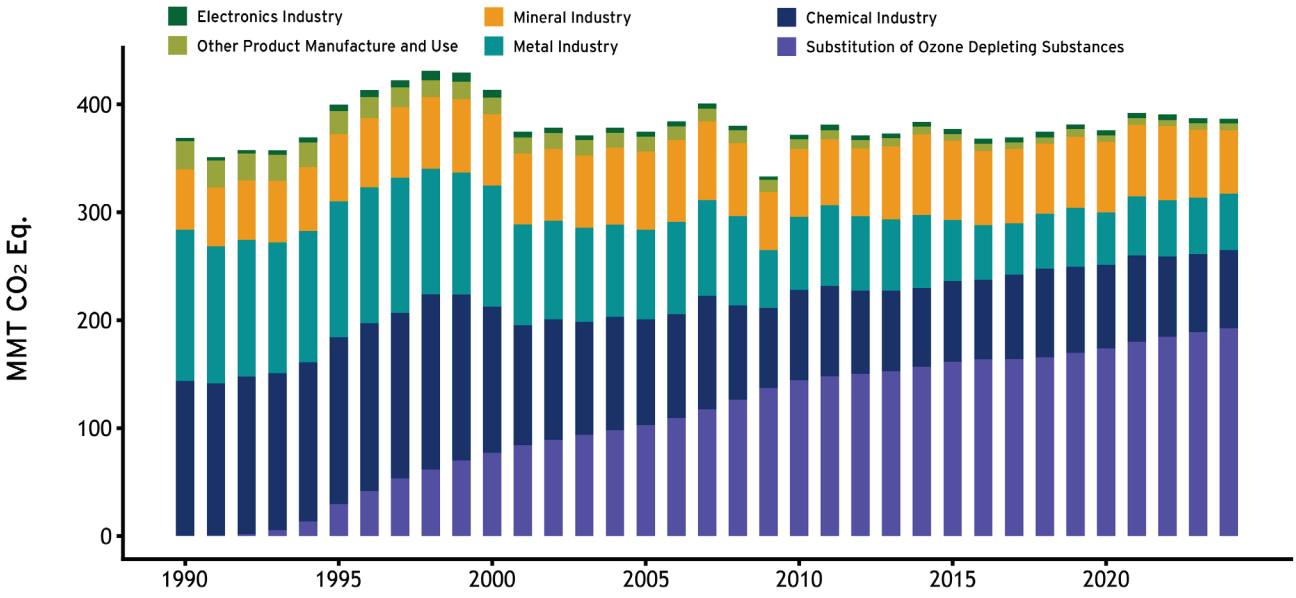
Industrial Processes and Product Use (IPPU) Emissions

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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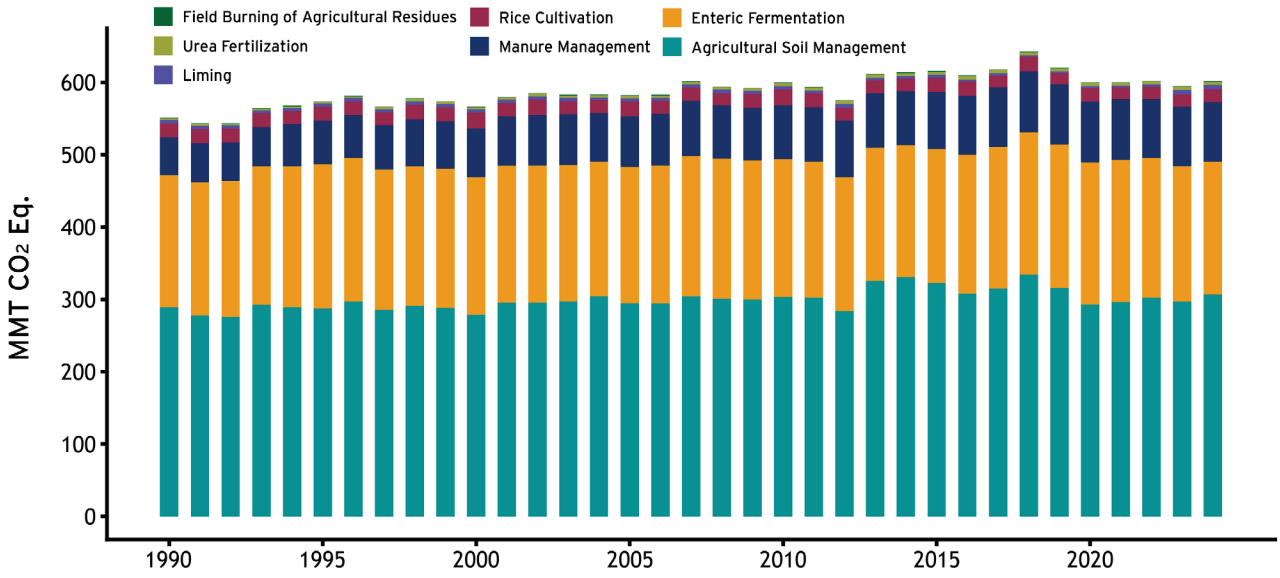
Agriculture

Chapter 5. Agriculture

Agricultural management activities including livestock production, crop cultivation, and agricultural land management produce greenhouse gas (GHG) emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).[34]

In 2024, emissions from this sector were 602.1 million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.), accounting for approximately 9.7 percent of total gross U.S. GHG emissions (see Table 5-1). Emissions in 2024 represent an increase of 9.3 percent since 1990 when the sector made up 8.4 percent of total gross emissions (see Figure 5-1).

Figure 5-1: Trends in Agriculture Sector Greenhouse Gas Emission Sources



Enteric fermentation represents not only the largest source of CH_4 in the agriculture sector, making up 68.7 percent of agricultural CH_4, but also the largest source of CH_4 in the *Greenhouse Gas Inventory and Analysis for the United States (GHGIA)* accounting for 26.8 percent of total U.S. CH_4 emissions. Recent enteric fermentation trends have largely followed trends in livestock populations. In 2024, enteric fermentation decreased by 1.7 percent relative to 2023, driven primarily by a decrease in beef and dairy cattle populations. Manure management represented 13.6 percent of total agriculture emissions. Together, enteric fermentation and manure management make up the "livestock management" sector, which makes up 44.1 percent of total agriculture emissions and 36.2 percent of total national CH_4 emissions.

[34] Consistent with Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC, 2006), additional CO_2, CH_4, and N_2O fluxes from land use and land-use conversion activities, such as cultivation of cropland, management on grasslands, grassland fires, aquaculture, and conversion of forest land to cropland, are presented in Chapter 6, *Land Use, Land-Use Change, and Forestry*. CO_2 emissions from stationary and mobile on-farm energy use and CH_4 and N_2O emissions from stationary on-farm energy use are reported in Chapter 3, *Energy*. CH_4 and N_2O emissions from mobile on-farm energy use are reported in Chapter 3 under mobile fossil fuel combustion emissions (EPA, 2025).

Agricultural soil management is the largest overall source of emissions in the agriculture sector, accounting for 50.9 percent of total sector emissions, and the largest N_2O source in the *GHGIA* (77.1 percent of total U.S. N_2O emissions) primarily from fertilizer application and increased nitrogen in soils.

Rice cultivation represents a smaller agriculture source category at 3 percent of total sectoral emissions, in part due to the limited geographic extent of rice cultivation in the United States. Rice cultivation emissions in 2024 are approximately equal to those in 1990.

Table 5-1: Emissions from Agriculture (MMT CO_2 Eq.)

Gas/Source	1990	2005	2020	2021	2022	2023	2024
CO_2	**7.0**	**7.9**	**7.6**	**6.9**	**8.1**	**10.1**	**10.6**
Liming	4.7	4.4	2.9	2.4	3.2	5.4	5.6
Urea Fertilization	2.3	3.6	4.7	4.5	4.8	4.7	5.1
CH_4	**241.4**	**264.4**	**282.5**	**279.9**	**274.8**	**270.5**	**267.8**
Enteric Fermentation	182.8	188.2	196.3	196.5	192.6	187.2	184.1
Manure Management	39.1	55.0	66.9	66.4	64.7	65.1	65.0
Rice Cultivation	18.9	20.6	18.6	16.3	16.8	17.5	18.1
Field Burning of Agricultural Residues	0.5	0.6	0.6	0.6	0.6	0.6	0.6
N_2O	**302.7**	**310.2**	**310.1**	**313.8**	**319.7**	**314.3**	**323.7**
Agricultural Soil Management	289.1	294.7	293.0	296.5	302.5	297.3	306.7
Manure Management	13.4	15.2	16.9	17.1	17.0	16.8	16.8
Field Burning of Agricultural Residues	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Total	**551.0**	**582.5**	**600.2**	**600.6**	**602.5**	**594.9**	**602.1**

Note: Totals may not sum due to independent rounding.

Unless otherwise noted, all estimates in this chapter are provided in MMT CO_2 Eq. Consistent with GHG inventories from other countries, this *GHGIA* 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 *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 4 (Agriculture, Forestry and Other Land Use [AFOLU]) 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 and management practices where available. Unless otherwise noted, methods are consistent with those used in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023 (Environmental Protection Agency [EPA], 2025)*, as noted in Table 5-2. Consistent with IPCC good practices, the inventory applies higher tier methods and approaches for more significant sources (e.g., Tier 2 and Tier 3 methods, which include use of country-specific methods and models, emission factors and other site-specific information) and as data allow for smaller sources.

To fill gaps in activity data typically occurring in the most recent years of the time series, several types of statistical techniques are used to extrapolate emission estimates (see Volume 1, Chapter 5 of IPCC, 2006). See Box 5-1 for more details on the specific extrapolation techniques used to forecast emissions estimates in the agriculture and land use, land-use change, and forestry sectors, as well as discussions within category Methods sections.

Table 5-2: Summary of Methods in the Agriculture Chapter

Category (CRT Code[a])	Gases	IPCC Methodological Tier	Methodological Refinements Compared to 1990–2023 Inventory (EPA, 2025)
Enteric Fermentation (3A)	CH_4	Tier 1 (other livestock), Tier 2 (cattle)	No change
Manure Management (3B)	CH_4, N_2O	Tier 1 (other livestock), Tier 2 (cattle)	No change
Rice Cultivation (3C)	CH_4	Tier 1, Tier 3	No change
Agricultural Soil Management (3D)	N_2O	Tier 1, Tier 3	No change
Liming (3G)	CO_2	Tier 2	No change
Urea Fertilization (3H)	CO_2	Tier 1	Updated primary activity data source
Field Burning of Agricultural Residues (FBAR) (3F)	CH_4, N_2O	Tier 2	No change

[a] Codes in parentheses represent common reporting table (CRT) codes. CRT codes are 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). Translating 3A: 3 = agriculture sector, A = enteric fermentation.

Box 5-1: AFOLU Extrapolation Techniques

To fill gaps in activity data typically occurring in the most recent years of the time series, several types of statistical techniques are used to extrapolate emission estimates (see Volume 1, Chapter 5 of IPCC, 2006). When possible, surrogate data that capture historical trends in activity data or emissions can be used to fill time series gaps. A correlation between the surrogate or proxy data and historical activity data or emissions estimates is built, and then the surrogate data is used to predict emissions during the time series gap using this statistical relationship. For example, to extrapolate agricultural soil management N_2O emissions for the latter part of the time series when management information from the U.S. Department of Agriculture (USDA) National Resource Inventory (NRI) is not available, a linear model correlating historical N_2O emissions prior to 2021 with total national nitrogen fertilizer consumption, annual precipitation data, and planted acreage of corn and soybeans is used to predict N_2O emissions using these surrogate data.

When suitable surrogate data are not available, an autoregressive moving average technique (ARMA) can be applied to forecast emission estimates for years in which key data are unavailable. Forecasted estimates are based on oscillations around a historical mean across the time series of existing emission estimates. Where a trend can be identified, an autoregressive integrated moving average (ARIMA) approach is applied to predict emissions based on recent trends in addition to underlying movement around the mean. In some cases, both a linear regression using surrogate data and ARMA errors are used in combination to more accurately fill time series gaps by explicitly incorporating known emission trend drivers via inclusion of the surrogate data (EPA, 2025). In other cases, statistical tests indicate that a simple linear trend extrapolation is the best fit model to explain historical variation in emissions, and recent emission trends alone were used to complete the time series (Brockwell & Davis, 2016).

Quality Assurance/Quality Control

For all categories, the IPCC general and category-specific quality assurance/quality control (QA/QC) procedures were implemented. These procedures involved checks specifically focused on the activity data and methodology used for estimating each source of emissions from the agriculture sector. Emission trends were investigated to determine whether any corrective actions were needed. Minor corrective actions were taken as necessary.

Uncertainty

The same uncertainty bounds from the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025) were applied for each category and subcategory (as applicable); see Table 5-16. A qualitative description of the uncertainties, along with the total category uncertainty estimate, is provided within each category. Future iterations and versions of this *GHGIA* will review and update the quantified uncertainty associated with activity data, emission factors, and other input parameters.

Future Areas for Improvement

Continuous improvement efforts are important for reflecting the latest science and reducing uncertainties in estimating emissions from agricultural management activities, especially for significant categories such as CH_4 emissions from livestock and N_2O emissions from agricultural soil management, to the extent practicable. For categories where the methodology has not changed in this *GHGIA* and remains consistent with previous analyses, improvements identified in EPA's assessment (EPA, 2025) will be reviewed. Any improvements that have been incorporated into this *GHGIA* will be discussed in the Methods and Recalculations sections of those respective categories.

There are categories where additional methodological improvements will be needed, mostly due to challenges with data availability. A thorough review of alternative data sources and methods/models will also consider time-series consistency and recalculations. These will likely occur in the following categories where additional analysis and/or modeling that relies on proprietary data (e.g., USDA NRI data used in the DayCent model) had previously been used:

- Rice Cultivation
- Agricultural Soil Management
- Field Burning of Agricultural Residues (FBAR)

Future versions of this *GHGIA* will specify more on scope, timing, and plans for phasing in improvements.

5.1 Enteric Fermentation (Source Category 3A)

CH_4 is generated during animal digestion as microbes present in livestock digestive tracts ferment food consumed by livestock, a process known as enteric fermentation. CH_4 produced during enteric fermentation is dependent on livestock characteristics like the size, growth stage, and type of digestive system and also varies with the quantity and quality of feedstock in an animal's diet.

In the United States, enteric fermentation is the largest source of CH_4 emissions across all Inventory sectors. The amount of CH_4 emitted by an individual animal depends mainly on its digestive physiology and the type and quantity of feed consumed. In the absence of changes in feeding practices, animal diets or productivity, livestock populations (herd sizes) are the primary driver of enteric fermentation emission trends.

In 2024, enteric fermentation resulted in emissions of 184.1 MMT CO_2 Eq. Enteric fermentation emissions in 2024 across all livestock types decreased by 1.7 percent relative to 2023, driven primarily by a decrease in beef cattle populations that led to a 2.0 percent decrease in beef cattle enteric fermentation emissions. Dairy cattle enteric fermentation emissions also declined in 2024 relative to 2023 (0.9 percent decrease) and while trends in cattle populations generally drive overall enteric fermentation emissions, the following livestock types also experienced declines in enteric fermentation emissions in 2024: horses, sheep, American bison, and mules and asses. Enteric fermentation emissions from swine and goats saw marginal emission increases in 2024 relative to 2023 (0.4 percent increase and 0.2 percent increase, respectively).

Across the time series, total enteric fermentation emissions peaked in 1995 (199.2 MMT CO_2 Eq.) and then fluctuated over time, with two other notable highs occurring in 2007 (194.5 MMT CO_2 Eq.) and 2019 (197.3 MMT CO_2 Eq.), as shown in Table 5-3. Emissions in 2024 were 0.7 percent lower than total enteric fermentation emissions in 1990 (182.8 MMT CO_2 Eq.).

Table 5-3. CH_4 Emissions from Enteric Fermentation (MMT CO_2 Eq.)

Livestock Type	1990	2005	2020	2021	2022	2023	2024
Beef Cattle	132.8	139.6	140.5	140.3	137.0	131.7	129.0
Dairy Cattle	43.3	41.3	48.8	49.4	48.9	48.8	48.3
Swine	2.3	2.6	3.2	3.1	3.1	3.1	3.2
Horses	0.8	2.0	1.3	1.3	1.2	1.2	1.1
Sheep	2.9	1.5	1.3	1.3	1.3	1.3	1.3
Goats	0.6	0.7	0.7	0.6	0.6	0.6	0.6
American Bison	0.1	0.5	0.4	0.4	0.4	0.4	0.4
Mules and Asses	+	0.1	0.1	0.1	0.1	0.1	0.1
Total	**182.8**	**188.2**	**196.3**	**196.5**	**192.6**	**187.2**	**184.1**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Methods

Methods used in this *GHGIA* are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). The "Simplified Approach" utilized and documented by EPA (2025) to estimate 2023 emission estimates was applied in this *GHGIA* to estimate 2024 enteric fermentation emission estimates for cattle populations. In this method, national cattle population data from the USDA National Agricultural Statistical Service (USDA-NASS) QuickStats database of annual survey data was pulled according to the cattle subpopulation categories used in USDA-NASS surveys listed in Table 5-4 for the years 2022 and 2024 (USDA, 2022a, 2022b, 2024a, 2024b, 2024c). Percent change in 2024 cattle populations reported by the survey relative to 2022 populations were used to project 2024 cattle populations based on the modeled average annual populations estimated using the most recent implementation of the Cattle Enteric Fermentation Model (CEFM) (ICF, 2006). Cattle populations were then multiplied by implied emission factors for each cattle subcategory, resulting in a national estimate of CH_4 emitted annually from cattle enteric fermentation.

Table 5-4: Cattle Subpopulation Categories for 2024 Population Estimates

CEFM Cattle Category	USDA-NASS QuickStats Cattle Category
Dairy Calves	Cattle, Calves
Dairy Cows	Cattle, Cows, Milk
Dairy Replacements 7–11 months	Cattle, Heifers, GE 500 lbs, Milk Replacement
Dairy Replacements 12–23 months	Cattle, Heifers, GE 500 lbs, Milk Replacement
Bulls	Cattle, Bulls, GE 500 lbs
Beef Calves	Cattle, Calves
Beef Cows	Cattle, Cows, Beef
Beef Replacements 7–11 months	Cattle, Heifers, GE 500 lbs, Beef Replacement
Beef Replacements 12–23 months	Cattle, Heifers, GE 500 lbs, Beef Replacement
Steer Stockers	Cattle, Steers, GE 500 lbs
Heifer Stockers	Cattle, Heifers, GE 500 lbs, Excl. Replacement
Steer Feedlot	Cattle, On Feed
Heifer Feedlot	Cattle, On Feed

For non-cattle livestock categories, national livestock population estimates for 2024 were downloaded from USDA-NASS QuickStats from a combination of USDA-NASS annual surveys and the USDA Census of Agriculture. See Table 5-5 for details regarding the source of population data for each non-cattle livestock type. Swine populations in 2024 are based on averaging reported hog inventories from each quarterly hog survey published by USDA-NASS (USDA, 2024a 2024d, 2024e, 2024f, 2024g).

For livestock populations derived from the USDA Census of Agriculture, updated population estimates from the 2022 Census of Agriculture were newly incorporated into livestock estimates in this *GHGIA* (USDA, 2024h). USDA Census of Agriculture estimates are available for 1987, 1992, 1997, 2002, 2007, 2012, 2017, and 2022 (USDA, 2024a). Population estimates are linearly interpolated between census years and extrapolated from 2022 to 2024 to complete the time series using an autoregressive moving average (ARMA) extrapolation. See Box 5-1 for more information on this statistical technique. Livestock populations were then multiplied by IPCC Tier 1 emission factors to estimate enteric fermentation emissions for each livestock type (IPCC, 2019).

Table 5-5: Data Sources for Non-Cattle Livestock Population Estimates

Livestock Type	Population Data Source	USDA-NASS QuickStats Query
Swine	USDA-NASS Quarterly Survey (USDA, 2024d, 2024e, 2024f, 2024g)	Hogs, Breeding Hogs, Market, less than 50 lb. Hogs, Market, 50 to 119 lb. Hogs, Market, 120 to 179 lb. Hogs, Market, GE 180 lb.
Horses	USDA Census of Agriculture (USDA, 2024h)	Equine, Horses, and Ponies
Sheep	USDA-NASS Annual Survey (USDA, 2024h)	Sheep, Including Lambs
Goats	USDA Census of Agriculture (USDA, 2024h)	Goats
American Bison	USDA Census of Agriculture (USDA, 2024h)	Specialty, Bison
Mules and Asses	USDA Census of Agriculture (USDA, 2024h)	Equine, Mules & Burros & Donkeys

Recalculations

Recalculations to estimates presented in this *GHGIA* were implemented to incorporate the most recent population estimates for horses, goats, American bison, and mules and asses from the 2022 USDA Census of Agriculture (USDA, 2024h). As a result, emissions for these livestock types were recalculated from 2018 to 2023. Population data for these livestock types were interpolated between the 2017 and 2022 Census of Agriculture reports and extrapolated from 2022 using an ARMA forecasting technique (see Box 5-1) to estimate populations for 2023 and 2024 to complete the time series. Across all animal types, this recalculation resulted in an average annual increase in enteric fermentation emissions of 0.02 percent (0.045 MMT CO_2 Eq.) over the 2018–2023 recalculation interval.

In addition to the recalculations above, a corrective recalculation was implemented after quality control checks identified an issue with the extrapolation of horse populations from the 1992 Census of Agriculture dating back to 1990. The issue was addressed for the current estimates, resulting in a small recalculation to the 1990 and 1991 enteric fermentation emission estimates for horses. On an average annual basis, 1990–1991 emissions decreased by 12.9 percent (−0.2 MMT CO_2 Eq.) relative to 1990–1991 emissions reported by EPA (2025).

Uncertainty

An uncertainty analysis for enteric fermentation emissions was last conducted for estimates reported by EPA (2003) for the inventory report covering the 1990–2001 time series using the 2006 Guidelines Approach 2 methodology (ICF, 2003; IPCC, 2006). This analysis revealed that beef cattle represent the largest source of CH_4 emissions while also resulting in the largest degree of uncertainty associated with those estimates. The largest uncertainty in beef cattle emission estimates originates from the high degree of uncertainty in beef cattle diet characteristics, especially for the grazing portion of the beef cattle population. The uncertainty bounds used by EPA (2003) at the 95% confidence level continued to be applied to new emission estimates for all reports published through EPA (2025), as the same underlying sources of information regarding cattle population demography, diet characteristics, and ruminant nutrition models continued to be used in subsequent reports.

For this current *GHGIA*, the overall uncertainty associated with enteric fermentation is assumed to be similar to prior estimates (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). In 2024, enteric fermentation CH_4 emissions were estimated to fall between 11 percent below and 18 percent above the total enteric fermentation CH_4 estimate of 184.1 MMT CO_2 Eq. (between 163.9 MMT CO_2 Eq. and 217.2 MMT CO_2 Eq.). This uncertainty estimate is included with other uncertainty estimates across all agriculture source categories in Table 5-16.

5.2 Manure Management (Source Category 3B)

Manure treatment, storage, and transport generate CH_4 and N_2O emissions. CH_4 is generated through the anaerobic decomposition of manure, while direct and indirect N_2O arises through nitrification and denitrification, including emissions from volatilization, runoff, and leaching.[35] Structural characteristics of the U.S. livestock production industry and climatic conditions affect biological processes, which influence CH_4 and N_2O potential. For CH_4, the manure management system, ambient temperature, moisture levels, and storage duration affect emissions. For N_2O, emissions vary based on manure composition and the type of storage system or treatment, which influences the amount of oxygen and liquid present within the system (IPCC, 2006).

Emissions in the United States vary by animal type, regional climates, and manure management systems in use. Increased use of liquid systems influences CH_4 trends, while nitrogen content and handling practices drive N_2O emissions. Similar to enteric fermentation emissions, trends in CH_4 and N_2O emissions from manure management mirror trends in livestock populations, particularly cattle and swine populations, as livestock population sizes determine the amount of manure produced and managed annually.

In 2024, manure management CH_4 emissions across all livestock types totaled 65.0 MMT CO_2 Eq., and manure management N_2O emissions totaled 16.8 MMT CO_2 Eq., as shown in Table 5-6. Relative to 2023 emissions, manure management CH_4 emissions decreased by 0.2 percent (0.2 MMT CO_2 Eq.), while N_2O emissions increased by 0.1 percent.

[35] The N_2O emissions generated by manure in the system pasture, range, and paddock lands occur directly and indirectly from the soil and are therefore reported under N_2O emissions from agricultural soil management (IPCC, 2006).

Table 5-6: CH_4 and N_2O Emissions from Manure Management (MMT CO_2 Eq.)

Gas/Livestock Type	1990	2005	2020	2021	2022	2023	2024
CH_4	**39.1**	**55.0**	**66.9**	**66.4**	**64.7**	**65.1**	**65.0**
Dairy Cattle	16.0	26.4	34.7	34.3	33.4	33.5	33.2
Swine	17.4	22.7	24.9	24.6	23.8	24.3	24.3
Poultry	3.8	3.4	3.0	3.0	3.0	3.0	3.0
Beef Cattle	1.8	2.2	4.2	4.4	4.3	4.2	4.2
Horses	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Sheep	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+
American Bison	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
N_2O	**13.4**	**15.2**	**16.9**	**17.1**	**17.0**	**16.8**	**16.8**
Beef Cattle	5.2	6.0	6.1	6.4	6.4	6.2	6.3
Dairy Cattle	5.5	5.5	6.2	6.3	6.2	6.1	6.0
Swine	1.1	1.5	1.9	1.8	1.8	1.8	1.8
Poultry	1.3	1.8	2.3	2.3	2.3	2.3	2.3
Sheep	0.1	0.3	0.3	0.3	0.3	0.3	0.3
Horses	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
American Bison	NA	NA	NA	NA	NA	NA	NA
Total	**52.5**	**70.2**	**83.8**	**83.6**	**81.7**	**81.9**	**81.8**

+ Does not exceed 0.05 MMT CO_2 Eq.

NA (Not Applicable).

Note: Totals may not sum due to independent rounding.

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). All livestock population data used to estimate manure management emissions are consistent with those used to estimate enteric fermentation. See description in Section 5.1 above for more information.

In addition to the population data for cattle, swine, horses, mules and asses, American bison, sheep, and goats used in the estimation of enteric fermentation emissions, an estimate of poultry populations is necessary to estimate manure management emissions from this animal type. Consistent with the method used to estimate 2023 poultry populations (EPA, 2025), 2024 poultry populations were collected from USDA-NASS annual production and inventory surveys (USDA, 2024a, 2024b, 2024c). See Table 5-7 for details regarding the source of population data for each poultry subcategory. Turkey and broiler populations are estimated from annual production data, where production data must be adjusted to account for a production interval that incorporates the average lifespan of each animal in the production cycle. Annual production data for turkeys are divided by a production interval of 3.0 to estimate average annual population, while annual production data for broilers are divided by a production interval of 5.5 to yield average annual broiler population.

Table 5-7. Data Sources for Poultry Population Estimates

Livestock Type	Population Data Source	USDA-NASS QuickStats Query
Hens (> 1 year)	USDA-NASS Annual Survey (USDA, 2024g)	Chickens, Layers
Pullets	USDA-NASS Annual Survey (USDA, 2024g)	Chickens, Pullets, Replacement
Chickens	USDA-NASS Annual Survey (USDA, 2024g)	Chickens, Roosters and Other
Broilers	USDA-NASS Annual Production Summary (USDA, 2024h)	Chickens, Broilers – Production
Turkeys	USDA-NASS Annual Production Summary (USDA, 2024h)	Turkeys – Production

To estimate 2024 manure management CH_4 and N_2O emissions, the "Simplified Approach" used by EPA (2025) was applied. National population estimates in 2024 were multiplied by 2022 animal-specific implied emission factors for CH_4 and N_2O emissions (a combined emission factor that encompasses both direct and indirect N_2O emissions per animal type) (EPA, 2025). Use of this method ensures time series consistency across the 1990–2024 emission estimates, in line with guidance provided in IPCC (2006).

Recalculations

As with enteric fermentation emission estimates presented in this *GHGIA*, recalculations were implemented due to incorporation of USDA-NASS 2022 Census of Agriculture data to replace population estimates from 2018 to 2023 that were extrapolated from the 2017 census for horses, goats, American bison, and mules and asses (USDA, 2024d).

Across all animal types, these implemented recalculations resulted in an average annual increase in manure management CH_4 emissions of 0.01 percent (0.006 MMT CO_2 Eq.) and a 0.01 percent increase in N_2O emissions (0.001 MMT CO_2 Eq.) over the 2018–2023 recalculation interval.

Uncertainty

For this current *GHGIA*, the overall uncertainty associated with manure management is assumed to be similar to prior estimates (ERG, 2003; EPA, 2003, 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 18 percent below (53.3 MMT CO_2 Eq.) and 20 percent above (78.0 MMT CO_2 Eq.) the manure management CH_4 emission estimate of 65.0 MMT CO_2 Eq. in 2024. The uncertainty range surrounding the manure management N_2O emission estimate was 16 percent below (14.1 MMT CO_2 Eq.) and 24 percent above (20.8 MMT CO_2 Eq.) the 2024 estimate of 16.8 MMT CO_2 Eq. This uncertainty estimate is included with other uncertainty estimates across all agriculture source categories in Table 5-16.

5.3 Rice Cultivation (Source Category 3C)

All rice produced in the United States is grown in irrigated fields (USDA ERS, 2025) that create anaerobic conditions, leading to CH_4. Water management plays a significant role in CH_4 production from rice cultivation, as well as factors such as drainage and aeration, amendment application (including fertilizer use), rice variety, and soil attributes.

In the United States, only a handful of states cultivate rice, with Arkansas, California, Louisiana, and Texas representing the states with the largest share of rice cultivation areas and emissions, in that order. Most farmers in these states apply fertilizer and, in Texas and Louisiana in particular, some farmers can reflood their fields after harvest and achieve a partial second or "ratoon" crop, which often leads to higher methane emissions (USDA ERS, 2025).

Emissions from rice cultivation in the United States were 18.1 MMT CO_2 Eq. in 2024 (see Table 5-8). Although there have been annual changes across the time series, emission estimates in 2024 were similar to those in 1990, with approximately the same amount of rice area being planted during those two years (USDA-NASS, 2026).

Table 5-8: CH_4 Emissions from Rice Cultivation (MMT CO_2 Eq.)

Source	1990	2005	2020	2021	2022	2023	2024
Rice Cultivation	18.9	20.6	18.6	16.3	16.8	17.5	18.1

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025).

To estimate rice methane emissions for years beyond the available USDA NRI data, a linear regression model with autoregressive integrated moving average (ARIMA) errors was used to forecast emissions estimates from 2021 to 2024, since the Tier 3 estimates from 1990 to 2020 were based on prior runs from the DayCent model, as described in Box 5-1. Rice methane emissions were forecasted as a function of planted rice area (surrogate data), as shown in Table 5-9 (USDA-NASS, 2026). Estimates from 1990 to 2020 are consistent with estimates from EPA (2025).

Table 5-9: Rice Area Planted (1,000 Acres)

Year	1990	2005	2020	2021	2022	2023	2024
Rice Area Planted	2,897	3,384	3,036	2,531	2,219	2,895	2,919

Recalculations

With the application of the updated forecasting approach, recalculations to the 2021–2023 time series ranged from −2.2 MMT CO_2 Eq. (−12 percent) to −1.2 MMT CO_2 Eq. (−6.6 percent). There were no recalculations implemented to 1990–2020 estimates.

Uncertainty

Uncertainty in rice cultivation CH_4 emission estimates stems from uncertainty associated with the management practice activity data, emission factors, uncertainty in the DayCent model structure, and variance in the underlying NRI sampling.

For this current *GHGIA*, the overall uncertainty of rice cultivation CH_4 is assumed to be similar to EPA findings (2025) given the use of the same basic methodology and data sources for most years, calculated using the 2006 IPCC Guidelines Approach 1 (for Tier 1 emissions and total emissions) and Approach 2 (for Tier 3 emissions) methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). There will be increased uncertainties associated with the use of the ARIMA forecasting approach that are not currently reflected in the uncertainty estimates above. This confidence level indicates a range of approximately 75 percent below and 75 percent above the total rice cultivation methane emissions in 2024. This uncertainty estimate is included with other uncertainty estimates across all agriculture source categories in Table 5-16.

5.4 Agricultural Soil Management (Source Category 3D)

Agricultural soil management includes N_2O emissions resulting from nitrogen inputs to managed agricultural soils. The application of nitrogen leads to direct N_2O emissions as N_2O is emitted from agricultural soils as an intermediary during the microbial processes of nitrification and denitrification. Management of agricultural soils also leads to indirect N_2O emissions when nitrogen inputs are transported off-site either via volatilization or leaching and runoff before ultimately being transformed to N_2O through the same microbial processes of nitrification and denitrification.

The methodology used to estimate the N_2O emissions from agricultural soil management incorporates nitrogen inputs from the following sources (IPCC, 2006):

- Synthetic nitrogen fertilizer
- Managed livestock manure
- Other organic materials (e.g., application of treated sewage sludge or other biosolids)
- Manure deposited directly on pasture, rangeland, or paddock soils by grazing livestock (i.e., unmanaged manure; see Section 5.2)
- Crop residue retention on crop fields

Other activities such as drainage of organic soils, tillage, and grazing management practices can alter N_2O emissions from agricultural soils. Trends in agricultural soil management emissions fluctuate across the time series and are predominantly influenced by the type, amount, and timing of nitrogen fertilizer applied to agricultural soils, cropping systems and cropland and rangeland management practices, and seasonal weather patterns. As estimated by EPA (2025), across the 1990–2023 time series, cropland accounted for 68 percent of total direct N_2O emissions and 79 percent of indirect N_2O emissions from agricultural soil management, while grassland accounted for 32 percent of direct N_2O emissions and 21 percent of indirect N_2O emissions.

Emissions of N_2O from agricultural soil management is the largest source of emissions in the agricultural sector across all gases, as well as the largest source of N_2O across all inventory sectors in the United States. In 2024, agricultural soil management direct N_2O emissions totaled 265.4 MMT CO_2 Eq. across both cropland and grassland soils, and indirect N_2O emissions totaled 28.5 MMT CO_2 Eq. (Table 5-10). Relative to 2023 emissions, direct N_2O emissions increased by 3.6 percent (9.5 MMT CO_2 Eq.) in 2024, while indirect N_2O emissions decreased by 0.3 percent (0.1 MMT CO_2 Eq.).

Table 5-10: N_2O Emissions from Agricultural Soil Management (MMT CO_2 Eq.)

Source	1990	2005	2020	2021	2022	2023	2024
Direct	259.2	266.2	263.5	264.9	271.0	265.9	275.4
Indirect	29.9	28.5	29.5	31.6	31.5	31.4	31.3
Total	**289.1**	**294.7**	**293.0**	**296.5**	**302.5**	**297.3**	**306.7**

Note: Totals may not sum due to independent rounding.

Methods

Historically, the majority of N_2O emissions from agricultural soil management have been estimated using Tier 3 methods that leverage the DayCent model, a process-based model that tracks carbon and nitrogen dynamics through a mass-balance approach through daily iterations of simulated microbial decomposition and plant productivity. The DayCent model incorporates numerous data products to accurately capture the impact of climate, land use and land management, fertilizer application, and geospatial variation in biogeochemical properties on nitrogen dynamics and N_2O emissions in agricultural systems across the United States. Tier 1 methods (IPCC, 2006) are used to estimate N_2O emissions from agricultural soils in systems where DayCent has not been parameterized to accurately model emissions from certain soil types (e.g., Histosols) or specialty crop types. This *GHGIA* leverages the 1990–2020 emissions estimates using the most recent DayCent model results and Tier 1 methods reported by EPA (2025). See EPA (2025) for more details regarding the DayCent model, Tier 1 estimation methodology, and activity data used to estimate 1990–2020 N_2O emissions from agricultural soil management.

To complete the time series and estimate agricultural soil management N_2O emissions from 2021 to 2024, this *GHGIA* leveraged an extrapolation approach that uses a linear model incorporating trends in surrogate data variables for national fertilizer consumption, planted acreage of corn and soybeans, and state-level precipitation data, as described in Box 5-1. This extrapolation technique is similar to that employed by EPA (2025) to extrapolate 2021–2023 N_2O emissions from agricultural soil management, but it incorporates national nitrogen fertilizer consumption data from the International Fertilizer Association (IFA) with 2024 total nitrogen fertilizer consumption extrapolated using a linear model to forecast fertilizer consumption based on the historical relationship between total national planted corn and soybean acres from 1990 to 2023 (USDA, 2024a, 2024b) and national fertilizer consumption from 1990 to 2023 (IFA, 2026a). In addition to national nitrogen fertilizer consumption data, a weighted national annual precipitation variable was created by weighting average state annual precipitation by each state's share of national planted soybean and corn acres (PRISM, n.d.; USDA, 2024a, 2024b). A linear model was then created where national precipitation data (from state precipitation data weighted by planted acreage) and national total nitrogen fertilizer consumption variables were used as surrogate data to explain historical variation in direct N_2O emissions from 1990 to 2020, and this linear model was used to extrapolate direct N_2O emissions from 2021 to 2024. Indirect N_2O emissions from 2021 to 2024 were extrapolated using an ARMA approach.

Recalculations

The implementation of a modified extrapolation technique to estimate direct N_2O emissions from 2021 to 2023 resulted in an average increase in emissions of 0.4 percent (1.1 MMT CO_2 Eq.) across the 2021–2023 recalculation interval relative to the estimates presented by EPA (2025). The modified extrapolation approach resulted in an average increase in emissions of 6.9 percent (2.0 MMT CO_2 Eq.) across the same recalculation interval relative to EPA (2025) results.

Uncertainty

For this current *GHGIA*, the overall uncertainty surrounding direct and indirect N_2O emissions from agricultural soil management is assumed to be similar to those presented by EPA (2025) given the use of the same basic methodology and data sources for most years. Uncertainty estimates presented by EPA (2025) incorporate uncertainty from DayCent model structure and assumptions, IPCC (2006) Tier 1 default emission factors, and additional error introduced through the use of extrapolation techniques to complete the time series. A Monte Carlo simulation (2006 IPCC Guidelines Approach 2 using 95 percent confidence intervals) was used to estimate the components of direct and indirect N_2O emissions derived from the DayCent model, while Approach 1, error propagation, from IPCC (2006), was used to estimate uncertainty associated with direct N_2O emissions estimated using the Tier 1 approach, the proportion of nitrogen that is volatilized, leached, or lost via runoff, and indirect N_2O emissions. This analysis indicates a range of approximately 28 percent above and below the 2024 direct N_2O emission estimate of 275. 4 MMT CO_2 Eq. (i.e., between 198.3 MMT CO_2 Eq. and 352.54 MMT CO_2 Eq.) and 52 percent below to 124 percent above the 2024 indirect N_2O emission estimate of 31.3 MMT CO_2 Eq. (i.e., between 15.0 MMT CO_2 Eq. and 70.2 MMT CO_2 Eq.). This uncertainty estimate is included with other uncertainty estimates across all agriculture source categories in Table 5-16.

5.5 Liming (Source Category 3G)

Agricultural liming is the practice of applying limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$), to agricultural soils. As these materials dissolve, they release CO_2 into the atmosphere. These materials help reduce soil acidity, creating better conditions for plant growth and improving crop yields.

Emissions from limestone and dolomite that are used in industrial processes (e.g., cement production, glass production) are reported in Chapter 4, *Industrial Processes and Product Use*.

