1 Introduction

This *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2023* (*Inventory*) identifies and quantifies the anthropogenic[1] emissions sources and removals (by sinks) of greenhouse gases in the U.S. It is an essential tool for understanding the relative magnitude of different sources and sinks across the U.S., as well as changes in these magnitudes over time. This chapter provides an overview of the annual *Inventory* compilation and review processes that contribute to the *Inventory's* transparency, accuracy, consistency, and, including institutional arrangements, methods, data sources, key categories, uncertainty, QA/QC, and improvement planning. Chapters 2 through 7 of this report are organized by the following inventory reporting sectors and their respective source and sink categories: Energy; Industrial Processes and Product Use (IPPU); Agriculture; Land Use, Land-Use Change, and Forestry (LULUCF); and Waste.

Box 1-1: Relationship to EPA's Greenhouse Gas Reporting Program

EPA also collects greenhouse gas emissions data from individual facilities and suppliers of certain fossil fuels and industrial gases through its Greenhouse Gas Reporting Program (GHGRP).[2] The GHGRP applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial greenhouse gas suppliers, and facilities that inject carbon dioxide (CO_2) underground for sequestration or other reasons and requires reporting by over 8,000 sources or suppliers in 46 industrial categories.[3] Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year. Facilities in most source categories[4] subject to GHGRP began reporting for the 2010 reporting year while additional types of industrial operations began reporting for the 2011 reporting year. Methodologies used in EPA's GHGRP are consistent with the *2006 IPCC Guidelines*. While the GHGRP does not provide full coverage of total annual U.S. greenhouse gas emissions and removals (e.g., the GHGRP excludes emissions from the Agriculture and Land Use, Land-Use Change, and Forestry sectors), it is an important input to the calculations of national-level emissions in this *Inventory*.

Data presented in this *Inventory* report and EPA's GHGRP are complementary. The GHGRP dataset continues to be an important resource for the *Inventory*, providing not only annual emissions

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1 The term "anthropogenic," in this context, refers to greenhouse gas emissions and removals that are a direct result of human activities or are the result of natural processes that have been affected by human activities (IPCC 2006).

2 On October 30, 2009, EPA promulgated a rule requiring annual reporting of greenhouse gas data from large greenhouse gas emissions sources in the United States. Implementation of the rule, codified at 40 CFR Part 98, is referred to as EPA's Greenhouse Gas Reporting Program (GHGRP).

3 See http://www.epa.gov/ghgreporting and http://ghgdata.epa.gov/ghgp/main.do.

4 See https://www.ccdsupport.com/confluence/pages/viewpage.action?pageId=322699300

information, but also other annual information such as activity data and emission factors that can improve and refine national emission estimates and trends over time. GHGRP data also allows EPA to disaggregate national inventory estimates in new ways that can highlight differences across regions and sub-categories of emissions, along with enhancing the application of QA/QC procedures and assessment of uncertainties. EPA uses annual GHGRP data in several categories to improve the national estimates presented in this *Inventory*, consistent with IPCC methodological guidance. See Annex 9 for more information on specific uses of GHGRP data in the *Inventory* (e.g., natural gas systems).

Additionally, this *Inventory* presents the calculated emissions and removals in a given year for the United States in a common manner that is in line with the inventory reporting guidelines for the reporting of inventories under the UNFCCC. Use of consistent methods by countries to calculate emissions and removals for their inventories helps to ensure that these reports are comparable. The presentation of emissions and removals provided in this *Inventory* does not preclude alternative examinations (e.g., economic sectors).

This report applies methods from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)*, the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands (2013 Supplement)*, and the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (2019 Refinement)*. The recently released *2019 Refinement* clarifies and elaborates on the existing guidance in the *2006 IPCC Guidelines* and provides updates to default values of emission factors and other parameters based on updated science. This report applies both the *2013 Supplement* and updated guidance in the *2019 Refinement* to improve accuracy and completeness of the Inventory. For more information on specific uses, see Section 1.5, Methodology and Data Sources.

1.1 Greenhouse Gases

Although the Earth's atmosphere consists mainly of oxygen and nitrogen, neither plays a significant role in enhancing the greenhouse effect because both are essentially transparent to terrestrial radiation. The greenhouse effect is primarily a function of the concentration of water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other trace gases in the atmosphere that absorb the terrestrial radiation leaving the surface of the Earth (IPCC 2021).

Naturally occurring greenhouse gases include water vapor, CO_2, CH_4, N_2O, and ozone (O_3). Other greenhouse gases—such as certain classes of halogenated substances that contain fluorine, chlorine, or bromine (i.e., halons)—are, for the most part, solely a product of industrial activities. Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are halocarbons that contain chlorine, while halocarbons that contain bromine are referred to as bromofluorocarbons. Stratospheric ozone depleting substances, such as CFCs, HCFCs, and halons, are covered under the Montreal Protocol on Substances that Deplete the Ozone Layer. Countries typically do not include these gases in national greenhouse gas inventories.[5] Some other fluorine-containing

[5] Emissions estimates of CFCs, HCFCs, halons and other ozone-depleting substances are included in this document for informational purposes.

halogenated substances—hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3)—do not deplete stratospheric ozone but are potent greenhouse gases and are included in this report.