Emissions from liming of agricultural soils in the United States were 5.6 MMT CO_2 Eq. in 2024 (see Table 5-11), with time-series trends following patterns in the amount of minerals applied to soils.

Table 5-11: CO_2 Emissions from Liming (MMT CO_2 Eq.)

Source	1990	2005	2020	2021	2022	2023	2024
Limestone	4.1	3.9	2.5	2.0	3.0	5.1	5.3
Dolomite	0.6	0.5	0.4	0.4	0.3	0.3	0.3
Total	**4.7**	**4.4**	**2.9**	**2.4**	**3.2**	**5.4**	**5.6**

Note: Totals may not sum due to independent rounding.

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). Total crushed stone data for 2022 and 2023 were available from the U.S. Geological Survey (USGS, 2025) (see Table 5-12), but disaggregated data on agricultural uses of crushed stone were not available at the time of this analysis and thus the proportions from 2023 were applied to 2024.

Table 5-12: Applied Minerals (MMT)

Mineral	1990	2005	2020	2021	2022	2023	2024
Limestone	19.0	18.1	11.6	9.3	13.7	23.6	24.5
Dolomite	2.4	1.9	1.6	1.6	1.1	1.2	1.4

Recalculations

With the incorporation of updated USGS activity data, recalculations were implemented in 2022 and 2023, resulting in a 0.03 MMT CO_2 Eq. and 0.1 MMT CO_2 Eq. increase, respectively, compared to EPA (2025). There were no recalculations to estimates from 1990 to 2021.

Uncertainty

Uncertainty stems from data on the amount of crushed stone applied to agricultural soils and the fraction of lime dissolved by nitric acid versus carbonic acid, as well as the portion of bicarbonate that leaches through the soil and is transported to the ocean (EPA, 2025).

For this current *GHGIA*, the overall uncertainty of liming emissions 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 85 percent below and 89 percent above the CO_2 emissions from liming estimate in 2024. This uncertainty estimate is included with other uncertainty estimates across all agriculture source categories in Table 5-16.

5.6 Urea Fertilization (Source Category 3H)

Urea is applied to soils primarily as a nitrogen fertilizer to support crop growth and improve yields. The use of urea ($CO(NH_2)_2$) as a fertilizer leads to GHG emissions through the release of CO_2 that was fixed during the industrial production process (IPCC, 2006).

Emissions from urea fertilization in the United States were 5.1 MMT CO_2 Eq. in 2024, as shown in Table 5-13.[36] CO_2 emissions increased by 121 percent between 1990 and 2024. This trend follows the overall trend of increased use of urea in the United States as a substitute for other nitrogen fertilizers.

Table 5-13: CO_2 Emissions from Urea Fertilization (MMT CO_2 Eq.)

Source	1990	2005	2020	2021	2022	2023	2024
Urea Fertilization	2.3	3.6	4.7	4.5	4.8	4.7	5.1

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). The primary activity data source was updated to the IFA (2026b). This dataset covers the entire 1990–2024 time series, which is presented in Table 5-14, replacing the linear regression model with ARMA errors that was previously applied to the 2017 through present time series by EPA (2025).

Table 5-14: Applied Urea (MMT)

Source	1990	2005	2020	2021	2022	2023	2024
Urea Fertilizer	3.1	4.9	6.5	6.1	6.6	6.4	6.9

Recalculations

The IFA activity data is approximately 3.5 percent different, on average, compared to the prior datasets used over the time series. From an emissions perspective, this resulted in an average decrease in emissions across the time series by 0.1 MMT CO_2 Eq., with the greatest differences coming during the years in which prior analysis (EPA, 2025) used an ARMA forecasting method.

[36] CO_2 emissions associated with urea used for non-agricultural purposes are reported in Chapter 4.

Uncertainty and QA/QC

When reviewing the IFA activity data source, statistical comparisons against the prior activity data were conducted for the whole time series.

Uncertainty in the urea fertilization estimates stems from the activity data and the IPCC default emission factor. For this current *GHGIA*, the overall uncertainty of urea fertilization is assumed to be similar to those presented by EPA (2025) given the use of the same basic methodology and data sources for most years, which were 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 43 percent below and 3 percent above the CO_2 estimate from urea fertilization in 2024. This uncertainty estimate is included with other uncertainty estimates across all agriculture source categories in Table 5-16.

5.7 Field Burning of Agricultural Residues (Source Category 3F)

The burning of agricultural residues in fields is one way farmers manage the large amounts of residues left over from crop production and leads to emissions of CH_4, N_2O, carbon monoxide (CO), and nitrogen dioxide (NOx)[37]. In the United States, residue burning occurs on a limited scale and is often subject to state and local air quality regulations.

Total emissions from field burning of agricultural residues in the United States were 0.8 MMT CO_2 Eq. in 2024, an 18.4 percent increase since 1990 (see Table 5-15). The increase in emissions since 1990 is driven in part by higher-yielding crop varieties that generate more residue, as well as by an expansion in the area where residue burning is practiced for certain crops such as wheat in the Pacific Northwest and sugarcane in Florida.

Table 5-15: CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (MMT CO_2 Eq.)

Gas/Crop Type	1990	2005	2020	2021	2022	2023	2024
CH_4	**0.5**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Sugarcane	0.1	0.2	0.1	0.2	0.2	0.2	0.2
Wheat	0.2	0.2	0.1	0.1	0.1	0.1	0.1
Maize	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Rice	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Soybeans	+	+	+	0.1	0.1	0.1	0.1
Cotton	+	+	+	+	+	+	+
Sorghum	+	+	+	+	+	+	+
Other Small Grains	+	+	+	+	+	+	+
Peanuts	+	+	+	+	+	+	+
Legume Hay	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+

(continued)

[37] The 2006 IPCC Guidelines does not consider field burning of annual crop residues to be a net source of CO_2 emissions because it is assumed that the carbon released to the atmosphere as CO_2 during burning is reabsorbed during the next growing season by the crop (IPCC, 2006).

Table 5-15: CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (MMT CO_2 Eq.) *(continued)*

Gas/Crop Type	1990	2005	2020	2021	2022	2023	2024
Oats	+	+	+	+	+	+	+
Grass Hay	+	+	+	+	+	+	+
Tobacco	+	+	+	+	+	+	+
Sunflower	+	+	+	+	+	+	+
Peas	+	+	+	+	+	+	+
Vegetables	+	+	+	+	+	+	+
Potatoes	+	+	+	+	+	+	+
Dry Beans	+	+	+	+	+	+	+
Sugar Beets	+	+	+	+	+	+	+
Lentils	+	+	+	+	+	+	+
Chickpeas	+	+	+	+	+	+	+
N_2O	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
Wheat	0.1	0.1	+	+	+	+	+
Maize	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Peanuts	+	+	+	+	+	+	+
Other Small Grains	+	+	+	+	+	+	+
Legume Hay	+	+	+	+	+	+	+
Sorghum	+	+	+	+	+	+	+
Grass Hay	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+

(continued)

Table 5-15: CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (MMT CO_2 Eq.) *(continued)*

Gas/Crop Type	1990	2005	2020	2021	2022	2023	2024
Oats	+	+	+	+	+	+	+
Potatoes	+	+	+	+	+	+	+
Peas	+	+	+	+	+	+	+
Tobacco	+	+	+	+	+	+	+
Sugar Beets	+	+	+	+	+	+	+
Sunflower	+	+	+	+	+	+	+
Vegetables	+	+	+	+	+	+	+
Dry Beans	+	+	+	+	+	+	+
Lentils	+	+	+	+	+	+	+
Chickpeas	+	+	+	+	+	+	+
Total	**0.7**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025).

For field burning of agricultural residues, a linear regression model with ARIMA errors, was used to forecast emissions from 2015 to 2024 (2021–2024 for sugarcane), as described in Box 5-1. Estimates from 1990 to 2014 (through 2020 for sugarcane) are consistent with estimates from prior analysis (EPA, 2025).

Recalculations

Using the updated forecasting approach resulted in minimal recalculations to the 2015–2023 time series. These recalculations range from −0.03 MMT CO_2 Eq. to 0.03 MMT CO_2 Eq. for CH_4 and less than −0.01 MMT CO_2 Eq. for N_2O compared to the 1990–2023 inventory (EPA, 2025). There were no recalculations implemented to estimates from 1990 to 2014.

Uncertainty

Uncertainty in the estimates of field burning of agricultural residues stems from multiple sources, including the use of an analysis of burned areas across six states that is extrapolated to the rest

of the United States, potential omission of burning associated with Kentucky bluegrass, and the underlying burned area and crop data products.

For this current *GHGIA*, the overall uncertainty of field burning of agricultural residues is assumed to be similar to those found by EPA (2025) given the use of the same basic methodology and data sources for most years, which were 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 14 percent below and 14 percent above the CH_4 estimate and 18 percent below and 18 percent above the N_2O estimate for field burning of agricultural residue emissions in 2024. This uncertainty estimate is included with other uncertainty estimates across all agriculture source categories in Table 5-16.

5.8 Agriculture Uncertainty Summary

Table 5-16 shows the uncertainty summary for each agriculture sector source. A discussion of the uncertainty ranges is included in each source category's respective chapter section.

Table 5-16: Quantitative Uncertainty Summary by Agricultural 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
Enteric Fermentation	CH_4	184.1	163.8	217.2	–11%	18%
Manure Management	CH_4	65.0	53.3	78.0	–18%	20%
Manure Management	N_2O	16.8	14.1	20.8	–16%	24%
Rice Cultivation	CH_4	18.1	4.5	31.7	–75%	75%
Direct Soil N_2O Emissions from Agricultural Soil Management	N_2O	275.4	198.3	352.5	–28%	28%
Indirect Soil N_2O Emissions from Agricultural Soil Management	N_2O	31.3	15.0	70.2	–52%	124%
Liming	CO_2	5.5	0.8	10.5	–85%	89%
Urea Fertilization	CO_2	5.1	2.9	5.2	–43%	3%
Field Burning of Agricultural Residues	CH_4	0.6	0.6	0.7	–14%	14%
Field Burning of Agricultural Residues	N_2O	0.2	0.2	0.2	–18%	18%

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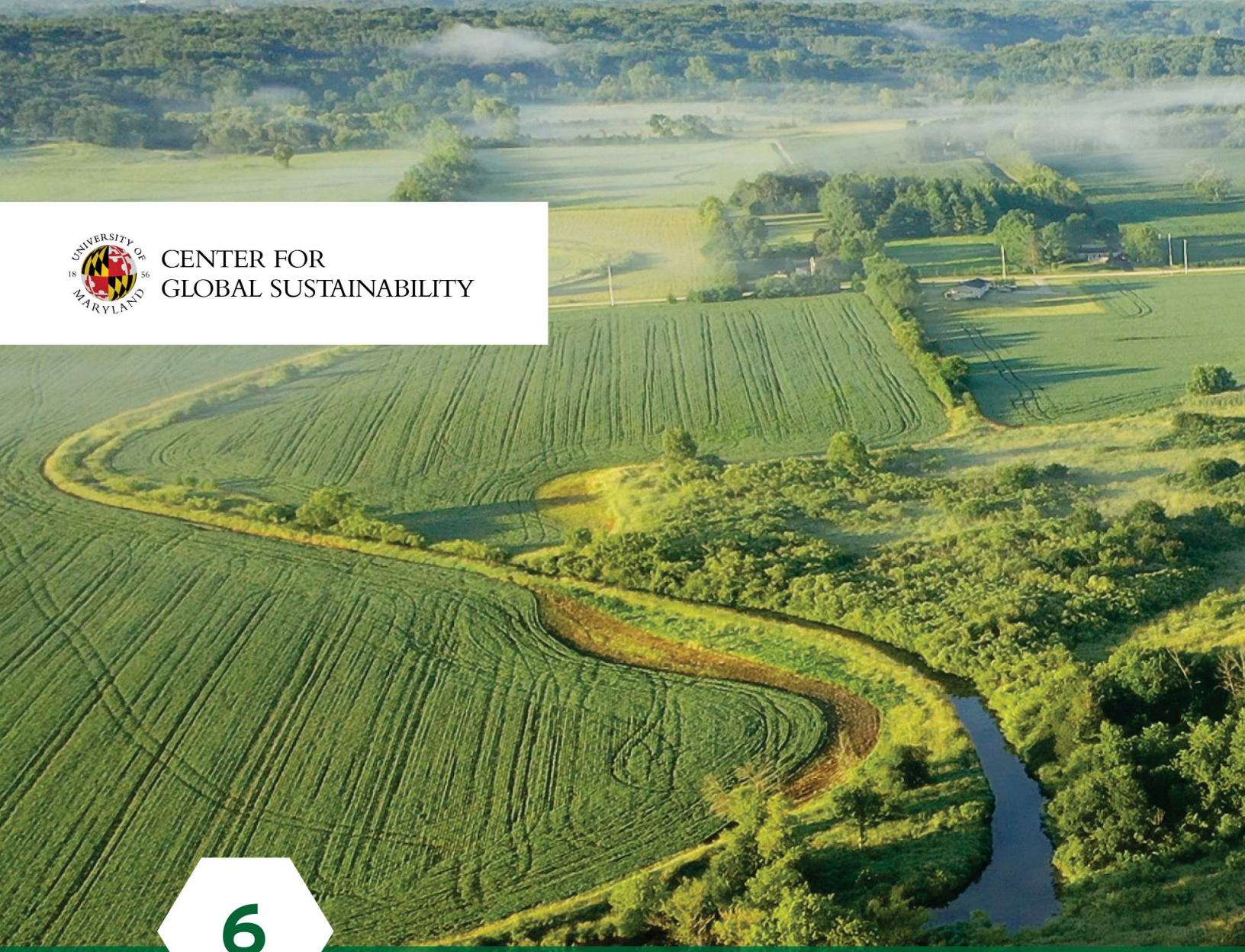
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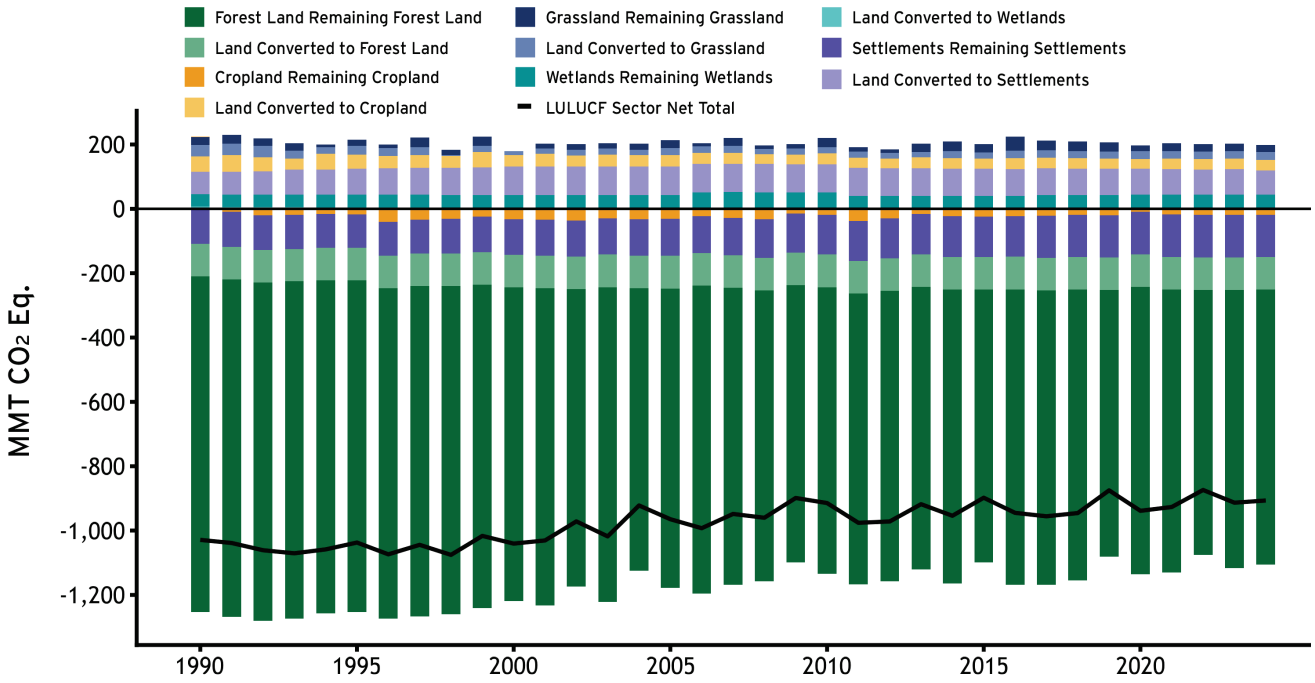
Land Use, Land-Use Change, and Forestry (LULUCF)



Chapter 6. Land Use, Land-Use Change, and Forestry

The land use, land-use change, and forestry (LULUCF) sector includes greenhouse gas (GHG) emissions and removals (referred to as a net flux) associated with changes within and conversions between the Intergovernmental Panel on Climate Change (IPCC) land-use categories, including forest land (including harvested wood products [HWP]), cropland, grassland, wetlands, settlements, and other land uses.

Figure 6-1: Trends in Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry



Note: Each category/bar includes estimates of annual net GHG fluxes, including non-CO_2 emissions and changes in ecosystem carbon stocks. The "LULUCF Sector Net Total" line reflects net total emissions and removals occurring across all land-use categories.

In 2024, the overall net flux from the LULUCF sector resulted in a removal[38] of 906.5 million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.) (see Table 6-1 and Figure 6-1). This represents an offset equivalent of approximately 14.6 percent of total (i.e., gross) GHG emissions

[38] Carbon sequestration estimates are expressed as net values, reflecting the balance between annual carbon gains and losses within a given pool. When losses exceed gains, the carbon stock declines and the pool functions as a source resulting in net emissions, whereas when gains exceed losses, the carbon stock increases and the pool acts as a sink and results in net removals of CO_2 from the atmosphere.

in 2024, primarily from existing forests. The total net flux reflects an increase in carbon stocks (i.e., net carbon dioxide [CO_2] removals) of 966.5 MMT CO_2 Eq. and emissions of methane (CH_4) and nitrous oxide (N_2O) of 54.9 and 5.1 MMT CO_2 Eq., respectively, driven by carbon being sequestered in existing forest land (forest land remaining forest land), trees in urban areas, and lands being converted to forests (e.g., afforestation). Although forests have remained a net carbon sink over the time series, the rate in which existing forest lands are sequestering carbon is slowing, resulting in an 18 percent decline in the forest land remaining forest land sink (less annual carbon sequestration) since 1990 (see Figure 6-1).

Flooded land remaining flooded land was the largest source of non-CO_2 emissions from LULUCF in 2024, accounting for 79.6 percent of the LULUCF sector non-CO_2 emissions. Non-CO_2 emissions from forest fires were the second largest source of LULUCF sector emissions, accounting for 7.3 percent of LULUCF non-CO_2 emissions in 2024.

Table 6-1: Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Land-Use Category	1990	2005	2020	2021	2022	2023	2024
Forest Land Remaining Forest Land	**(1,043.1)**	**(930.9)**	**(892.9)**	**(879.0)**	**(822.9)**	**(864.9)**	**(854.8)**
Changes in Forest Carbon Stocks[a]	(1,049.0)	(949.0)	(919.3)	(903.7)	(839.1)	(871.3)	(859.7)
Non-CO_2 Emissions from Forest Fires[b]	5.8	17.6	26.0	24.3	15.7	6.0	4.4
N_2O Emissions from Forest Soils[b]	0.1	0.4	0.4	0.4	0.4	0.4	0.4
Non-CO_2 Emissions from Drained Organic Soils[b]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Land Converted to Forest Land	**(100.8)**	**(101.2)**	**(100.9)**	**(100.9)**	**(100.8)**	**(100.8)**	**(100.9)**
Changes in Forest Carbon Stocks	(100.8)	(101.2)	(100.9)	(100.9)	(100.8)	(100.8)	(100.9)
Cropland Remaining Cropland	**1.0**	**(31.0)**	**(9.6)**	**(17.7)**	**(18.6)**	**(18.1)**	**(18.0)**
Changes in Ecosystem Carbon Stocks[c]	1.0	(31.0)	(9.6)	(17.7)	(18.6)	(18.1)	(18.0)

(continued)

Table 6-1: Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.) (*continued*)

Land-Use Category	1990	2005	2020	2021	2022	2023	2024
Land Converted to Cropland	**48.5**	**35.5**	**29.6**	**32.2**	**32.3**	**32.5**	**32.6**
Changes in all Ecosystem Carbon Stocks	48.5	35.5	29.6	32.2	32.3	32.5	32.6
Grassland Remaining Grassland	**24.2**	**24.5**	**17.0**	**24.7**	**23.2**	**23.2**	**22.9**
Changes in All Ecosystem Carbon Stocks	24.0	23.7	15.9	23.7	22.5	22.5	22.2
Non-CO_2 Emissions from Grassland Fires[d]	0.2	0.8	1.1	0.9	0.6	0.7	0.7
Land Converted to Grassland	**35.6**	**21.9**	**25.1**	**23.0**	**23.7**	**24.1**	**24.7**
Changes in all Ecosystem Carbon Stocks	35.6	21.9	25.1	23.0	23.7	24.1	24.7
Wetlands Remaining Wetlands	**38.5**	**40.9**	**44.0**	**43.9**	**44.0**	**43.9**	**44.0**
Changes in Organic Soil Carbon Stocks in Peatlands	1.1	1.1	0.6	0.5	0.6	0.5	0.6
Non-CO_2 Emissions from Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Changes in Biomass, DOM, and Soil Carbon Stocks in Coastal Wetlands	(10.8)	(10.1)	(8.6)	(8.5)	(8.4)	(8.4)	(8.3)
CH_4 Emissions from Coastal Wetlands Remaining Coastal Wetlands	4.2	4.2	4.1	4.0	3.9	3.9	3.8

(continued)

Table 6-1: Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.) (*continued*)

Land-Use Category	1990	2005	2020	2021	2022	2023	2024
N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	0.1	0.2	0.1	0.1	0.1	0.1	0.1
CH_4 Emissions from Flooded Land Remaining Flooded Land	43.9	45.5	47.7	47.7	47.7	47.8	47.8
Land Converted to Wetlands	**6.7**	**1.9**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**
Changes in Biomass, DOM, and Soil Carbon Stocks in Land Converted to Coastal Wetlands	0.5	0.5	+	+	+	+	+
CH_4 Emissions from Land Converted to Coastal Wetlands	0.3	0.3	0.2	0.2	0.2	0.2	0.2
Changes in Land Converted to Flooded Land	3.3	0.6	0.3	0.3	0.3	0.3	0.3
CH_4 Emissions from Land Converted to Flooded Land	2.7	0.5	0.2	0.2	0.2	0.2	0.2
Settlements Remaining Settlements	**(109.1)**	**(115.2)**	**(131.9)**	**(132.5)**	**(132.6)**	**(132.6)**	**(131.9)**
Changes in Organic Soil Carbon Stocks	9.9	10.1	15.1	15.4	15.8	16.3	16.7
Changes in Settlement Tree Carbon Stocks	(96.5)	(117.0)	(136.6)	(137.6)	(138.4)	(139.0)	(139.9)

(continued)

Table 6-1: Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.) (*continued*)

Land-Use Category	1990	2005	2020	2021	2022	2023	2024
N_2O Emissions from Settlement Soils[e]	2.1	3.1	2.3	2.3	2.3	2.3	2.3
Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills	(24.5)	(11.4)	(12.8)	(12.5)	(12.3)	(12.1)	(11.0)
Land Converted to Settlements	**69.5**	**89.0**	**80.3**	**78.8**	**77.3**	**78.4**	**74.1**
Changes in all Ecosystem Carbon Stocks	69.5	89.0	80.3	78.8	77.3	78.4	74.1
LULUCF Emissions[f]	**59.4**	**72.6**	**82.2**	**80.3**	**71.3**	**61.7**	**60.0**
CH_4	54.6	61.3	69.2	67.8	61.9	56.1	54.9
N_2O	4.8	11.3	13.0	12.5	9.3	5.6	5.1
LULUCF Carbon Stock Change[g]	(1,088.3)	(1,037.3)	(1,020.7)	(1,007.0)	(945.1)	(975.0)	(966.5)
LULUCF Sector Net Total[h]	**(1,028.9)**	**(964.7)**	**(938.6)**	**(926.7)**	**(873.8)**	**(913.4)**	**(906.5)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] Includes the net changes to carbon stocks stored in all forest ecosystem pools and harvested wood products.

[b] Estimates include emissions from both forest land remaining forest land and land converted to forest land.

[c] Estimates include the net changes to carbon stocks stored in all aboveground biomass, mineral soils and organic soils ecosystem pools.

[d] Estimates include CH_4 and N_2O emissions from fires on both grassland remaining grassland and land converted to grassland.

[e] Estimates include N_2O emissions from nitrogen fertilizer additions on both settlements remaining settlements and land converted to settlements.

[f] LULUCF emissions include the CH_4 and N_2O emissions reported for peatlands remaining peatlands, forest fires, drained organic soils, grassland fires, and coastal wetlands remaining coastal wetlands; CH_4 emissions from land converted to coastal wetlands, flooded land remaining flooded land, and land converted to flooded land; and N_2O emissions from forest soils and settlement soils.

[g] LULUCF carbon stock change includes any carbon stock gains and losses from all land use and land-use conversion categories.

[h] The LULUCF sector net total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus LULUCF net carbon stock changes in units of MMT CO_2 Eq.

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

Unless otherwise noted, all estimates in this chapter are provided in MMT CO_2 Eq. Consistent with GHG inventories from other countries, this *Greenhouse Gas Inventory and Analysis for the United States (GHGIA)* 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 *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 4 (Agriculture, Forestry and Other Lands [AFOLU]) of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (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 the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (Environmental Protection Agency [EPA], 2025), as noted in Table 6-2. Consistent with IPCC good practices, the inventory applies higher tier methods and approaches for more significant sources (e.g., Tier 2 and Tier 3 methods, which include use of country-specific methods and models, emission factors and other site-specific information), and where feasible for smaller sources.

To fill gaps in activity data typically occurring in the most recent years of the time series, several types of statistical techniques are used to extrapolate emissions estimates (see Volume 1, Chapter 5 of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* [IPCC, 2006]). See Box 5-1 in the *Agriculture* chapter for more details on the specific extrapolation techniques used to forecast agriculture and LULUCF emissions, as well as discussion within category Methods sections.

Table 6-2: Summary of Methods in the LULUCF Chapter

Land-Use Category (CRT Code[a])	Gases	IPCC Methodological Tier	Methodological Refinements Compared to 1990–2023 Inventory (EPA, 2025)
U.S. Land Representation	**NA**	**Approach 3**	**No change**
Forest Land Remaining Forest Land (4A1)			
Changes in Forest Carbon Stocks	CO_2	Tier 3	Entire CONUS is estimated with the same methodology
Non-CO_2 Emissions from Forest Fires	CH_4, N_2O	Tier 1, Tier 3	No change
N_2O Emissions from Forest Soils	N_2O	Tier 1	No change

(continued)

Table 6-2: Summary of Methods in the LULUCF Chapter (*continued*)

Land-Use Category (CRT Code[a])	Gases	IPCC Methodological Tier	Methodological Refinements Compared to 1990–2023 Inventory (EPA, 2025)
Non-CO_2 Emissions from Drained Organic Soils	CH_4, N_2O	Tier 1	No change
Land Converted to Forest Land (4A2)			
Changes in Forest Carbon Stocks	CO_2	Tier 3	No change
Cropland Remaining Cropland (4B1)			
Changes in Ecosystem Carbon Stocks	CO_2	Tier 1, Tier 2, Tier 3	No change
Land Converted to Cropland (4B2)			
Changes in All Ecosystem Carbon Stocks	CO_2	Tier 1, Tier 2, Tier 3	No change
Grassland Remaining Grassland (4C1)			
Changes in All Ecosystem Carbon Stocks	CO_2	Tier 2, Tier 3	No change
Non-CO_2 Emissions from Grassland Fires	CH_4, N_2O	Tier 1	No change
Land Converted to Grassland (4C2)			
Changes in all Ecosystem Carbon Stocks	CO_2	Tier 1, Tier 2, Tier 3	No change
Wetlands Remaining Wetlands (4D1)			

(continued)

Table 6-2: Summary of Methods in the LULUCF Chapter (*continued*)

Land-Use Category (CRT Code[a])	Gases	IPCC Methodological Tier	Methodological Refinements Compared to 1990–2023 Inventory (EPA, 2025)
Changes in Organic Soil Carbon Stocks in Peatlands	CO_2	Tier 1	No change
Non-CO_2 Emissions from Peatlands Remaining Peatlands	CH_4, N_2O	Tier 1	No change
Changes in Biomass, DOM, and Soil Carbon Stocks in Coastal Wetlands	CO_2	Tier 1, Tier 2	2021 C-CAP activity data was incorporated
CH_4 Emissions from Coastal Wetlands Remaining Coastal Wetlands	CH_4	Tier 1	2021 C-CAP activity data was incorporated
N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	N_2O	Tier 1	No change
CH_4 Emissions from Flooded Land Remaining Flooded Land	CH_4	Tier 1	No change
Land Converted to Wetlands (4D2)			
Changes in Biomass, DOM, and Soil Carbon Stocks in Land Converted to Coastal Wetlands	CO_2	Tier 1, Tier 2	2021 C-CAP activity data was incorporated
CH_4 Emissions from Land Converted to Coastal Wetlands	CH_4	Tier 1	2021 C-CAP activity data was incorporated
Changes in Carbon Stocks in Land Converted to Flooded Land	CO_2	Tier 1	No change
CH_4 Emissions from Land Converted to Flooded Land	CH_4	Tier 1	No change

(continued)

Table 6-2: Summary of Methods in the LULUCF Chapter (*continued*)

Land-Use Category (CRT Code[a])	Gases	IPCC Methodological Tier	Methodological Refinements Compared to 1990–2023 Inventory (EPA, 2025)
Settlements Remaining Settlements (4E1)			
Changes in Organic Soil Carbon Stocks	CO_2	Tier 2	No change
Changes in Settlement Tree Carbon Stocks	CO_2	Tier 2, Tier 3	No change
N_2O Emissions from Settlement Soils	N_2O	Tier 1	No change
Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills	CO_2	Country-specific	No change
Land Converted to Settlements (4E2)			
Changes in All Ecosystem Carbon Stocks	CO_2	Tier 1, Tier 2	No change

[a] Codes in parentheses represent common reporting table (CRT) codes. CRT codes are 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). Translating 4A1: 4 = LULUCF sector, A = forest subsector/land-use category, 1 = land-use conversion category (i.e., forest land remaining forest land).

General Concepts Applicable to All Land-Use Categories

Below are general concepts that apply to all land-use categories (e.g., forest land, cropland) and are relevant to understanding emission and sink estimation approaches across this sector:

- This GHGIA estimates carbon stock changes across five major long-term carbon pools in terrestrial ecosystems (IPCC, 2006): aboveground biomass (carbon stored in all living plant biomass above the soil surface), belowground biomass (carbon contained in living roots of vegetation), dead wood (carbon stored in nonliving woody biomass such as standing dead trees, downed deadwood, and coarse woody debris), litter (carbon contained in smaller dead organic matter [DOM] lying on the soil surface), and soil organic carbon (carbon stored in soil organic matter). Not all carbon pools, such as DOM and litter, are accounted for in each land-use category, as each pool may not experience significant fluxes and instead is assumed to exist at a steady state under specific land uses.
- Emissions or removals in this GHGIA are estimated from the net annual change in carbon stocks across the main ecosystem pools (living biomass, dead wood, litter, and soil organic

matter) within each land-use category (IPCC, 2006). As a consequence, estimates presented in this GHGIA do not explicitly account for many short-term ecosystem carbon fluxes, such as carbon uptake and release from non-woody or rapidly cycling plant biomass (e.g., annual crops), autotrophic and heterotrophic soil respiration, and other fast carbon turnover processes. These fluxes largely cancel out over annual time scales and are only reflected indirectly through their contribution to net changes in the long-term carbon stocks that are reported.

- For the purposes of this GHGIA and pursuant to IPCC Guidelines, organic and mineral soils are considered distinct soil types that do not occur in the same geospatially explicit location. Organic soils, also referred to as histosols, are defined as soils with 12 to 20 percent organic carbon by weight, depending on clay content (Brady & Weil, 1999; Natural Resources Conservation Service [NRCS], 1999). All other soils in the *GHGIA* are considered mineral soils. Land-use areas and corresponding emissions and removals estimates throughout the LULUCF sector are often estimated separately by soil type.
- Land-use categories are classified into two groups: lands remaining in the same use and lands undergoing land-use change. If a parcel of land has not changed use category within the past 20 years, it is considered "remaining" in its current category, in line with the *2006 IPCC Guidelines* (IPCC, 2006). If a change has occurred within the last 20 years, the land is categorized as undergoing land-use change, defined by its current use and its most recent previous use (e.g., wetland converted to settlement). After this 20-year transition period in the new land-use change category, the land is then reclassified as remaining in that land-use category.
- As further described in the *Inventory of U.S. Greenhouse Gas Sources and Sinks: 1990–2023* (EPA, 2025) and the 2006 IPCC Guidelines (IPCC, 2006), given the complexity of tracking and estimating GHGs from the LULUCF sector and the need for practical inventory methods, all anthropogenic GHG emissions and removals associated with land use and management occur on managed land and should be reported in this GHGIA; here, the use of *managed land* serves as a proxy for anthropogenic activities (see Section 6.1).
- All net annual CO_2 emissions and removals associated with biomass are reported in the AFOLU sector. CO_2 emissions from biomass combustion used for energy are only recorded as a memo in the energy sector; these [memo] emissions are not included in the energy sector total to avoid double counting (IPCC, 2006). For example, if forests are harvested to produce energy, emissions from bioenergy combustion are reported for informational purposes only in the energy sector because the changes in forest carbon stocks are estimated in the LULUCF sector. See IPCC Frequently Asked Questions.[39]

Quality Assurance/Quality Control

For all categories, the IPCC general and category-specific quality assurance/quality control (QA/QC) procedures were implemented. The procedures that were implemented involved checks that specifically focused on the activity data and methodology used for estimating each source of

[39] https://www.ipcc-nggip.iges.or.jp/faq/faq.html

emissions and removals from the LULUCF sector. Emissions and removals 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 *Inventory of U.S. Greenhouse Gas Sources and Sinks: 1990–2023* (EPA, 2025) were applied for each category and subcategory (as applicable) (see Table 6-45). A qualitative description of the uncertainties, along with the total category uncertainty estimate is provided within each category. Future iterations/versions of this *GHGIA* will review and update the quantified uncertainty associated with activity data, emission factors, and other input parameters.

Future Areas for Improvement

Continuous improvement efforts are important for reflecting the latest science, reducing uncertainties to the extent practical in estimating emissions from land use and land-use change activities, especially for significant categories. For categories where the methodology has not changed in this *GHGIA* and is consistent with prior analysis, we endeavor to address those planned improvements identified in EPA (2025). Any improvements that have been incorporated into this *GHGIA* will be discussed in the Methods and Recalculations sections of those respective categories.

There are categories where additional methodological improvements will be needed, mostly due to challenges with data availability. A thorough review of alternative data sources and methods/models will also consider time-series consistency and recalculations. These are likely to occur in the following categories, often where modeling that relies on proprietary data (e.g., U.S. Department of Agriculture [USDA] National Resources Inventory [NRI] data used in the DayCent model) had previously been used:

- U.S. Land Representation
- Forest Land Remaining Forest Land — N_2O Emissions from Forest Soils
- Cropland Remaining Cropland — Changes in Ecosystem Carbon Stocks
- Lands Converted to Cropland — Changes in All Ecosystem Carbon Stocks
- Grassland Remaining Grassland — Changes in All Ecosystem Carbon Stocks, Non-CO_2 Emissions from Grassland Fires
- Lands Converted to Grassland — Changes in all Ecosystem Carbon Stocks
- Settlements Remaining Settlements — Changes in Organic Soil Carbon Stocks
- Lands Converted to Settlements — Changes in All Ecosystem Carbon Stocks

Future versions of this *GHGIA* will specify more on scope, timing, and plans for phasing in improvements.

6.1 U.S. Land Representation

Information on land-use classification is needed to estimate GHG fluxes associated with activities in the LULUCF sector. The goal of a land representation analysis is to adequately, consistently, completely, and transparently (IPCC, 2006) represent these land-use categories and conversions to estimate changes in carbon stocks and non-CO_2 GHG fluxes.

Land-use categories include forest land, cropland, grassland, wetlands, settlements and other lands (see the General Concepts Applicable to All Land-Use Categories section). Within this *GHGIA*, land-use subcategories are also included for specific activities (e.g., flooded lands and coastal wetlands within the broader wetlands land-use category). These land-use categories and applicable subcategories are further stratified based on land management practices and factors including climate, soils, and ecological zones. See EPA (2025) for additional information pertaining to the definitions used to characterize land-use across the United States within this classification scheme and to estimate land-use areas.

Building upon the discussion in General Concepts Applicable to All Land-Use Categories section, in the United States and consistent with IPCC definitions, managed land is land in which the condition has been directly shaped or maintained through human intervention for purposes such as production (e.g., timber harvesting, livestock grazing, and managed land includes all croplands), infrastructure and development (managed land includes all settlement areas), resource extraction, conservation, or other uses (EPA, 2025). See Tables 6-3 and 6-4 for the land representation breakdown by managed and unmanaged land use and land-use change categories (Walters et al., 2026).

Table 6-3: Managed and Unmanaged Land Area by Land-Use Categories for All 50 States (Thousands of Hectares)

Land Use Categories	1990	2005	2020	2021	2022	2023	2024
Managed Lands	**886,533**	**886,530**	**886,531**	**886,531**	**886,531**	**886,531**	**886,531**
Forest	279,928	280,391	281,105	281,104	281,105	281,106	281,107
Cropland	173,868	165,576	158,658	158,410	158,229	158,141	158,076
Grassland	339,812	339,940	329,729	329,235	328,865	328,631	328,466
Settlements	33,558	40,387	50,115	50,600	50,826	51,049	51,241
Wetlands	38,759	38,919	44,711	44,972	45,298	45,516	45,603
Other	20,608	21,317	22,212	22,211	22,207	22,087	22,038
Unmanaged Lands	**49,708**	**49,711**	**49,710**	**49,710**	**49,710**	**49,710**	**49,710**
Forest	8,886	8,903	8,954	8,956	8,957	8,957	8,958

(continued)

Table 6-3: Managed and Unmanaged Land Area by Land-Use Categories for All 50 States (Thousands of Hectares) (*continued*)

Land Use Categories	1990	2005	2020	2021	2022	2023	2024
Cropland	0	0	0	0	0	0	0
Grassland	25,846	25,909	26,007	26,006	26,005	26,004	26,002
Settlements	0	0	0	0	0	0	0
Wetlands	4,242	4,180	4,055	4,055	4,055	4,056	4,056
Other	10,734	10,718	10,693	10,693	10,693	10,693	10,693
Total Land Areas	**936,241**	**936,241**	**936,241**	**936,241**	**936,241**	**936,241**	**936,241**
Forest	288,814	289,294	290,059	290,059	290,062	290,064	290,065
Cropland	173,868	165,576	158,658	158,410	158,229	158,141	158,076
Grassland	365,658	365,849	355,737	355,241	354,870	354,635	354,469
Settlements	33,558	40,387	50,115	50,600	50,826	51,049	51,241
Wetlands	43,001	43,099	48,766	49,027	49,353	49,572	49,659
Other	31,342	32,035	32,905	32,904	32,900	32,780	32,731

Note: Totals may not sum due to independent rounding.