Several substances influence the global radiation budget but are short-lived and therefore not well-mixed, leading to spatially variable radiative forcing effects. The most important of these substances are water vapor, aerosols, and tropospheric (ground level) ozone (O_3).

Tropospheric ozone is formed from chemical reactions in the atmosphere of precursor pollutants, which include volatile organic compounds (VOCs), CH_4, and nitrogen oxides (NO_x), in the presence of ultraviolet light (sunlight).

Aerosols are extremely small particles or liquid droplets suspended in the Earth's atmosphere that are often composed of sulfur compounds, carbonaceous combustion products (e.g., black carbon), crustal materials (e.g., dust) and other human-induced pollutants. They can affect the absorptive characteristics of the atmosphere (e.g., scattering incoming sunlight away from the Earth's surface, or, in the case of black carbon, absorbing sunlight) and can play a role in affecting cloud formation and lifetime, as well as the radiative forcing of clouds and precipitation patterns.

In addition, carbon monoxide (CO), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2) have direct influences on radiative forcing, but those are generally smaller than their indirect influences through their contributions to ozone, aerosols, and the lifetime of methane.

CO_2, CH_4, and N_2O are continuously emitted to and removed from the atmosphere by natural processes on Earth. However, anthropogenic activities (e.g., fossil fuel combustion, cement production, land-use, land-use change, and forestry, agriculture, or waste management) can cause additional quantities of these and other greenhouse gases to be emitted or sequestered, thereby changing their global average atmospheric concentrations. Natural activities, such as plant and animal respiration and seasonal cycles of plant growth and decay, are examples of processes that only cycle carbon or nitrogen between the atmosphere and organic biomass. Such processes, except when directly or indirectly perturbed out of equilibrium by anthropogenic activities, generally do not alter average atmospheric greenhouse gas concentrations over decadal timeframes. Climatic changes resulting from anthropogenic activities, however, can have positive or negative feedback effects on these natural systems. Atmospheric concentrations of these gases, along with their rates of growth and atmospheric lifetimes, are presented in Table 1-1.

For further information on greenhouse gases, radiative forcing, and implications for climate change, see the recent scientific assessment reports from the IPCC,[6] the U.S. Global Change Research Program (USGCRP),[7] and the National Academies of Sciences, Engineering, and Medicine (NAS).[8]

[6] See https://www.ipcc.ch/report/ar6/wg1/.

[7] See https://nca2018.globalchange.gov/.

[8] See https://www.nationalacademies.org/topics/climate.

Table 1-1: Global Atmospheric Concentration, Rate of Concentration Change, and Atmospheric Lifetime of Selected Greenhouse Gases

Atmospheric Variable	CO_2	CH_4	N_2O	SF_6	CF_4
Pre-industrial atmospheric concentration	280 ppm	0.730 ppm	0.270 ppm	0.01 ppt	34.1 ppt
Atmospheric concentration	421.08 ppm[a,b]	1.922 ppm[c]	0.337 ppm[d]	11.40 ppt[e]	85.5 ppt[f]
Rate of concentration change	2.35 ppm/yr[g]	8.82 ppb/yr[g,h]	1.02 ppb/yr[g]	0.33 ppt/yr[g]	0.81 ppt/yr[f]
Atmospheric lifetime (years)	See footnote[i]	11.8[j]	109[j]	About 1,000[k]	50,000

[a] The atmospheric CO_2 concentration is the 2023 annual average at the Mauna Loa, HI station. Due to the eruption of the Mauna Loa Volcano, measurements from Mauna Loa Observatory were suspended as of Nov. 29, 2022, and resumed in July 2023. Observations starting from December 2022 to July 4, 2023, are from a site at the Mauna Kea Observatories, approximately 21 miles north of the Mauna Loa Observatory (NOAA/ESRL 2025a).

[b] The global atmospheric CO_2 concentration, computed using an average of sampling sites across the world, was 419.33 parts per million (ppm) in 2023.

[c] The values presented are global 2023 annual average mole fractions (NOAA/ESRL 2025b).

[d] The values presented are global 2023 annual average mole fractions (NOAA/ESRL 2025c).

[e] The values presented are global 2023 annual average mole fractions expressed as parts per trillion (ppt) (NOAA/ESRL 2025d).

[f] The 2019 CF_4 global mean atmospheric concentration is from the Advanced Global Atmospheric Gases Experiment (IPCC 2021).

[g] The rate of concentration change for CO_2 is an average of the rates from 2008 through 2023 and has fluctuated between 1.54 to 3.36 ppm per year over this period (NOAA/ESRL 2025a). The rate of concentration change for CH_4, N_2O, and SF_6, is the average rate of change between 2008 and 2024 (NOAA/ESRL 2025b; NOAA/ESRL 2025c; NOAA/ESRL 2025d). The rate of concentration change for CF_4 is the average rate of change between 2011 and 2019 (IPCC 2021).

[h] The growth rate for atmospheric CH_4 decreased from over 10 ppb/year in the 1980s to nearly zero in the early 2000s; recently, the growth rate has been about 8.39 ppb/year (NOAA/ESRL 2025b).

[i] For a given amount of CO_2 emitted, some fraction of the atmospheric increase in concentration is quickly absorbed by the oceans and terrestrial vegetation, some fraction of the atmospheric increase will only slowly decrease over a number of years, and a small portion of the increase will remain for many centuries or more.

[j] This table reports the "perturbation lifetime" for both CH_4 and N_2O, which takes into account the interactions between emissions of the gas and its own atmospheric residence time.

[k] The lifetime for SF_6 was revised from 3,200 years to about 1,000 years based on recent studies (IPCC 2021).

Sources: Pre-industrial atmospheric concentrations and atmospheric lifetimes for CO_2, CH_4 and N_2O are from IPCC (2021), pre-industrial atmospheric concentration for SF_6 is from Rigby (2010), and pre-industrial atmospheric concentration for CF_4 is from Meinshausen (2017).

A brief description of each greenhouse gas, its sources, and its role in the atmosphere follows.

- *Water Vapor (H_2O):* Water vapor is the largest contributor to the natural greenhouse effect. Water vapor is fundamentally different from other greenhouse gases in that it can condense and rain out when it reaches high concentrations, and the total amount of water vapor in the atmosphere is in part a function of the Earth's temperature. While some human activities such as evaporation from irrigated crops or power plant cooling release water vapor into the air, these activities have been determined to have a negligible effect on global climate (IPCC 2021). The lifetime of water vapor in the troposphere is on the order of 10 days. Water vapor can also contribute to cloud formation, and clouds can have both warming and cooling effects by either trapping or reflecting heat. The relationship between warming and water vapor concentrations causes a positive (or amplifying) feedback loop (i.e., temperature increases cause greater atmospheric water vapor concentration which leads to further increases in temperatures). Aircraft emissions can create contrails, which may also develop into contrail-induced cirrus clouds, with complex regional and temporal net radiative forcing effects that currently have a low level of scientific certainty (IPCC 2021).

- *Carbon Dioxide (CO_2):* In nature, carbon is cycled between various atmospheric, oceanic, land biotic, marine biotic, and mineral reservoirs. The largest fluxes occur between the atmosphere and terrestrial biota, and between the atmosphere and surface water of the oceans. In the atmosphere, carbon predominantly exists in its oxidized form as CO_2. Atmospheric CO_2 is part of this global carbon cycle, and therefore its fate is a complex function of geochemical and biological processes. Carbon dioxide concentrations in the atmosphere increased from approximately 280 parts per million by volume (ppm) in pre-industrial times to 421.08 ppm in 2023, a 50.4 percent increase (IPCC 2021; NOAA/ESRL 2025a).[9, 10] The IPCC states that "Observed increases in well-mixed greenhouse gas (GHG) concentrations since around 1750 are unequivocally caused by human activities" (IPCC 2021). The predominant source of anthropogenic CO_2 emissions is the combustion of fossil fuels. Forest clearing, other biomass burning, and some non-energy production processes (e.g., cement production) also emit notable quantities of CO_2.
- *Methane (CH_4):* Methane is primarily produced through anaerobic decomposition of organic matter in biological systems. Agricultural processes such as wetland rice cultivation, enteric fermentation in animals, and the decomposition of animal wastes emit CH_4, as does the decomposition of municipal solid wastes and treatment of wastewater. Methane is also emitted during the production and distribution of natural gas and petroleum and is released as a byproduct of coal mining and incomplete fossil fuel combustion. Atmospheric concentrations of CH_4 have increased by about 163.3 percent since 1750, from a pre-industrial value of about 730 parts per billion (ppb) to 1,922 ppb in 2023,[11] although the rate of increase decreased to near zero in the early 2000s and has recently increased again to about 8.39 ppb/year. The IPCC has estimated that about half of the current CH_4 flux to the atmosphere (and the entirety of the increase in concentration) is anthropogenic, from human activities such as agriculture, fossil fuel production and use, and waste disposal (IPCC 2021).

  Methane is primarily removed from the atmosphere through a reaction with the hydroxyl radical (OH) and is ultimately converted to CO_2. Minor removal processes also include reaction with chlorine in the marine boundary layer, soil sinks, and stratospheric reactions. Increasing emissions of CH_4 reduce the concentration of OH, creating a feedback loop that increases the atmospheric lifetime of CH_4 (IPCC 2021). Methane's reactions in the atmosphere also lead to production of tropospheric ozone and stratospheric water vapor, both of which also contribute to climate change. Tropospheric ozone also has negative effects on human health and plant productivity.
- *Nitrous Oxide (N_2O):* Anthropogenic sources of N_2O emissions include agricultural soils, especially production of nitrogen-fixing crops and forages, the use of synthetic and manure fertilizers, and manure deposition by livestock; fossil fuel combustion, especially from mobile combustion; adipic (nylon) and nitric acid production; wastewater treatment and waste incineration; and biomass burning. The atmospheric concentration of N_2O has

[9] The pre-industrial period is considered as the time preceding the year 1750 (IPCC 2021).