Table 6-4: Land Use and Land-Use Change for the U.S. Managed Land Base for All 50 States (Thousands of Hectares)

Land Use and Land-Use Change Categories[a]	1990	2005	2020	2021	2022	2023	2024
Total Forest Land	**279,928**	**280,391**	**281,105**	**281,104**	**281,105**	**281,106**	**281,107**
FF	278,868	279,307	279,971	279,979	279,985	279,985	279,988
CF	154	133	106	104	101	101	101
GF	842	861	959	951	943	939	937
WF	14	16	29	33	41	47	48
SF	10	10	21	20	20	21	21
OF	40	66	19	17	15	14	12

(continued)

Table 6-4: Land Use and Land-Use Change for the U.S. Managed Land Base for All 50 States (Thousands of Hectares) (*continued*)

Land Use and Land-Use Change Categories[a]	1990	2005	2020	2021	2022	2023	2024
Total Cropland	**173,868**	**165,576**	**158,658**	**158,410**	**158,229**	**158,141**	**158,076**
CC	161,578	150,307	148,742	149,278	149,768	150,047	150,796
FC	144	67	42	41	40	40	39
GC	11,723	14,662	9,564	8,801	8,156	7,805	7,011
WC	146	191	87	84	75	71	67
SC	89	106	101	97	92	85	80
OC	187	244	121	109	98	94	83
Total Grassland	**339,812**	**339,940**	**329,729**	**329,235**	**328,865**	**328,631**	**328,466**
GG	330,270	319,209	314,085	314,456	315,025	315,516	316,817
FG	577	1,537	3,880	3,859	3,582	3,311	3,035
CG	8,246	17,196	10,575	9,803	9,218	8,757	7,553
WG	258	530	182	208	183	150	149
SG	58	146	150	142	135	134	132
OG	404	1,322	858	767	722	764	780
Total Wetlands	**38,759**	**38,919**	**44,711**	**44,972**	**45,298**	**45,516**	**45,603**
WW	38,077	37,404	38,485	38,769	39,109	39,398	39,513
FW	29	46	167	190	211	228	237
CW	202	536	1,167	1,155	1,133	1,094	1,076
GW	397	848	4,550	4,525	4,523	4,469	4,462
SW	3	1	106	91	90	90	90
OW	51	84	236	242	232	238	226
Total Settlements	**33,558**	**40,387**	**50,115**	**50,600**	**50,826**	**51,049**	**51,241**
SS	30,701	32,067	42,936	43,575	44,137	44,679	45,167

(continued)

Table 6-4: Land Use and Land-Use Change for the U.S. Managed Land Base for All 50 States (Thousands of Hectares) (*continued*)

Land Use and Land-Use Change Categories[a]	1990	2005	2020	2021	2022	2023	2024
FS	257	414	415	406	384	374	371
CS	1,241	3,577	2,651	2,565	2,435	2,300	2,163
GS	1,299	4,096	3,926	3,837	3,666	3,497	3,350
WS	5	31	46	69	66	66	64
OS	55	202	141	147	139	133	126
Total Other Land	**20,608**	**21,317**	**22,212**	**22,211**	**22,207**	**22,087**	**22,038**
OO	19,689	19,004	19,338	19,455	19,519	19,590	19,639
FO	36	70	93	93	93	77	77
CO	298	606	573	516	471	432	394
GO	465	1,404	1,933	1,876	1,848	1,716	1,664
WO	118	223	229	224	230	226	219
SO	3	11	46	47	46	46	45
Total	**886,533**	**886,530**	**886,531**	**886,531**	**886,531**	**886,531**	**886,531**

[a] C = cropland; F = forest land; G = grassland; O = other lands; S = settlements; W = wetlands. Lands remaining in the same land-use category are identified with the land-use abbreviation given twice (e.g., "GG" is grassland remaining grassland), and land-use change categories are identified with the previous land use abbreviation followed by the new land-use abbreviation (e.g., "WO" is wetland converted to other land).

Notes: All land areas reported in this table are considered managed. See the Planned Improvements section of EPA (2025) for discussion on plans to include U.S. territories in future Inventories and address land representation issues with wetlands. Totals may not sum due to independent rounding.

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). See Section 6.1 of EPA (2025) for more details on the specific approach for harmonizing data for the land representation, definitions of land-use categories, and more details on the managed land proxy approach. This *GHGIA* used land-use area data based on an IPCC Approach 3, which reflects spatially explicit data on land use and conversions.

Four primary datasets have been used to estimate land use and land-use change area estimates for the United States: the USDA NRI,[40] the USDA Forest Service (USFS) Forest Inventory and

[40] NRI data are available at https://www.nrcs.usda.gov/nri

Analysis (FIA) database,[41] the Multi-Resolution Land Characteristics Consortium National Land Cover Dataset (NLCD),[42] and the National Oceanic and Atmospheric Administration (NOAA) Coastal Change Analysis Program (C-CAP).[43]

Recalculations

The land representation estimates were recalculated from *the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025) with updated FIA data, National Land Cover Database (NLCD) (U.S. Geological Survey [USGS], 2024), and Coastal Change Analysis Program (C-CAP) (NOAA, 2024a; Walters et al., 2026). In terms of total managed land area, recalculations across the time series were almost zero; however, recalculations resulted in changes in area between the six land-use categories. The greatest changes were seen for wetlands, other lands, and settlements, with wetlands area increasing by an average of 3.5 percent across the 1990–2023 time series, followed by other lands at 3.0 percent and settlements by 1.8 percent. Changes were greater toward the end of the time series (i.e., 2018 onward), particularly for wetlands.

[41] FIA data are available at https://research.fs.usda.gov/programs/fia

[42] NLCD data are available at https://www.mrlc.gov/

[43] C-CAP data are available at https://coast.noaa.gov/digitalcoast/data/ccapregional.html

6.2 Forest Land

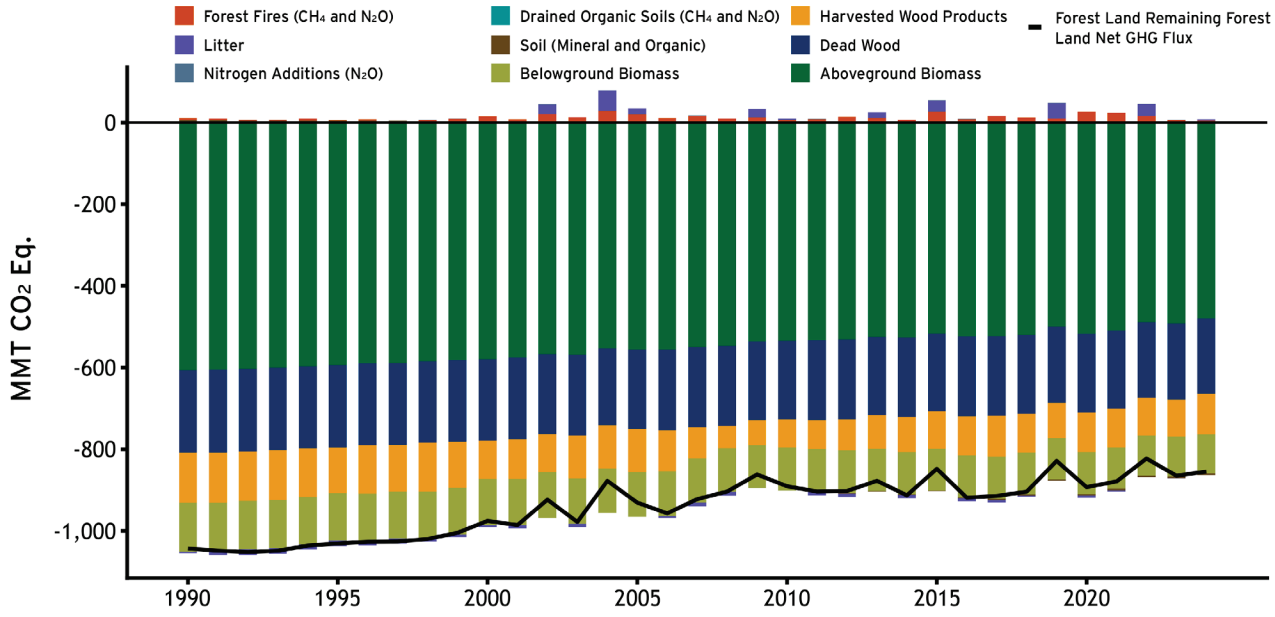
This land-use category includes all land with woody vegetation consistent with the USFS FIA definition of forest, as discussed in EPA (2025). GHG emissions and removals from forest land vary according to site-specific factors, forest or plantation types, stages of stand development, and forest land management practices (IPCC, 2006).

6.2.1 Forest Land Remaining Forest Land (Source Category 4A1)

Forest Land Remaining Forest Land is composed of the following (see Figure 6-2):

- Changes in Forest Carbon Stocks, including harvest wood products (CO_2)
- Non-CO_2 Forest Fires (CH_4, N_2O)
- N_2O from N Additions to Forest Soils (N_2O)
- Emissions from Drained Organic Soils on Forest Land (CH_4, N_2O)

Figure 6-2: Annual Net Forest Land Remaining Forest Land GHG Flux



Note: Each category/bar includes estimates of annual net changes in all ecosystem carbon stocks and non-CO_2 emissions (where indicated). The "Forest Land Remaining Forest Land Net GHG Flux" line reflects the combined total emissions and removals occurring across all forest land remaining forest land carbon pools/subcategories.

Changes in Forest Carbon Stocks

Carbon moves continuously between forest carbon pools and the atmosphere through natural processes such as photosynthesis, respiration, decomposition, and disturbances (e.g., fires or pest outbreaks), as well as through human activities like harvesting, thinning, and replanting. As previously noted in this chapter and consistent with IPCC guidance, net carbon stock change estimates include aboveground biomass, belowground biomass, dead wood, litter and soil organic carbon, and harvested wood products in use and those stored in solid waste disposal sites.

Changes in carbon stocks in the forest ecosystem and harvested wood pools associated with forest land remaining forest land were estimated to result in the net removal of 859.7 MMT CO_2 Eq. in 2024 (see Table 6-5). The estimated net uptake of carbon in the forest ecosystem was 759.2 MMT CO_2 Eq. in 2024 (Walters et al., 2026). As shown in Table 6-5, although there has been net carbon sequestration over the time series, the rate at which carbon is stored per acre (forest carbon density) is slowing, resulting in a decline in the forest land sink strength. This is in large part due to aging U.S. forests and increases in the frequency and severity of forest disturbances. From 1990 to 2024, the main factors affecting carbon fluxes on forest land were forest management, natural disturbances (e.g., wildfire; see Box 6-1), and past and current land-use changes.

Table 6-5: Net Annual CO_2 Flux from Forest Ecosystem Pools in Forest Land Remaining Forest Land and Harvested Wood Pools (MMT CO_2 Eq.)

Carbon Pool	1990	2005	2020	2021	2022	2023	2024
Forest Ecosystem	**(925.2)**	**(842.9)**	**(822.5)**	**(809.1)**	**(746.3)**	**(780.4)**	**(759.2)**
Aboveground Biomass	(606.6)	(555.7)	(517.6)	(510.1)	(489.1)	(491.8)	(480.0)
Belowground Biomass	(119.1)	(109.5)	(102.4)	(101.1)	(97.4)	(97.4)	(95.1)
Dead Wood	(201.5)	(194.3)	(192.9)	(191.1)	(185.3)	(186.5)	(183.8)
Litter	(3.6)	14.3	(6.0)	(3.2)	29.6	(0.8)	3.4
Soil (Mineral)	6.1	2.7	(3.8)	(3.7)	(4.2)	(4.1)	(3.9)
Soil (Organic)	(0.5)	(0.4)	0.2	0.2	0.2	0.1	0.1
Harvested Wood	**(123.8)**	**(106.0)**	**(96.8)**	**(94.7)**	**(92.8)**	**(90.9)**	**(100.5)**
Products in Use	(54.8)	(42.6)	(32.3)	(30.4)	(28.8)	(27.4)	(35.5)
Solid Waste Disposal Sites (SWDS)	(69.0)	(63.4)	(64.5)	(64.3)	(63.9)	(63.5)	(64.9)
Total Net Flux	**(1,049.0)**	**(949.0)**	**(919.3)**	**(903.7)**	**(839.1)**	**(871.3)**	**(859.7)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration. Forest ecosystem does not currently include CO_2 flux from drained organic soil.

Box 6-1: CO_2 Emissions from Forest Fires

The U.S. forest inventory approach implicitly includes all carbon losses caused by disturbances such as forest fires, disease, insect outbreaks, and other drivers of forest biomass loss. In the event that a fire disturbance removes carbon from the forest, the National Forest Inventory reflects this loss of carbon when carbon stocks are remeasured following the disturbance and are compared to prior carbon stock estimates. Due to stakeholder interest, CO_2 emissions (Walters et al., 2026) from fire disturbance are presented in Table 6-6 for informational purposes.

Table 6-6: Estimates of CO_2 (MMT per Year) Emissions from Forest Fires

Emission Source	1990	2005	2020	2021	2022	2023	2024
Fires – CONUS and HI	13.1	30.4	216.8	201.2	84.3	39.7	24.3
Fires – AK	41.9	132.6	0.9	6.9	56.1	14.1	18.1
Total	**55.0**	**163.1**	**217.7**	**208.1**	**140.4**	**53.9**	**42.4**

Note: Totals may not sum due to independent rounding.

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). The methods used to estimate forest carbon stock and stock changes are consistent across the conterminous United States (CONUS), as well as southeast Alaska. Methods differ for Hawaii and interior Alaska, as described by EPA (2025). The U.S. Forest Service FIA is the foundation to estimate carbon stocks and fluxes on forest land in the United States (Domke et al., 2022; Walters et al., 2026; Westfall et al., 2024).

Recalculations

Updated FIA data and implementation of a consistent methodological approach across CONUS resulted in recalculations compared to prior analysis (EPA, 2025). The largest emissions and removal recalculation was seen in dead wood, with an average increase of 10.8 MMT CO_2 Eq. (loss of carbon) (a 5.2 percent decrease in carbon sequestration) across the time series. Overall, total changes in forest carbon stocks resulted in an average change of 10.4 MMT CO_2 Eq. (decrease in carbon sequestration) (−1.1 percent) compared to EPA (2025) data.

Uncertainty

Estimates of forest carbon stocks are based on carbon estimates assigned to each national forest inventory plot. National forest inventory sampling errors and modeling errors introduce uncertainty in these estimates. Uncertainties associated with HWP are introduced from the production, trade, use, storage, and other data and parameters used to estimate HWP.

For this current *GHGIA*, the overall uncertainty of changes in forest carbon stocks 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 1 and Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). This confidence level indicates a range of approximately 9 percent below and 8.9 percent above the total forest net CO_2 flux in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 6-45.

Non-CO_2 Emissions from Forest Fires

As previously noted, the U.S. forest inventory approach used to calculate net forest carbon stocks includes all carbon losses due to fires; therefore, only non-CO_2 emissions from forest fires are presented in this section. These estimates reflect the combined total of both prescribed fires and wildfires. Totals also reflect both emissions from forest fires on forest land remaining forest land and land converted to forest land.

Fire patterns and resulting emissions are very dynamic across the time series. In 2024, non-CO_2 emissions from forest fires were estimated to be 2.5 MMT CO_2 Eq. of CH_4 and 1.9 MMT CO_2 Eq. of N_2O (see Table 6-7). Across the time series, 2015 was the largest fire emissions year with an estimate of 26.6 MMT CO_2 Eq. In the United States, higher fuel loads and the increased length of the fire season and fire weather (e.g., drought, persistent heat) has led to increased fire severity and extent (Hoover & Smith, 2025).

Table 6-7: Non-CO_2 Emissions from Forest Fires (MMT CO_2 Eq.)

Gas	1990	2005	2020	2021	2022	2023	2024
CH_4	3.3	10.4	16.4	15.1	9.5	3.6	2.5
N_2O	2.4	7.2	9.6	9.2	6.2	2.4	1.9
Total	**5.8**	**17.6**	**26.0**	**24.3**	**15.7**	**6.0**	**4.4**

Note: Totals may not sum due to independent rounding.

Methods

Overall calculation methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). Emissions of non-CO_2 gases from forest fires were estimated using forest area burned, fuel, consumption, and emissions data consistent with latest IPCC methods (IPCC, 2019; Walters et al., 2026).

Recalculations

Recalculations were implemented resulting from updates to the Monitoring Trends in Burn Severity (MTBS, n.d.) burned area activity data incorporated into fire non-CO_2 emissions estimates. These recalculations resulted in an average increase of 1.2 MMT CO_2 Eq. in total non-CO_2 forest fire emissions across the time series, representing a 19.8 average percent increase. The largest recalculation increase occurred in 2016, with a 104.7 percent increase compared to EPA (2025) data.

Uncertainty

For this current *GHGIA*, the overall uncertainty of non-CO_2 emissions from forest fires was assumed to be similar to EPA (2025) given the use of the same 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 22 percent below and 22 percent above the CH_4 and N_2O emissions from forest fires in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 6-45.

N_2O Emissions from Nitrogen Additions to Forest Soils

Additions of nitrogen fertilizers to forest land leads to direct and indirect N_2O emissions. Estimates of N_2O emissions from nitrogen additions to forest soils reflect both forest land remaining forest land as well as land converted to forest land.

Direct soil N_2O emissions from forest land remaining forest land and land converted to forest land in 2024 were 0.3 MMT CO_2 Eq. (1.2 kt), and the indirect emissions were 0.1 MMT CO_2 Eq. (0.4 kt) (see Table 6-8). Total emissions for 2024 were 0.4 MMT CO_2 Eq. (1.5 kt), up 455 percent compared to 1990.

Table 6-8: N_2O Fluxes from Forest Soils (MMT CO_2 Eq. and kt N_2O)

N_2O Fluxes from Forest Soils	1990	2005	2020	2021	2022	2023	2024
Direct N_2O Fluxes from Soils							
MMT CO_2 Eq.	0.1	0.3	0.3	0.3	0.3	0.3	0.3
kt N_2O	0.2	1.2	1.2	1.2	1.2	1.2	1.2
Indirect N_2O Fluxes from Soils							
MMT CO_2 Eq.	+	0.1	0.1	0.1	0.1	0.1	0.1
kt N_2O	0.1	0.4	0.4	0.4	0.4	0.4	0.4
Total (MMT CO_2 Eq.)	**0.1**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Total (kt N_2O)	**0.3**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**

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

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). Tier 1 methodology and emission factors were applied.

Recalculations

No recalculations were implemented for this current *GHGIA*.

Uncertainty

N_2O emissions from nitrogen additions to forest soils are influenced not only by nitrogen inputs and the amount of fertilized area but also by many other factors including soil carbon, oxygen availability, soil moisture, pH, temperature, tree planting, and harvesting cycles. The way these factors intersect is complex and leads to high uncertainty in the N_2O flux. Uncertainties exist in the fertilization rates, annual area of forest lands receiving fertilizer, and the emission factors (EPA, 2025).

For this current *GHGIA*, the overall uncertainty of N_2O emissions from nitrogen additions to forest soils is assumed to be similar to EPA (2025) given the use of the same 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 86 percent below and 250 percent above the direct N_2O flux, and 94 percent below and 267 percent above the indirect N_2O flux from nitrogen additions in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 6-45.

Emissions from Drained Organic Soils on Forest Land

The draining of organic soils on forest land leads to N_2O emissions. According to the IPCC (2014), organic soils that have been drained are those that existed as drained in the past and still persist in a drained condition or are newly drained soils within the inventory time series. In forest lands, soils are drained often to support forest management. Emissions from drained organic soils are influenced by land use, geographic region and climate, nutrient status, drainage level, exposure, and disturbance.

Total annual non-CO_2 emissions on forest land with drained organic soils in 2024 are estimated as 0.1 MMT CO_2 Eq. per year, as shown in Table 6-9. Totals reflect both estimates from forest land remaining forest land and land converted to forest land.

Table 6-9: Non-CO_2 Emissions from Drained Organic Forest Soils (MMT CO_2 Eq.)

Non-CO_2 Emissions from Drained Organic Soils	1990	2005	2020	2021	2022	2023	2024
CH_4 (MMT CO_2 Eq.)	+	+	+	+	+	+	+
N_2O (MMT CO_2 Eq.)	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**0.1**	**0.1**	**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.

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). Tier 1 methodology and emission factors were applied in line with IPCC (2014).

Recalculations

No recalculations were implemented for this current *GHGIA*.

Uncertainty

Uncertainties are primarily based on the sampling error associated with drained organic forest soil area and IPCC default emission factors. For the current *GHGIA*, the overall uncertainty of non-CO_2 emissions from drained organic forest soils is assumed to be similar to EPA (2025) given the use of the same methodology and data sources, 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 69 percent below and 82 percent above the CH_4 estimate, and 118 percent below and 132 percent above the N_2O estimate, with a total of uncertainty of 107 percent below and 121 percent above. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 6-45.

6.2.2 Land Converted to Forest Land (Source Category 4A2)

Land converted to forest land captures carbon stock changes on lands converted from non-forest uses to forest. Generally, afforestation and reforestation of forests result in net carbon removals. Changes in carbon stocks in lands converted to forest land were estimated to result in net removal of 100.9 MMT CO_2 Eq. in 2024 (see Table 6-10).

Table 6-10: Net CO_2 Flux from Forest Carbon Pools in Land Converted to Forest Land by Land-Use Change Category (MMT CO_2 Eq.)

Land Use/Carbon Pool	1990	2005	2020	2021	2022	2023	2024
Cropland Converted to Forest Land	**(18.4)**	**(18.2)**	**(18.0)**	**(18.0)**	**(18.0)**	**(18.0)**	**(18.0)**
Aboveground Biomass	(10.1)	(10.0)	(10.0)	(10.0)	(10.0)	(10.0)	(10.0)
Belowground Biomass	(1.7)	(1.7)	(1.7)	(1.7)	(1.7)	(1.7)	(1.7)
Dead Wood	(3.2)	(3.2)	(3.2)	(3.2)	(3.2)	(3.2)	(3.2)
Litter	(3.2)	(3.1)	(3.1)	(3.1)	(3.1)	(3.1)	(3.1)
Mineral soil	(0.2)	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Grassland Converted to Forest Land	**(37.8)**	**(38.2)**	**(38.6)**	**(38.6)**	**(38.6)**	**(38.6)**	**(38.6)**
Aboveground Biomass	(21.6)	(21.7)	(22.0)	(22.0)	(22.0)	(22.0)	(22.0)
Belowground Biomass	(2.7)	(2.7)	(2.7)	(2.7)	(2.7)	(2.7)	(2.7)
Dead Wood	(5.8)	(5.9)	(5.9)	(5.9)	(5.9)	(5.9)	(5.9)
Litter	(7.8)	(7.9)	(8.0)	(8.0)	(8.0)	(8.0)	(8.0)
Mineral soil	+	+	+	+	+	+	+
Other Land Converted to Forest Land	**(4.0)**	**(4.3)**	**(3.9)**	**(3.8)**	**(3.8)**	**(3.8)**	**(3.9)**
Aboveground Biomass	(1.6)	(1.7)	(1.7)	(1.7)	(1.7)	(1.7)	(1.7)
Belowground Biomass	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Dead Wood	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)
Litter	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)
Mineral soil	(0.4)	(0.6)	(0.2)	(0.2)	(0.1)	(0.1)	(0.2)

(continued)

Table 6-10: Net CO_2 Flux from Forest Carbon Pools in Land Converted to Forest Land by Land-Use Change Category (MMT CO_2 Eq.) (*continued*)

Land Use/Carbon Pool	1990	2005	2020	2021	2022	2023	2024
Settlements Converted to Forest Land	**(32.9)**	**(32.7)**	**(32.6)**	**(32.5)**	**(32.5)**	**(32.5)**	**(32.5)**
Aboveground Biomass	(18.8)	(18.7)	(18.6)	(18.6)	(18.6)	(18.6)	(18.6)
Belowground Biomass	(3.1)	(3.1)	(3.1)	(3.1)	(3.1)	(3.1)	(3.1)
Dead Wood	(6.2)	(6.2)	(6.2)	(6.2)	(6.2)	(6.2)	(6.2)
Litter	(4.7)	(4.7)	(4.7)	(4.7)	(4.7)	(4.7)	(4.7)
Mineral soil	+	+	+	+	+	+	+
Wetlands Converted to Forest Land	**(7.7)**	**(7.7)**	**(7.8)**	**(7.8)**	**(7.8)**	**(7.8)**	**(7.8)**
Aboveground Biomass	(4.1)	(4.1)	(4.1)	(4.1)	(4.1)	(4.1)	(4.1)
Belowground Biomass	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)
Dead Wood	(1.5)	(1.5)	(1.5)	(1.5)	(1.5)	(1.5)	(1.5)
Litter	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)
Mineral soil	+	+	+	+	+	+	+
Total Aboveground Biomass Flux	**(56.1)**	**(56.2)**	**(56.3)**	**(56.3)**	**(56.3)**	**(56.3)**	**(56.3)**
Total Belowground Biomass Flux	**(8.5)**	**(8.5)**	**(8.5)**	**(8.5)**	**(8.5)**	**(8.5)**	**(8.5)**
Total Dead Wood Flux	**(17.5)**	**(17.6)**	**(17.6)**	**(17.6)**	**(17.6)**	**(17.6)**	**(17.6)**
Total Litter Flux	**(18.0)**	**(18.1)**	**(18.2)**	**(18.2)**	**(18.2)**	**(18.2)**	**(18.2)**
Total SOC (mineral) Flux	**(0.7)**	**(0.9)**	**(0.3)**	**(0.3)**	**(0.2)**	**(0.2)**	**(0.3)**
Total Net Flux	**(100.8)**	**(101.2)**	**(100.9)**	**(100.9)**	**(100.8)**	**(100.8)**	**(100.9)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.
Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration. Forest ecosystem carbon stock changes from land conversion in interior Alaska, Hawaii, and the U.S. territories are currently included in the forest land remaining forest land section because there is insufficient data to separate changes in forest areas in these regions.

Methods

Methods are based on the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025; Westfall et al., 2024). For all carbon pools, estimates for the 1990–2024 time series were based on the work of Walters et al. (2026).

Recalculations

The methodological approach described above resulted in recalculations to all years of the 1990–2023 time series compared to EPA (2025). Total net carbon flux in this current *GHGIA* is approximately 2.9 percent less compared to prior analysis (EPA, 2025). On average across the time series, total net carbon flux decreased (less sequestration) by 2.6 MMT CO_2 Eq. (—2.5 percent).

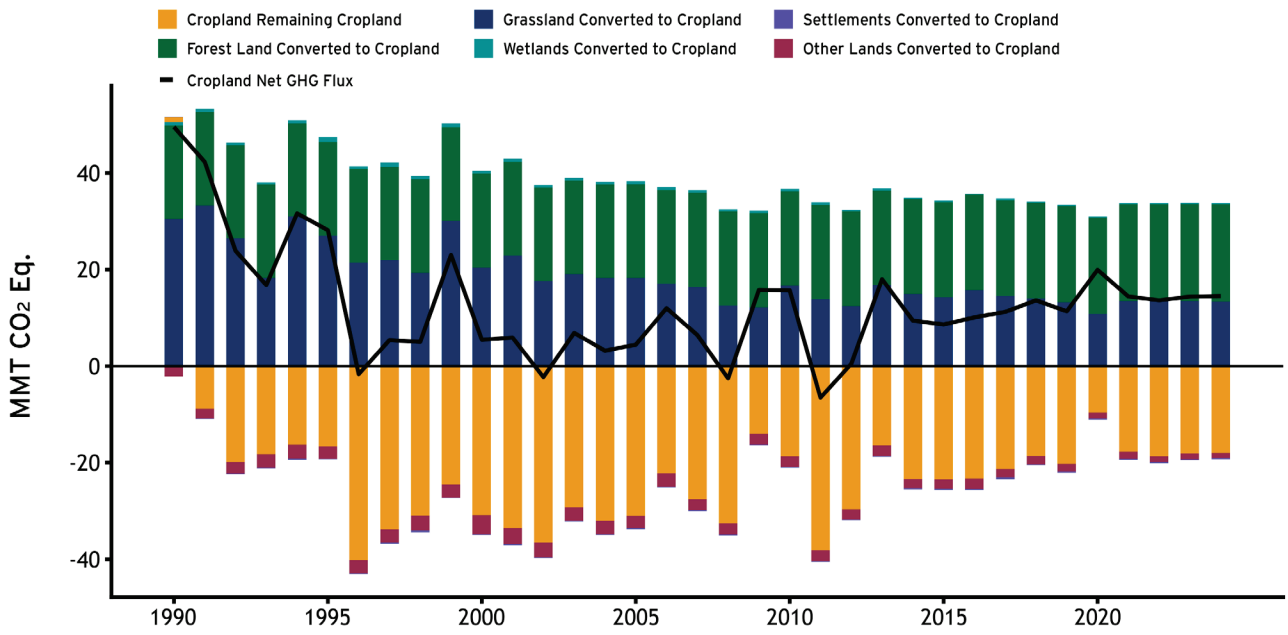
Uncertainty

For this current *GHGIA*, the overall uncertainty of net carbon fluxes from lands converted to forest land is assumed to be similar to EPA (2025) given the use of the same underlying methodology and data sources, calculated using the 2006 IPCC Guidelines Approach 1 and Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). The EPA (2025) confidence level indicates a range of approximately 11 percent below and 11 percent above the total lands converted to forest lands net flux. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 6-45.

6.3 Cropland

This land-use category includes areas used for the production of crops for harvest and includes both cultivated and noncultivated lands, as discussed in EPA (2025). The definition of cropland is based on USDA NRI. The amount of carbon stored in and emitted or removed from permanent cropland depends on crop type, management practices, and soil and climate variables (IPCC, 2006). Figure 6-3 depicts the total emissions and removals contributions occurring on all cropland areas, including cropland remaining cropland and lands converted from each individual land-use category to cropland.

Figure 6-3: Trends in Emissions and Removals from Croplands



Note: Each category/bar includes estimates of annual net changes in all ecosystem carbon stocks for that land-use category. The 'Cropland Net GHG Flux' line reflects the combined total of all emissions and removals occurring across cropland remaining cropland and all land converted to cropland categories.

6.3.1 Cropland Remaining Cropland (Source Category 4B1)

The management of agricultural soils has an impact on soil conditions, soil microbial activity, and plant-soil interactions, and thus net carbon stocks. Example cropland management activities include planting, tillage, crop rotation and cover crop usage, residue management, and soil inputs. In addition to mineral and organic soil carbon, the carbon stored in perennial woody crops and agroforestry systems is also estimated.

In 2024, mineral soils were estimated to sequester 47.3 MMT CO_2 Eq., a 20.7 percent increase in carbon sequestration since 1990. Organic soils contributed emissions of 30.1 MMT CO_2 Eq. in 2024. In total, U.S. agricultural soils in cropland remaining cropland sequestered approximately 18.0 MMT CO_2 Eq. in 2024 (see Table 6-11). Soil organic carbon stock increases in cropland remaining cropland across the time series can be attributed, in part, to increased adoption of cropland management practices such as conservation tillage, winter cover crops, land set-asides, and precision agriculture. Adoption of these practices varies geographically, and research continues to assess the location-specific impact of these practices on soil organic carbon stocks, as well as the permanence of such effects (Ogle et al., 2023).

Table 6-11: Net CO_2 Flux from Live Biomass and Soil Carbon Stock Changes in Cropland Remaining Cropland (MMT CO_2 Eq.)

Carbon Pool	1990	2005	2020	2021	2022	2023	2024
Aboveground Live Biomass	6.1	0.6	0.8	0.8	0.8	0.8	0.8
Mineral Soils	(39.2)	(61.8)	(38.2)	(46.6)	(47.7)	(47.3)	(47.3)
Organic Soils	34.2	30.2	29.4	29.7	29.9	30.0	30.1
Total Net Flux	**1.0**	**(31.0)**	**(9.6)**	**(17.7)**	**(18.6)**	**(18.1)**	**(18.0)**

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

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025).

For biomass (non-woodland herbaceous biomass), a linear regression model with autoregressive integrated moving average (ARIMA) errors was used to forecast the net carbon flux for cropland remaining cropland from 2018 to 2024. Estimates from 1990 to 2017 are consistent with estimates from prior analysis (EPA, 2025).

For organic soils and mineral soils, a linear regression model with ARIMA errors was used to forecast the net carbon flux estimates from 2021 to 2024, since the 1990–2020 time series was based on prior runs from the DayCent model. Estimates from 1990 to 2020 are consistent with estimates from EPA (2025). For Tier 3 mineral soils, the same ARIMA approach was used with the addition of soybean and corn crop yield explanatory variables (surrogate data) (USDA National Agricultural Statistical Service [USDA-NASS], 2026a, 2026b) to forecast net carbon flux from 2021 to 2024.

Recalculations

With the application of the updated forecasting approach, recalculations to the 2017–2023 time series ranged from −0.9 MMT CO_2 Eq. (4.83 percent) to 14.2 MMT CO_2 Eq. (44.38 percent) compared to the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025) for

cropland remaining cropland. The years 2021–2023 saw the greatest recalculations, primarily from mineral soils. There were no recalculations to estimates from 1990 to 2017.

Uncertainty

Uncertainty in cropland remaining cropland emissions estimates stems from uncertainty associated with the management activity data, DayCent model parameterization and structure, and the emissions factors used. Additional uncertainty is contributed by the scaling of modeled emissions at individual NRI points to produce nationally comprehensive emissions estimates in EPA (2025). Finally, lack of estimation of agroforestry systems (currently not estimated due to a lack of activity data) also contributes to overall uncertainty in this source category, though this contribution is currently not quantified.

For this current *GHGIA*, the overall uncertainty of net carbon fluxes from cropland remaining cropland is assumed to be similar to EPA (2025) given the use of the same underlying methodology and data sources that served as the basis for forecasting the end of the time series, calculated using the 2006 IPCC Guidelines Approach 1 and Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). There will be increased uncertainties associated with the use of the ARIMA forecasting approach that are not currently reflected in the uncertainty estimates below. The EPA (2025) confidence level indicates a range of approximately 229 percent below and 229 percent above the total cropland remaining cropland net flux. For the Tier 3 mineral soils carbon stocks (the largest contributor to net carbon flux), the uncertainty range is 112 percent below and 112 percent above, and 65 percent below and 65 percent above for organic soils. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 6-45.

6.3.2 Land Converted to Cropland (Source Category 4B2)

Land converted to cropland reflects emissions and removals associated with conversion of other land categories to cropland primarily to be used to produce food, fiber, or forage. For example, conversion of forest land to cropland (i.e., deforestation) and conversion of grassland to cropland are the most significant sources of emissions from lands converted to croplands in the United States.

In 2024, land converted to cropland emitted approximately 32.6 MMT CO_2 Eq. as shown in Table 6-12. The largest losses of carbon came from aboveground biomass followed by mineral soils. Although total aboveground biomass was the largest loss of carbon in 2024, mineral soils have seen the greatest losses of carbon since 1990.

Table 6-12: Net CO_2 Flux from Soil, Dead Organic Matter, and Biomass Carbon Stock Changes in Land Converted to Cropland by Land-Use Change Category (MMT CO_2 Eq.)

Land Use/Carbon Pool	1990	2005	2020	2021	2022	2023	2024
Grassland Converted to Cropland	**30.5**	**18.3**	**10.8**	**13.5**	**13.5**	**13.5**	**13.4**
Aboveground Live Biomass	3.3	1.2	0.3	0.3	0.3	0.3	0.3
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	0.1	0.1	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	24.6	13.7	8.0	10.6	10.6	10.7	10.6
Organic Soils	2.4	3.3	2.4	2.5	2.5	2.4	2.3
Forest Converted to Cropland	**19.4**	**19.4**	**20.0**	**20.0**	**20.1**	**20.1**	**20.2**
Aboveground Live Biomass	10.9	11.1	11.5	11.6	11.6	11.6	11.6
Belowground Live Biomass	1.9	1.9	2.0	2.0	2.0	2.0	2.0
Dead Wood	3.0	3.0	3.0	3.0	3.1	3.1	3.1
Litter	3.1	3.2	3.3	3.3	3.3	3.3	3.3
Mineral Soils	0.4	0.2	0.1	0.1	0.1	0.1	0.1
Organic Soils	0.1	+	+	+	+	+	+

(continued)

Table 6-12: Net CO_2 Flux from Soil, Dead Organic Matter, and Biomass Carbon Stock Changes in Land Converted to Cropland by Land-Use Change Category (MMT CO_2 Eq.) (*continued*)

Land Use/Carbon Pool	1990	2005	2020	2021	2022	2023	2024
Other Lands Converted to Cropland	**(2.1)**	**(2.6)**	**(1.3)**	**(1.4)**	**(1.3)**	**(1.2)**	**(1.0)**
Aboveground Live Biomass	(0.3)	(0.0)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Mineral Soils	(1.9)	(2.6)	(1.2)	(1.4)	(1.2)	(1.1)	(1.0)
Organic Soils	0.1	0.1	+	+	+	+	+
Settlements Converted to Cropland	**+**	**(0.2)**	**(0.2)**	**(0.2)**	**(0.2)**	**(0.2)**	**(0.2)**
Aboveground Live Biomass	0.1	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Mineral Soils	(0.1)	(0.1)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Cropland	**0.7**	**0.6**	**0.3**	**0.3**	**0.3**	**0.2**	**0.2**
Aboveground Live Biomass	0.0	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Mineral Soils	0.2	0.2	0.2	0.2	0.1	0.1	0.1
Organic Soils	0.5	0.5	0.2	0.2	0.2	0.2	0.2
Aboveground Live Biomass	**14.0**	**12.1**	**11.6**	**11.6**	**11.6**	**11.7**	**11.7**
Belowground Live Biomass	**1.9**	**1.9**	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**
Dead Wood	**3.0**	**3.0**	**3.1**	**3.1**	**3.1**	**3.1**	**3.1**
Litter	**3.2**	**3.2**	**3.3**	**3.3**	**3.3**	**3.3**	**3.4**
Total Mineral Soil Flux	**23.2**	**11.3**	**6.9**	**9.3**	**9.4**	**9.7**	**9.7**
Total Organic Soil Flux	**3.2**	**3.9**	**2.7**	**2.9**	**2.8**	**2.7**	**2.6**
Total Net Flux	**48.5**	**35.5**	**29.6**	**32.2**	**32.3**	**32.5**	**32.6**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

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

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025).

For estimating biomass (aboveground and belowground) and DOM (dead wood and litter), a linear regression model with ARIMA errors was used to forecast the net carbon flux for land converted

to cropland from 2018 to 2024, as described in Box 5-1. Estimates from 1990 to 2017 are consistent with estimates from prior analysis (EPA, 2025).

For estimating organic soils and mineral soils, a linear regression model with ARIMA errors forecasted net carbon fluxes of land converted to cropland from 2021 to 2024. Observations (prior estimates from EPA [2025]) from 1990 to 2020 were used as the basis for forecasting as these were the latest time series available using runs from the DayCent model.

Recalculations

Using the updated forecasting approach resulted in recalculations to the 2018—2023 time series. These recalculations range from −3.1 MMT CO_2 Eq. (−8.66 percent) to 0.3 MMT CO_2 Eq. (1.2 percent) compared to the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025) for land converted to cropland. There were no recalculations to estimates from 1990 to 2017.