[10] Carbon dioxide concentrations during the last 1,000 years of the pre-industrial period (i.e., 750 to 1750), a time of relative climate stability, fluctuated by about ±10 ppm around 280 ppm (IPCC 2021).

[11] This value is the global 2023 annual average mole fraction (NOAA/ESRL 2025b).

increased by 24.8 percent since 1750, from a pre-industrial value of about 270 ppb to 337 ppb in 2023,[12] a concentration that has not been exceeded in at least the last 800 thousand years. Nitrous oxide is primarily removed from the atmosphere by the photolytic action of sunlight in the stratosphere (IPCC 2021). Nitrous oxide also contributes to depletion of stratospheric ozone.

- *Ozone (O_3):* Ozone is present in both the upper stratosphere,[13] where it shields the Earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere,[14] where it is the main component of anthropogenic photochemical "smog." During the last two decades, emissions of anthropogenic chlorine and bromine-containing halocarbons, such as CFCs, have depleted stratospheric ozone concentrations. This loss of ozone in the stratosphere has resulted in negative radiative forcing, representing an indirect effect of anthropogenic emissions of chlorine and bromine compounds (IPCC 2021). The depletion of stratospheric ozone and its radiative forcing remained relatively unchanged since 2000 for the last two decades and is starting to decline; recovery is expected to occur shortly after the middle of the twenty-first century (WMO/UNEP 2018). Tropospheric ozone is produced from complex chemical reactions of volatile organic compounds and CH_4 mixing with NO_x in the presence of sunlight. The tropospheric concentrations of ozone and these other pollutants are short-lived and, therefore, spatially variable (IPCC 2021).
- *Halocarbons, Sulfur Hexafluoride (SF_6), and Nitrogen Trifluoride (NF_3):* Halocarbons are, for the most part, man-made chemicals that have direct radiative forcing effects and could also have an indirect effect. Halocarbons that contain chlorine (e.g., CFCs, HCFCs, methyl chloroform, and carbon tetrachloride) and bromine (e.g., halons, methyl bromide, and hydrobromofluorocarbons) result in stratospheric ozone depletion and are controlled under the Montreal Protocol on Substances that Deplete the Ozone Layer. Although most CFCs and HCFCs are potent global warming gases, their net radiative forcing effect on the atmosphere is reduced because they cause stratospheric ozone depletion. The United States phased out the production and importation of halons by 1994 and of CFCs by 1996. A cap was placed on the production and importation of HCFCs in the United States, beginning in 1996, and then followed by intermediate requirements and a complete phase-out by the year 2030. Ozone depleting gases are reported in this Inventory under Annex 6.2 for informational purposes.

  Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3) are not ozone depleting substances. The most common HFCs are, however, powerful greenhouse gases. Hydrofluorocarbons are primarily used as replacements for ozone depleting substances but are also emitted as a byproduct of the HCFC-22 (chlorodifluoromethane) manufacturing process. Other contributing sources to

[12] This value is the global 2023 annual average (NOAA/ESRL 2025c).

[13] The stratosphere is the layer from the troposphere up to roughly 50 kilometers. In the lower regions the temperature is nearly constant but in the upper layer the temperature increases rapidly because of sunlight absorption by the ozone layer. The ozone-layer is the part of the stratosphere from 19 kilometers up to 48 kilometers where the concentration of ozone reaches up to 10 parts per million.

[14] The troposphere is the layer from the ground up to 11 kilometers near the poles and up to 16 kilometers in equatorial regions (i.e., the lowest layer of the atmosphere where people live). It contains roughly 80 percent of the mass of all gases in the atmosphere and is the site for most weather processes, including most of the water vapor and clouds.

HFC emissions include the electronics industry and magnesium production and processing. Perfluorocarbons, SF_6, and NF_3 are predominantly emitted from various industrial processes including aluminum smelting, semiconductor manufacturing, electric power transmission and distribution, and magnesium casting.

Precursor Greenhouse Gases

Precursor greenhouse gases are not direct greenhouse gases, but can indirectly impact Earth's radiative balance, by altering the concentrations of other greenhouse gases (e.g., tropospheric ozone) and atmospheric aerosol (e.g., particulate sulfate). A brief description of each precursor greenhouse gas, its sources, and its role in the atmosphere follows. Precursors from sectors included in this report are summarized and reported in Chapter 2.3 of the *Inventory*.