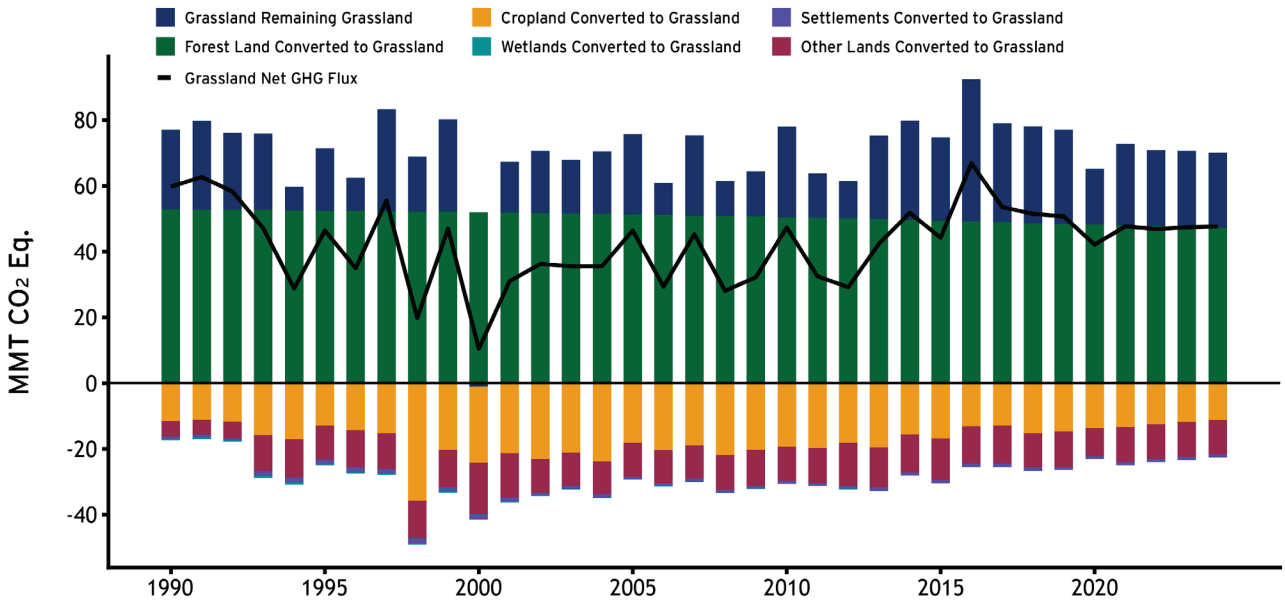
Uncertainty

For this current *GHGIA*, the overall uncertainty of net carbon fluxes from land converted to cropland is assumed to be similar to EPA (2025) given the use of the same underlying methodology and data sources that served as the basis for forecasting the end of the time series, calculated using the 2006 IPCC Guidelines Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). There will be increased uncertainties associated with the use of the ARIMA forecasting approach that are not currently reflected in the uncertainty estimates below. The EPA (2025) confidence level indicates a range of approximately 105 percent below and 105 percent above the total land converted to cropland net flux. Uncertainty assessments 2024 are summarized at the end of this chapter in Table 6-45.

6.4 Grassland

This land-use category includes lands that do not meet the definition of cropland and whose vegetation is dominated by perennial grasses, grass-like plants (i.e., sedges and rushes), forbs, or shrubs, including pasture and rangeland that are primarily used for livestock grazing, and woodlands that do not meet the forest land definition (EPA, 2025). The definition of grassland is based on USDA NRI. Figure 6-4 depicts the total emissions and removals contributions occurring on all grassland areas, including grassland remaining grassland and lands converted from each individual land-use category to grassland.

Figure 6-4: Trends in Emissions and Removals from Grasslands



Note: Each category/bar includes estimates of annual net changes in all ecosystem carbon stocks. Grassland remaining grassland also includes CH_4 and N_2O estimates from grassland fires. The "Grassland Net GHG Flux" line reflects the combined total emissions and removals occurring on grassland remaining grassland and all land converted to grassland categories.

6.4.1 Grassland Remaining Grassland (Source Category 4C1)

Grassland remaining grassland includes carbon stock changes in all six carbon pools, with the largest annual carbon stock changes occurring the mineral and organic soil carbon pool. Grazing intensity and conservation management, as well as climate variability, have an influence on carbon fluxes in grassland ecosystems (EPA, 2025).

In 2024, the net change in total carbon stocks resulted in CO_2 emissions of 22.0 MMT CO_2 Eq., 7.34 percent lower than 1990 (see Table 6-13). These losses are primarily due to net losses in mineral and organic soil carbon. From 1990 to 2024, there has been large variation in carbon

stocks from grassland remaining grasslands. For example, estimates of these total CO_2 fluxes range from 31.0 MMT CO_2 Eq. (emissions) in 1997 to −2.0 MMT CO_2 Eq. (sequestration) in 2000; the average annual change of carbon losses was 20.3 MMT CO_2 Eq. These changes result from variability in weather patterns and the corresponding effects of their interaction with land management practices.

Table 6-13: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes in Grassland Remaining Grassland (MMT CO_2 Eq.)

Carbon Pool	1990	2005	2020	2021	2022	2023	2024
Aboveground Live Biomass	(2.5)	(2.1)	(1.3)	(1.2)	(1.1)	(1.1)	(1.0)
Belowground Live Biomass	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Dead Wood	2.7	2.6	2.6	2.6	2.6	2.5	2.5
Litter	(0.4)	(0.2)	0.1	0.1	0.1	0.1	0.2
Mineral Soils	18.6	18.6	9.3	17.1	15.8	15.7	15.3
Organic Soils	6.1	5.1	5.5	5.4	5.4	5.4	5.5
Total Net Flux	**24.0**	**23.7**	**15.9**	**23.7**	**22.5**	**22.5**	**22.2**

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

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025).

For estimating biomass (woodland aboveground and belowground biomass) and DOM (dead wood and litter), a linear regression model with ARIMA errors was used to forecast the net carbon flux of grassland remaining grassland from 2018 to 2024, as described in Box 5-1 of the *Agriculture* chapter. Estimates from 1990 to 2017 are consistent with estimates from the prior analysis (EPA, 2025).

For estimating organic and mineral soils, a linear regression model with ARIMA errors was used to net carbon fluxes from 2021 to 2024. Years 1990–2020 were used as the basis for forecasting the use of runs from the DayCent model.

For the additions of biosolids, 2023 activity data values were held constant for 2024 due to data availability.

Recalculations

Using the updated forecasting approach resulted in recalculations to the 2017–2023 time series. These recalculations range from 0.04 MMT CO_2 Eq. (0.1 percent difference) to 13.5 MMT CO_2 Eq. (131.6 percent difference) compared to the *Inventory of Greenhouse Gas Emissions and Sinks:*

1990–2023 (EPA, 2025) for grassland remaining grassland. There were no recalculations to estimates from 1990 to 2017.

Uncertainty

For this current *GHGIA*, the overall uncertainty of net carbon fluxes from grassland remaining grassland is assumed to be similar to EPA (2025) given the use of the same underlying methodology and data sources that served as the basis for forecasting the end of the time series, calculated using the 2006 IPCC Guidelines Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). There will be increased uncertainties associated with the use of the ARIMA forecasting approach that are not currently reflected in the uncertainty estimates below. The EPA (2025) confidence level indicates a range of approximately 561 percent below and 561 percent above the total grassland remaining grassland net flux estimate. Uncertainty assessments and 2024 are summarized at the end of this chapter in Table 6-45.

Non-CO_2 Emissions from Grassland Fires

Fires on grassland can occur naturally but are also prescribed for vegetation management and livestock grazing. Biomass burning emits non-CO_2 GHGs such as CH_4 and N_2O, as well as CO and NOx. Any impact of grassland fires on carbon and CO_2 emissions and removals in grassland carbon pools is implicitly captured in the emissions and removals reported in the grassland ecosystem carbon stock changes section above (see Table 6-13). Emissions reported in this section include both emissions from grassland fires occurring on grassland remaining grassland as well as land converted to grassland.

Because the source of grassland fire ignition can be both natural and anthropogenic as part of rangeland management strategies, total burned grassland area and therefore grassland fire emissions vary widely across the time series due to both climatic patterns and shifts in management practices. Methane emissions from grassland fires in 2024 were 0.4 MMT CO_2 Eq., 4.3 percent lower than 2023 emissions and 213.5 percent higher than 1990 emissions, while N_2O emissions from grassland fires in 2024 were 0.3 MMT CO_2 Eq., 4.4 percent lower than 2023 emissions and 213.4 percent higher than 1990 emissions (see Table 6-14).

Table 6-14: CH_4 and N_2O Emissions from Biomass Burning in Grassland (MMT CO_2 Eq.)

Gas	1990	2005	2020	2021	2022	2023	2024
CH_4	0.1	0.4	0.6	0.5	0.3	0.4	0.4
N_2O	0.1	0.4	0.5	0.4	0.3	0.3	0.3
Total	**0.2**	**0.8**	**1.1**	**0.9**	**0.6**	**0.7**	**0.7**

Note: Totals may not sum due to independent rounding.

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). As in the EPA (2025) report and as described in Box 5-1, an autoregressive moving

average (ARMA) extrapolation was applied to extrapolate CH_4 and N_2O emissions from historical emissions estimates for years 2021–2024 of the time series.

Recalculations

No recalculations were implemented for this source category compared to EPA (2025).

Uncertainty

The uncertainty associated with non-CO_2 emissions from biomass burning on grasslands is assumed to be similar to EPA (2025) given the use of the same underlying methodology and data sources. Uncertainty in emissions estimates for this source category were calculated using the 2006 IPCC Guidelines Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). Reported uncertainty is primarily derived from model errors associated with the application of the ARMA extrapolation relative to historical emissions estimates. For both CH_4 and N_2O emissions from grassland fires, the EPA (2025) confidence level indicates a range of approximately 100 percent below and 120 percent above the reported emissions estimates. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 6-45.

6.4.2 Land Converted to Grassland (Source Category 4C2)

Land converted to grassland includes carbon stock changes resulting from the conversation of other land uses to grasslands, which can impact carbon depending on the prior land use category and subsequent management. Forest to grassland conversions result in large emissions due to the loss of forest aboveground biomass, in particular, following conversion, whereas the conversion of cropland to grassland results in gains in soil carbon stocks with the cessation of intensive soil management that occurs in croplands. Across grassland ecosystems more broadly, prevailing weather and rangeland management and livestock grazing intensity can shape grassland vegetation and ecosystem carbon stocks, particularly soil carbon stocks.

In 2024, total land converted to grassland was a net source of emissions with a net carbon stock change of 24.7 MMT CO_2 Eq. (see Table 6-15).

Table 6-15: Net CO_2 Flux from Soil, Dead Organic Matter, and Biomass Carbon Stock Changes for Land Converted to Grassland (MMT CO_2 Eq.)

Land Use/Carbon Pool	1990	2005	2020	2021	2022	2023	2024
Cropland Converted to Grassland	**(11.5)**	**(18.1)**	**(13.6)**	**(13.3)**	**(12.5)**	**(11.9)**	**(11.2)**
Aboveground Live Biomass	(1.4)	(1.3)	(4.4)	(4.4)	(4.4)	(4.4)	(4.4)
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.0)	(0.0)
Litter	(0.1)	+	+	+	+	+	+
Mineral Soils	(10.4)	(18.1)	(10.1)	(9.7)	(8.8)	(8.2)	(7.4)
Organic Soils	0.6	1.4	1.0	0.9	0.9	0.8	0.8
Forest Converted to Grassland	**52.9**	**51.4**	**48.2**	**48.0**	**47.7**	**47.5**	**47.2**
Aboveground Live Biomass	34.3	33.0	30.7	30.6	30.4	30.2	30.0
Belowground Live Biomass	4.7	4.6	4.3	4.3	4.3	4.2	4.2
Dead Wood	5.4	5.3	5.2	5.1	5.1	5.1	5.1
Litter	8.6	8.4	8.0	8.0	8.0	7.9	7.9
Mineral Soils	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Organic Soils	0.0	0.1	0.1	0.1	0.1	0.1	0.1

(continued)

Table 6-15: Net CO_2 Flux from Soil, Dead Organic Matter, and Biomass Carbon Stock Changes for Land Converted to Grassland (MMT CO_2 Eq.) (*continued*)

Land Use/Carbon Pool	1990	2005	2020	2021	2022	2023	2024
Other Lands Converted to Grassland	**(4.8)**	**(10.3)**	**(8.6)**	**(10.7)**	**(10.6)**	**(10.5)**	**(10.5)**
Aboveground Live Biomass	(0.9)	(0.8)	(0.5)	(0.5)	(0.5)	(0.6)	(0.6)
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Mineral Soils	(3.8)	(9.4)	(8.1)	(10.1)	(10.0)	(9.9)	(9.8)
Organic Soils	+	+	0.1	0.1	0.1	0.1	0.1
Settlements Converted to Grassland	**(0.6)**	**(0.9)**	**(0.9)**	**(0.9)**	**(0.9)**	**(0.9)**	**(0.9)**
Aboveground Live Biomass	(0.2)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Litter	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Mineral Soils	(0.1)	(0.3)	(0.4)	(0.5)	(0.5)	(0.5)	(0.5)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Grassland	**(0.4)**	**(0.1)**	**(0.0)**	**(0.0)**	**(0.0)**	**(0.0)**	**(0.0)**
Aboveground Live Biomass	(0.4)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Aboveground Live Biomass	**31.4**	**30.4**	**25.4**	**25.2**	**25.0**	**24.8**	**24.6**
Belowground Live Biomass	**4.7**	**4.5**	**4.2**	**4.2**	**4.2**	**4.2**	**4.2**
Dead Wood	**5.1**	**5.1**	**5.0**	**5.0**	**4.9**	**4.9**	**4.9**

(continued)

Table 6-15: Net CO_2 Flux from Soil, Dead Organic Matter, and Biomass Carbon Stock Changes for Land Converted to Grassland (MMT CO_2 Eq.) (*continued*)

Land Use/Carbon Pool	1990	2005	2020	2021	2022	2023	2024
Litter	8.3	8.2	7.8	7.8	7.7	7.7	7.7
Total Mineral Soil Flux	(14.6)	(27.9)	(18.7)	(20.5)	(19.5)	(18.7)	(17.9)
Total Organic Soil Flux	0.7	1.8	1.4	1.4	1.3	1.2	1.2
Total Net Flux	35.6	21.9	25.1	23.0	23.7	24.1	24.7

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

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

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025).

For estimating biomass (including woodland conversion aboveground and belowground biomass) and DOM (dead wood and litter), a linear regression model with ARIMA errors was used to forecast the net carbon flux of land converted to grassland from 2018 to 2024. Estimates from 1990 to 2017 are consistent with estimates from prior analysis (EPA, 2025).

For estimating organic and mineral soils, a linear regression model with ARIMA errors was used to forecast net carbon fluxes of land converted to grassland from 2021 to 2024. Observations (prior estimates [EPA, 2025]) from 1990 to 2020 were used as the basis for forecasting as these were the latest time series available using runs from the DayCent model.

Recalculations

Using the updated forecasting approach resulted in recalculations to the 2017–2023 time series. These recalculations result in increases to emissions ranging from 1.1 MMT CO_2 Eq. (4.4 percent) to 3.3 MMT CO_2 Eq. (15.7 percent) compared to the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025) for land converted to grassland. There were no recalculations to estimates from 1990 to 2017.

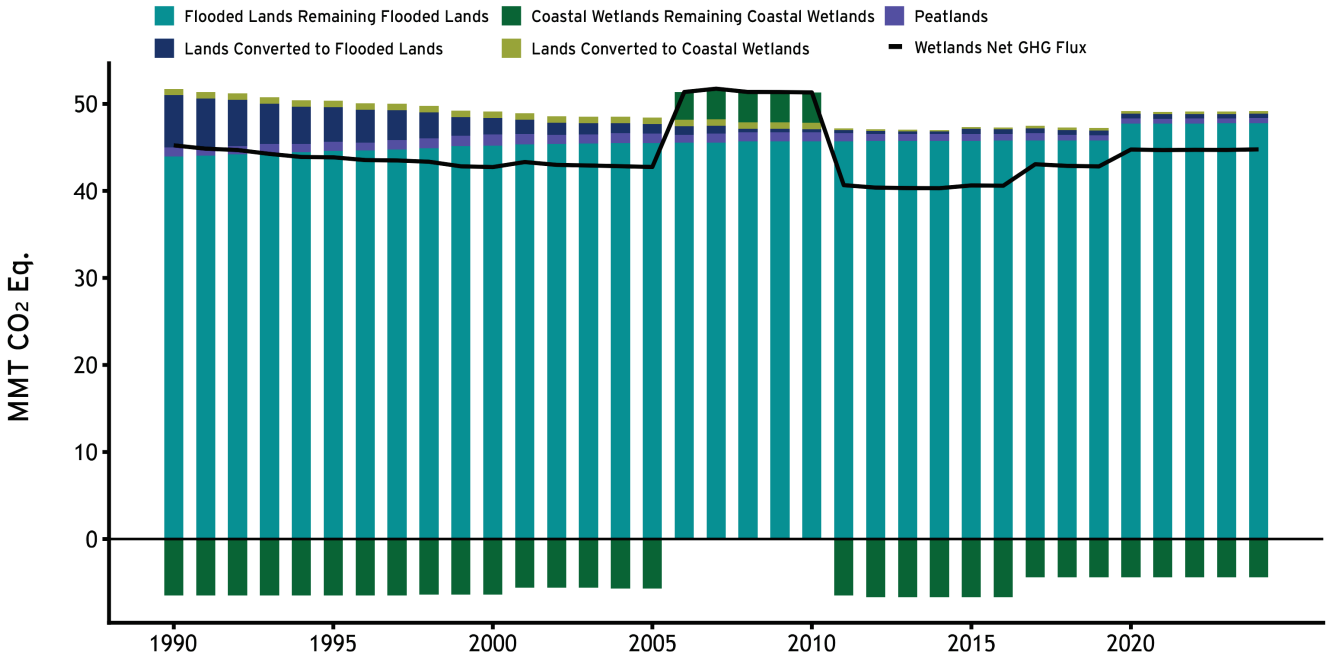
Uncertainty

For this current *GHGIA*, the overall uncertainty of net carbon fluxes from land converted to grassland is assumed to be similar to EPA (2025) given the use of the same underlying methodology and data sources that served as the basis for forecasting the end of the time series, calculated using the 2006 IPCC Guidelines Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). There will be increased uncertainties associated with the use of the ARIMA forecasting approach that are not currently reflected in the uncertainty estimates below. The EPA (2025) confidence level indicates a range of approximately 206 percent below and 206 percent above the total land converted to grassland net flux estimate. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 6-45.

6.5 Wetlands

This land-use category includes areas of peat extraction and land that is covered or saturated by water for all or part of the year, including lakes, reservoirs, and rivers, as well as all coastal wetlands, consistent with EPA (2025) definitions. It is important to note that some lands that are covered or saturated by water are not included as a wetland in this *GHGIA* because they meet the definition of another land-use category, as discussed further by EPA (2025). Figure 6-5 depicts the total emissions and removals contributions occurring on all wetland areas, including wetlands remaining wetlands and lands converted from each individual land-use category to wetlands.

Figure 6-5: Trends in Emissions and Removals from Wetlands



Note: Peatlands estimates include CO_2, CH_4, and N_2O estimates. Coastal wetlands remaining coastal wetlands and lands converted to coastal wetlands includes all net changes in biomass, dead organic matter, soil carbon stocks in coastal wetlands, as well as CH_4 and N_2O (aquaculture) emissions. Flooded lands remaining flooded lands includes total CH_4 emissions and lands converted to flooded lands includes both CO_2 and CH_4 emissions. The "Total Wetlands Net GHG Flux" line reflects the combined total of all emissions and removals occurring across wetland remaining wetland and land converted to wetlands categories.

6.5.1 Wetlands Remaining Wetlands (Source Category 4D1)

Emissions and removals reported in the wetlands remaining wetlands land-use category include:

- Peatlands Remaining Peatlands (CO_2, CH_4, and N_2O)
- Coastal Wetlands Remaining Coastal Wetlands (CO_2, CH_4, N_2O)

- Flooded Land Remaining Flooded Land (CH_4)

Peatlands Remaining Peatlands

Managed peatlands are peatlands that are undergoing active peat extraction. This category includes on-site emissions from peat during extraction and off-site emissions from the horticultural use of peat (IPCC, 2006).

In 2024, total emissions from peatlands remaining peatlands were estimated to be 0.6 MMT CO_2 Eq., comprised mostly of CO_2 (see Table 6-16). Total emissions in 2024 were 12.2 percent greater than total emissions in 2023.

Table 6-16: Emissions from Peatlands Remaining Peatlands (MMT CO_2 Eq.)

Gas	1990	2005	2020	2021	2022	2023	2024
CO_2	1.1	1.1	0.6	0.5	0.6	0.5	0.6
Off-Site	1.0	1.0	0.5	0.5	0.5	0.5	0.5
On-Site	0.1	0.1	+	+	+	+	+
CH_4 (on-site)	+	+	+	+	+	+	+
N_2O (on-site)	+	+	+	+	+	+	+
Total	**1.1**	**1.1**	**0.6**	**0.6**	**0.6**	**0.5**	**0.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). Activity data for peat production in the United States were updated with the latest U.S. Geological Survey data (USGS, 2025) as shown in Tables 6-17 and 6-18, although no new data was available for Alaska.

Table 6-17: Peat Production of Conterminous 48 States (kt)

Type of Deposit	1990	2005	2020	2021	2022	2023	2024
Nutrient-Rich	595.1	657.6	343.4	291.6	308.7	279.0	315.0
Nutrient-Poor	55.4	27.4	10.6	32.4	34.3	31.0	35.0
Total Production	**692.0**	**685.0**	**354.0**	**324.0**	**343.0**	**310.0**	**350.0**

Note: Totals may not sum due to independent rounding.

Table 6-18: Peat Production of Alaska (Thousand Cubic Meters)

Alaska Peat Production	1990	2005	2020	2021	2022	2023	2024
Total Production	**49.7**	**47.8**	**93.1**	**93.1**	**93.1**	**93.1**	**93.1**

Table 6-19: Peat Production Areas (Hectares)

Area of Peat Production	1990	2005	2020	2021	2022	2023	2024
Conterminous 48 States							
Area of Drained Land	6,574	6,508	3,363	3,078	3,259	2,945	3,325
Area of Ditches	346	343	177	162	172	155	175
Total Production	**6,920**	**6,850**	**3,540**	**3,240**	**3,430**	**3,100**	**3,500**
Alaska							
Area of Drained Land	272	99	407	398	398	398	398
Area of Ditches	14	5	21	21	21	21	21
Total Production	**286**	**104**	**428**	**419**	**419**	**419**	**419**

Note: Totals may not sum due to independent rounding.

Recalculations

Recalculations to the years 2022 and 2023 are associated with the use of updated USGS activity data (USGS, 2025). Incorporating the latest peat production data resulted in recalculations across the 2022–2023 recalculation window ranging from −0.01 MMT CO_2 Eq. to −0.08 MMT CO_2 Eq. (an average of -0.4 percent) compared to the *Inventory of Greenhouse Gas Emissions and Sinks: 1990-2023* (EPA, 2025). There were no recalculations to the 1990–2021 time series.

Uncertainty

Uncertainty associated with peatlands emissions stems from the CONUS and Alaska peat production data and other factors used to estimate emissions such as bulk density.

For this current *GHGIA*, the overall uncertainty of peatland emissions is assumed to be similar to EPA (2025) given the use of the same underlying methodology and data sources that served as the basis for forecasting the end of the time series, calculated using the 2006 IPCC Guidelines Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). The EPA (2025) confidence level indicates a range of approximately 15 percent below and 16 percent above the CO_2 estimate, 58 percent below and 80 percent above for CH_4, and 53 percent below and 54 percent above for the N_2O emissions estimate for peatlands. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 6-45.

Coastal Wetlands Remaining Coastal Wetlands

Coastal wetlands include all privately and publicly owned mangroves and tidal marsh wetland areas (seagrasses are not currently estimated) along the oceanic shores that lie within the land representation of the United States. Currently, coastal wetlands in Alaska, Hawaii, and U.S. territories are not estimated. Soil carbon stock changes are estimated in organic and mineral soils, as are CH_4 emissions from microbial activity in certain coastal wetlands with lower salinity. Large emissions often occur when vegetated coastal wetlands are converted to unvegetated open water coastal wetlands following anthropogenic wetland degradation or the loss of coastal wetlands following large storms such as hurricanes or flooding from intense rain events. Conversion of vegetated coastal wetlands to open water results in the immediate loss of soil carbon stocks accumulated over decades to centuries as well as biomass carbon stocks.

In 2024, net biomass carbon fluxes in vegetated coastal wetlands remaining vegetated coastal wetlands resulted in emissions of 1.0 MMT CO_2 Eq., consistent with 2023 emissions but substantially higher than 1990 estimates, when biomass fluxes from vegetated coastal wetlands resulted in a marginal carbon sink (−0.01 MMT Eq. CO_2). Net soil carbon fluxes in vegetated coastal wetlands remaining vegetated coastal wetlands in 2024 resulted in net removals of 12.0 MMT CO_2 Eq., a 0.5 percent decrease in removals relative to 2023 and a 4.1 percent decrease in removals relative to 1990. This trend corresponds to a decrease in overall vegetated coastal wetland area over the time series.

In vegetated coastal wetlands converted to unvegetated open water coastal wetlands, net biomass fluxes in 2024 resulted in net emissions of 0.13 MMT CO_2 Eq., net DOM carbon fluxes resulted in a small flux of emissions of 0.004 MMT CO_2 Eq., and net soil carbon fluxes resulted in emissions of 2.8 MMT CO_2 Eq. Emissions across all carbon pool stock changes in vegetated coastal wetlands converted to unvegetated open water in 2024 were consistent with 2023 estimates, while emissions relative to 1990 emissions were 67.0 percent higher. Trends in these emissions reflect an acceleration in loss of palustrine and estuarine emergent coastal wetlands to open water across the time series.

In contrast, enhanced conversion of unvegetated open water coastal wetlands converted to vegetated coastal wetlands resulted in net removals of 0.2 MMT CO_2 Eq. from biomass carbon fluxes, 0.004 MMT CO_2 Eq. from accumulated DOM, and 2.8 MMT CO_2 Eq. in net soil organic carbon sequestration (see Table 6-20). The magnitude of these removals is consistent with 2023 estimates, while removals relative to 1990 estimates are 467.0 percent higher for biomass carbon fluxes and 530.8 percent higher for soil organic carbon fluxes, while an extremely small net sequestration in the DOM carbon pool present in 1990 was completely eliminated in 2024. The significant conversion restoration of palustrine emergent wetlands from open water coastal wetlands in all climate zones across the time series was the key driver behind these emission trends.

Table 6-20: Emissions and Removals from Coastal Wetlands Remaining Coastal Wetlands (MMT CO_2 Eq.)

Land Use/Carbon Pool	1990	2005	2020	2021	2022	2023	2024
Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands	**(12.6)**	**(12.6)**	**(11.3)**	**(11.2)**	**(11.2)**	**(11.1)**	**(11.1)**
Biomass Carbon Flux	+	+	1.0	1.0	1.0	1.0	1.0
Soil Carbon Flux	(12.5)	(12.6)	(12.3)	(12.2)	(12.1)	(12.1)	(12.0)
Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands	**1.8**	**2.6**	**3.0**	**3.0**	**3.0**	**3.0**	**3.0**
Biomass Carbon Flux	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Dead Organic Matter Carbon Flux	+	+	+	+	+	+	+
Soil Carbon Flux	1.7	2.5	2.8	2.8	2.8	2.8	2.8
Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands	**+**	**(0.1)**	**(0.2)**	**(0.2)**	**(0.2)**	**(0.2)**	**(0.2)**
Biomass Carbon Flux	+	(0.1)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Dead Organic Matter Carbon Flux	+	+	0.0	0.0	0.0	0.0	0.0
Soil Carbon Flux	+	+	+	+	+	+	+
CH_4 Flux from Coastal Wetlands Remaining Coastal Wetlands	**4.2**	**4.2**	**4.1**	**4.0**	**3.9**	**3.9**	**3.8**
N_2O Flux from Aquaculture in Coastal Wetlands (MMT CO_2 Eq.)	**0.1**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Total Biomass Carbon Flux	**+**	**+**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**
Total Dead Organic Matter Carbon Flux	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Total Soil Carbon Flux	**(10.8)**	**(10.1)**	**(9.5)**	**(9.4)**	**(9.2)**	**(9.3)**	**(9.2)**
Total CH_4 Emissions	**4.2**	**4.2**	**4.1**	**4.0**	**3.9**	**3.9**	**3.8**
Total N_2O Emissions	**0.1**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Total Carbon Flux	**(10.8)**	**(10.1)**	**(8.6)**	**(8.5)**	**(8.4)**	**(8.4)**	**(8.3)**
Total Net Flux from Coastal Wetlands Remaining Coastal Wetlands	**(6.5)**	**(5.7)**	**(4.4)**	**(4.4)**	**(4.4)**	**(4.4)**	**(4.4)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). To determine coastal wetland areas, the most recent release of the C-CAP data product containing 2021 land cover estimates was used as the key activity data for the coastal wetland estimates was integrated into emissions calculations for this *GHGIA* (NOAA, 2024b). Coastal wetland areas were derived from 30-meter resolution C-CAP land cover data products for the years 1996, 2001, 2011, 2016 (NOAA, 2024a), and 2021 (NOAA, 2024b). The same seaward and inland geospatial boundaries used to define coastal wetlands in EPA (2025) were applied to the 2021 C-CAP product to isolate coastal wetlands that meet the land-use definition for the purposes of this *GHGIA* consistently across the time series. Area of coastal wetlands remaining coastal wetlands is presented in Table 6-21.

To extend the time series back to 1990 and forecast land cover estimates through 2024, annualized changes in vegetated coastal wetland remaining vegetated coastal wetlands, conversions of vegetated coastal wetland to and from unvegetated open water, and conversions of land from other land uses to coastal wetlands consistent with the closest date of available C-CAP product were applied to each remaining year of the time series. This extrapolation technique mirrors the technique applied in EPA (2025) to fill activity data gaps for years of the time series for which C-CAP data were unavailable.

Table 6-21: Area of Coastal Wetlands Remaining Coastal Wetlands (hectares)

Land Use	1990	2005	2020	2021	2022	2023	2024
Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands	2,975,477	2,985,783	2,893,307	2,893,307	2,853,934	2,834,231	2,814,529
Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands	1,720	2,515	2,854	2,854	2,854	2,854	2,854
Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands	952	1,769	6,438	6,438	6,438	6,438	6,438

Recalculations

In this *GHGIA*, 2021 C-CAP land cover estimates were integrated into estimates, replacing coastal wetland areas from 2017 to 2023 that had been extrapolated from the 2016 C-CAP land cover product (NOAA, 2024a). This resulted in a recalculation of coastal wetland remaining coastal

wetland ecosystem carbon flux estimates as well as CH_4 emission estimates. Across the 2021–2023 recalculation time series, the average annual impact of this recalculation was a 2.0 percent (0.2 MMT CO_2 Eq.) decrease in removals across all carbon fluxes and a 5.8 percent (0.3 MMT CO_2 Eq.) decrease in CH_4 emissions in vegetated coastal wetlands remaining vegetated coastal wetlands. In vegetated coastal wetlands converted to unvegetated open water, the recalculation resulted in an average annual increase in emissions of 92.8 percent (1.4 MMT CO_2 Eq.) across all carbon pool fluxes from 2017 to 2023. In unvegetated open water coastal wetlands converted to vegetated coastal wetlands, the recalculation resulted in a 353.8 percent increase (0.2 MMT CO_2 Eq.) in removals on an annual basis across all carbon fluxes, indicating that extrapolations applied in EPA (2025) to complete the time series underestimated the restoration of coastal wetlands from open water coastal wetland ecosystems.

Uncertainty

Uncertainty in overall coastal wetlands remaining coastal wetlands emissions stems from multiple sources, including the following: error associated in characterizing coastal wetland spatial extent from remote sensing imagery in the NOAA C-CAP land cover product, error in Tier 2 soil and biomass stock change factors derived from the literature, error in IPCC default emission factors (IPCC, 2013) for coastal wetland CH_4 emissions, and error in other IPCC default parameters such as root-to-shoot ratios. Additional uncertainty arises from the following sources, though these sources of error are not currently incorporated into the quantitative estimate of uncertainty presented here, primarily due to lack of data: assignment of climate region to coastal wetland areas by state and delineation of salinity conditions that allow for microbial methanogenesis and CH_4 emissions in estuarine coastal wetlands. See EPA (2025) for more details on uncertainty estimation for this source category.

For this current *GHGIA*, the overall uncertainty of coastal wetlands remaining coastal wetlands emissions and removals is assumed to be similar to EPA (2025) given the use of the same underlying methodology and data sources in this *GHGIA*. Previous uncertainty estimates reported by EPA (2025) were calculated using the 2006 IPCC Guidelines Approach 1: Error Propagation methodology (IPCC, 2006). The Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023 (EPA, 2025) presents upper and lower bounds defining the 95% confidence interval, with a range of approximately 36.5 percent below and 36.5 percent above total flux estimates in vegetated coastal wetlands remaining vegetated coastal wetlands, 32.0 percent below and 32.0 percent above total flux estimates in vegetated coastal wetlands converted to unvegetated open water coastal wetlands, and 33.3 percent below and 33.3 percent above total flux estimates for unvegetated open water coastal wetlands converted to vegetated coastal wetlands. Additional uncertainty information for individual carbon pool fluxes and gases associated with 2024 emissions is available at the end of this chapter in Table 6-45.

N_2O Emissions from Aquaculture in Coastal Wetlands

N_2O emissions from aquaculture production result from the nitrification and denitrification of nitrogen-rich feed. NOAA estimates that the United States produced approximately 688 million pounds of farmed seafood[44] (NOAA, 2026) in 2023, the most recent year of available data.

In 2024, aquaculture production in the United States resulted in 0.1 MMT CO_2 Eq. (0.5 kt N_2O) emissions, as shown in Table 6-22. The industry, and resulting emissions from production, has had fluctuations since 1990.

Table 6-22: N_2O Emissions from Aquaculture in Coastal Wetlands (MMT CO_2 Eq. and kt N_2O)

Emissions	1990	2005	2020	2021	2022	2023	2024
Emissions (MMT CO_2 Eq.)	0.1	0.2	0.1	0.1	0.1	0.1	0.1
Emissions (kt N_2O)	0.4	0.6	0.5	0.5	0.5	0.5	0.5

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). Updated aquaculture production data was available through the most recent two NOAA Fisheries of the United States reports (NOAA, 2025, 2026). Values from 2019 were used to estimate emissions for 2020 and 2021. The production values for 2023 were used to calculate emissions for 2024. Aquaculture production data is presented in Table 6-23.

Table 6-23. Aquaculture Production (kg)

Activity	1990	2005	2020	2021	2022	2023	2024
Production	259,697	350,387	298,336	298,336	300,732	312,072	312,072

Recalculations

Updated activity data, as noted in the Methods section, resulted in recalculations to the years 2022 and 2023. These recalculations resulted in insignificant changes compared to EPA (2025).

Uncertainty

There is uncertainty regarding the estimate due to the inclusion of non-coastal wetland area fish production being included in the total production values used to estimate N_2O emissions. For this current *GHGIA*, the overall uncertainty of aquaculture production emissions is assumed to be similar to EPA (2025) given the use of the same underlying methodology and data sources that served as the basis for forecasting the end of the time series, calculated using the 2006 IPCC Guidelines Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). The EPA (2025) confidence level indicates a range of approximately 116 percent below and

[44] "*Seafood* includes wild and farmed aquatic organisms raised or fished for food production (both marine and freshwater harvested)" (NOAA, 2026).

116 percent above the N_2O emissions estimate for aquaculture production. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 6-45.

Flooded Land Remaining Flooded Land

Flooded land remaining flooded land includes GHG emissions and carbon stock changes occurring on lands that remain flooded over time, including reservoirs and other managed water bodies (IPCC, 2019) often used for hydroelectric power, irrigation, drinking water supply, flood control, and other water management purposes.

Flooded land can emit CH_4due to anaerobic decomposition of submerged organic matter, particularly in recently inundated areas and in systems with high organic inputs, high biomass production, and low oxygen status (IPCC, 2019). The trophic status of waterbodies can have a significant effect on CH_4 potential but is not directly factored into the current *GHGIA* methods. Methane is the primary source of emissions, but CO_2 and N_2O emissions may also occur, depending on hydrologic and nutrient conditions (included in other sections of this *GHGIA*).

Methane emissions from reservoirs totaled 28.2 MMT CO_2 Eq. in 2024. Since 1990, the increase in CH_4 emissions is attributable to reservoirs transitioning from land converted to flooded land into the flooded land remaining flooded land. The majority of emissions are located in tropical climate states, primarily along the Gulf Coast. Emissions from other constructed waterbodies have remained relatively constant since 1990, totaling 17.6 MMT CO_2 Eq. in 2024. Total CH_4emissions from flooded land remaining flooded land were approximately 45.8 MMT CO_2 Eq. Emissions from reservoirs and other constructed waterbodies are presented in Tables 6-24 through 6-27.

Table 6-24: CH_4 Emissions from Flooded Land Remaining Flooded Land—Reservoirs (MMT CO_2 Eq.)

Source	1990	2005	2020	2021	2022	2023	2024
Reservoirs							
Surface Emissions	24.2	25.6	25.8	25.8	25.8	25.8	25.8
Downstream Emissions	2.2	2.3	2.3	2.3	2.3	2.3	2.3
Total	**26.4**	**27.9**	**28.1**	**28.2**	**28.2**	**28.2**	**28.2**

Note: Totals may not sum to due independent rounding.

Table 6-25: Surface and Downstream CH_4 Emissions from Reservoirs in Flooded Land Remaining Flooded Land in 2024 (kt CH_4)

State	Surface	Downstream	Total
Alabama	22	2	**24**
Alaska	1	+	**1**
Arizona	14	1	**15**
Arkansas	25	2	**27**
California	36	3	**40**
Colorado	6	1	**7**
Connecticut	3	+	**3**
Delaware	4	+	**4**
District of Columbia	1	+	**1**
Florida	99	9	**108**
Georgia	33	3	**36**
Hawaii	1	+	**1**
Idaho	11	1	**12**
Illinois	16	1	**17**
Indiana	5	+	**5**
Iowa	6	1	**7**
Kansas	10	1	**10**
Kentucky	14	1	**15**
Louisiana	56	5	**61**
Maine	14	1	**16**
Maryland	12	1	**13**
Massachusetts	5	+	**5**
Michigan	9	1	**10**
Minnesota	20	2	**22**
Mississippi	19	2	**21**
Missouri	16	1	**17**
Montana	15	1	**17**
Nebraska	6	1	**7**
Nevada	17	2	**18**
New Hampshire	3	+	**4**
New Jersey	9	1	**10**
New Mexico	6	1	**7**

(continued)

Table 6-25: Surface and Downstream CH_4 Emissions from Reservoirs in Flooded Land Remaining Flooded Land in 2024 (kt CH_4) (*continued*)

State	Surface	Downstream	Total
New York	17	1	**18**
North Carolina	32	3	**35**
North Dakota	14	1	**15**
Ohio	7	1	**7**
Oklahoma	25	2	**28**
Oregon	15	1	**16**
Pennsylvania	7	1	**8**
Puerto Rico	+	+	**+**
Rhode Island	1	+	**1**
South Carolina	36	3	**40**
South Dakota	12	1	**13**
Tennessee	19	2	**21**
Texas	131	12	**143**
Utah	21	2	**23**
Vermont	5	+	**5**
Virginia	24	2	**27**
Washington	22	2	**23**
West Virginia	3	+	**3**
Wisconsin	11	1	**11**
Wyoming	7	1	**8**
Total	**993**	**83**	**1,006**

+ Does not exceed than 0.5 kt.

Note: Totals may not sum due to independent rounding.

Table 6-26: CH_4 Emissions from Flooded Land Remaining Flooded Land—Other Constructed Waterbodies (MMT CO_2 Eq.)

Source	1990	2005	2020	2021	2022	2023	2024
Other Constructed Waterbodies							
Canals and Ditches	7.2	7.2	7.2	7.2	7.2	7.2	7.2
Freshwater Ponds	10.3	10.4	10.4	10.4	10.4	10.4	10.4
Total	**17.5**	**17.6**	**17.6**	**17.6**	**17.6**	**17.6**	**17.6**

Note: Totals may not sum due to independent rounding.

Table 6-27: CH_4 Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land in 2024 (kt CH_4)

State	Canals and Ditches	Freshwater Ponds	Total
Alabama	+	10.4	**10.8**
Alaska	+	+	**+**
Arizona	1.8	0.6	**2.3**
Arkansas	6.3	8.1	**14.4**
California	21.6	6.4	**28**
Colorado	6.9	3.2	**10.1**
Connecticut	+	1.7	**1.8**
Delaware	1	0.8	**1.8**
District of Columbia	+	+	**+**
Florida	50.4	27	**77.4**
Georgia	2.6	20.6	**23.2**
Hawaii	+	+	**0.7**
Idaho	7.5	1.2	**8.7**
Illinois	8.1	10.4	**18.5**
Indiana	8.7	9.6	**18.3**
Iowa	10.1	8.9	**19**
Kansas	1.8	14.8	**16.6**
Kentucky	0.6	7.5	**8.1**
Louisiana	12.2	4.4	**16.6**
Maine	0.6	3.3	**3.9**
Maryland	+	3.7	**4**
Massachusetts	1.3	2	**3.3**
Michigan	5.6	8.6	**14.2**
Minnesota	14.8	10.1	**24.8**
Mississippi	5.1	12.6	**17.7**
Missouri	6.6	19.8	**26.4**

(continued)

Table 6-27: CH_4 Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land in 2024 (kt CH_4) (*continued*)

State	Canals and Ditches	Freshwater Ponds	Total
Montana	6.4	8.8	**15.2**
Nebraska	7.7	7.3	**14.9**
Nevada	1.8	+	**2.1**
New Hampshire	+	1	**1.1**
New Jersey	2.1	2.5	**4.5**
New Mexico	+	2.1	**2.4**
New York	3.7	7.8	**11.4**
North Carolina	6.2	11.2	**17.4**
North Dakota	4.3	19.3	**23.6**
Ohio	1.8	9.3	**11.1**
Oklahoma	0.9	19	**19.9**
Oregon	5.3	2.3	**7.6**
Pennsylvania	+	4	**4.2**
Puerto Rico	+	+	**+**
Rhode Island	+	+	**+**
South Carolina	3.4	9.6	**13**
South Dakota	4.7	14.8	**19.5**
Tennessee	2.3	6.3	**8.6**
Texas	17.5	30.1	**47.6**
Utah	3.8	1.3	**5.1**
Vermont	+	0.7	**1.1**
Virginia	1.3	7	**8.3**
Washington	3.3	1.5	**4.8**
West Virginia	+	2	**2**
Wisconsin	0.7	3.6	**4.4**
Wyoming	5	3.6	**8.6**
Total	**258.4**	**371.9**	**630.3**

+ Indicates values less than 0.5 kt.

Note: Totals may not sum due to independent rounding.

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). The flooded lands analysis was updated to matriculate existing waterbodies in land converted to flooded land (e.g., dams, reservoirs, ponds) to flooded land remaining flooded land flooded lands based on age consistent with the 20-year transition approach per IPCC guidance. This is reflected in the state-level surface area shown in Tables 6-28 through 6-30.

Table 6-28: State Breakdown of Surface Area in Flooded Land Remaining Flooded Land—Reservoirs (millions of ha)

State	1990	2005	2020	2021	2022	2023	2024
Alabama	0.22	0.22	0.22	0.22	0.22	0.22	0.22
Alaska	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Arizona	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Arkansas	0.25	0.28	0.28	0.28	0.28	0.28	0.28
California	0.34	0.35	0.35	0.35	0.35	0.35	0.35
Colorado	0.07	0.08	0.08	0.08	0.08	0.08	0.08
Connecticut	0.03	0.03	0.04	0.04	0.04	0.04	0.04
Delaware	0.05	0.05	0.05	0.05	0.05	0.05	0.05
District of Columbia	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Florida	0.69	0.70	0.70	0.70	0.70	0.70	0.70
Georgia	0.27	0.28	0.28	0.28	0.28	0.28	0.28
Hawaii	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Idaho	0.16	0.18	0.18	0.18	0.18	0.18	0.18
Illinois	0.15	0.16	0.20	0.20	0.20	0.20	0.20
Indiana	0.05	0.06	0.06	0.06	0.06	0.06	0.06
Iowa	0.08	0.09	0.09	0.09	0.09	0.09	0.09
Kansas	0.09	0.10	0.10	0.10	0.10	0.10	0.10
Kentucky	0.16	0.17	0.17	0.17	0.17	0.17	0.17
Louisiana	0.39	0.40	0.40	0.40	0.40	0.40	0.40
Maine	0.25	0.26	0.27	0.27	0.27	0.27	0.27
Maryland	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Massachusetts	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Michigan	0.15	0.16	0.17	0.17	0.17	0.17	0.17

(continued)

Table 6-28: State Breakdown of Surface Area in Flooded Land Remaining Flooded Land–Reservoirs (millions of ha) (*continued*)

State	1990	2005	2020	2021	2022	2023	2024
Minnesota	0.36	0.36	0.37	0.37	0.37	0.37	0.37
Mississippi	0.17	0.18	0.18	0.18	0.18	0.18	0.18
Missouri	0.18	0.20	0.20	0.20	0.20	0.20	0.20
Montana	0.27	0.28	0.28	0.28	0.28	0.28	0.28
Nebraska	0.06	0.07	0.07	0.07	0.07	0.07	0.07
Nevada	0.08	0.09	0.09	0.09	0.09	0.09	0.09
New Hampshire	0.06	0.06	0.06	0.06	0.06	0.06	0.06
New Jersey	0.12	0.12	0.12	0.12	0.12	0.12	0.12
New Mexico	0.05	0.05	0.05	0.05	0.05	0.05	0.05
New York	0.28	0.28	0.29	0.29	0.29	0.29	0.29
North Carolina	0.39	0.40	0.40	0.40	0.40	0.40	0.40
North Dakota	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Ohio	0.08	0.09	0.09	0.09	0.09	0.09	0.09
Oklahoma	0.26	0.29	0.29	0.29	0.29	0.29	0.29
Oregon	0.20	0.21	0.21	0.21	0.21	0.21	0.21
Pennsylvania	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Puerto Rico	+	+	+	+	+	+	+
Rhode Island	0.02	0.02	0.02	0.02	0.02	0.02	0.02
South Carolina	0.30	0.31	0.32	0.32	0.32	0.32	0.32
South Dakota	0.22	0.22	0.23	0.23	0.23	0.23	0.23
Tennessee	0.18	0.23	0.23	0.23	0.23	0.23	0.23
Texas	0.60	0.67	0.67	0.67	0.67	0.67	0.67
Utah	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Vermont	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Virginia	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Washington	0.22	0.22	0.22	0.22	0.22	0.22	0.22
West Virginia	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Wisconsin	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Wyoming	0.11	0.13	0.13	0.13	0.13	0.13	0.13
Total	**9.06**	**9.51**	**9.63**	**9.63**	**9.63**	**9.64**	**9.64**

+ Indicates values less than 0.005 million ha.

Note: Totals may not sum due to independent rounding.

Table 6-29: State Breakdown of Surface Area in Flooded Land Remaining Flooded Land—Canals and Ditches (hectares)

State	1990	2005	2020	2021	2022	2023	2024
Alabama	1,125	1,125	1,125	1,125	1,125	1,125	1,125
Alaska	217	217	217	217	217	217	217
Arizona	4,221	4,221	4,221	4,221	4,221	4,221	4,221
Arkansas	15,155	15,155	15,155	15,155	15,155	15,155	15,155
California	51,834	51,834	51,834	51,834	51,834	51,834	51,834
Colorado	16,694	16,694	16,694	16,694	16,694	16,694	16,694
Connecticut	249	249	249	249	249	249	249
Delaware	2,405	2,405	2,405	2,405	2,405	2,405	2,405
District of Columbia	4	4	4	4	4	4	4
Florida	121,192	121,192	121,192	121,192	121,192	121,192	121,192
Georgia	6,175	6,175	6,175	6,175	6,175	6,175	6,175
Hawaii	1,170	1,170	1,170	1,170	1,170	1,170	1,170
Idaho	18,080	18,080	18,080	18,080	18,080	18,080	18,080
Illinois	19,394	19,394	19,394	19,394	19,394	19,394	19,394
Indiana	21,026	21,026	21,026	21,026	21,026	21,026	21,026
Iowa	24,174	24,174	24,174	24,174	24,174	24,174	24,174
Kansas	4,397	4,397	4,397	4,397	4,397	4,397	4,397
Kentucky	1,506	1,506	1,506	1,506	1,506	1,506	1,506
Louisiana	29,310	29,310	29,310	29,310	29,310	29,310	29,310
Maine	1,422	1,422	1,422	1,422	1,422	1,422	1,422
Maryland	641	641	641	641	641	641	641
Massachusetts	3,239	3,239	3,239	3,239	3,239	3,239	3,239
Michigan	13,361	13,361	13,361	13,361	13,361	13,361	13,361
Minnesota	35,480	35,480	35,480	35,480	35,480	35,480	35,480
Mississippi	12,196	12,196	12,196	12,196	12,196	12,196	12,196
Missouri	15,804	15,804	15,804	15,804	15,804	15,804	15,804

(continued)

Table 6-29: State Breakdown of Surface Area in Flooded Land Remaining Flooded Land—Canals and Ditches (hectares) (*continued*)

State	1990	2005	2020	2021	2022	2023	2024
Montana	15,453	15,453	15,453	15,453	15,453	15,453	15,453
Nebraska	18,429	18,429	18,429	18,429	18,429	18,429	18,429
Nevada	4,324	4,324	4,324	4,324	4,324	4,324	4,324
New Hampshire	462	462	462	462	462	462	462
New Jersey	4,936	4,936	4,936	4,936	4,936	4,936	4,936
New Mexico	750	750	750	750	750	750	750
New York	8,809	8,809	8,809	8,809	8,809	8,809	8,809
North Carolina	14,873	14,873	14,873	14,873	14,873	14,873	14,873
North Dakota	10,230	10,230	10,230	10,230	10,230	10,230	10,230
Ohio	4,282	4,282	4,282	4,282	4,282	4,282	4,282
Oklahoma	2,068	2,068	2,068	2,068	2,068	2,068	2,068
Oregon	12,753	12,753	12,753	12,753	12,753	12,753	12,753
Pennsylvania	393	393	393	393	393	393	393
Puerto Rico	656	656	656	656	656	656	656
Rhode Island	6	6	6	6	6	6	6
South Carolina	8,064	8,064	8,064	8,064	8,064	8,064	8,064
South Dakota	11,402	11,402	11,402	11,402	11,402	11,402	11,402
Tennessee	5,494	5,494	5,494	5,494	5,494	5,494	5,494
Texas	41,969	41,969	41,969	41,969	41,969	41,969	41,969
Utah	9,196	9,196	9,196	9,196	9,196	9,196	9,196
Vermont	1,120	1,120	1,120	1,120	1,120	1,120	1,120
Virginia	3,138	3,138	3,138	3,138	3,138	3,138	3,138
Washington	8,010	8,010	8,010	8,010	8,010	8,010	8,010
West Virginia	40	40	40	40	40	40	40
Wisconsin	1,779	1,779	1,779	1,779	1,779	1,779	1,779
Wyoming	12,110	12,110	12,110	12,110	12,110	12,110	12,110
Total	**621,220**	**621,220**	**621,220**	**621,220**	**621,220**	**621,220**	**621,220**

Note: Totals may not sum due to independent rounding.

Table 6-30: State Breakdown of Surface Area in Flooded Land Remaining Flooded Land–Freshwater Ponds (hectares)

State	1990	2005	2020	2021	2022	2023	2024
Alabama	56,255	56,619	56,643	56,643	56,643	56,643	56,643
Alaska	2,192	2,199	2,199	2,199	2,199	2,199	2,199
Arizona	3,016	3,056	3,069	3,069	3,069	3,069	3,069
Arkansas	43,706	44,041	44,043	44,043	44,043	44,043	44,043
California	34,981	35,155	35,230	35,230	35,236	35,242	35,245
Colorado	17,161	17,380	17,412	17,412	17,412	17,415	17,425
Connecticut	9,464	9,534	9,539	9,539	9,539	9,539	9,539
Delaware	4,099	4,102	4,102	4,102	4,102	4,102	4,102
District of Columbia	11	11	11	11	11	11	11
Florida	147,166	147,252	147,283	147,288	147,290	147,290	147,293
Georgia	110,800	112,443	112,521	112,521	112,521	112,521	112,524
Hawaii	921	929	931	931	931	931	931
Idaho	6,293	6,394	6,394	6,395	6,395	6,395	6,395
Illinois	56,236	56,752	56,844	56,845	56,849	56,850	56,850
Indiana	51,757	52,209	52,286	52,286	52,295	52,302	52,307
Iowa	45,414	47,366	48,676	48,770	48,800	48,809	48,822
Kansas	78,258	80,482	80,581	80,603	80,604	80,618	80,637
Kentucky	40,608	40,967	41,001	41,001	41,001	41,001	41,001
Louisiana	24,017	24,137	24,153	24,153	24,153	24,154	24,162
Maine	18,046	18,070	18,079	18,079	18,079	18,079	18,079
Maryland	20,045	20,214	20,274	20,276	20,277	20,277	20,278
Massachusetts	10,733	10,776	10,826	10,827	10,831	10,833	10,836
Michigan	46,821	46,960	47,011	47,011	47,011	47,011	47,011
Minnesota	54,666	54,905	54,982	54,991	54,999	54,999	54,999
Mississippi	68,315	68,638	68,765	68,771	68,779	68,789	68,792
Missouri	104,956	108,267	108,399	108,406	108,411	108,417	108,430
Montana	47,596	47,942	47,963	47,963	47,963	48,049	48,049

(continued)

Table 6-30: State Breakdown of Surface Area in Flooded Land Remaining Flooded Land–Freshwater Ponds (hectares) (*continued*)

State	1990	2005	2020	2021	2022	2023	2024
Missouri	104,956	108,267	108,399	108,406	108,411	108,417	108,430
Montana	47,596	47,942	47,963	47,963	47,963	48,049	48,049
Nebraska	38,290	39,492	39,720	39,729	39,733	39,742	39,752
Nevada	1,833	1,836	1,875	1,880	1,883	1,887	1,887
New Hampshire	5,084	5,184	5,228	5,229	5,229	5,229	5,229
New Jersey	13,577	13,603	13,617	13,617	13,617	13,617	13,617
New Mexico	11,202	11,226	11,251	11,254	11,258	11,260	11,260
New York	42,126	42,381	42,494	42,499	42,499	42,510	42,510
North Carolina	60,787	61,231	61,315	61,317	61,318	61,318	61,318
North Dakota	105,261	105,382	105,502	105,510	105,513	105,524	105,528
Ohio	50,221	50,562	50,787	50,799	50,801	50,818	50,820
Oklahoma	101,972	103,867	103,960	103,966	103,974	103,977	103,996
Oregon	12,490	12,643	12,690	12,690	12,690	12,690	12,707
Pennsylvania	21,686	21,917	21,955	21,956	21,956	21,956	21,956
Puerto Rico	406	406	406	406	406	406	406
Rhode Island	2,198	2,206	2,213	2,213	2,213	2,213	2,213
South Carolina	51,627	52,222	52,455	52,455	52,455	52,455	52,455
South Dakota	80,332	80,600	80,679	80,687	80,687	80,702	80,709
Tennessee	33,954	34,346	34,390	34,390	34,391	34,391	34,391
Texas	161,800	164,486	164,580	164,581	164,581	164,588	164,589
Utah	6,898	6,983	6,994	6,994	6,994	7,004	7,004
Vermont	3,509	3,576	3,587	3,587	3,587	3,587	3,587
Virginia	38,292	38,350	38,354	38,354	38,354	38,354	38,354
Washington	7,943	8,071	8,113	8,115	8,116	8,117	8,117
West Virginia	10,738	10,853	10,887	10,887	10,887	10,887	10,893
Wisconsin	19,591	19,738	19,747	19,747	19,747	19,747	19,757
Wyoming	19,059	19,280	19,377	19,379	19,383	19,421	19,429
Total	**2,004,411**	**2,027,241**	**2,031,395**	**2,031,606**	**2,031,716**	**2,031,987**	**2,032,157**

Note: Totals may not sum due to independent rounding.

Recalculations

No recalculations were implemented for this current *GHGIA*.

Uncertainty

Uncertainty stems from the spatial data (area estimates) from the underlying activity data (e.g., National Hydrography Dataset [NHD], National Wetlands Inventory [NWI], and the National Inventory of Dams [NID]). For this current *GHGIA*, the overall uncertainty of CH_4emissions from flooded land remaining flooded land is assumed to be similar to EPA (2025) given the use of the same underlying methodology and data sources that served as the basis for forecasting the end of the time series, calculated using the 2006 IPCC Guidelines Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). The EPA (2025) confidence level indicates a range of approximately 0.8 percent below and 2 percent above the reservoir CH_4 estimate and 1.4 percent below and 1.2 percent above the other constructed waterbodies CH_4 estimate. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 6-45.

6.5.2 Land Converted to Wetlands (Source Category 4D2)

Land Converted to Coastal Wetlands

Land converted to coastal wetlands includes carbon stock changes associated with lands converted from other land uses to coastal wetlands, often through restoration activities, sediment deposition, or other natural processes that reestablish tidal influence. In the United States, certain regions see increased carbon sequestration through restoration initiatives. Conversion of cropland, grassland, settlements, and other land to coastal wetlands generally results in increased carbon sinks due to larger biomass and soil carbon stocks and accumulation rates in coastal wetlands relative to carbon stocks in other land-use categories. In contrast, conversion of forests to coastal wetlands results in loss of biomass and DOM carbon stocks, buffered to some extent by increases in soil carbon stocks when forests are converted to coastal wetlands. These competing dynamics have resulted in net fluxes from land converted to coastal wetland oscillating between marginal source and sink status, largely following trends in forest area converted to coastal wetlands.

In 2024, conversion of lands from other land uses to coastal wetlands resulted in emissions of 0.20 MMT CO_2 Eq., losses of DOM following land-use conversion to coastal wetlands resulted in emissions of 0.04 MMT CO_2 Eq., and soil carbon stock changes across all land-use categories converted to coastal wetlands resulted in net removals of 0.12 MMT CO_2 Eq. Methane emissions from lands converted to coastal wetlands were 0.17 MMT CO_2 Eq. in 2024, predominantly driven by the conversion of forests to palustrine scrub/shrub and palustrine emergent wetlands. Although there was no change in biomass carbon stock losses or DOM carbon stock losses resulting from land-use conversion to coastal wetlands in 2024 relative to 2023, emissions resulting from stock changes in these two carbon pools declined by 67.5 percent and 60.1 percent since 1990, respectively. CO_2 removals in soil carbon stocks declined by 7.6 percent in 2024 relative to 2023, while annual soil carbon sequestration rates declined by 52.4 percent across the time series. Methane emissions from lands converted to coastal wetlands decreased by 3.9 percent relative to 2023 and by 39.3 percent since 1990. See Table 6-31.

Table 6-31: Net GHG Flux from Carbon Stock Changes in Land Converted to Vegetated Coastal Wetlands (MMT CO_2 Eq.)

Land Use/Carbon Pool	1990	2005	2020	2021	2022	2023	2024
Cropland Converted to Vegetated Coastal Wetlands	+	+	+	+	+	+	+
Biomass Carbon Stock	+	+	+	+	+	+	+
Soil Carbon Stock	+	+	+	+	+	+	+
Forest Land Converted to Vegetated Coastal Wetlands	0.5	0.5	0.1	0.1	0.1	0.1	0.1
Biomass Carbon Stock	0.6	0.6	0.2	0.2	0.2	0.2	0.2
Dead Organic Matter Carbon Flux	0.1	0.1	+	+	+	+	+
Soil Carbon Stock	(0.2)	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Grassland Converted to Vegetated Coastal Wetlands	+	+	+	+	+	+	+
Biomass Carbon Stock	+	+	+	+	+	+	+
Soil Carbon Stock	+	+	+	+	+	+	+
Other Land Converted to Vegetated Coastal Wetlands	+	+	+	+	+	+	+
Biomass Carbon Stock	+	+	+	+	+	+	+
Soil Carbon Stock	+	+	+	+	+	+	+
Settlements Converted to Vegetated Coastal Wetlands	+	+	+	+	+	+	+
Biomass Carbon Stock	+	+	+	+	+	+	+
Soil Carbon Stock	+	+	+	+	+	+	+
Total Biomass Flux	0.6	0.6	0.2	0.2	0.2	0.2	0.2
Total Dead Organic Matter Flux	0.1	0.1	+	+	+	+	+
Total Soil Carbon Flux	(0.3)	(0.3)	(0.2)	(0.2)	(0.1)	(0.1)	(0.1)
Total Carbon Flux	0.5	0.5	0.1	0.1	0.1	0.1	0.1
Total CH_4 Emissions from Land Converted to Coastal Wetlands	0.3	0.3	0.2	0.2	0.2	0.2	0.2
Total Net Flux	0.7	0.7	0.3	0.3	0.3	0.3	0.3

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

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

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). To determine coastal wetland areas and conversion of lands from other land uses to coastal wetlands, the most recent release of the C-CAP data product containing 2021 land cover estimates was used as the key activity data for the coastal wetland estimates was integrated into emissions calculations for this *GHGIA* (NOAA, 2024b). Coastal wetland areas were derived from 30-meter resolution C-CAP land cover data products, with coastal areas in the 2016 C-CAP product (NOAA, 2024a) compared to the 2021 C-CAP product to identify land areas that had been converted from other land uses to coastal wetlands over the intervening 5-year period. The same seaward and inland geospatial boundaries used to define coastal wetlands in EPA (2025) were applied to the 2021 C-CAP product to isolate coastal wetlands that meet the land-use definition for the purposes of this *GHGIA* consistently across the time series.

To extend the time series back to 1990 and forecast land cover estimates through 2024, annualized changes in vegetated coastal wetland remaining vegetated coastal wetlands, conversions of land from other land uses to coastal wetlands consistent with the closest date of available C-CAP product were applied to each remaining year of the time series. This extrapolation technique mirrors the technique applied in EPA (2025) to fill activity data gaps for years of the time series for which C-CAP data are unavailable.

Recalculations

In this *GHGIA*, 2021 C-CAP land cover estimates were integrated into estimates, replacing coastal wetland areas from 2017 to 2023 that had been extrapolated from the 2016 C-CAP land cover product (NOAA, 2024a). This resulted in a recalculation of lands converted to coastal wetlands ecosystem carbon flux estimates as well as CH_4 emission estimates from lands converted to coastal wetlands. Across the 2021–2023 recalculation time series, the average annual impact of this recalculation on lands converted to coastal wetlands biomass flux estimates was a 58.7 percent (0.073 MMT CO_2 Eq.) increase in emissions, the impact on soil carbon fluxes was a 0.7 percent (0.001 MMT CO_2 Eq.) increase in removals, and the impact on DOM carbon fluxes was a 53.6 percent (0.015 MMT CO_2 Eq.) increase in emissions. Finally, the impact of this recalculation on CH_4 emissions in lands converted to coastal wetlands was an average annual increase in emissions of 4.7 percent (0.008 MMT CO_2 Eq.) across the 2017–2023 recalculation period.

Uncertainty

Alongside the factors contributing to uncertainty in emissions and removals estimates listed in the coastal wetlands remaining coastal wetlands emissions section of this *GHGIA*, additional uncertainty is contributed by the use of default carbon stock factors (IPCC, 2006, 2013) that are used to estimate carbon stocks occurring on converted lands prior to conversion to coastal wetlands.

For this current *GHGIA*, the overall uncertainty in lands converted to coastal wetlands emissions and removals estimates is assumed to be similar to EPA (2025) given the use of the same underlying methodology and data sources in this *GHGIA*. Previous uncertainty estimates reported by EPA (2025) were calculated using the 2006 IPCC Guidelines Approach 1: Error Propagation methodology (IPCC, 2006). The *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025) presents upper and lower bounds defining the 95% confidence interval, with a range

of approximately 42.2 percent below and 42.2 percent above reported emissions estimates for total emissions in 2024, including carbon fluxes in biomass, soil, and DOM pools as well as CH_4 emissions estimates. Additional uncertainty information for individual carbon pool fluxes and gases associated with 2024 emissions and removals is available at the end of this chapter in Table 6-45.

Land Converted to Flooded Lands

Land converted to flooded lands includes those lands converted to flooded land waterbodies such as reservoirs. As discussed in the flooded land remaining flooded land category, CH_4, CO_2, and N_2O are produced in flooded land waterbodies through the natural breakdown of organic matter; however, N_2O emissions are included in other categories.

In 2024, total CH_4 emissions from land converted to flooded land (including both reservoirs and freshwater ponds) were 0.2 MMT CO_2 Eq., while total CO_2 emissions were 0.3 MMT CO_2 Eq., as shown in Tables 6-32 through 6-37. Consistent with the trend discussed in flooded land remaining flooded land, there has been a decrease in emissions from land converted flooded land as waterbodies have transitioned from land converted to flooded land into the flooded land remaining flooded land.

Table 6-32: CH_4 Emissions from Land Converted to Flooded Land—Reservoirs (MMT CO_2 Eq.)

Source	1990	2005	2020	2021	2022	2023	2024
Reservoirs							
Surface Emissions	2.4	0.4	0.2	0.2	0.2	0.2	0.2
Downstream Emissions	0.2	+	+	+	+	+	+
Total	**2.6**	**0.5**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding.

Table 6-33: CO_2 Emissions from Land Converted to Flooded Land—Reservoirs (MMT CO_2 Eq.)

Source	1990	2005	2020	2021	2022	2023	2024
Reservoirs	3.2	0.6	0.3	0.3	0.3	0.3	0.3

Table 6-34: Methane and CO_2 Emissions from Reservoirs in Land Converted to Flooded Land in 2024 (kt CH_4; kt CO_2)

	CH_4			CO_2
State	Surface	Downstream	Total	Surface
Alabama	+	+	+	+
Alaska	+	+	+	+
Arizona	+	+	+	+
Arkansas	+	+	+	+
California	+	+	+	+
Colorado	+	+	+	1.3
Connecticut	+	+	+	+
Delaware	+	+	+	+
District of Columbia	+	+	+	+
Florida	+	+	+	7.5
Georgia	+	+	+	0.8
Hawaii	+	+	+	+
Idaho	+	+	+	1.5
Illinois	+	+	+	4.1
Indiana	+	+	+	+
Iowa	+	+	+	0.7
Kansas	+	+	+	+
Kentucky	+	+	+	+
Louisiana	+	+	+	+
Maine	+	+	+	+
Maryland	+	+	+	+
Massachusetts	+	+	+	4.3
Michigan	+	+	+	+
Minnesota	4.6	+	**5.0**	203.2
Mississippi	+	+	+	+
Missouri	+	+	+	+
Montana	+	+	+	+

(continued)

Table 6-34: Methane and CO_2 Emissions from Reservoirs in Land Converted to Flooded Land in 2024 (kt CH_4; kt CO_2) (*continued*)

	CH_4			CO_2
State	Surface	Downstream	Total	Surface
Nebraska	+	+	+	0.9
Nevada	+	+	+	+
New Hampshire	+	+	+	+
New Jersey	+	+	+	+
New Mexico	+	+	+	0.7
New York	+	+	+	+
North Carolina	+	+	+	1.8
North Dakota	0.5	+	**0.5**	22.2
Ohio	+	+	+	+
Oklahoma	+	+	+	+
Oregon	+	+	+	+
Pennsylvania	+	+	+	0.5
Puerto Rico	+	+	+	+
Rhode Island	+	+	+	+
South Carolina	+	+	+	+
South Dakota	+	+	+	+
Tennessee	+	+	+	+
Texas	+	+	+	+
Utah	+	+	+	0.8
Vermont	+	+	+	+
Virginia	+	+	+	+
Washington	+	+	+	+
West Virginia	+	+	+	+
Wisconsin	+	+	+	+
Wyoming	+	+	+	0.5

+ Does not exceed 0.05 kt.

Table 6-35: CH_4 Emissions from Land Converted to Flooded Land—Other Constructed Waterbodies (MMT CO_2 Eq.)

Source	1990	2005	2020	2021	2022	2023	2024
Freshwater Ponds	0.1	+	+	+	+	+	+

+ Does not exceed 0.05 MMT CO_2 Eq.

Table 6-36: CO_2 Emissions from Land Converted to Flooded Land—Other Constructed Waterbodies (MMT CO_2 Eq.)

Source	1990	2005	2020	2021	2022	2023	2024
Freshwater Ponds	0.1	+	+	+	+	+	+

+ Does not exceed 0.05 MMT CO_2 Eq.

Table 6-37: Methane and CO_2 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land in 2024 (MT CO_2 Eq.)

	Freshwater Ponds		
State	CH_4	CO_2	Total
Alabama	1	1	**1**
Alaska	+	+	**+**
Arizona	+	+	**+**
Arkansas	1	1	**3**
California	27	32	**59**
Colorado	224	177	**401**
Connecticut	+	+	**1**
Delaware	+	+	**1**
District of Columbia	+	+	**+**
Florida	+	+	**+**
Georgia	247	445	**693**
Hawaii	+	+	**+**
Idaho	4	5	**9**
Illinois	73	63	**136**
Indiana	+	+	**+**

(continued)

Table 6-37: Methane and CO_2 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land in 2024 (MT CO_2 Eq.) (*continued*)

	Freshwater Ponds		
State	CH_4	CO_2	Total
Iowa	224	214	**438**
Kansas	274	287	**561**
Kentucky	13	13	**26**
Louisiana	17	34	**50**
Maine	1	1	**2**
Maryland	44	46	**90**
Massachusetts	289	264	**553**
Michigan	48	35	**84**
Minnesota	170	124	**294**
Mississippi	339	525	**864**
Missouri	112	117	**229**
Montana	69	50	**119**
Nebraska	352	310	**662**
Nevada	83	65	**148**
New Hampshire	90	66	**156**
New Jersey	+	+	**+**
New Mexico	58	59	**117**
New York	46	34	**80**
North Carolina	141	147	**288**
North Dakota	207	151	**358**
Ohio	172	163	**335**
Oklahoma	219	239	**458**
Oregon	+	+	**1**
Pennsylvania	20	19	**39**
Puerto Rico	+	+	**+**

(continued)

Table 6-37: Methane and CO_2 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land in 2024 (MT CO_2 Eq.) (*continued*)

	Freshwater Ponds		
State	CH_4	CO_2	Total
Rhode Island	+	+	+
South Carolina	47	49	**95**
South Dakota	424	310	**734**
Tennessee	10	11	**21**
Texas	85	145	**230**
Utah	51	38	**89**
Vermont	16	11	**27**
Virginia	11	12	**23**
Washington	90	87	**177**
West Virginia	109	114	**223**
Wisconsin	55	40	**96**
Wyoming	130	95	**225**
Total	**4,594**	**4,600**	**9,194**

+ Does not exceed 0.5 MT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). The flooded lands analysis was updated to matriculate existing waterbodies in land converted to flooded land (e.g., dams, reservoirs, ponds) to flooded land remaining flooded land flooded lands based on age, consistent with the 20-year transition approach per IPCC guidance (see Tables 6-38 and 6-39). This is reflected in the state-level surface area tables below. No new data from NWI, NHD, NID, or other activity data were incorporated.

Table 6-38: State Breakdown of Surface Area in Land Converted to Flooded Land—Reservoirs (thousands of ha)

State	1990	2005	2020	2021	2022	2023	2024
Alabama	8.6	0.1	+	+	+	+	+
Alaska	0.6	+	+	+	+	+	+
Arizona	0.1	0.1	+	+	+	+	+
Arkansas	33.5	2.9	+	+	+	+	+
California	15.7	1.8	0.1	0.1	0.1	0.1	0.1
Colorado	7.4	1.3	0.4	0.4	0.4	0.4	0.3
Connecticut	1.2	1.1	+	+	+	+	+
Delaware	+	+	+	+	+	+	+
District of Columbia	+	+	+	+	+	+	+
Florida	10.1	3.2	1.5	1.3	1.3	1.3	0.7
Georgia	15.6	0.0	0.1	0.1	0.1	0.1	0.1
Hawaii	+	+	+	+	+	+	+
Idaho	17.8	1.0	0.4	0.4	0.4	0.4	0.4
Illinois	49.3	39.2	1.3	0.8	0.8	0.8	0.8
Indiana	9.8	0.2	+	+	+	+	+
Iowa	9.5	2.2	0.5	0.5	0.4	0.4	0.1
Kansas	9.7	0.4	0.1	0.1	+	+	+
Kentucky	3.8	0.1	+	+	+	+	+
Louisiana	8.8	3.0	0.9	+	+	+	+
Maine	11.4	4.5	+	+	+	+	+
Maryland	0.6	+	+	+	+	+	+
Massachusetts	1.4	0.2	1.0	1.0	1.0	1.0	1.0
Michigan	11.9	1.0	0.1	0.1	0.1	0.1	0.1

(continued)

Table 6-38: State Breakdown of Surface Area in Land Converted to Flooded Land—Reservoirs (thousands of ha) (*continued*)

State	1990	2005	2020	2021	2022	2023	2024
Minnesota	8.1	5.1	53.8	53.7	53.5	54.3	54.3
Mississippi	5.2	2.5	0.1	0.1	0.1	0.1	0.1
Missouri	16.3	0.1	+	+	+	+	+
Montana	14.3	3.9	2.1	2.1	2.1	+	+
Nebraska	5.4	1.3	0.2	0.2	0.2	0.2	0.2
Nevada	1.3	1.1	0.1	0.1	0.1	0.1	0.1
New Hampshire	0.4	+	+	+	+	+	+
New Jersey	0.6	0.5	+	+	+	+	+
New Mexico	3.6	1.5	0.2	0.2	0.2	0.1	0.1
New York	13.9	12.0	0.1	0.1	0.1	0.1	0.1
North Carolina	11.6	0.3	0.4	0.4	0.4	0.4	0.3
North Dakota	1.9	3.5	6.4	6.3	6.0	6.0	5.9
Ohio	6.6	0.5	0.2	0.2	0.1	0.1	0.1
Oklahoma	34.0	6.8	+	+	+	+	+
Oregon	9.7	0.3	0.2	0.1	0.1	0.0	0.0
Pennsylvania	6.9	0.3	0.1	0.1	0.1	0.1	0.1
Puerto Rico	+	+	+	+	+	+	+
Rhode Island	0.1	+	+	+	+	+	+
South Carolina	17.7	9.5	+	+	+	+	+
South Dakota	0.6	3.9	+	+	+	+	+
Tennessee	58.5	0.0	0.1	0.1	0.1	0.1	0.1
Texas	72.3	0.5	+	+	+	+	+
Utah	1.8	0.1	0.2	0.2	0.2	0.2	0.2
Vermont	0.2	0.1	+	+	+	+	+

(continued)

Table 6-38: State Breakdown of Surface Area in Land Converted to Flooded Land—Reservoirs (thousands of ha) (*continued*)

State	1990	2005	2020	2021	2022	2023	2024
Virginia	6.6	0.2	+	+	+	+	+
Washington	5.6	1.1	+	+	+	+	+
West Virginia	3.4	1.6	0.2	0.2	0.1	0.1	0.1
Wisconsin	1.9	0.3	0.1	0.1	0.1	0.1	0.1
Wyoming	14.6	5.2	0.2	0.2	0.2	0.1	0.1
Total	**549.9**	**124.7**	**71.2**	**69.3**	**68.4**	**66.9**	**65.7**

+ Does not exceed 0.05 kha.

Note: Totals may not sum due to independent rounding.

Table 6-39: State Breakdown of Surface Area in Land Converted to Flooded Land–Freshwater Ponds (hectares)

State	1990	2005	2020	2021	2022	2023	2024
Alabama	381	24	1	1	+	+	+
Alaska	6	+	+	+	+	+	+
Arizona	41	13	+	+	+	+	+
Arkansas	336	2	+	+	+	+	+
California	226	90	20	20	14	7	5
Colorado	225	49	56	56	56	53	44
Connecticut	74	5	+	+	+	+	+
Delaware	4	+	+	+	+	+	+
District of Columbia	+	+	+	+	+	+	+
Florida	100	41	11	5	3	3	+
Georgia	1,690	86	51	51	51	51	48
Hawaii	7	2	+	+	+	+	+
Idaho	101	1	1	1	1	1	1
Illinois	539	102	20	18	15	14	14
Indiana	469	98	22	22	12	6	0
Iowa	2,328	1,460	189	96	66	57	44
Kansas	2,252	162	99	78	82	72	53
Kentucky	375	35	3	3	3	3	3
Louisiana	130	25	12	12	12	11	3
Maine	29	9	+	+	+	+	+
Maryland	214	64	13	11	10	9	9
Massachusetts	57	68	66	65	61	60	56
Michigan	149	51	9	9	9	9	9
Minnesota	275	96	50	42	34	34	33
Mississippi	348	165	92	86	78	69	66
Missouri	3,363	169	52	45	41	35	22
Montana	359	106	99	99	99	13	13

(continued)

Table 6-39: State Breakdown of Surface Area in Land Converted to Flooded Land—Freshwater Ponds (hectares) (*continued*)

State	1990	2005	2020	2021	2022	2023	2024
Nebraska	1,272	274	100	91	88	79	69
Nevada	17	51	28	23	21	16	16
New Hampshire	140	45	18	18	18	18	18
New Jersey	35	14	+	+	+	+	+
New Mexico	24	34	20	17	13	11	11
New York	304	130	25	20	20	9	9
North Carolina	482	90	30	28	28	28	28
North Dakota	149	160	66	58	55	44	40
Ohio	411	265	67	55	53	36	33
Oklahoma	1,923	144	79	73	64	62	43
Oregon	179	64	17	16	16	16	0
Pennsylvania	247	39	4	4	4	4	4
Puerto Rico	+	+	+	+	+	+	+
Rhode Island	9	7	+	+	+	+	+
South Carolina	756	234	9	9	9	9	9
South Dakota	285	114	113	105	105	90	83
Tennessee	406	46	3	3	3	3	2
Texas	2,738	107	26	25	25	18	17
Utah	85	21	20	20	20	10	10
Vermont	72	11	3	3	3	3	3
Virginia	58	4	2	2	2	2	2
Washington	146	46	20	20	19	18	18
West Virginia	121	47	28	28	28	28	21
Wisconsin	149	19	21	21	21	21	11
Wyoming	277	150	78	75	72	34	25
Total	**24,363**	**5,037**	**1,645**	**1,435**	**1,333**	**1,066**	**897**

+ Does not exceed 0.05 ha.

Note: Totals may not sum due to independent rounding.

Recalculations

No recalculations were implemented for this current *GHGIA*.