- *Carbon Monoxide (CO):* Carbon monoxide has an indirect radiative forcing effect by elevating concentrations of CH_4 and tropospheric ozone through chemical reactions with other atmospheric constituents (e.g., the hydroxyl radical, OH) that would otherwise assist in destroying CH_4 and tropospheric ozone. Carbon monoxide is created when carbon-containing fuels are burned incompletely. Through natural processes in the atmosphere, it is eventually oxidized to CO_2 (IPCC 2026). Carbon monoxide concentrations are both short-lived in the atmosphere and spatially variable. National CO emissions are summarized and reported in Chapter 2.3 of this report.
- *Ammonia (NH_3):* The climate change effects of ammonia are indirect by contributing to aerosol burden and aerosol nucleation. This process occurs through the reaction of NH_3 with nitric and sulfuric acid (IPCC 2021). Ammonia also contributes to nitrogen deposition which enhances N_2O emissions from soils (IPCC 2021; IPCC 2006). Ammonia is emitted during livestock management activities and crop production through the application of mineral nitrogen fertilizers (IPCC 2021). For this reason, NH_3 concentrations tend to peak over large agricultural areas in the United States and have been increasing throughout the U.S. in recent decades. National NH_3 emissions are summarized and reported in Chapter 2.3 of this report.
- *Nitrogen Oxides (NO_x):* The primary climate change effects of nitrogen oxides (i.e., NO and NO_2) are indirect. Warming effects can occur due to reactions leading to the formation of ozone in the troposphere, but cooling effects can occur due to the role of NO_x as a precursor to nitrate particles (i.e., aerosols) and due to destruction of stratospheric ozone when emitted from very high-altitude aircraft.[15] Additionally, NO_x emissions are also likely to decrease CH_4 concentrations, thus having a negative radiative forcing effect (IPCC 2021). Nitrogen oxides are created from lightning, soil microbial activity, biomass burning (both natural and anthropogenic fires) fuel combustion, and, in the stratosphere, from the photo-degradation of N_2O. Concentrations of NO_x are both relatively short-lived in the atmosphere and spatially variable. National NO_x emissions are summarized and reported in Chapter 2.3 of this report.

[15] NO_x emissions injected higher in the stratosphere, primarily from fuel combustion emissions from high altitude supersonic aircraft, can lead to stratospheric ozone depletion.

- *Non-methane Volatile Organic Compounds (NMVOCs):* Non-methane volatile organic compounds include substances such as propane, butane, and ethane. These compounds participate, along with NO_x, in the formation of tropospheric ozone and other photochemical oxidants. NMVOCs are emitted primarily from transportation and industrial processes, as well as biomass burning and non-industrial consumption of organic solvents (IPCC 2026). Concentrations of NMVOCs tend to be both short-lived in the atmosphere and spatially variable (IPCC 2021). National NMVOCs are summarized and reported in Chapter 2.3 of this report.

Aerosols

Aerosols are extremely small particles or liquid droplets found in the atmosphere that are either directly emitted into or are created through chemical reactions in the Earth's atmosphere. Aerosols or their chemical precursors can be emitted by natural events such as dust storms, biogenic or volcanic activity, or by anthropogenic processes such as transportation, coal combustion, cement manufacturing, waste incineration, or biomass burning. Various categories of aerosols exist from both natural and anthropogenic sources, such as soil dust, sea salt, biogenic aerosols, sulfates, nitrates, volcanic aerosols, industrial dust, and carbonaceous[16] aerosols (e.g., black carbon, organic carbon). Aerosols can be removed from the atmosphere relatively rapidly by precipitation or through more complex processes under dry conditions.

Aerosols affect radiative forcing differently than greenhouse gases. Their radiative effects occur through direct and indirect mechanisms: directly by scattering and absorbing solar radiation (and to a lesser extent scattering, absorption, and emission of terrestrial radiation); and indirectly by increasing cloud droplets and ice crystals that modify the formation, precipitation efficiency, and radiative properties of clouds (IPCC 2021). Despite advances in understanding of cloud-aerosol interactions, the contribution of aerosols to radiative forcing are difficult to quantify because aerosols generally have short atmospheric lifetimes, and have number concentrations, size distributions, and compositions that vary regionally, spatially, and temporally (IPCC 2021).

The net effect of aerosols on the Earth's radiative forcing is believed to be negative (i.e., net cooling effect on the climate). In fact, aerosols contributed a cooling influence of about 0.6 degrees Celsius. Due to the high uncertainty in aerosol radiative forcing, estimates range from almost no net global influence to as much as 1.4 degrees of cooling, offsetting a substantial portion of greenhouse gas warming (IPCC 2021). Because aerosols remain in the atmosphere for only days to weeks, their concentrations respond rapidly to changes in emissions.[17] Not all aerosols have a cooling effect. Current research suggests that another constituent of aerosols, black carbon, has a positive radiative forcing by heating the Earth's atmosphere and causing surface warming when deposited on ice and snow (IPCC 2021). Black carbon also influences cloud development, but the direction and magnitude of this forcing is an area of active research.

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[16] Carbonaceous aerosols are aerosols that are comprised mainly of carbon and hydrogen. Those carbonaceous aerosols with more hydrogen are classified as "organic carbon", and are generally reflective, while the aerosols that are nearly pure carbon are classified as "black carbon" (also referred to as "soot") and can absorb light (IPCC 2021).

[17] Volcanic activity can inject significant quantities of aerosol producing sulfur dioxide and other sulfur compounds into the stratosphere, which can result in a longer lasting negative forcing effect (i.e., a few years) (IPCC 2021).