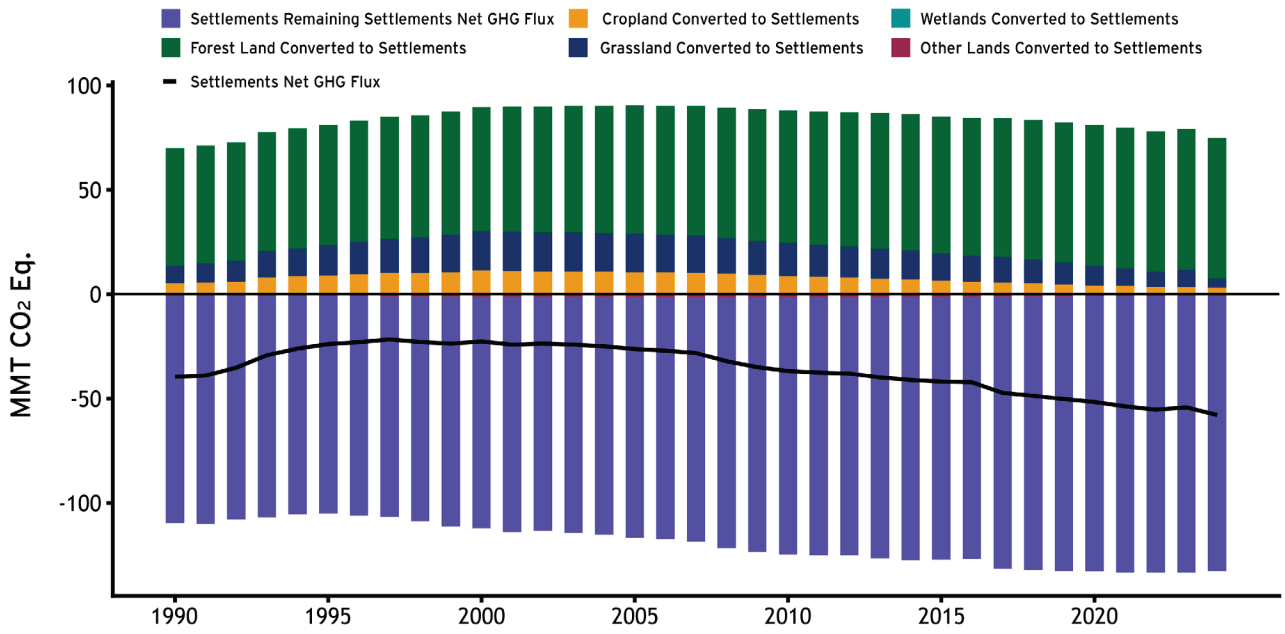
Uncertainty

Uncertainty stems from the spatial data (area estimates) from the underlying activity data (e.g., NHD, NWI, and NID). For this current *GHGIA*, the overall uncertainty of $CH_4$and CO_2 emissions from flooded land remaining flooded land is assumed to be similar to EPA (2025) given the use of the same underlying methodology and data sources that served as the basis for forecasting the end of the time series, calculated using the 2006 IPCC Guidelines Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). The EPA (2025) confidence level indicates a range of approximately 13.1 percent below and 12.7 percent above total (CH_4 and CO_2, MMT CO_2 Eq.) reservoir emissions and 1.4 percent below and 1.2 percent above the other constructed waterbodies emissions estimate. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 6-45.

6.6 Settlements

This land-use category includes all developed land, including transportation infrastructure and human settlements (residential, industrial, and commercial land) (IPCC, 2006), consistent with EPA (2025) definitions. The definition of settlements is based on USDA NRI. Figure 6-6 depicts the total emissions and removals contributions occurring on all settlement areas, including settlements remaining settlements and lands converted from each individual land-use category to settlements.

Figure 6-6: Trends in Emissions and Removals from Settlements



Note: The "Settlements Remaining Settlements Net GHG Flux" bar reflects the net carbon flux in settlement trees, net carbon flux in landfilled yard trimmings and food scraps, net soil carbon flux in settlements remaining settlements, and N_2O emissions from all settlement soils. Each land converted to settlement category/bar includes estimates of annual net changes in all ecosystem carbon stocks. The "Settlements Net GHG Flux" line reflects the combined total of all emissions and removals occurring across settlements remaining settlements and all land converted to settlements categories.

6.6.1 Settlements Remaining Settlements (Source Category 4E1)

Emissions and removals reported in the settlements remaining settlements category include:

- Soil Carbon Stock Changes – CO_2 Emissions from Drained Organic Soils (CO_2)
- Changes in Carbon Stocks in Settlement Trees (CO_2)
- N_2O Emissions from Settlement Soils (N_2O)
- Carbon Stock Changes in Landfilled Yard Trimmings and Food Scraps (CO_2)

Soil Carbon Stock Changes

Settlements remaining settlements includes carbon stock change estimates from the management of soils in developed areas, primarily from the drainage of organic soils. This *GHGIA* only estimates soil carbon stock changes from organic soils, consistent with IPCC Tier 1 method.

In 2024, CO_2 emissions from drained organic soils in settlements were 16.7 MMT CO_2 Eq. (4.6 MMT carbon), as shown in Table 6-40. Since 1990, emissions have increased by 69 percent due to an increase in area of drained organic soils in settlements, often to support infrastructure development.

Table 6-40: Net CO_2 Flux from Soil Carbon Stock Changes in Settlements Remaining Settlements (MMT CO_2 Eq.)

Soil Type	1990	2005	2020	2021	2022	2023	2024
Organic Soils	9.9	10.1	15.1	15.4	15.8	16.3	16.7

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). Areas of drained organic soils in settlements were not compiled for this analysis. A linear regression model with ARIMA errors was used to forecast the net CO_2 flux from soil carbon stock changes in settlements remaining settlements from 2021 to 2024, as described in Box 5-1.

Recalculations

Using the updated forecasting approach resulted in recalculations to the 2021 to 2023 time series. These recalculations result in annual changes of approximately 0.2 MMT CO_2 Eq. (—1.2 percent) compared to the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). There were no recalculations to estimates from 1990 to 2020.

Uncertainty

For this current *GHGIA*, the overall uncertainty of CO_2 emissions from drained organic soils in settlements remaining settlements is assumed to be similar to EPA (2025) given the use of the same underlying methodology and data sources that served as the basis for forecasting the end of the time series, calculated using the 2006 IPCC Guidelines Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). There will be increased uncertainties associated with the use of the ARIMA forecasting approach that are not currently reflected in the uncertainty estimates below. The EPA (2025) confidence level indicates a range of approximately 59 percent below and 59 percent above the estimate of CO_2 emissions from drained organic soils in settlements remaining settlements. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 6-45.

Changes in Carbon Stocks in Settlement Trees

Settlement trees include estimates of carbon stock changes from trees in settlement areas. Total carbon stock change estimates are impacted by settlement area, urban forest management, and other tree cover changes. Estimates include net flux from trees in both settlements remaining settlements and lands converted to settlements.

In 2024, net carbon sequestration from settlement trees was estimated to be 139.9 MMT CO_2 Eq. (see Table 6-41). Across the 1990–2024 time series, settlement trees sequestered an annual net average of 119.3 MMT CO_2 Eq. Driven by increases in settlement areas and tree cover, sequestration has increased 45 percent since 1990.

Table 6-41: Net Flux from Trees in Settlements Remaining Settlements (MMT CO_2 Eq. and MMT Carbon)

Year	1990	2005	2020	2021	2022	2023	2024
MMT CO_2 Eq.	(96.5)	(117.0)	(136.6)	(137.6)	(138.4)	(139.0)	(139.9)
MMT Carbon	(26.3)	(31.9)	(37.3)	(37.5)	(37.7)	(37.9)	(38.2)

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

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). Percent tree cover by state for 2024 held constant with 2023; area estimates by state were updated to calculate percent settlement tree cover area by state and estimate net CO_2 fluxes.

Recalculations

No recalculations were implemented for this current *GHGIA*.

Uncertainty

In general, there is uncertainty associated with settlement area estimates, percent tree cover, and estimates of gross and net sequestration. There is also uncertainty associated with the biomass model used to estimate biomass of subsequent carbon stocks, conversation factors, and tree decomposition assumptions. More details are provided in EPA (2025).

For this current *GHGIA*, the overall uncertainty of net fluxes emissions from settlement trees is assumed to be similar to EPA (2025) given the use of the same underlying methodology and data sources that served as the basis for forecasting the end of the time series, calculated using the 2006 IPCC Guidelines Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). There will be increased uncertainties associated with maintaining canopy cover consistent with 2023, as well as updated settlement area estimates, that are not currently reflected in the uncertainty estimates below. The EPA (2025) confidence level indicates a range of approximately 50 percent below and 52 percent above the settlement trees net flux estimate. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 6-45.

N_2O Emissions from Settlement Soils

N_2O emissions from settlement soils occur from nitrification and denitrification processes in soils within settlement areas. These emissions occur via fertilizer application and other inputs to, for example, residential lawns, parks, and golf courses, resulting in direct and indirect N_2O emissions.

In 2024, N_2O emissions from soils in settlements remaining settlements were 2.3 MMT CO_2 Eq., as shown in Table 6-42. Estimates show an overall 9 percent increase from 1990 to 2024, driven primarily by the expansion of settlement areas and the associated ride in synthetic nitrogen fertilizer use, which reached its highest levels between 2006 and 2008. Year-to-year fluctuations in these emissions are attributed to direct application of soil inputs and the area of drained organic soils.

Table 6-42: N_2O Emissions from Soils in Settlements Remaining Settlements (MMT CO_2 Eq.)

N_2O Emissions from Soils	1990	2005	2020	2021	2022	2023	2024
Direct N_2O Emissions from Soils	**1.7**	**2.6**	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**
Synthetic Fertilizers	0.8	1.5	0.7	0.6	0.6	0.6	0.6
Biosolids	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Drained Organic Soils	0.8	1.0	1.2	1.2	1.2	1.2	1.2
Indirect N_2O Emissions from Soils	**0.3**	**0.5**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Total	**2.1**	**3.1**	**2.3**	**2.3**	**2.3**	**2.3**	**2.3**

Note: Totals may not sum due to independent rounding.

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025).

A linear regression model with ARIMA errors was used to forecast direct organic soils N_2O emissions, including the nitrogen fertilizer applied to settlements, for the years 2021 to 2024. Updated sludge data was not available at the time of this analysis, so the 2023 values were held constant for 2024.

Recalculations

Using the updated forecasting approach resulted in recalculations to the 2021 to 2023 time series. These recalculations resulted in changes ranging from 0.10 MMT CO_2 Eq. (—4.1 percent) to 0.28 MMT CO_2 Eq. (-11.0 percent) compared to the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). There were no recalculations to estimates from 1990 to 2020.

Uncertainty

For this current *GHGIA*, the overall uncertainty of N_2O emissions from soils in settlements remaining settlements is assumed to be similar to EPA (2025) given the use of the same underlying methodology and data sources that served as the basis for forecasting the end of the time series, calculated using the 2006 IPCC Guidelines Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). There will be increased uncertainties associated with the use of the ARIMA forecasting approach that are not currently reflected in the uncertainty estimates below. The EPA (2025) confidence level indicates a range of approximately 47 percent below and 54 percent above direct N_2O estimate and approximately 76 percent below and 218 percent above the indirect N_2O estimate for N_2O emissions form soils in settlements remaining settlements. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 6-45.

Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills

The carbon contained in landfilled yard trimmings and food scraps, which make up a significant portion of the municipal waste stream, can be stored for very long periods of time.

In 2024, the net change in landfilled yard trimmings and food scrap carbon stocks was 11.0 MMT CO_2 Eq. (3.0 MMT carbon). Since 1990, total net flux of carbon stocks has decreased (less sequestration) by approximately 55 percent (see Table 6-43). Over this time period, there has been an increase in food scrap disposal in landfills and a decrease of disposal of yard trimmings landfills.

Table 6-43: Net Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills (MMT CO_2 Eq.)

Carbon Pool	1990	2005	2020	2021	2022	2023	2024
Yard Trimmings	**(20.1)**	**(7.5)**	**(8.2)**	**(8.2)**	**(8.2)**	**(8.2)**	**(8.2)**
Grass	(1.7)	(0.6)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)
Leaves	(8.7)	(3.4)	(3.8)	(3.8)	(3.8)	(3.8)	(3.8)
Branches	(9.8)	(3.4)	(3.7)	(3.7)	(3.6)	(3.6)	(3.6)
Food Scraps	**(4.4)**	**(3.9)**	**(4.5)**	**(4.3)**	**(4.1)**	**(3.9)**	**(2.8)**
Total Net Flux	**(24.5)**	**(11.4)**	**(12.8)**	**(12.5)**	**(12.3)**	**(12.1)**	**(11.0)**

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

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). Updated activity data has been identified but further investigation is needed before

incorporating into this analysis. As a result, no new activity data were used; the data from 2023 was held constant for 2024.

Recalculations

No recalculations were implemented for this current *GHGIA*.

Uncertainty

The uncertainty of landfilled yard trimmings and food scraps estimates comes from uncertainty of the underlying data and factors including data on total landfill disposal, initial carbon content, moisture content, decay rate, and proportion of carbon stored (EPA, 2025). There is also uncertainty associated with the proportion of disposed materials between the various pools and subpools (e.g., branches versus leaves).

For this current *GHGIA*, the overall uncertainty of landfilled yard trimmings and food scraps is assumed to be similar to EPA (2025) given the use of the same underlying methodology and data sources that served as the basis for forecasting the end of the time series, calculated using the 2006 IPCC Guidelines Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). The EPA (2025) confidence level indicates a range of approximately 57 percent below and 56 percent above net flux estimates of carbon stocks from landfilled yard trimmings and food scraps. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 6-45.

6.6.2 Land Converted to Settlements (Source Category 4E2)

Land converted to settlements includes carbon stock changes resulting from conversion of other lands to developed uses. Forest land converted to settlements, in particular, can lead to large losses of carbon. Long-term trends in losses of carbon reflect patterns of urban expansion and infrastructure development.

In 2024, the total net flux from land converted to settlements was 74.1 MMT CO_2 Eq., a 6.6 percent increase in CO_2 emissions compared to 1990 (see Table 6-44). Seventy-five percent of the average total loss of carbon comes from forest land conversion, leading to large losses of aboveground biomass, in particular, and other carbon pools.

Table 6-44: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes for Land Converted to Settlements (MMT CO_2 Eq.)

Land Use/Carbon Pool	1990	2005	2020	2021	2022	2023	2024
Cropland Converted to Settlements	**5.3**	**9.9**	**4.0**	**3.7**	**3.4**	**3.2**	**3.0**
Total Live Biomass	2.6	1.7	1.0	1.0	1.0	1.1	1.1
Mineral Soils	2.1	6.9	2.6	2.3	2.0	1.8	1.7
Organic Soils	0.5	1.2	0.4	0.4	0.3	0.3	0.2
Forest Land Converted to Settlements	**56.1**	**61.4**	**67.4**	**67.4**	**67.4**	**67.4**	**67.4**
Aboveground Live Biomass	32.5	35.2	38.7	38.7	38.7	38.7	38.7
Belowground Live Biomass	5.6	6.1	6.7	6.7	6.7	6.7	6.7
Dead Wood	9.1	9.9	10.9	10.9	10.9	10.9	10.9
Litter	7.8	8.5	9.4	9.4	9.4	9.4	9.4
Mineral Soils	1.0	1.5	1.5	1.5	1.5	1.5	1.5
Organic Soils	0.1	0.2	0.3	0.2	0.2	0.2	0.2
Grassland Converted to Settlements	**8.5**	**18.4**	**9.6**	**8.3**	**7.1**	**8.4**	**4.3**
Other Grassland Conversion Total Live Biomass1	2.9	2.7	1.6	1.7	1.7	1.7	1.7
Woodland Conversion Aboveground Live Biomass	0.4	0.4	0.5	0.5	0.5	0.5	0.5
Woodland Conversion Belowground Live Biomass	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Dead Wood	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Litter	0.2	0.2	0.2	0.2	0.2	2.9	0.2
Mineral Soils	4.3	13.7	6.5	5.3	4.1	2.9	1.5
Organic Soils	0.5	1.3	0.5	0.4	0.4	0.3	0.2
Other Lands Converted to Settlements	**(0.4)**	**(1.4)**	**(0.8)**	**(0.9)**	**(0.8)**	**(0.7)**	**(0.7)**
Mineral Soils	(0.4)	(1.5)	(0.9)	(0.9)	(0.8)	(0.7)	(0.7)
Organic Soils	+	0.1	+	+	+	+	+

(continued)

Table 6-44: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes for Land Converted to Settlements (MMT CO_2 Eq.) (*continued*)

Land Use/Carbon Pool	1990	2005	2020	2021	2022	2023	2024
Wetlands Converted to Settlements	**+**	**0.6**	**0.1**	**0.2**	**0.2**	**0.1**	**0.1**
Mineral Soils	+	0.1	+	+	+	+	+
Organic Soils	+	0.6	+	0.2	0.1	0.1	0.1
Total Aboveground Biomass Flux	**38.4**	**40.0**	**41.8**	**41.9**	**41.9**	**42.0**	**42.0**
Total Belowground Biomass Flux	**5.7**	**6.2**	**6.8**	**6.8**	**6.8**	**6.8**	**6.8**
Total Dead Wood Flux	**9.2**	**10.1**	**11.1**	**11.1**	**11.1**	**11.1**	**11.1**
Total Litter Flux	**8.0**	**8.7**	**9.6**	**9.6**	**9.6**	**12.2**	**9.6**
Total Mineral Soil Flux	**7.0**	**20.7**	**9.8**	**8.2**	**6.8**	**5.4**	**4.0**
Total Organic Soil Flux	**1.2**	**3.4**	**1.3**	**1.3**	**1.1**	**0.9**	**0.7**
Total Net Flux	**69.5**	**89.0**	**80.3**	**78.8**	**77.3**	**78.4**	**74.1**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

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

Methods

Methods are consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025).

A linear regression model with ARIMA errors was used to forecast soil carbon stock changes (non-federal land mineral soils, federal land mineral soils, and organic soils) from land converted to settlements emissions from 2021 to 2024. Biomass carbon losses from the cropland converted to settlements, grassland converted to settlements, and forest land converted to settlements held constant with 2023 levels.

Recalculations

Using the updated forecasting approach resulted in recalculations to the 2021 to 2023 time series. These recalculations resulted in changes ranging from 0.9 MMT CO_2 Eq. (1 percent difference) to 2.5 MMT CO_2 Eq. (3 percent difference) compared to the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). There were no recalculations to estimates from 1990 to 2020.

Uncertainty

For this current *GHGIA*, the overall uncertainty of the net flux from land converted to settlements is assumed to be similar to EPA (2025) given the use of the same underlying methodology and

data sources that served as the basis for forecasting the end of the time series, calculated using the 2006 IPCC Guidelines Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). There will be increased uncertainties associated with the use of the ARIMA forecasting approach that are not currently reflected in the uncertainty estimates below. The EPA (2025) confidence level indicates a range of approximately 36 percent below and 36 percent above the net flux estimate from land converted to settlements. EPA (2025) provided uncertainty estimates for each carbon pool by land use conversion category. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 6-45.

6.7 Other Land

6.7.1 Other Land Remaining Other Land (Source Category 4F1)

It is currently not possible to estimate CO_2, CH_4, or N_2O fluxes on other land remaining other land at this time. See Section 6.1 for area estimates of other land remaining other land.

6.7.2 Land Converted to Other Land (Source Category 4F2)

It is currently not possible to separate CO_2, CH_4, or N_2O fluxes on land converted to other land from fluxes on other land remaining other land at this time. See Section 6.1 for area estimates of land converted to other land.

6.8 LULUCF Uncertainty Summary

Table 6-45 shows the uncertainty summary for each LULUCF sector source and sink. A discussion of the uncertainty ranges is included in each source and/or sink category's respective chapter section.

Table 6-45: Quantitative Uncertainty Summary by LULUCF Sector Source/Sink

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
Forest Land Remaining Forest Land						
Forest Ecosystem Carbon Pools	CO_2	(759.2)	(686.3)	(832.1)	–9.6%	9.6%
Harvested Wood Products	CO_2	(100.5)	(72.2)	(125.3)	–28.1%	24.7%
Total Forest Stock Changes	*CO_2*	*(859.7)*	*(782.3)*	*(936.2)*	*–9%*	*8.9%*
Non-CO_2 Emissions from Forest Fires	CH_4	2.5	2.0	3.1	–22%	22%
Non-CO_2 Emissions from Forest Fires	N_2O	1.9	1.5	2.3	–22%	22%
Direct N_2O Fluxes from Forest Soils	N_2O	0.3	+	1.1	–86%	250%
Indirect N_2O Fluxes from Forest Soils	N_2O	0.1	+	0.4	–94%	267%
Drained Organic Forest Soils	CH_4	+	+	+	–69%	82%
Drained Organic Forest Soils	N_2O	0.1	+	0.1	–118%	132%
Land Converted to Forest Land						
Cropland Converted to Forest Land (CF)	*CO_2*	*(18.0)*	*(9.4)*	*(26.7)*	*–48%*	*48%*
CF Aboveground Biomass	CO_2	(10.0)	(1.5)	(18.5)	–85%	85%
CF Belowground Biomass	CO_2	(1.7)	(0.6)	(2.7)	–62%	62%

(continued)

Table 6-45: Quantitative Uncertainty Summary by LULUCF Sector Source/Sink (*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
CF Dead Wood	CO_2	(3.2)	(1.9)	(4.4)	–39%	39%
CF Litter	CO_2	(3.1)	(2.1)	(4.2)	–34%	34%
CF Mineral Soils	CO_2	(0.1)	(0.2)	0.1	–207%	207%
Grassland Converted to Forest Land (GF)	*CO_2*	*(38.6)*	*(36.3)*	*(41.0)*	*–6%*	*6%*
GF Aboveground Biomass	CO_2	(22.0)	(20.6)	(23.3)	–6%	6%
GF Belowground Biomass	CO_2	(2.7)	(2.5)	(3.0)	–10%	10%
GF Dead Wood	CO_2	(5.9)	(5.8)	(6.0)	–2%	2%
GF Litter	CO_2	(8.0)	(7.5)	(8.5)	–6%	6%
GF Mineral Soils	CO_2	+	(0.2)	0.2	–49,176%	49,176%
Other Lands Converted to Forest Land (OF)	*CO_2*	*(3.9)*	*(2.2)*	*(5.5)*	*–43%*	*43%*
OF Aboveground Biomass	CO_2	(1.7)	(0.1)	(3.3)	–95%	95%
OF Belowground Biomass	CO_2	(0.3)	0.1	(0.6)	–123%	123%
OF Dead Wood	CO_2	(0.8)	(0.3)	(1.2)	–57%	57%
OF Litter	CO_2	(0.9)	(0.4)	(1.5)	–56%	56%
OF Mineral Soils	CO_2	(0.2)	(1.0)	0.6	–412%	412%
Settlements Converted to Forest Land (SF)	*CO_2*	*(32.5)*	*(26.0)*	*(39.0)*	*–20%*	*20%*
SF Aboveground Biomass	CO_2	(18.6)	(12.2)	(24.9)	–34%	34%
SF Belowground Biomass	CO_2	(3.1)	(1.8)	(4.4)	–42%	42%
SF Dead Wood	CO_2	(6.2)	(5.0)	(7.4)	–19%	19%
SF Litter	CO_2	(4.7)	(3.8)	(5.6)	–19%	19%
SF Mineral Soils	CO_2	+	+	+	–55%	55%

(continued)

Table 6-45: Quantitative Uncertainty Summary by LULUCF Sector Source/Sink (*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
Wetlands Converted to Forest Land (WF)	*CO_2*	*(7.8)*	*(7.7)*	*(8.0)*	*–2%*	*2%*
WF Aboveground Biomass	CO_2	(4.1)	(4.0)	(4.3)	–3%	3%
WF Belowground Biomass	CO_2	(0.7)	(0.7)	(0.8)	–4%	4%
WF Dead Wood	CO_2	(1.5)	(1.5)	(1.6)	–3%	3%
WF Litter	CO_2	(1.4)	(1.3)	(1.4)	–4%	4%
WF Mineral Soils	CO_2	+	+	+	0%	0%
Total LF Aboveground Biomass	*CO_2*	*(56.3)*	*(45.6)*	*(67.0)*	*–19%*	*19%*
Total LF Belowground Biomass	*CO_2*	*(8.5)*	*(6.8)*	*(10.2)*	*–20%*	*20%*
Total LF Dead Wood	*CO_2*	*(17.6)*	*(15.9)*	*(19.4)*	*–10%*	*10%*
Total LF Litter	*CO_2*	*(18.2)*	*(16.5)*	*(19.6)*	*–9%*	*8%*
Total LF Mineral Soils	*CO_2*	*(0.3)*	*(0.2)*	*(0.4)*	*–42%*	*42%*
Total Lands Converted to Forest Lands (LF)	*CO_2*	*(100.9)*	*(89.8)*	*(112.0)*	*–11%*	*11%*
Cropland Remaining Cropland						
Biomass carbon stocks	CO_2	(0.8)	139.0	(140.6)	–17,828%	17,828%
Mineral soil carbon stocks Tier 3	CO_2	(45.5)	5.5	(96.5)	–112%	112%
Mineral soil carbon stocks Tier 2	CO_2	(1.8)	1.2	(4.8)	–166%	166%
Organic soil carbon stocks	CO_2	30.1	10.5	49.7	–65%	65%
Total Cropland Remaining Cropland	*CO_2*	*(18.0)*	*23.2*	*(59.3)*	*–229%*	*229%*

(continued)

Table 6-45: Quantitative Uncertainty Summary by LULUCF Sector Source/Sink (*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
Land Converted to Cropland						
Grassland Converted to Cropland Land (GC)	*CO_2*	*13.4*	*(13.4)*	*40.2*	*–200%*	*200%*
GC Aboveground Biomass	CO_2	0.3	(34.2)	34.8	–11,309%	11,309%
GC Belowground Biomass	CO_2	+	+	+	–100%	67%
GC Dead Wood	CO_2	+	+	0.1	–100%	121%
GC Litter	CO_2	+	+	0.1	–100%	148%
GC Mineral Soils Tier 3	CO_2	8.7	(12.9)	30.3	–249%	249%
GC Mineral Soils Tier 2	CO_2	1.1	0.1	2.0	–87%	87%
GC Organic Soils	CO_2	2.3	(0.1)	4.8	–105%	105%
Forest Land Converted to Cropland Land (FC)	*CO_2*	*20.2*	*4.0*	*36.3*	*–80%*	*80%*
FC Aboveground Biomass	CO_2	11.6	(3.1)	26.4	–127%	127%
FC Belowground Biomass	CO_2	2.0	(0.6)	4.6	–128%	127%
FC Dead Wood	CO_2	3.1	(0.8)	6.9	–127%	127%
FC Litter	CO_2	3.3	(0.9)	7.5	–127%	127%
FC Mineral Soils Tier 2	CO_2	0.1	+	0.3	–134%	134%
FC Organic Soils	CO_2	+	(0.1)	0.1	–504%	504%
Other Lands Converted to Cropland (OC)	*CO_2*	*(1.0)*	*0.4*	*(2.4)*	*–135%*	*135%*
OC Aboveground Biomass	CO_2	(0.1)	0.4	(0.6)	–564%	564%
OC Mineral Soils Tier 2	CO_2	(1.0)	0.3	(2.3)	–135%	135%

(continued)

Table 6-45: Quantitative Uncertainty Summary by LULUCF Sector Source/Sink (*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
OC Organic Soils	CO_2	+	+	+	0%	0%
Settlements Converted to Cropland (SC)	*CO_2*	*(0.2)*	*0.1*	*(0.5)*	*–142%*	*142%*
SC Aboveground Biomass	CO_2	(0.1)	0.2	(0.4)	–306%	306%
SC Mineral Soils Tier 2	CO_2	(0.2)	+	(0.3)	–77%	77%
SC Organic Soils	CO_2	+	+	0.1	–152%	152%
Wetlands Converted to Cropland (WC)	*CO_2*	*0.2*	*(0.5)*	*1.0*	*–320%*	*320%*
WC Aboveground Biomass	CO_2	(0.1)	0.3	(0.4)	–383%	383%
WC Mineral Soils Tier 2	CO_2	0.1	(0.1)	0.3	–144%	144%
WC Organic Soils	CO_2	0.2	(0.4)	0.8	–303%	303%
Total LC Aboveground Biomass	*CO_2*	*11.7*	*(11.9)*	*35.3*	*–202%*	*202%*
Total LC Belowground Biomass	*CO_2*	*2.0*	*(0.5)*	*4.6*	*–126%*	*126%*
Total LC Dead Wood	*CO_2*	*3.1*	*(0.8)*	*7.0*	*–125%*	*125%*
Total LC Litter	*CO_2*	*3.4*	*(0.8)*	*7.6*	*–125%*	*126%*
Total LC Mineral Soils Tier 3	*CO_2*	*8.7*	*(12.9)*	*30.3*	*–249%*	*249%*
Total LC Mineral Soils Tier 2	*CO_2*	*1.1*	*(0.8)*	*2.9*	*–171%*	*171%*
Total LC Organic Soils	*CO_2*	*2.6*	*0.1*	*5.2*	*–98%*	*98%*
Total Lands Converted to Cropland (LC)	*CO_2*	*32.6*	*(1.6)*	*66.7*	*–105%*	*105%*

(continued)

Table 6-45: Quantitative Uncertainty Summary by LULUCF Sector Source/Sink (*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
Grassland Remaining Grassland						
Woodland Aboveground live biomass	CO_2	(1.0)	(0.9)	(1.1)	–12%	10%
Woodland Belowground live biomass	CO_2	(0.2)	(0.2)	(0.2)	–8%	8%
Woodland Dead wood	CO_2	2.5	2.2	2.9	–13%	13%
Woodland Litter	CO_2	0.2	0.2	0.2	–9%	9%
Mineral soils carbon stocks Tier 3	CO_2	16.2	(106.1)	138.6	–753%	753%
Mineral Soils carbon stocks Tier 2	CO_2	0.1	(0.2)	0.4	–491%	491%
Mineral soils carbon stocks, Biosolids Tier 2	CO_2	(1.0)	(0.5)	(1.5)	–50%	50%
Organic soil carbon stocks	CO_2	5.5	1.0	9.9	–82%	82%
Total Grassland Remaining Grassland carbon stock change	*CO_2*	*22.2*	*(102.5)*	*146.9*	*–561%*	*561%*
Grassland burning	CH_4	0.4	+	0.8	–100%	120%
Grassland burning	N_2O	0.3	+	0.7	–100%	120%
Land Converted to Grassland						
Cropland Converted to Grassland (CG)	*CO_2*	*(11.2)*	*5.6*	*(27.9)*	*–150%*	*150%*
CG Aboveground Biomass	CO_2	(4.4)	11.5	(20.3)	–362%	362%
CG Belowground Biomass	CO_2	+	+	+	–97%	100%
CG Dead wood	CO_2	+	+	(0.1)	–95%	100%
CG litter	CO_2	+	+	(0.1)	–95%	100%
CG Mineral soil Tier 3	CO_2	(5.6)	3.8	(14.9)	–168%	168%

(continued)

Table 6-45: Quantitative Uncertainty Summary by LULUCF Sector Source/Sink (*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
CG Mineral soil Tier 2	CO_2	(1.9)	0.6	(4.3)	–132%	132%
CG Organic soils	CO_2	0.8	(0.1)	1.6	–113%	113%
Forest Land Converted to Grassland (FG)	*CO_2*	*47.2*	*14.2*	*80.3*	*–70%*	*70%*
FG Aboveground Biomass	CO_2	30.0	(1.2)	61.3	–104%	104%
FG Belowground Biomass	CO_2	4.2	(0.2)	8.7	–104%	105%
FG Dead wood	CO_2	5.1	(0.2)	10.4	–104%	104%
FG litter	CO_2	7.9	16.1	16.1	104%	104%
FG Mineral soil Tier 2	CO_2	(0.1)	(0.3)	(0.3)	140%	140%
FG Organic soils	CO_2	0.1	0.2	0.2	143%	143%
Other Lands Converted to Grassland (OG)	*CO_2*	*(10.5)*	*(1.6)*	*(19.3)*	*–85%*	*85%*
OG Aboveground Biomass	CO_2	(0.6)	1.2	(2.3)	–313%	313%
OG Belowground Biomass	CO_2	+	+	+	–100%	100%
OG Dead wood	CO_2	+	+	(0.1)	–70%	100%
OG litter	CO_2	(0.1)	+	(0.1)	–59%	47%
OG Mineral soil Tier 2	CO_2	(9.8)	(2.7)	(17.0)	–73%	73%
OG Organic soils	CO_2	0.1	(0.1)	0.2	–212%	212%
Settlements Converted to Grassland (SG)	*CO_2*	*(0.9)*	*+*	*(1.8)*	*–97%*	*96%*
SG Aboveground Biomass	CO_2	(0.3)	0.3	(0.8)	–208%	208%
SG Belowground Biomass	CO_2	+	+	+	–45%	100%
SG Dead wood	CO_2	(0.1)	(0.1)	(0.1)	62%	46%

(continued)

Table 6-45: Quantitative Uncertainty Summary by LULUCF Sector Source/Sink (*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
SG litter	CO_2	(0.1)	(0.1)	(0.1)	55%	61%
SG Mineral soil Tier 2	CO_2	(0.5)	(0.7)	(0.7)	54%	43%
SG Organic soils	CO_2	+	+	+	–451%	451%
Wetlands Converted to Grassland (WG)	*CO_2*	*+*	*0.2*	*(0.2)*	*–3,705%*	*3,705%*
WG Aboveground Biomass	CO_2	(0.2)	0.6	(0.9)	–411%	410%
WG Belowground Biomass	CO_2	+	+	+	–100%	100%
WG Dead wood	CO_2	+	+	+	–46%	100%
WG litter	CO_2	+	+	+	–138%	100%
WG Mineral soil Tier 2	CO_2	+	+	+	–213%	213%
WG Organic soils	CO_2	0.2	(0.1)	0.6	–147%	147%
Total LG Aboveground Biomass	*CO_2*	*24.6*	*(12.3)*	*61.6*	*–150%*	*150%*
Total LG Belowground Biomass	*CO_2*	*4.2*	*(0.3)*	*8.6*	*–106%*	*106%*
Total LG Dead Wood	*CO_2*	*4.9*	*(0.4)*	*10.2*	*–108%*	*108%*
Total LG Litter	*CO_2*	*7.7*	*(0.5)*	*15.9*	*–107%*	*107%*
Total LG Mineral Soils Tier 3	*CO_2*	*(5.6)*	*3.8*	*(14.9)*	*–168%*	*168%*
Total LG Mineral Soils Tier 2	*CO_2*	*(12.3)*	*(4.8)*	*(19.8)*	*–61%*	*61%*
Total LG Organic Soils	*CO_2*	*1.2*	*0.1*	*2.2*	*–88%*	*88%*
Total Lands Converted to Grassland (LG)	*CO_2*	*24.7*	*(26.2)*	*75.5*	*–206%*	*206%*

(continued)

Table 6-45: Quantitative Uncertainty Summary by LULUCF Sector Source/Sink (*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
Wetlands Remaining Wetlands						
Peatlands Remaining Peatlands	CO_2	0.6	0.5	0.7	–15%	16%
Peatlands Remaining Peatlands	CH_4	+	+	+	–58%	80%
Peatlands Remaining Peatlands	N_2O	+	+	+	–53%	54%
Coastal Wetlands Remaining Coastal Wetlands						
Vegetated Coastal Wetlands Remaining Coastal Wetlands, Biomass carbon stock change	CO_2	1.0	0.7	1.2	–24.1%	24.1%
Vegetated Coastal Wetlands Remaining Coastal Wetlands, soil carbon stock change	CO_2	(12.0)	(9.9)	(14.2)	–17.7%	17.7%
Vegetated Coastal Wetlands Remaining Coastal Wetlands, CH_4 emissions	CH_4	3.8	2.7	5.0	–29.9%	29.9%
Vegetated Coastal Wetlands Converted to Unvegetated Coastal Wetlands, Biomass carbon stock change	CO_2	0.1	0.1	0.1	–24.1%	24.1%
Vegetated Coastal Wetlands Converted to Unvegetated Coastal Wetlands, dead organic matter carbon stock change	CO_2	+	+	+	–25.8%	25.8%
Vegetated Coastal Wetlands Converted to Unvegetated Coastal Wetlands, soil carbon stock change	CO_2	2.8	2.4	3.2	–15.0%	15.0%

(continued)

Table 6-45: Quantitative Uncertainty Summary by LULUCF Sector Source/Sink (*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
Unvegetated Coastal Wetlands Converted to vegetated Coastal Wetlands, Biomass carbon stock change	CO_2	(0.2)	(0.2)	(0.2)	–20.0%	20.0%
Unvegetated Coastal Wetlands Converted to vegetated Coastal Wetlands, dead organic matter carbon stock change	CO_2	+	+	+	–25.8%	25.8%
Unvegetated Coastal Wetlands Converted to vegetated Coastal Wetlands, soil carbon stock change	CO_2	+	+	+	–17.7%	17.7%
Aquaculture Production	N_2O	0.1	+	0.3	–116%	116%
Flooded Land Remaining Flooded Land						
Reservoirs–surface	CH_4	27.8	27.3	28.2	–1.7%	1.3%
Reservoirs–downstream	CH_4	2.3	2.2	2.7	–4.3%	15.7%
Canals and ditches	CH_4	7.2	6.8	7.6	–6.0%	5.5%
Freshwater ponds	CH_4	10.4	10.4	10.4	–0.04%	0.04%
Land Converted to Wetlands						
Land Converted to Coastal Wetlands						
Land Converted to vegetated coastal wetlands, biomass C stock flux	CO_2	0.2	0.2	0.2	–20.0%	20.0%
Land Converted to vegetated coastal wetlands, dead organic matter flux	CO_2	+	+	0.1	–25.8%	25.8%
Land Converted to vegetated coastal wetlands, soil C stock flux	CO_2	(0.1)	(0.1)	(0.1)	–17.7%	17.7%

(continued)

Table 6-45: Quantitative Uncertainty Summary by LULUCF Sector Source/Sink (*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
Land Converted to vegetated coastal wetlands, CH_4 emissions	CH_4	0.1	0.1	0.2	–29.9%	29.9%
Land Converted to Flooded Land						
Reservoirs–surface	CH_4	0.2	0.1	0.2	–12.7%	12.9%
Reservoirs–surface	CO_2	0.3	0.3	0.3	–13.3%	13.6%
Reservoirs–downstream	CH_4	+	+	0.1	–63.4%	239.6%
Freshwater ponds	CH_4	+	+	+	–1.6%	1.3%
Freshwater ponds	CO_2	+	+	+	–1.4%	1.4%
Settlements Remaining Settlements						
Soil carbon stock changes–drained organic soils	CO_2	16.7	6.9	26.6	–59%	59%
Changes in C stocks in Settlement Trees	CO_2	(139.9)	(70.0)	(212.7)	–50%	52%
Direct N_2O emissions from settlement soils	N_2O	2.0	1.1	3.1	–47%	54%
Indirect N_2O emissions from settlement soils	N_2O	0.3	0.1	0.8	–76%	218%
CO_2 Flux from Yard Trimmings and Food Scraps	CO_2	(11.0)	(4.7)	(17.1)	–57%	56%
Land Converted to Settlements						
Cropland Converted to Settlements (CS)	*CO_2*	*3.0*	*(0.3)*	*6.3*	*–109%*	*109%*
CS Total biomass	CO_2	1.1	(2.1)	4.2	–293%	293%
CS Mineral soil carbon stocks	CO_2	1.7	(0.3)	3.7	–117%	117%
CS organic soil carbon stocks	CO_2	0.2	(0.1)	0.6	–148%	148%

(continued)

Table 6-45: Quantitative Uncertainty Summary by LULUCF Sector Source/Sink (*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
Forest Land Converted to Settlements (FS)	*CO_2*	*67.4*	*41.1*	*93.7*	*–39%*	*39%*
FS aboveground biomass carbon stocks	CO_2	38.7	14.7	62.7	–62%	62%
FS belowground biomass carbon stocks	CO_2	6.7	2.6	10.9	–62%	62%
FS dead wood	CO_2	10.9	4.1	17.7	–62%	62%
FS litter	CO_2	9.4	3.6	15.2	–62%	62%
FS Mineral soil carbon stocks	CO_2	1.5	1.0	1.9	–28%	28%
FS organic soil carbon stocks	CO_2	0.2	+	0.5	–115%	115%
Grassland Converted to Settlements (GS)	*CO_2*	*4.3*	*1.5*	*7.1*	*–66%*	*66%*
Other grassland (non-woodland) total live biomass	CO_2	1.7	(1.8)	5.3	–208%	208%
Woodland aboveground biomass carbon stocks	CO_2	0.5	0.2	0.8	–62%	61%
Woodland belowground biomass carbon stocks	CO_2	0.1	+	0.1	–44%	0%
GS dead wood	CO_2	0.2	0.1	0.3	–62%	70%
GS litter	CO_2	0.2	0.1	0.3	–61%	57%
GS mineral soil carbon stocks	CO_2	1.5	0.3	2.7	–80%	80%
GS organic soil carbon stocks	CO_2	0.2	(0.1)	0.5	–157%	157%
Other Lands Converted to Settlements (OS)	*CO_2*	*(0.7)*	*+*	*(1.3)*	*–99%*	*99%*
OS mineral soil carbon stocks	CO_2	(0.7)	(1.3)	(1.3)	93%	93%

(continued)

Table 6-45: Quantitative Uncertainty Summary by LULUCF Sector Source/Sink (*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
OS organic soil carbon stocks	CO_2	+	(0.1)	+	–591%	0%
Wetlands Converted to Settlements (WS)	*CO_2*	*0.1*	*(0.6)*	*0.2*	*–910%*	*126%*
WS mineral soils carbon stocks	CO_2	+	+	+	–126%	126%
WS organic soils carbon stocks	CO_2	0.1	(0.9)	1.0	–1,831%	1,831%
LS aboveground biomass carbon stocks	*CO_2*	*42.0*	*17.6*	*66.3*	*–58%*	*58%*
LS belowground biomass carbon stocks	*CO_2*	*6.8*	*2.6*	*11.0*	*–62%*	*62%*
LS dead wood	*CO_2*	*11.1*	*4.3*	*17.9*	*–61%*	*61%*
LS litter	*CO_2*	*9.6*	*3.7*	*15.4*	*–61%*	*61%*
LS mineral soil carbon stocks	*CO_2*	*4.0*	*1.5*	*6.5*	*–62%*	*62%*
LS organic soil carbon stocks	*CO_2*	*0.7*	*(4.8)*	*6.3*	*–766%*	*766%*
Total Land Converted to Settlements (LS)	*CO_2*	74.1	47.4	100.8	–36%	36%

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Note: Parentheses indicate negative values or net sequestration.