1.2 Global Warming Potentials

A global warming potential (GWP) is a quantified measure of the relative globally averaged radiative forcing impacts of emissions of a particular greenhouse gas over time (see Table 1-2). It is defined as the accumulated radiative forcing within a specific time horizon caused by emitting 1 kilogram (kg) of the gas, relative to that of the reference gas CO_2 (IPCC 2021). Direct radiative effects occur when the gas itself absorbs radiation. Indirect radiative forcing occurs when chemical transformations involving the original gas produce a gas or gases that are greenhouse gases, or when a gas influences other radiatively important processes such as the atmospheric lifetimes of other gases. The reference gas used is CO_2, and therefore GWP-weighted emissions are measured in CO_2 equivalent (CO_2 Eq.).[18] For example, the relationship between a kg of emissions of a gas and a kg of CO_2 Eq. emissions can be expressed as follows and also adapted to other units (e.g. metric tons, etc.):

Equation 1-1: Calculating CO_2 Equivalent Emissions

$$\text{kg } CO_2 \text{ Eq.} = (\text{kg emission of gas}) \times (\text{GWP})$$

where,

kg CO_2 Eq.	=	kilograms of CO_2 equivalent
kg	=	kilograms (equivalent to a thousand metric grams)
GWP	=	Global warming potential

GWP values allow for a comparison of the impacts of emissions and reductions of different gases. According to the IPCC, GWPs typically have an uncertainty of ±40 percent.

Table 1-2: Global Warming Potentials and Atmospheric Lifetimes (Years) Used in this Report

Gas	Atmospheric Lifetime	GWP[a]
CO_2	See footnote[b]	1
CH_4[c]	12.4	28
N_2O	121	265
HFC-23	222	12,400
HFC-32	5.2	677
HFC-41[d]	2.8	116
HFC-125	28.2	3,170
HFC-134a	13.4	1,300
HFC-143a	47.1	4,800
HFC-152a	1.5	138
HFC-227ea	38.9	3,350
HFC-236fa	242	8,060
CF_4	50,000	6,630
C_2F_6	10,000	11,100

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

C_3F_8	2,600	8,900
c-C_4F_8	3,200	9,540
SF_6	3,200	23,500
NF_3	500	16,100
Other Fluorinated Gases		**See Annex 6**

[a] 100-year time horizon.

[b] For a given amount of CO_2 emitted, some fraction of the atmospheric increase in concentration is quickly absorbed by the oceans and terrestrial vegetation, some fraction of the atmospheric increase will only slowly decrease over a number of years, and a small portion of the increase will remain for many centuries or more.

[c] The GWP of CH_4 includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO_2 is not included.

[d] See Table A-1 of 40 CFR Part 98

Source: IPCC (2013).

All estimates are provided throughout the report in both MMT CO_2 equivalents and unweighted units. Consistent with greenhouse gas inventories from other countries, this report uses 100-year GWP values from Table 8.A.1 in Appendix 8.A of the IPCC *Fifth Assessment Report* (AR5) for calculating CO_2-equivalent emissions.

This reflects updated science and ensures that national greenhouse gas inventories reported by all nations are comparable. A comparison of emission values with the previously used 100-year GWP values from IPCC *Fourth Assessment Report* (AR4) (IPCC 2007), and the IPCC *Sixth Assessment Report* (AR6) (IPCC 2021) values can be found in Annex 6.1 of this report. The 100-year GWP values used in this report are listed in Table 1-2.

Greenhouse gases with atmospheric lifetimes longer than a couple of years (e.g., CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, NF_3) tend to be evenly distributed throughout the atmosphere, and consequently global average concentrations can be determined. The short-lived gases such as water vapor, carbon monoxide, tropospheric ozone, ozone precursors (e.g., NO_x, and NMVOCs), and tropospheric aerosols (e.g., SO_2 products and carbonaceous particles), however, vary regionally, and consequently it is difficult to quantify their global radiative forcing impacts.

Box 1-2: The IPCC Sixth Assessment Report and Global Warming Potentials

In 2021, the IPCC published its *Sixth Assessment Report* (AR6), which updated its comprehensive scientific assessment of climate change. Within the AR6 report, the GWP values of gases were revised relative to previous IPCC assessment reports, e.g., the IPCC *Fifth Assessment Report* (AR5) (IPCC 2014). Although the AR5 GWP values are used throughout this report, it is straightforward to review the changes to the GWP values and their impact on estimates of the total GWP-weighted emissions of the United States. In the AR6, the IPCC used more recent estimates of the atmospheric lifetimes and radiative efficiencies of some gases and updated background concentrations. The AR6 now includes climate-carbon feedback effects for non-CO_2 gases, improving the consistency between treatment of CO_2 and non-CO_2 gases. Indirect effects of gases on other atmospheric constituents (such as the effect of methane on ozone) have also been updated to match more recent science.

Table 1-3 presents the new GWP values, relative to those presented in the AR5, using the 100-year time horizon. All estimates provided throughout this report are also presented in unweighted units. For informational purposes, emission estimates that use 100-year GWPs from other recent IPCC Assessment Reports are presented in detail in Annex 6.1 of this report.