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7

Waste

Chapter 7. Waste

Waste management activities—including landfilling, wastewater treatment, and waste combustion—produce greenhouse gas (GHG) emissions such as methane (CH_4) and nitrous oxide (N_2O). Solid waste disposal to landfills is the primary source of waste-management–related emissions, accounting for nearly 72 percent of total waste-management–related emissions. Emissions from wastewater are the next largest source, contributing 25 percent, and the remaining sources contribute just under 3 percent (i.e., from composting and stand-alone anaerobic digestion facilities). Landfills and wastewater are significant sources of methane, with landfills being the third largest source of methane (CH_4). Wastewater treatment also contributes nearly 92 percent of this sector's nitrous oxide (N_2O) emissions and is the second largest source of N_2O overall.

In 2024, emissions from this sector were 166 million metric tons (MMT) CO_2 equivalent (Eq.), accounting for approximately 2.7 percent of gross U.S. GHG emissions as shown in Table 7-1. Emissions decreased nearly 30 percent from 1990 and remained relatively flat from 2023 as shown in Figure 7-1. The decrease since 1990 is largely due to greater use of landfill gas collection and control systems, closure of older landfills, better management practices, and increased diversion of organic waste through state and local policy and regulations targeting reduction of food waste (EPA, 2025).

Emissions from the incineration of waste are accounted for in the energy sector rather than in the waste sector because almost all incineration of municipal solid waste (MSW) in the United States occurs at waste-to-energy facilities where useful energy is recovered. The energy sector also includes an estimate of emissions from burning waste tires and hazardous industrial waste, because virtually all the combustion occurs in industrial and utility boilers that recover energy (EPA, 2025).

Figure 7-1: Trends in Waste Sector Greenhouse Gas Source

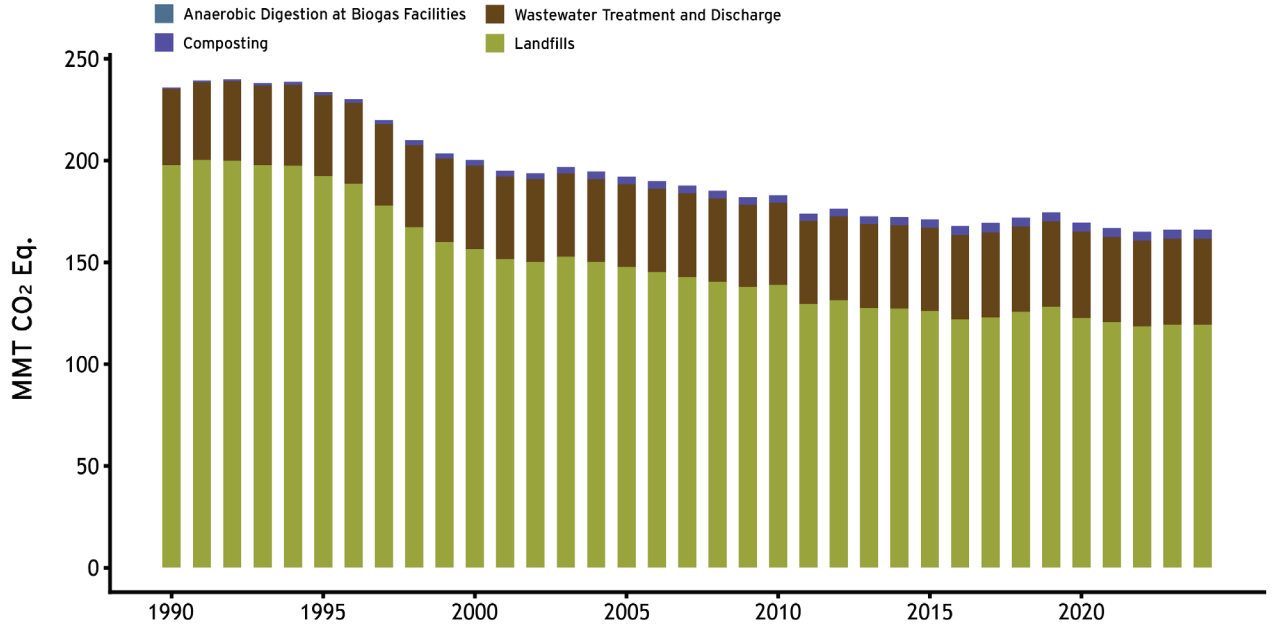


Table 7-1: Emissions from Waste (MMT CO_2 Eq.)

Gas/Source	1990	2005	2020	2021	2022	2023	2024
CH_4	**220.9**	**172.4**	**146.1**	**143.9**	**142.2**	**143.2**	**143.0**
Landfills	197.8	147.7	122.6	120.7	118.6	119.4	119.4
Wastewater Treatment	22.7	22.7	21.0	20.7	20.9	21.2	21.0
Composting	0.4	2.1	2.6	2.6	2.6	2.6	2.6
Anaerobic Digestion at Biogas Facilities	+	+	+	+	+	+	+
N_2O	**15.1**	**19.5**	**23.4**	**22.9**	**23.0**	**22.8**	**23.0**
Wastewater Treatment	14.8	18.1	21.6	21.1	21.2	21.0	21.1
Composting	0.3	1.5	1.8	1.8	1.8	1.8	1.9
Total	**235.9**	**192.0**	**169.5**	**166.8**	**165.2**	**166.0**	**166.0**

+ Does not exceed 0.5 kilotons (kt).

Note: Totals may not sum due to independent rounding.

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 5 (Waste) 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* (EPA, 2025). 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 using country-specific methods and models, emission factors, and site-specific information) and as data allow for smaller sources, as shown in Table 7-2.

Table 7-2: Method Summary

Category (CRT Code) [a]	Gas(s)	IPCC Methodological Tier	Methodological Refinement Compared to 1990–2023 (EPA, 2025)
Landfills (5A1)			
MSW Landfills	CH_4	Model, country-specific	No change
Industrial Landfills	CH_4	Country-specific	No change
Composting (5B1)	CH_4, N_2O	Tier 1	No change
Anaerobic Digestion at Biogas Facilities (5B2)	CH_4	Tier 1	No change
Waste Incineration (5C1)	CO_2, CH_4, N_2O	See Chapter 3.3	
Wastewater (5D)			
Domestic	CH_4	Tier 1, Tier 2	No change
	N_2O	Tier 1, Tier 2, Tier 3	
Industrial	CH_4	Tier 1, Tier 2, country-specific	No change
	N_2O	Tier 1	

[a] Codes in parentheses represent common reporting table (CRT) codes. The CRT codes are 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). Translating 5A1: 4 = waste sector, A = solid waste disposal subsector, 1 = landfills category (e.g., managed waste disposal sites).

Quality Assurance/Quality Control

To ensure the quality of the waste sector GHG emission estimates, the IPCC general procedures were implemented for quality assurance/quality checking for all categories. Category-specific procedures will be phased in, especially for significant categories in future versions of this report. The procedures that were implemented involved checks specifically focusing on the activity data and methodology used for estimating each source of emissions from the waste 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 7-9. A qualitative description of the uncertainties, along with the quantitative uncertainty estimate, is provided within each category.

Future Areas for Improvement

Continuous improvement efforts are important for reflecting the latest science, reducing uncertainties to the extent practicable in estimating emissions from waste management activities, especially for significant categories such as methane emissions from landfills and, wastewater, and nitrous oxide emissions from wastewater. For categories where the methodology has not changed in this report and remains consistent with previous analyses, we plan to review improvements identified in the *1990–2023 Inventory* (EPA, 2025). Any changes that have been incorporated into this report are discussed in the Methods and Recalculations sections of those respective categories.

Below are anticipated actions for potentially more significant methodological changes and/or refinements, to improve inventory transparency and address existing and new challenges with data availability.

- Include an overview of waste management in the United States in the introduction to this chapter.
- Review literature, federal, trade statistics to identify updated data on waste generation, composition, associated management pathways including gas recovery and use for the United States to improve consistency and completeness of estimates over the time series.
- Review any available 2024 Greenhouse Gas Reporting Program (GHGRP) data for additional updates and recalculations.
- Review recent studies estimating methane emissions from landfills using independent methods, including studies based on atmospheric measurements (e.g., Cusworth et al., 2024; Nesser et al., 2024) and engage with researchers on approaches to improve data, emission factors, and/or methods for quantifying emissions.
- Review studies on reported GHGRP data and associated methods (e.g., Stark et al., 2024).
- Review recent studies estimating methane and nitrous oxide emissions from and wastewater treatment using independent methods, including studies based on atmospheric and other measurements (e.g., Sieranen et al., 2024; Song et al., 2023; Song et al., 2024; Song et al. 2026).
- Review available data that could improve estimation parameters, and/or methods for quantifying emissions, such as new survey data published by U.S. Environmental Protection Agency (EPA; e.g., EPA Clean Watersheds Survey; EPA's Anaerobic Digestion Data Collection Project 2022 and 2023 data), along with new reporting to existing compliance and permitting databases.

Future versions of this report will specify more on scope, timing, and plans for phasing in improvements.

7.1 Landfills (Source Category 5A1)

Methane (CH_4) is released from solid waste management, primarily from landfills. In the United States, landfilling is the most common way to manage solid waste, along with recycling, composting, and waste-to-energy incineration. MSW landfills manage household and similar wastes by placing waste in lined areas, covering it daily with soil, and using systems to collect liquids (leachates) and gases. Industrial waste landfills are built in a similar way but are used for non-hazardous industrial and commercial waste. MSW and industrial waste landfills in the United States must meet federal, state, and local regulations to minimize potential environmental, health, and safety impacts.[45] Since 2011, landfills that accepted MSW on or after January 1, 1980 and generate methane in amounts equivalent to 25,000 metric tons of CO_2 Eq. or more per year were subject to reporting annual emissions under EPA's GHGRP.

Once waste is deposited in a landfill, organic materials, such as food, paper, and yard debris, begin to decompose. At first, decomposition occurs in the presence of oxygen, but as oxygen is used up, the process becomes anaerobic (occurring absent of oxygen). Under these conditions, bacteria produce landfill gas, which is made up of roughly equal parts methane (CH_4) and carbon dioxide (CO_2), along with small amounts of other gases (e.g., non-methane volatile organic compounds [NMVOCs] and volatile organic compounds [VOCs]) produced during decomposition and volatilization processes). In GHG inventories, only CH_4 emissions from landfills are estimated, because net CO_2 flux from carbon stock changes of materials of biogenic origin in landfills are reported under the land use, land-use change, and forestry (LULUCF) sector estimates and not reported here to avoid double counting of emissions from biomass-related stock changes (see Chapter 6 of this *GHGIA*). Nitrous oxide (NO_2) emissions (e.g., from sludge application) are assumed to be insignificant (IPCC, 2006).

Methane emissions from landfills depend on several factors, including the amount of waste in place and its composition, landfill design and operating conditions, how much methane is captured and controlled (e.g., the amount of methane captured and either flared or used for energy), and how much CH_4 is reduced (oxidized) as it passes through the landfill cover. Understanding changes in landfilled waste composition over time, particularly for degradable materials in MSW landfills, is important for estimating GHG emissions. Diverting these materials from landfills reduces both CH_4 generation potential and emissions. Although landfill management practices can vary, most follow similar practices, such as applying cover materials to reduce odors and protect public health. The type of cover material (e.g., soil, clay, or alternative materials) can also influence CH_4 oxidation rates (EPA, 2025). Methane production usually begins within the first year after waste is placed in a landfill and can continue for decades as the waste slowly decomposes (IPCC, 2006). Recent measurement studies suggest methane emissions may be higher than previously thought (see references in the "Future Areas for Improvement" included in the introduction to this chapter).

In 2024, landfill CH_4 emissions were approximately 119.4 MMT CO_2 Eq. Emissions from MSW landfills accounted for approximately 84 percent of total landfill emissions (100.6 MMT CO_2 Eq.),

[45] More information on landfill management in the U.S. and applicable regulations can be found at https://www.epa.gov/landfills.

while industrial waste landfills accounted for the remainder (18.8 MMT CO_2 Eq.). Net CH_4 emissions from MSW landfills decreased since 1990 largely because of increased use of landfill gas collection and control systems, closure of older landfills, better management practices, and increased diversion of organics through state and local policy and regulations (see Table 7-3). Landfill gas collection and control is not accounted for at industrial waste landfills in this chapter (see the Methodology discussion for more information).

Table 7-3: Methane Emissions from Landfills MMT CO_2 Eq.

Gas/Source	1990	2005	2020	2021	2022	2023	2024
MSW CH_4 Generation [a]	230.0	303.7	339.4	334.1	329.3	335.7	335.7
Industrial CH_4 Generation	13.6	17.9	21.0	21.0	21.0	20.9	20.9
MSW CH_4 Recovered [a]	(23.8)	(148.4)	(206.4)	(203.4)	(200.0)	(204.9)	(204.9)
MSW CH_4 Oxidized [a]	(20.6)	(23.6)	(29.3)	(28.9)	(29.5)	(30.2)	(30.2)
Industrial CH_4 Oxidized	(1.4)	(1.8)	(2.1)	(2.1)	(2.1)	(2.1)	(2.1)
MSW Net CH_4 Emissions	**185.5**	**131.6**	**103.7**	**101.8**	**99.8**	**100.6**	**100.6**
Industrial CH_4 Emissions [b]	**12.2**	**16.1**	**18.9**	**18.9**	**18.9**	**18.8**	**18.8**
Total Emissions	**197.8**	**147.7**	**122.6**	**120.7**	**118.6**	**119.4**	**119.4**

[a] For years 1990–2004, emissions from MSW landfills are estimated using the first-order decay methodology. A methodological change occurs in 2005. For 2005–2024, directly reported net CH_4 emissions from the EPA's GHGRP data and additional emissions from landfills not reporting to GHGRP are added applying a scale-up factor. More details on the scale-up factor and how it was developed can be found in Annex 5. These data incorporate CH_4 recovered and oxidized for MSW landfills. As such, CH_4 generation, CH_4 oxidation, and CH_4 recovery are not calculated separately.

[b] Methane recovery is not calculated for industrial landfills because this is not a common practice in the United States (EPA, 2025).

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

The total amount of MSW generated is expected to increase as the U.S. population continues to grow. The annual volume of MSW generated and disposed of in MSW landfills varies over time and is influenced by a range of factors, including economic activity, population growth, consumption patterns, and the availability of waste reduction programs such as recycling. The estimated quantity of landfilled waste increased by nearly 19 percent, from about 205 MMT in 1990 to 244 MMT in 2008, before declining by 9 percent to 221 MMT in 2024 (see Table 7-4).

In contrast, the amount of waste disposed of in industrial waste landfills—primarily from the pulp and paper and food processing sectors—has remained relatively stable since 1990. Volumes ranged from 9.0 MMT in 1991 to a peak of 12.2 MMT in 1997 and then declined to 10.1 MMT in 2024 (see Annex 5). Methane (CH_4) emissions from these landfills have likewise remained relatively consistent since the early 2000s, ranging from 19.7 MMT CO_2 Eq. in 2005 to 19.5 MMT CO_2 Eq. in

2024. These estimates focus on sectors that generate organic byproducts capable of producing methane, specifically pulp and paper and food processing. Food and beverage processing facilities have made attempts to reduce organic waste sent to industrial waste landfills—construction and demolition landfills, another category of industrial waste landfill, may receive some degradable materials (e.g., treated wood), but these waste streams are unlikely to produce significant methane emissions and are therefore less relevant for national GHG inventories (EPA, 2025). Future inventories will investigate drivers in trends for industrial waste landfills (e.g., diversion to incineration and recycling/reuse of industrial waste materials, especially organics).

Table 7-4: Solid Waste in MSW and Industrial Waste Landfills Contributing to CH_4 Emissions (MMT unless otherwise noted)

Activity	1990	2005	2020	2021	2022	2023	2024
Total MSW Generated [a]	270	368	333	334	336	338	342
Total MSW Landfilled	205	234	215	216	217	219	221
MSW Last 30 Years [b]	4,876	5,992	6,551	6,561	6,584	6,612	6,635
MSW Since 1940 [c]	6,808	9,925	13,153	13,369	13,585	13,804	14,025
Total Industrial Waste Landfilled [d]	10.2	11.6	10.9	11.0	10.6	10.2	10.1

[a] This estimate represents the waste that has been in place for 30 years or less, which contributes about 90 percent of the CH_4 generation. Values are based on various data sources unchanged from the *1990–2023 Inventory* (EPA, 2025) for years 1940–2024. Updated U.S. Census Data were incorporated for recent years for the United States, District of Columbia, and Puerto Rico and over the time series for territories.

[b] This estimate is the cumulative amount of waste that has been placed in landfills for the 30 years prior to the year indicated and is the sum of the annual disposal rates used in the first order decay model. Values are based on the *1990–2023 Inventory* (EPA, 2025) and extrapolated data are based on annual population updates from the U.S. Census Bureau (2024, 2025).

[c] This estimate represents the cumulative amount of waste that has been placed in landfills since 1940 to the year indicated and is the sum of the annual disposal rates used in the first order decay model. Values are based on the *1990–2023 Inventory* (EPA, 2025) and extrapolated data are based on annual population updates from the U.S. Census Bureau (2024, 2025).

[d] Estimates in this row only include estimated waste landfilled from the food and beverage, and pulp and paper sectors. The waste landfilled is estimated using a single waste disposal factor across the time series for each sector. Data are not available to accurately estimate total industrial waste generated for disposal in industrial waste landfills for any industrial sector.

Note: Totals may not sum due to independent rounding.

Methods

MSW Landfills. The methodological approach for estimating MSW Landfill emissions is generally consistent with the approach described in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). Based on available data, both IPCC Tier 2 and 3 approaches are applied to develop a consistent time series of estimated emissions.

Calculations for MSW landfills rely heavily on net methane emissions reported by facilities subject to EPA's GHGRP for 2010–2024. Data for 2024, as well as any updates to previously reported data, were not available at the time this report was prepared. Therefore, the 2024 estimates in

this analysis assume that reported 2023 GHGRP net emissions, recovery, and derived parameters (e.g., weighted average oxidation factors) remain unchanged. For 1990–2009, the methodology uses state survey data (e.g., BioCycle State of Survey reports) on total waste accepted by MSW landfills, to which a national waste disposal factor is applied. Population estimates are used to interpolate annual estimates of waste disposed for years where state survey data are unavailable.

Industrial Waste Landfills. The methodological approach for estimating Industrial Waste Landfill 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 using an IPCC Tier 2 approach implemented through the IPCC waste model adapted for activity in the United States (IPCC, 2006).

Industrial waste disposed and landfilled over the time series is estimated based on disposal rates from a historical EPA survey and industry data applied to annual industrial production data rather than disposal data due to a lack of data. The *GHGIA* methodology assumes most of the organic waste placed in industrial waste landfills originates from the food processing and pulp and paper sectors; this *GHGIA*'s estimates incorporate updated industrial production data from the United States Department of Agriculture's (USDA's) National Agricultural Service Statistics (2025a, 2025b, 2025c, 2025d, 2026) and the Food and Agricultural Organization of the United Nations (FAO, 2026).

Methane recovery at industrial waste landfills is assumed to be insignificant based on available data collected under EPA's GHGRP for industrial waste landfills (EPA, 2025). Additional detail on the methods, data sources, and assumptions can be found in Annex 5 to this report.

Recalculations

Methods and activity data are generally consistent with the *1990–2023 Inventory* (EPA, 2025), incorporating updated activity data where available, namely for industrial waste landfills.

Industrial Waste Landfills. The estimates reflect updates to annual production of paper and paperboard and wood pulp for 2019–2023 (FAO, 2026) and food production data for recent years (i.e., meat, poultry, fruits, and vegetables) (USDA, 2025a, 2025b, 2025c, 2025d, 2026). The revisions to prior data had insignificant impacts across the time series as compared to the *1990–2023 Inventory* (EPA, 2025) (averaging <0.05 percent decrease). Revisions to annual data had no significant impact on total landfill emission estimates and trends, with an average decrease of less than 0.01 percent across the time series.

Uncertainty

Uncertainty in CH_4 emission estimates from landfills is associated with a number of factors. For MSW landfills uncertainty is associated with

- activity data (e.g., diverse and periodic data sources on historical and current waste generation and landfilled, the number of non-reporting landfills below GHGRP reporting thresholds, landfill gas recovered);
- the representativeness of assumed decay and oxidation rates; and

- degradable organic carbon (DOC) for U.S. landfills, including those used in reported net emissions under GHGRP.

In addition, emissions have been estimated to be higher than those presented here when using other methods to quantify emissions (e.g., calculating emissions based on inverse modeling from atmospheric observations). For industrial waste landfills, uncertainty is associated with lack of data and assumptions to approximate key data (e.g., assumptions on disposal rates, industrial waste landfilled), and, similar to MSW landfills, the representativeness of assumptions on methane generation, oxidation rates, and recovery at industrial waste landfills in the United States.

For this current report, the overall uncertainty associated with national estimates of CH_4 from landfills is assumed to be similar to the *1990–2023 Inventory* (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 9 percent below and 14 percent above the emission estimate in 2024. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 7-10. For MSW landfills, additional uncertainty arises from using 2023 reported emissions and parameters to estimate 2024 emissions, which may over- or underestimate activity trends due to changes in characteristics, including management practices at U.S. landfills.

7.2 Wastewater Treatment and Discharge (Source Category 5D)

Treatment and discharge of wastewater can produce methane (CH_4) and nitrous oxide (N_2O) emissions. Wastewater from homes and industries is treated to remove organic material, solids, nutrients, and other contaminants. In the United States, nearly 80 percent of wastewater is treated in centralized systems, while about 19 percent is treated in on-site systems such as septic tanks. Industrial wastewater may be treated on-site or combined with domestic wastewater in centralized systems (EPA, 2025; IPCC, 2006).

Treatment processes in centralized systems vary but typically include physical removal of solids and biological processes that break down organic material. Wastewater is typically collected using sewer systems and then further treated using primary, secondary, and/or tertiary treatment methods followed by discharge. Each management phase can create anaerobic conditions (e.g., anaerobic phases during tertiary treatment in constructed wetlands and lagoons) contributing to CH_4 ultimately emitted from the treatment system. Sludge produced during secondary treatment may also generate CH_4 if it is further treated in anaerobic digesters. Although some facilities recover or flare this gas reducing CH_4 emissions, some emissions still occur from unintentional leakages (EPA, 2025). Per IPCC guidelines (2019), emissions from anaerobic sludge digestion—including biogas recovery and flaring operations, where the digester's primary use is for treatment of wastewater treatment solids—are estimated and reported under wastewater treatment whereas on-farm and stand-alone digestors (e.g., for processing food waste) are reported in Chapter 5, Agriculture under Section 5.2 and later within this chapter in Section 7.4 , respectively. Emissions from flooded lands or constructed waterbodies (not used for wastewater treatment) are estimated and reported in Chapter 6, under Sections 6.8: Wetlands Remaining Wetlands and 6.9: Lands Converted to Wetlands.

Nitrous oxide is formed during processes that convert nitrogen in wastewater, particularly during nitrification and denitrification. These emissions are often released to the air during treatment, especially in aerated parts of the treatment process (IPCC, 2019).

On-site systems, such as septic tanks, treat wastewater through settling and anaerobic sludge digestion. This digestion produces CH_4 (and biogenic CO_2), which is typically vented, and can also release N_2O and biogenic CO_2 from dispersing effluent through the soil (EPA, 2025).

Wastewater discharges containing dissolved CH_4 and N_2O and additional organic matter can also lead to emissions when treated effluent is released into rivers, lakes, or other water bodies. Methane emissions are generally higher for discharges to slow-moving waterbodies (e.g., lakes and reservoirs), whereas N_2O emissions are higher when discharging to nutrient-impacted or eutrophic waters (IPCC, 2019).

In addition to the configuration and operation of treatment systems (e.g., management under anaerobic conditions), the main factors affecting CH_4 emissions is the amount of organic material in the wastewater, often measured as biochemical oxygen demand (BOD) or chemical oxygen

demand (COD). Higher values generally mean higher emissions. N_2O emissions depend on the amount of nitrogen and how the treatment system is operated (EPA, 2025; IPCC, 2019). Recent studies suggest CH_4 emissions may be lower than previously thought, while N_2O emissions may be higher (see relevant references in the "Future Areas for Improvement" subsection included in the introduction to this chapter).

Total methane (CH_4) emissions from wastewater treatment and discharge were 21 MMT CO_2 Eq. in 2024, including 14 MMT CO_2 Eq. from domestic wastewater treatment and discharge, and 7 MMT CO_2 Eq. from industrial wastewater treatment and discharge (Table 7-5). Methane emissions from domestic wastewater remained fairly steady from 1990 through 2000 but have decreased since that time due to decreasing use of anaerobic systems, including reduced use of on-site septic systems and central anaerobic treatment systems (EPA, 2025). Methane emissions from industrial wastewater emissions have generally increased across the time series, with some fluctuations corresponding to production changes from the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, petroleum refining, and brewery industries.

Nitrous oxide (N_2O) emissions from wastewater treatment and discharge in 2024 totaled 21.1 MMT CO_2Eq., including 20.6 MMT CO_2 Eq. from domestic wastewater and 0.5 MMT CO_2 Eq. from industrial wastewater (see Table 7-5). N_2O emissions from domestic wastewater have steadily increased over time due to U.S. population growth and increased protein intake. Emissions from industrial wastewater sources have also increased over time with production changes associated with the treatment of wastewater, namely from meat and poultry processing and petroleum refining, but also with contributions from pulp and paper manufacturing and brewery industries.

In total, the wastewater treatment and discharge category emitted 42.1 MMT CO_2 Eq. in 2024.

Table 7-5: Emissions from Wastewater Treatment and Discharge (MMT CO_2 Eq.)

Activity	1990	2005	2020	2021	2022	2023	2024
CH_4	**22.7**	**22.7**	**21.0**	**20.7**	**20.9**	**21.2**	**21.0**
Domestic Treatment	15.1	14.6	11.7	11.4	11.7	12.1	12.0
Domestic Effluent	1.4	1.4	2.1	2.1	2.0	2.0	2.0
Industrial Treatment [a]	5.5	6.1	6.6	6.7	6.7	6.6	6.5
Industrial Effluent [a]	0.7	0.6	0.5	0.5	0.5	0.5	0.5
N_2O	**14.8**	**18.1**	**21.6**	**21.1**	**21.2**	**21.0**	**21.1**
Domestic Treatment	10.5	13.7	16.7	16.3	16.5	16.4	16.6
Domestic Effluent	3.9	3.9	4.5	4.3	4.2	4.1	4.0
Industrial Treatment [b]	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Industrial Effluent [b]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total Emissions	**37.5**	**40.7**	**42.5**	**41.8**	**42.1**	**42.2**	**42.1**

[a] Industrial activity for CH_4 includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, petroleum refining, and breweries industries.

[b] Industrial activity for N_2O includes the pulp and paper manufacturing, meat and poultry processing, starch-based ethanol production, and petroleum refining.

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

Methods

The methodological approach for estimating emissions from treatment and discharge of domestic and industrial wastewater is consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025).

The estimates reflect updated data where available. For example, the domestic wastewater estimates are based on updated population data but use the same shares of septic and centralized treatment systems (i.e., publicly owned treatment works) as the *1990–2023 Inventory* (EPA, 2025) given no new housing survey data were available from the U.S. Census. The industrial wastewater estimates reflect updated industrial production data on food products (i.e., meat poultry, fruits, vegetables) from USDA National Agricultural Statistics (USDA, 2025a, 2025b, 2025c, 2025d, 2026a), pulp and paper production from the FAO Statistical Division (FAOSTAT; FAO, 2026a), ethanol grain use from the Renewable Fuel Association (2026), ethanol production from USDA (2026b), petroleum production data from the Energy Information Administration (EIA, 2026), and updated brewery production data from the Alcohol and Tobacco Tax and Trade Bureau's beer statistics (2025). The estimates also reflect updated available per capita protein data from FAO given lack of domestic data sources (FAO, 2026b).

Additional detail on the methods, data sources, and assumptions can be found in Annex 5 to this *GHGIA*.

Recalculations

Methods and activity data are generally consistent with the *1990–2023 Inventory* (EPA, 2025), incorporating updated activity data where available as described below.

- ***Domestic Wastewater.*** The estimates reflect updates to annual population data for the United States, including territories for consistency with the latest published U.S. Census (U.S. Census Bureau, 2024, 2025). The population data were updated for the continental United States, District of Columbia, and Puerto Rico for 2010–2023 and updated across the full time series for other U.S. territories. Revised available protein supply data were updated for 2010–2023 (FAO, 2026b). The revisions had insignificant impacts across the time series as compared to the *1990–2023 Inventory* (averaging <0.2 percent).
- ***Industrial Wastewater.*** The estimates reflect updates to annual production of paper and paperboard and wood pulp for 2019–2023 (FAO, 2023, see USA Tables; FAO 2026a, 2026b), food production data for recent years (i.e., meat, poultry, fruits, and vegetables) (USDA, 2025a, 2025b, 2025c, 2025d, 2026), petroleum production (EIA, 2026); ethanol production (USDA, 2026b); and brewery production (Alcohol and Tobacco Tax and Trade Bureau, 2025). The revisions to recent prior data had insignificant impacts across the time series as compared to the *1990–2023 Inventory (EPA, 2025)* (averaging <0.05 percent).

Revisions to annual data had no significant impact on estimated wastewater emission and trends, with an average slight decrease of less than 0.2 percent across the time series.

Uncertainty

Uncertainty in emission estimates from wastewater is associated with a number of factors. For domestic treatment the uncertainty is primarily due to assumptions to estimate types of treatment in place, and representativeness of surrogate data and assumptions to approximate key estimation parameters in reflecting operational wastewater treatment and discharge systems over time in the United States. Similar factors impact industrial wastewater estimates. As noted, recent independent studies also suggest potential overestimation of CH_4 emissions and underestimation of N_2O emissions (see the "Future Areas for Improvement" in the introduction to this chapter).

For this current report, the uncertainty associated with national estimates of CH_4 and N_2O from wastewater is assumed to be similar to the *1990–2023 Inventory* (EPA, 2025), given the use of the same methodology and data sources for all years, calculated using the *2006 IPCC Guidelines* Approach 2 methodology for uncertainty at the 95 percent confidence level (IPCC, 2006). In 2024, this confidence level indicates a range of approximately 28 percent below and 32 percent above estimated CH_4 emissions and approximately 37 below and 193 percent above estimated N_2O emissions. Uncertainty assessments for 2024 are summarized at the end of this chapter in Table 7-10.

7.3 Composting (Source Category 5B1)

Composting is commonly used in the United States to manage organic wastes such as food scraps, yard trimmings, and wastewater sludge and/or biosolids (BioCycle, 2017, 2023, 2025; USCC, 2025). It reduces methane-generating waste sent to landfills, destroys pathogens, and produces a usable soil amendment that can offset chemical fertilizer use. This source category includes large-scale, commercial composting operations, primarily windrow systems handling yard trimmings, consistent with national survey data (BioCycle, 2017; EPA, 2025; Environmental Research & Education Foundation, 2024). Windrow systems, including windrow systems combined with other systems, account for the largest share of systems in use at food waste composting facilities (nearly 49 percent of systems) (BioCycle, 2017). The estimates exclude waste composted using other methods (e.g., aerated static piles) due to limited data availability. They also do not currently include residential or community composting.

Composting is primarily an aerobic process that converts organic carbon to CO_2; however, localized anaerobic conditions can produce CH_4, and N_2O may form depending on nitrogen content and management practices. Most CH_4 generated is oxidized within the compost pile, resulting in relatively low emissions overall. The estimated CH_4 released into the atmosphere ranges from less than 1 percent to a few percent of the initial carbon content in the material. Composting emissions vary depending on factors such as the waste composition (e.g., residential yard waste, food scraps, wood chips, peat), and process conditions (e.g., temperature, moisture content, aeration). Further, net carbon dioxide flux from carbon stock changes of materials of biogenic origin being composted are reported under the LULUCF sector estimates and not reported here to avoid double counting of emissions from biomass-related stock changes (see Chapter 6 of this *GHGIA*) (IPCC, 2006).

In 2024, composting emissions were estimated at 2.6 MMT CO_2 Eq. for CH_4 and 1.9 MMT CO_2 Eq. for N_2O and have increased fivefold since 1990 (see Table 7-6). Growth in composting has been driven largely by state and local policies restricting landfill disposal of organic waste and expanding collection programs. From 1990 to 2024, the amount of waste composted increased from 3,810 kt to 23,378 kt, with emissions of CH_4 and N_2O rising proportionally (see Table 7-7). These policies, along with increased infrastructure and diversion efforts, have significantly increased the amount of organic waste processed through composting rather than landfilled (EPA, 2025).

Table 7-6: Emissions from Composting (MMT CO_2 Eq.)

Activity	1990	2005	2020	2021	2022	2023	2024
CH_4	0.4	2.1	2.6	2.6	2.6	2.6	2.6
N_2O	0.30	1.5	1.8	1.8	1.8	1.8	1.9
Total	0.7	3.6	4.4	4.4	4.4	4.4	4.5

Note: Totals may not sum due to independent rounding.

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

Activity	1990	2005	2020	2021	2022	2023	2024
Waste Composted	3,810	18,655	22,802	22,836	22,964	23,153	23,378

Methods

The methodological approach for estimating emissions from composting is consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025). Consistent with the previous *Inventory*, the estimate of the annual amount of waste composted for 2019–2024 was developed by extrapolation due to lack of annual national compost data by applying the 2018 compost per capita ratio to corresponding updated annual population data from U.S. Census (U.S. Census Bureau, 2024, 2025).

Recalculations

Methods and activity data are generally consistent with the *Inventory* (EPA, 2025), incorporating updated annual population data from the U.S. Census (U.S. Census Bureau, 2024, 2025) for 2018 to 2024. The revisions had insignificant impacts on 2019–2023 estimates as compared to the *Inventory* (EPA, 2025). On average, recalculated emissions decreased by 0.04 percent, due to a slightly lower estimated composting per capita ratio which in turn caused slight decreases in estimated waste composted, and associated emissions for those years.

Uncertainty

Uncertainty in emission estimates from composting is primarily associated assumptions with the waste quantities composted and associated methods for composting, and average characteristics impacting methane generation for each method in practice in the United States.

For this current report, the uncertainty associated with national estimates of CH_4 and N_2O emissions from composting is assumed to be similar to the *1990–2023 Inventory* (EPA, 2025), given the use of the same methodology and data sources for all years and calculated using the *2006 IPCC Guidelines* Approach 1 methodology or error propagation method (IPCC, 2006). The combined uncertainty associated with activity data and default emissions factors indicates a range of approximately 58 percent below and 58 percent above estimated CH_4 emissions in 2024. Uncertainty assessments for 2024 from all waste source categories are summarized at the end of this chapter in Table 7-10.

7.4 Anaerobic Digestion at Biogas Facilities (Source Category 5B2)

Anaerobic digestion is a biological process that occurs inside an enclosed, air-tight vessel (i.e., the anaerobic digester) where microorganisms break down organic matter such as food waste in the absence of oxygen, producing biogas and digestate (i.e., nutrient rich, solid and liquid material left after the digestion process) (EPA, 2025c). The resulting biogas consists primarily of methane (CH_4) and biogenic carbon dioxide (CO_2), with small amounts of other gases, and is flared, used for energy (commonly used for on-site heat, electricity), or upgraded to renewable natural gas and sold. The digestate is often applied as a soil amendment or fertilizer to agricultural fields, land reclamation, or other suitable uses. Under proper operating conditions with regular maintenance, CH_4 emissions are expected to be minimal. Methane emissions can occur from inefficiently operated systems, contaminants in the waste stream (e.g., inert materials such as microplastics), leaks at system connection points, or pressure build-ups which may lead to leaks. Carbon dioxide emissions are biogenic and reported separately (IPCC, 2006).

Anaerobic digesters vary by operating temperature, feedstock type, moisture content, and system design. They may operate under mesophilic or thermophilic conditions and process a wide range of organic materials, including food waste, wastewater solids, manure, and industrial residues. Many systems use co-digestion to enhance methane production by combining multiple feedstocks (EPA, 2025b, 2025c). Digesters are also classified as wet or dry systems based on solids content and may operate in batch or continuous modes. N_2O emissions are assumed to be negligible (IPCC, 2006).

In national GHG inventories, anaerobic digestion systems are generally categorized as stand-alone biogas facilities, on-farm digesters, or systems at water resource recovery facilities. This section focuses on stand-alone facilities, which process waste from single or multiple sources. Emissions from on-farm digesters are included in the manure management category estimates in Chapter 5 (agriculture sector) and emissions from systems at water resource recovery facilities are included in the wastewater treatment and discharge category estimates within this chapter.