Table 1-3: Comparison of 100-Year GWP values

	100-Year GWP Values		Change Relative to AR5
Gas	AR5[a]	AR6[b]	AR6[b]
CO_2	1	1	NC
CH_4[d]	28	27	(1)
N_2O	265	273	8
HFC-23	12,400	14,600	2,200
HFC-32	677	771	94
HFC-41	116	135	19
HFC-125	3,170	3,740	570
HFC-134a	1,300	1,530	230
HFC-143a	4,800	5,810	1,010
HFC-152a	138	164	26
HFC-227ea	3,350	3,600	250
HFC-236fa	8,060	8,690	630
CF_4	6,630	7,380	750
C_2F_6	11,100	12,400	1,300
C_3F_8	8,900	9,290	390
c-C_4F_8	9,540	10,200	660
SF_6	23,500	24,300	800
NF_3	16,100	17,400	1,300

NC (No Change)
[a] The GWP values in this column reflect values used in this report from AR5 excluding climate-carbon feedbacks and the value for fossil methane.
[b] The GWP values in this column are from the AR6 report.
[c] The GWP of CH_4 includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. Including the indirect effect due to the production of CO_2 resulting from methane oxidation would lead to an increase in AR5 methane GWP values by 2 for fossil methane and is not shown in this table.
Note: Parentheses indicate negative values.
Sources: IPCC (2021), IPCC (2013), IPCC (2007), IPCC (2001), IPCC (1996).

1.3 National Inventory Arrangements

The U.S. Environmental Protection Agency (EPA), in cooperation with other U.S. government agencies, prepares and publishes the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. A wide range of agencies and individuals are involved in supplying data to, planning methodological approaches and improvements, reviewing, or preparing portions of the *Inventory*—including federal and state government authorities, research and academic institutions, industry associations, and private consultants.

Within EPA, the Office of Atmospheric Protection (OAP) is the lead office responsible for the emission and removal calculations provided in the *Inventory*, as well as the completion of the National Inventory Report including the CRTs. EPA's Office of Transportation and Air Quality (OTAQ) and Office of Research and Development (ORD) are also involved in calculating emissions and removals for the *Inventory*. EPA's OAP serves as the national inventory focal point for this report,

including responding to technical questions and comments on the U.S. Inventory. EPA staff coordinate the annual methodological choice, activity data collection, emission and removal calculations, uncertainty assessment, QA/QC processes, and improvement planning at the individual source and sink category level. EPA's inventory coordinator leads overall compilation and publication of the entire *Inventory* and is responsible for the synthesis of information along with the consistent application of cross-cutting IPCC good practice across the *Inventory*.

Several other government agencies contribute to the collection and analysis of the underlying activity data used in the *Inventory* calculations and to the calculation of estimates integrated in the report. These agencies include the U.S. Department of Agriculture (USDA), National Oceanic and Atmospheric Administration (NOAA), the U.S. Geological Survey (USGS), the Federal Highway Administration (FHWA), the Department of Transportation (DOT), the Bureau of Transportation Statistics (BTS), the Department of Commerce (DOC), and the Federal Aviation Administration (FAA). Academic and research centers also provide activity data and calculations to EPA, as well as individual companies participating in voluntary outreach efforts with EPA. Other U.S. agencies also provide official data for use in the *Inventory* such as the U.S. Department of Energy's and the U.S. Department of Defense. For more information on the source data provided by U.S. government agencies and external groups, see the *Methodology and Data Sources* section of this chapter. EPA engages with agencies regularly on data needs and improvements to ensure sufficient activity collection for annual compilation of estimates.

1.4 Inventory Preparation Process

This section describes EPA's approach to preparing the annual U.S. *Inventory*, which includes both this report and associated tables (e.g., Common Reporting Tables or "CRTs"). The inventory coordinator at EPA, with support from the cross-cutting compilation staff, is responsible for coordinating aggregation of all emission and removal estimates, conducting the overall uncertainty analysis of *Inventory* emissions and trends over time, and ensuring consistency and quality throughout this report and associated tables. Emission and removal calculations, including associated uncertainty analysis for individual sources and/or sink categories, are the responsibility of individual source and sink category leads who are most familiar with each category, underlying data, and the unique national circumstances relevant to its emissions or removals profile. Using IPCC methodological decision trees and suggested good practice guidance, the individual leads determine the most appropriate methodology and collect the relevant activity data to use in the calculations, based upon their expertise, as well as coordinate with researchers and expert consultants familiar with the sources and sinks. Each year, the coordinator oversees the multi-stage process for collecting information from each category lead to compile all information and data for the *Inventory*.