From 1990 to 2024, the amount of waste managed by these facilities increased substantially, driven by growing interest in biogas as a renewable energy source and efforts to divert organic waste from landfills. However, estimates for 1990–2015 and some recent years (i.e., 2020–2021 and 2024) rely on extrapolation and interpolation due to limited data availability (EPA, 2025b).

Table 7-8: Emissions from Stand-Alone Anaerobic Digestion at Biogas Facilities (metric tons [MT] CO_2 Eq.)

Activity	1990	2005	2020	2021	2022	2023	2024
CH_4 Generated	22,129	66,388	328,348	347,874	334,093	146,700	240,397
CH_4 Recovered	(21,023)	(63,069)	(311,931)	(330,480)	(317,388)	(139,365)	(228,377)
Net CH_4 Emissions	**1,106**	**3,319**	**16,417**	**17,394**	**16,705**	**7,335**	**12,020**

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

Table 7-9: Waste Digested and Estimated Operational Facilities

Activity	1990	2005	2020	2021	2022	2023	2024
Waste Digested (kt)	988	2,964	14,658	15,530	14,915	6,549	10,732
Estimated Operational Facilities (count)	4	12	54	54	96	96	96

Source: EPA, 2025b

Methods

The methodological approach for estimating emissions is consistent with the *Inventory of Greenhouse Gas Emissions and Sinks: 1990–2023* (EPA, 2025a). The estimates incorporate recently published survey data findings from the EPA's Anaerobic Digestion Data Collection Project for 2022 and 2023 (2025a), and 2022 and 2023 data were averaged to approximate 2024 activity data on waste processed and operational facilities. Methane recovered was extrapolated based on activity data (i.e., waste digested) multiplied by a 5 percent default leakage factor (IPCC, 2006). Approximately 80–90 percent of all anaerobic digestion facilities used some or all of the CH_4 generated (EPA, 2025b). The methodology assumes that all CH_4 generated by stand-alone anaerobic digesters is used and approximately 5 percent is leakage and therefore the amount emitted to the atmosphere.

Recalculations

Recalculations were implemented to incorporate 2022 and 2023 survey data from EPA (2025b). Recalculated emissions decrease in 2022 and 2023, by 1 percent and 56 percent respectively, consistent with decreases in revised estimated annual waste digested for those years relative to EPA (2025a).

Uncertainty

Uncertainty in emission estimates from stand-alone anaerobic digestion is associated with a few key factors, namely incomplete, periodic survey data which likely underestimates digestion activity, including biogas recovery, flaring, and energy uses based on low survey response rates.

The survey methods have also been refined over time so EPA urges data users to exercise caution in comparing data across surveys as they may not accurately reflect activity trends.

For this current report, the uncertainty associated with national estimates of CH_4 from stand-alone anaerobic digestion is assumed to be similar to EPA (2025a), given the use of the same basic methodology and data sources for all years and calculated using the *2006 IPCC Guidelines* Approach 1 methodology or error propagation method (IPCC, 2006). The combined uncertainty associated with activity data and default emissions factors indicates a range of approximately 54 percent below and 54 percent above estimated CH_4 emissions in 2024. Uncertainty assessments for 2024 from all waste source categories are summarized at the end of this chapter in Table 7-10.

7.5 Waste Incineration (Source Category 5C1)

Emissions of carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) from waste incineration are reported in the energy sector because most waste combustion in the United States occurs at waste-to-energy facilities and industrial boilers that recover energy. In 2024, waste combustion resulted in 12.2 MMT CO_2 Eq. of emissions. See Section 3.3 of Chapter 3 on energy for more information.

Non-hazardous industrial and medical waste incineration are additional sources of emissions from waste combustion; however, data for these sources are limited and emissions are not estimated. An analysis of medical waste incineration (EPA, 2025) indicates emissions are less than 500 kt CO_2 Eq. per year and are therefore considered insignificant for national inventory reporting. A similar analysis of sewage sludge incineration, based on total sludge generation and assumed incineration rates, also found emissions below 500 kt CO_2 Eq. per year and insignificant. See information in Annex 5 to this *GHGIA*.

7.6 Waste Uncertainty Summary

Table 7-10 shows the uncertainty summary for each waste sector source. A discussion of the uncertainty ranges is included in each source category's respective chapter section.

Table 7-10: Quantitative Uncertainty Summary by Waste 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
Landfills (Total)	**CH_4**	**119.4**	**108.7**	**136.1**	**–9%**	**14%**
MSW Landfills	CH_4	100.6	98.6	120.7	–2%	20%
Industrial Landfills	CH_4	18.8	16.0	26.1	–15%	39%
Wastewater Treatment	**CH_4**	**21.0**	**15.1**	**27.7**	**–28%**	**32%**
Domestic	CH_4	14.0	9.4	19.7	–33%	41%
Industrial	CH_4	7.0	4.1	11.1	–42%	58%
Wastewater Treatment	**N_2O**	**21.1**	**13.4**	**62.1**	**–37%**	**193%**
Domestic	N_2O	20.7	12.4	61.1	–40%	195%
Industrial	N_2O	0.5	0.5	1.5	–2%	199%
Composting	**CH_4**	**2.6**	**1.1**	**4.1**	**–58%**	**58%**
Composting	**N_2O**	**1.9**	**0.8**	**3.0**	**–58%**	**58%**
Anaerobic digestion at biogas facilities	**CH_4**	**0.01**	**0.00**	**0.02**	**–54%**	**54%**

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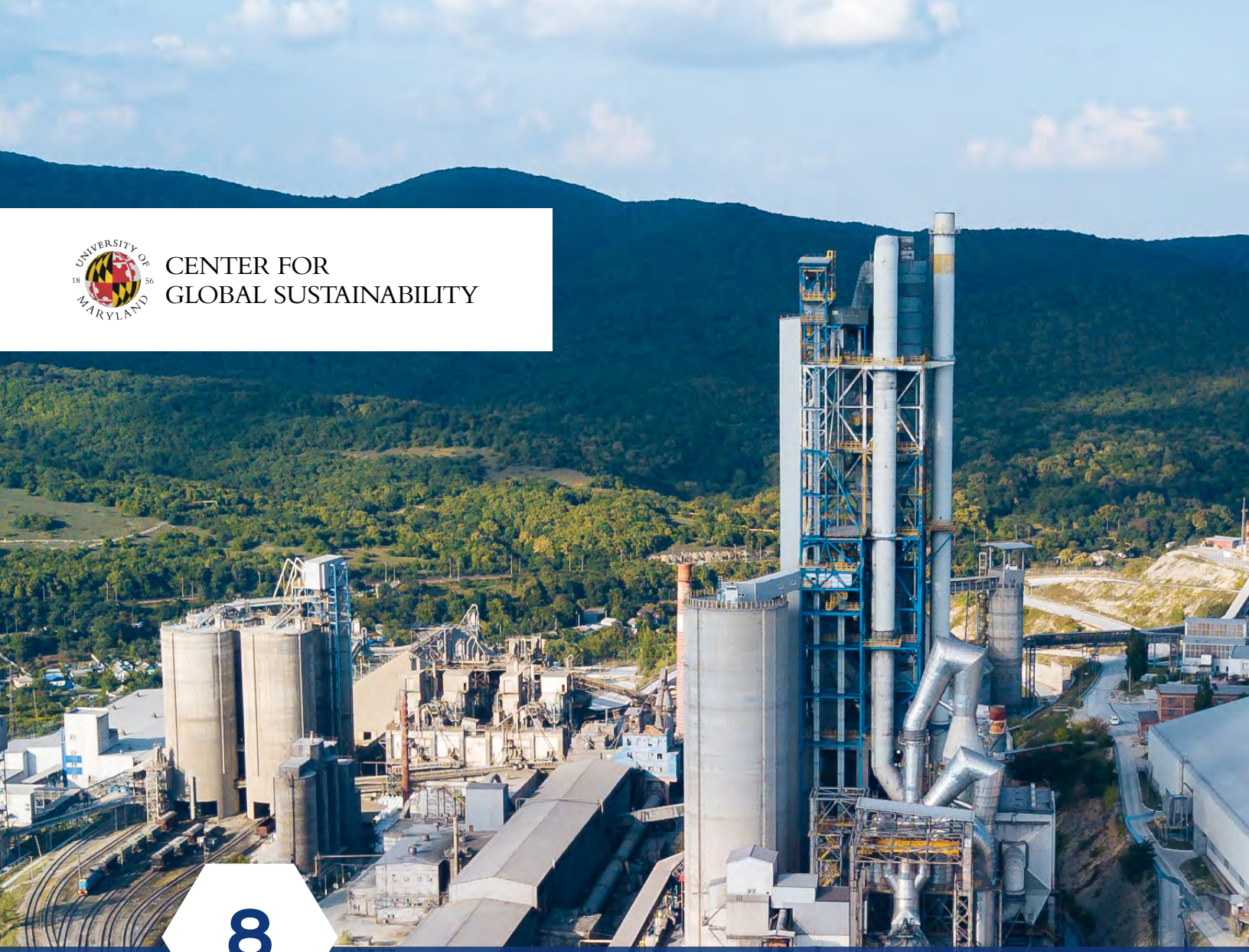
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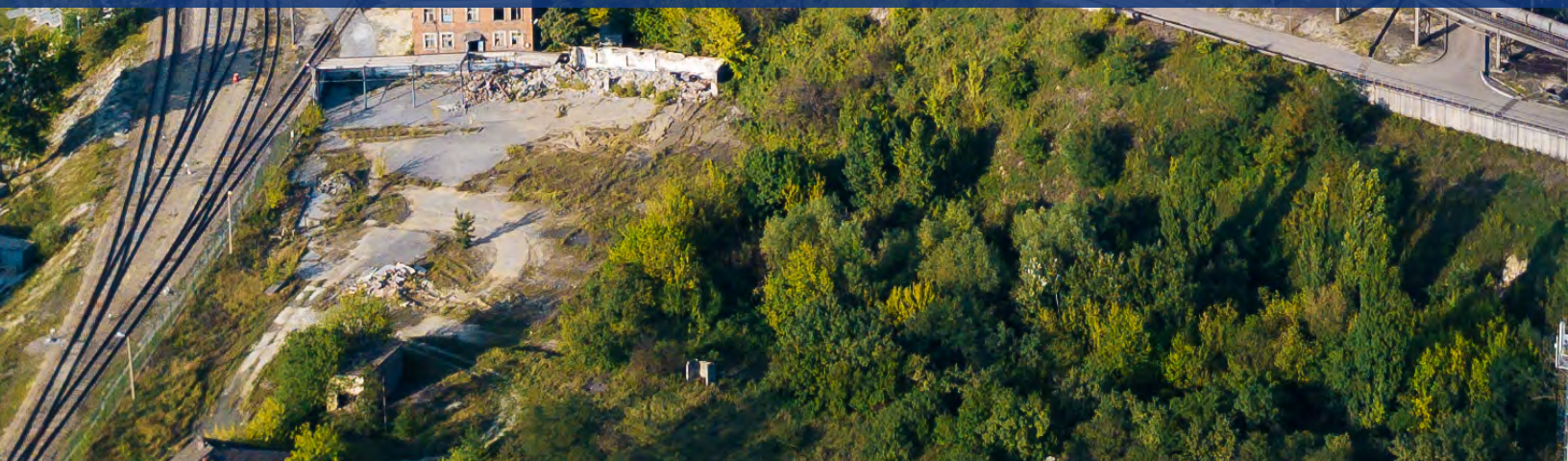
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8

Other



Chapter 8. Other

This chapter is reserved for emissions and removals from sources and/or sinks that are not allocated to specific sources within other sectors. No greenhouse gas emissions are currently reported under the "Other (6)"[46] inventory sector but may be reported in future inventories.

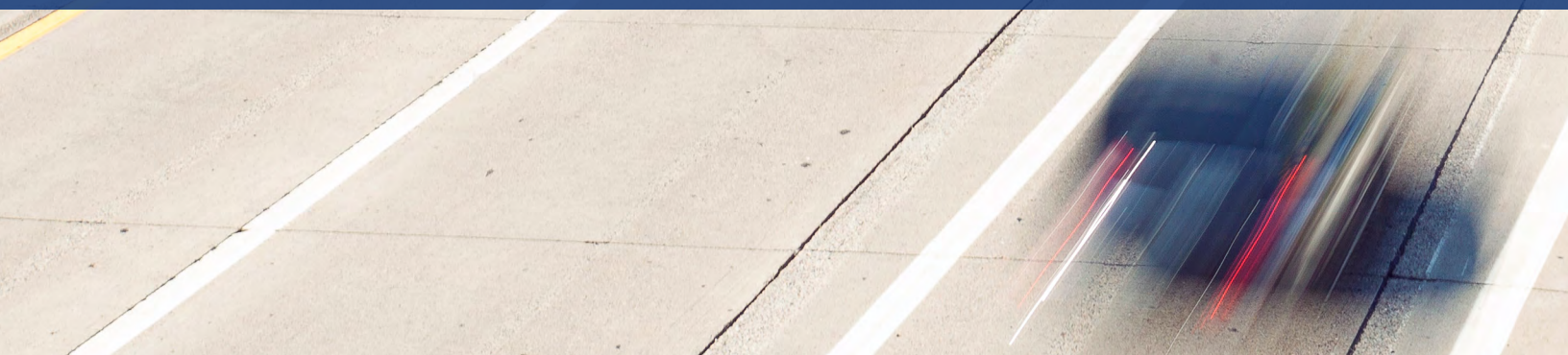
[46] Codes in parentheses represent common reporting table (CRT) codes. The CRT code is a classification system to organize quantitative reporting of detailed emission and removal data in standardized data tables (i.e. CRTs) to facilitate comparison of national inventory data and trends. The code reflects classification levels, e.g. sector, subsector, category, subcategory, etc. Translating: 6 = Other Sector.



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9

Recalculations and Improvements



Chapter 9. Recalculations and Improvements

This chapter summarizes recalculations relative to previous estimates in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (Environmental Protection Agency [EPA] 2025). This *Greenhouse Gas Inventory and Analysis for the United States* (*GHGIA*) estimates are updated annually to incorporate updated annual activity data, refine methods, data, and/or other key parameters, apply more significant methodological changes based on new science and research, information identified in reviews and to correct errors identified from implementing quality assurance and quality control procedures. It is Intergovernmental Panel on Climate Change good practice to recalculate the entire time series from the initial year to the latest year to ensure time series consistency; however, the scope of the recalculation depends on the scope of the update. Updates to recent years of annual statistical data occur regularly, and changes may impact only recent years of the time series.

9.1 Recalculations and Rationale

This *GHGIA* includes some methodological refinements but mostly routine annual activity data updates. The updates with impacts exceeding 0.05 percent of gross emissions (3.1 million metric tons [MMT] of carbon dioxide equivalent [CO_2 Eq.]) in 2023 are described in Table 9-1 below. More details on specific recalculations can be found within the source and/or sink section within this *GHGIA*.

Table 9-1: Significant Recalculations and Impacts

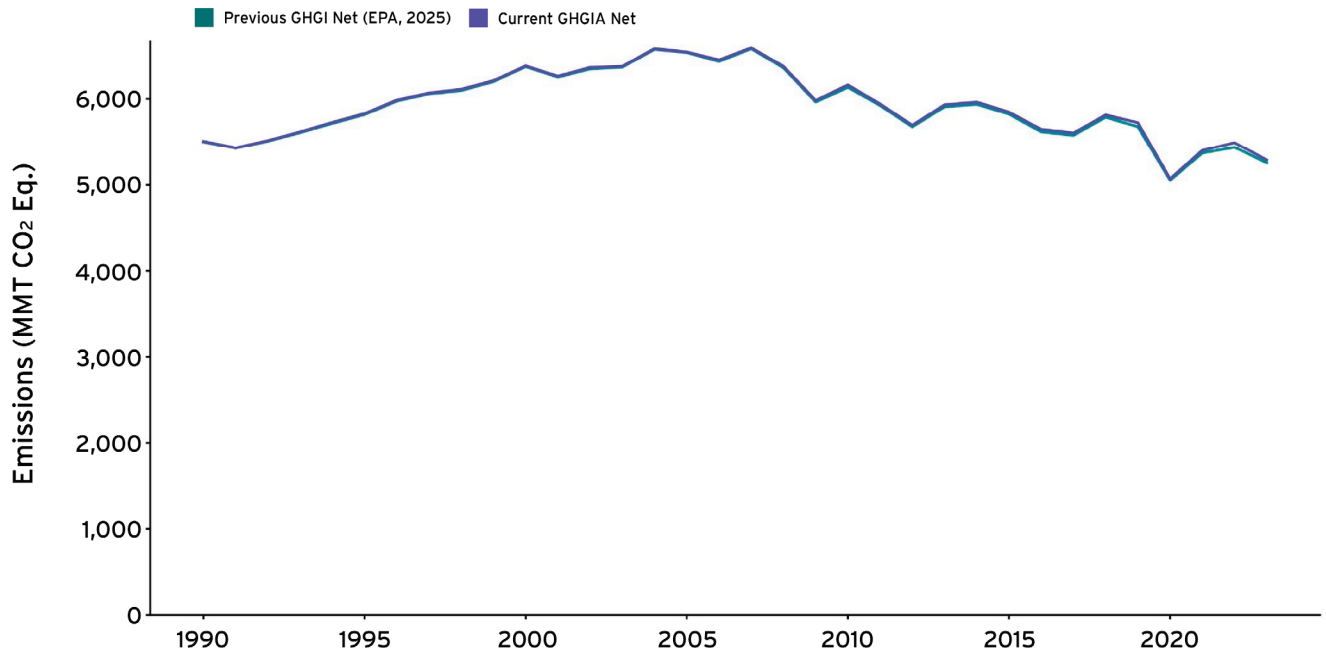
Sector	Category and Greenhouse Gas	Recalculation Reason	Change in 2023 Emissions (MMT CO_2 Eq.)	Average Annual Change (MMT CO_2 Eq. and Percent)
Energy	Fossil Fuel Combustion – Transportation (CO_2)	Updated activity data (see Chapter 3.1 for details)	41.2	0.5 (0.03%)
Energy	Fossil Fuel Combustion – Non-energy use of fuels (CO_2)	Updated activity data (see Chapter 3.2 for details)	–17.5	–0.2 (–0.4%)
Energy	Fossil Fuel Combustion – Commercial (CO_2)	Updated activity data (see Chapter 3.1 for details)	–14.6	0.03 (0.02%)
LULUCF	Cropland Remaining Cropland	Addressed time series consistency (see Chapter 6.4 and Box 5-1 for details)	12.4	1.1 (0.06%)
LULUCF	Forest Land Remaining Forest Land (CO_2)	Updated activity data and consistent methodology for contiguous United States (see Chapter 6.2 for details)	8.66	10.4 (1.1%)
Energy	Fossil Fuel Combustion – Residential (CO_2)	Updated activity data (see Chapter 3.1 for details)	–6.4	–0.02 (–0.01%)
LULUCF	Wetlands Remaining Wetlands	Updated activity data (see Chapter 6.8 for details)	4.2	0.7 (0.02%)
LULUCF	Land Converted to Grassland	Addressed time series consistency (see Chapter 6.7 and Box 5-1 for details)	3.2	1.1 (0.06%)
LULUCF	Land Converted to Cropland	Addressed time series consistency (see Chapter 6.5 and Box 5-1 for details)	–3.1	1.1 (0.06%)

LULUCF = Land Use, Land-Use Change, and Forestry

9.2 Implications for Emission and Removal Levels and Trends

The impact of recalculations made for this current *GHGIA* on net emissions is shown in Figure 9-1. Supplemental data tables published with this *GHGIA* for download include disaggregated impacts over the time series for all sources.

Figure 9-1: Impacts from Recalculations on Net Emissions



The average annual impact on net emissions was 16.5 MMT CO_2 Eq. over the time series 1990–2023. In 2023, the recalculations resulted in an increase of 32.2 MMT CO_2 Eq. or 0.6 percent of the current emissions in 2023.

The changes in 2023 emissions by greenhouse gas are shown in Figure 9-2, and the changes by sector are shown in Figure 9-3.

Figure 9-2: Impacts from Recalculations by Gas on 2023 Net Emissions (Absolute Change)

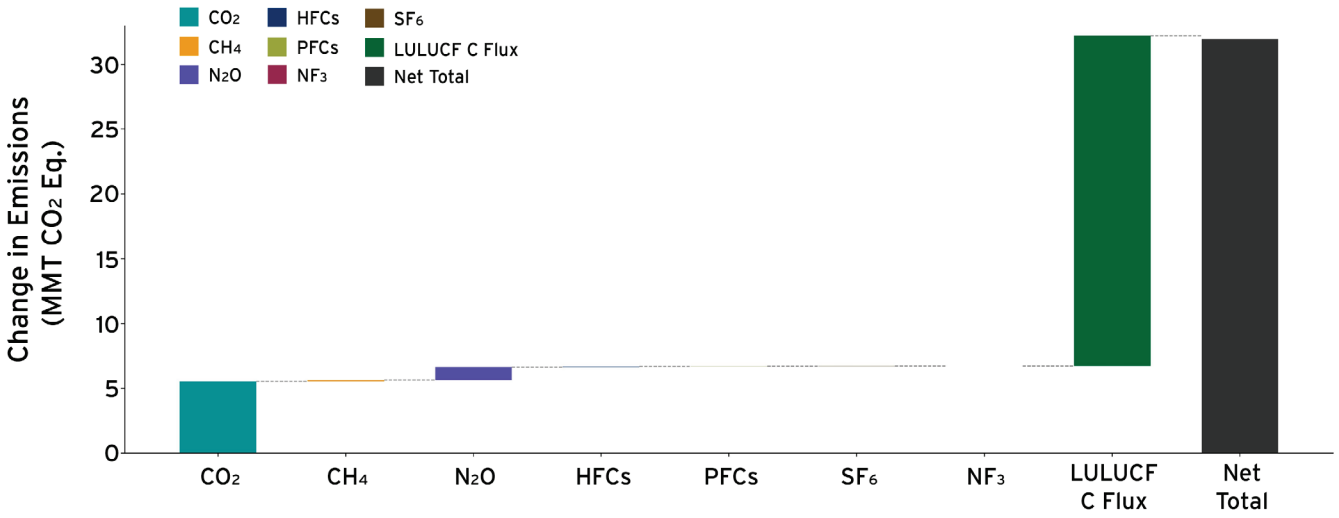
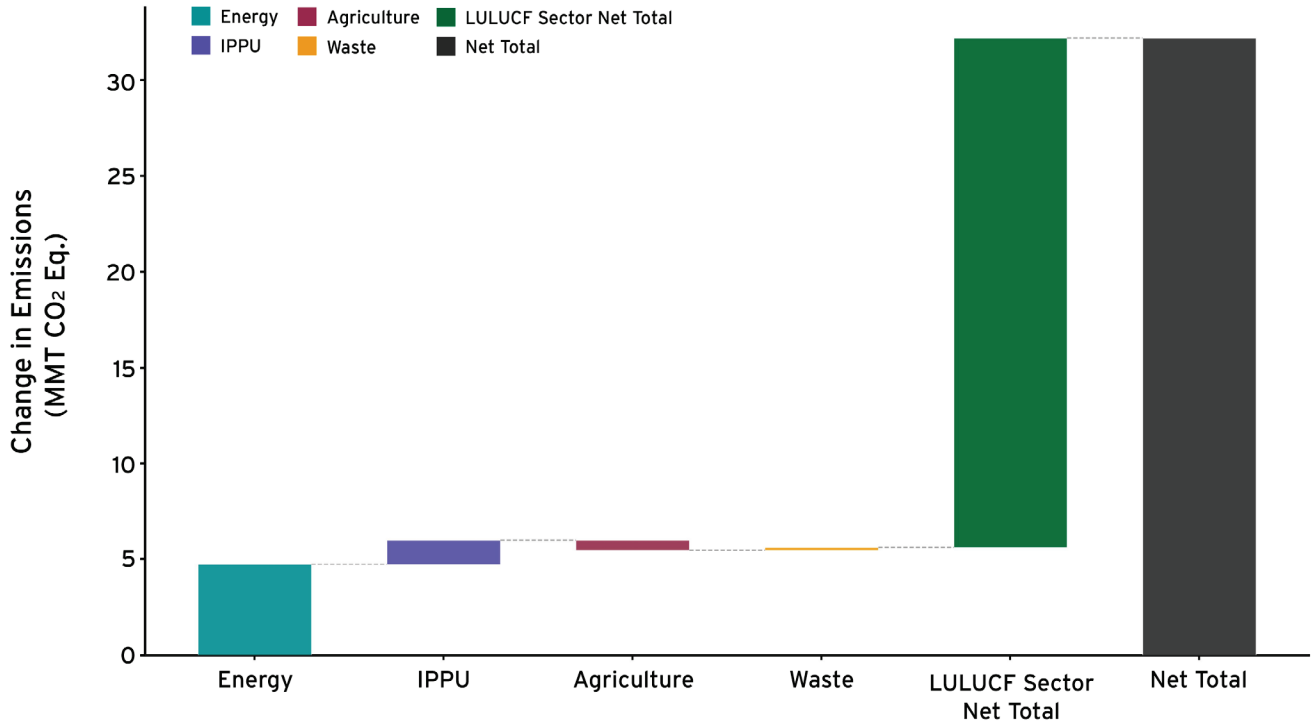
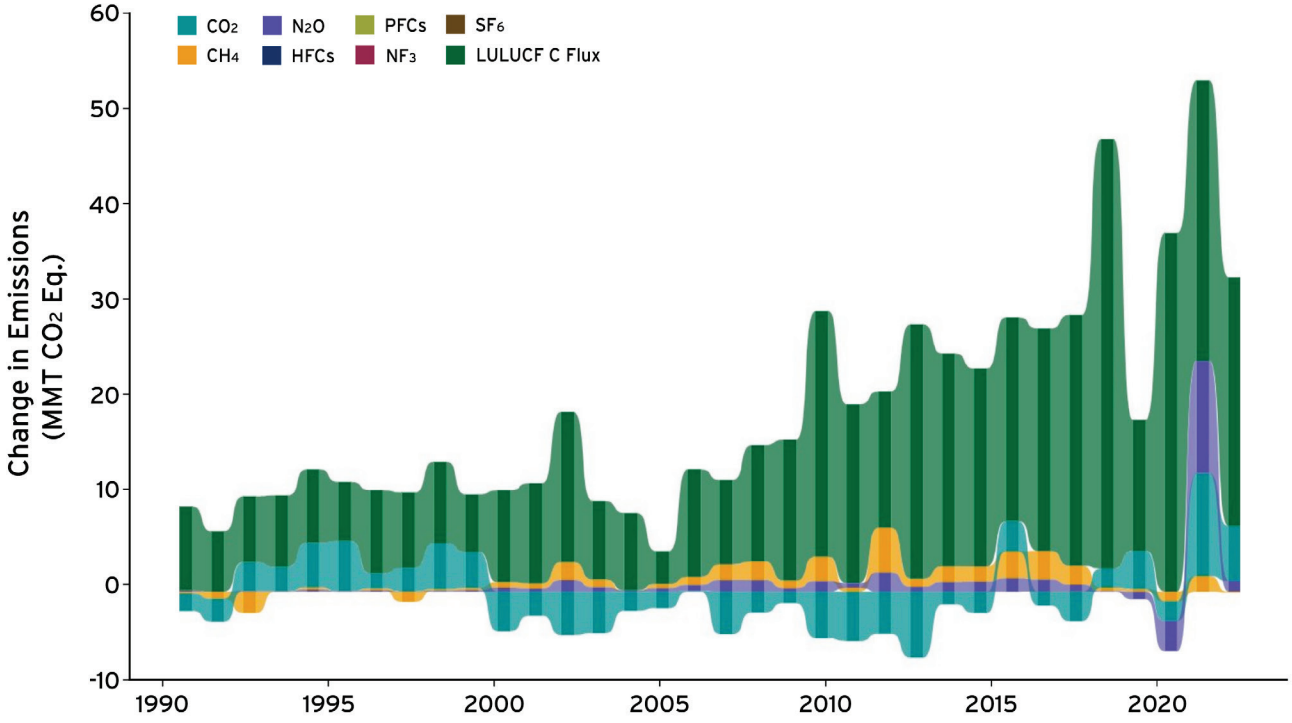


Figure 9-3: Impacts from Recalculation by Sector on 2023 Net Emissions (Absolute Change)



As shown in Figure 9-3, in 2023 the recalculations impact to net emissions was primarily in CO_2 emissions from the Energy and LULUCF sectors. Those same trends generally hold across the time series also, as seen in Figure 9-4 and Figure 9-5, which show the impacts of recalculations across the time series by gas and by sector, respectively.

Figure 9-4: Impacts from Recalculations by Gas on Net Emissions Over Time



Note: CH_4 and N_2O emission changes include LULUCF CH_4 and N_2O emissions.

Figure 9-5: Impacts from Recalculation by Sector on Net Emissions Over Time

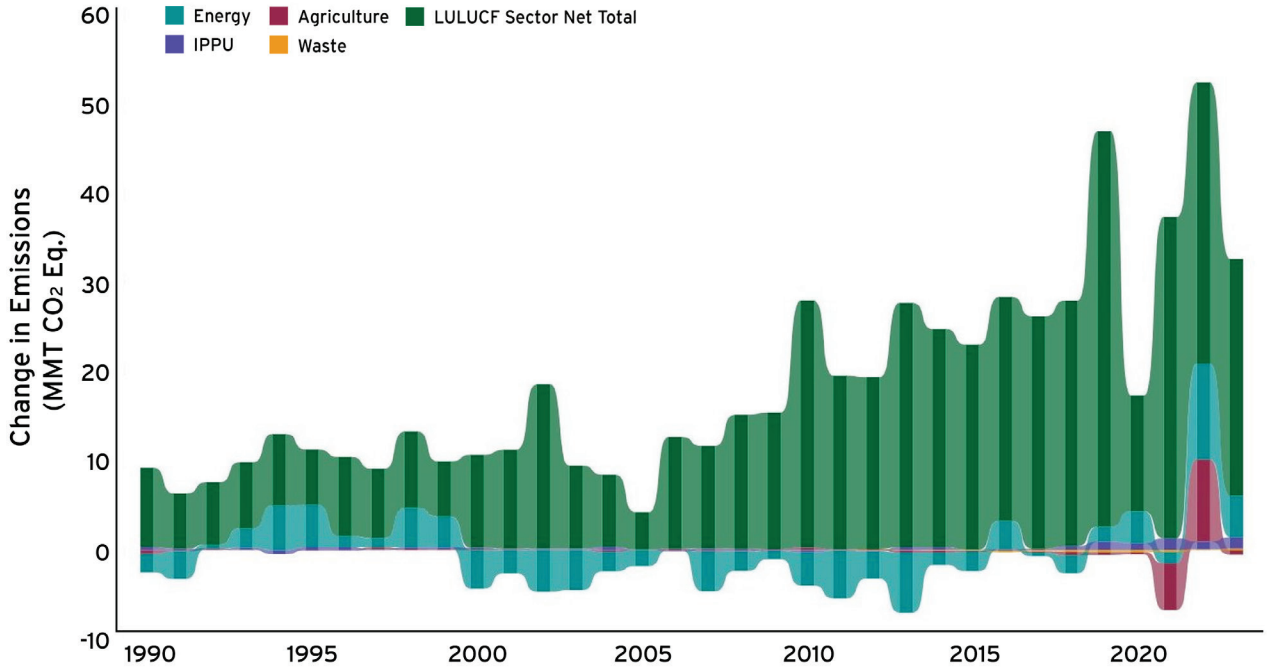


Figure 9-6 shows the impacts of recalculations across time specifically for changes in the energy sector for fossil fuel combustion CO_2 emissions by end use sector and emissions from non-energy use (NEU). As seen in Table 9-1, those were the energy sector sources that were most impacted by recalculations. The recalculations generally followed certain trends over time. Recalculation in NEU emissions generally resulted in opposite changes in industrial sector emissions, reflecting the linkages between those sources. The NEU estimates entail adjusting industrial sector energy use, therefore showing the opposite effects from recalculations. Similarly, changes in transportation sector emissions generally show opposite impacts on other sectors due to the shifting of estimates from one sector to the other. Section 3.1 has more details on the recalculations.

Figure 9-6: Impacts from Recalculations in Energy Subsectors

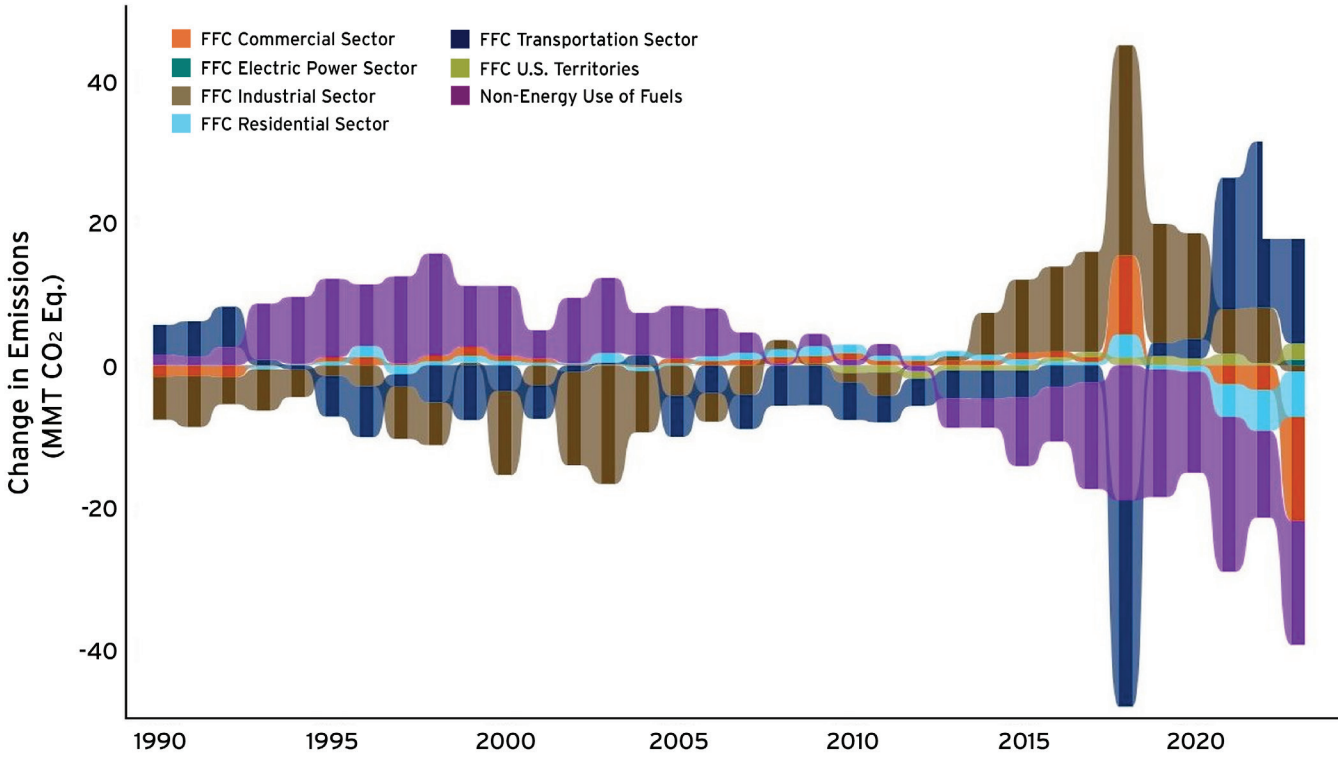
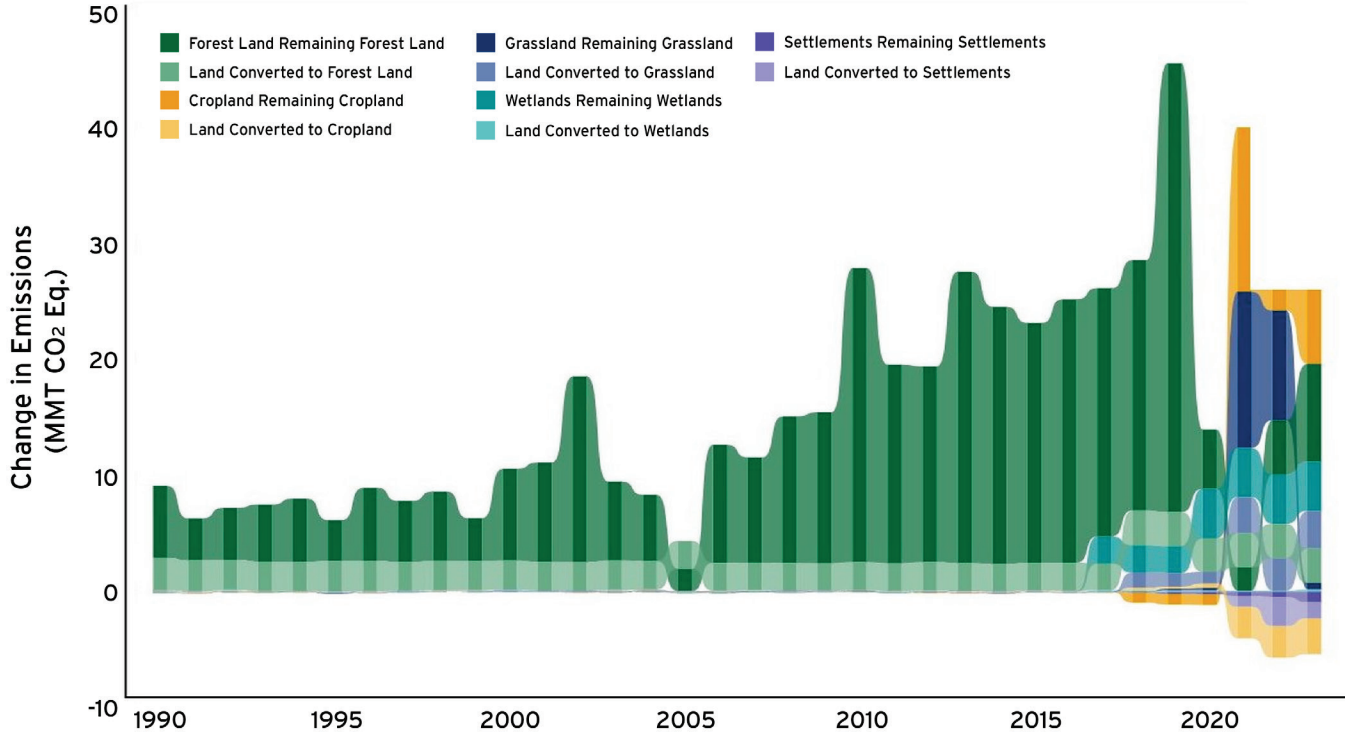


Figure 9-7 shows the impacts of recalculations across time specifically for changes in the LULUCF sector. The impacts across time were mostly from recalculations to the forest land remaining forest land category, where updated activity data and use of consistent methodologies for states in the contiguous United States were implemented. In addition, other more recent changes stemmed from recalculations to coastal wetlands remaining coastal wetlands resulting from incorporation of the latest National Oceanic and Atmospheric Administration Coastal Change Analysis Program data and updates to the Agriculture, Forestry, and Other Land Use extrapolations (see Box 5-1).

Figure 9-7: Impacts from Recalculations in the LULUCF Sector



9.3 Future Improvement Areas

In this *GHGIA*, improvement areas are noted in the introduction to each sectoral chapters. This section will be updated in future Inventories to summarize notable improvement plans and updates in response to reviews.

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