Methods Selection, Data Collection, and Estimate Development

EPA and other agency source and sink category leads coordinate the collection of input data (e.g., activity data and other information) and, as necessary, evaluate or develop the estimation methodology for the individual source and/or sink categories. Unless there are improvements ready to incorporate (e.g., methodological refinements), the methodology for the previous year is applied to the current year of the *Inventory*, and inventory analysts collect any new data or update data that have changed from the previous year. If estimates for a new source or sink category are being developed for the first time, or if the methodology is changing for an existing category, then the category lead will develop and implement the new or refined methodology, gather the appropriate activity data and other information for the entire time series, and conduct any further category-specific review with involvement of relevant experts from industry, government, and universities (see Chapter 9 and Box ES-3 on EPA's approach to recalculations). Once the methodology is in place and the data are collected, the category leads calculate emission and removal estimates. The leads then update or create the relevant report text and accompanying annexes for the *Inventory*. Category leads are also responsible for completing the relevant sectoral background tables of the CRTs, conducting quality control (QC) checks, preparing relevant category materials for quality assurance (QA), or expert reviews, category-level uncertainty assessments, and reviewing data for publication in EPA's GHG Data Explorer.[19]

In the *Inventory*, the treatment of confidential business information (CBI) is based on EPA internal guidelines, as well as regulations[20] applicable to the data used. EPA has specific procedures in place to safeguard CBI during the inventory compilation process. When information derived from CBI data is used for development of inventory calculations, EPA procedures ensure that these confidential data are sufficiently aggregated to protect confidentiality while still providing useful information for analysis. For example, within the Energy and Industrial Processes and Product Use (IPPU) sectors, EPA has used aggregated facility-level data from the Greenhouse Gas Reporting Program (GHGRP) to develop, inform, and/or QA U.S. emission estimates. In 2014, EPA's GHGRP, with industry engagement, compiled criteria that would be used for aggregating its confidential data to shield the underlying CBI from public disclosure.[21] In the *Inventory*, EPA is publishing only data values that meet the GHGRP aggregation criteria.[22] Specific uses of aggregated facility-level data are described in the respective methodological sections within those chapters. In addition, EPA uses historical data reported voluntarily to EPA through various voluntary initiatives with U.S. industry (e.g., EPA Voluntary Aluminum Industrial Partnership [VAIP]) and follows guidelines established under the voluntary programs for managing CBI.

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[19] See https://cfpub.epa.gov/ghgdata/inventoryexplorer/.

[20] 40 CFR Part 2, Subpart B titled "Confidentiality of Business Information" which is the regulation establishing rules governing handling of data entitled to confidentiality treatment. See https://www.ecfr.gov/cgi-bin/textidx?SID=a764235c9eadf9afe05fe04c07a28939&mc=true&node=sp40.1.2.b&rgn=div6

[21] Federal Register Notice on "Greenhouse Gas Reporting Program: Publication of Aggregated Greenhouse Gas Data." See pp. 79 and 110 of notice at https://www.gpo.gov/fdsys/pkg/FR-2014-06-09/pdf/2014-13425.pdf.

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

Data Compilation and Archiving

The inventory coordinator at EPA, with support from the data manager, collects the source and sink data for each category and estimates and aggregates the emission and removal estimates into a summary data file that links the individual source and sink category data files together. This summary data file contains all of the essential data in one central location, in formats commonly used in the *Inventory* document. In addition to the data from each category, other national trend and related data are also gathered in the summary sheet for use in the *Executive Summary*, *Introduction*, and *Trends* chapters of the *Inventory* report. Trend analysis necessitates gathering supplemental data to understand and explain trends, including annual economic activity (e.g., gross domestic product), population, and the annual use of electricity, energy, fossil and non-fossil fuels.

Similarly, analysis of the key categories in the current *Inventory* and analysis of recalculations impacts compared to the previous inventory cycle are completed in a separate data file based on output from the summary data file. The uncertainty estimates for each source and sink category are also aggregated into uncertainty summary data files that are used to conduct the overall *Inventory* uncertainty analysis (see Section 1.8).

A cloud-based management system, maintained within EPA's IT infrastructure by the inventory coordinator, provides a platform for facilitating collaboration on inventory preparation during each compilation phase and the efficient storage and archiving of electronic document and data files each annual cycle. Previous final published inventories are also maintained on a report archive page on EPA's Greenhouse Gas Emissions website.[23]

National Inventory Report Preparation

This report is compiled from the sections developed by each source or sink category lead using a standard template to ensure comparable information across inventory categories within each sector. The inventory coordinator at EPA, with support from the document manager, collects the source and sink categories' report chapters and methodological annexes. In addition, the inventory coordinator prepares a brief overview of each chapter that summarizes the emissions and removals from all sources and sinks discussed in the chapters. The *Executive Summary*, *Introduction*, *Trends in Greenhouse Gas Emissions and Removals*, and *Recalculations and Improvements* chapters are also drafted at this time to reflect the trends and impact from improvements for the time series of the current *Inventory*. Finally, the uncertainty analysis and key category analysis are compiled and updated in the report as part of final analysis steps. Throughout the report, text boxes are also created to provide additional documentation (e.g., definitions) and/or to examine the data aggregated in different ways than as presented in the main text of the report.

Commonly-used international tables, or CRTs are another format for transparently publishing *Inventory* data. The tables are compiled from individual time series input data sheets completed by each category lead, which contain emissions and/or removals and activity data, estimates,

[23] See https://www.epa.gov/ghgemissions/us-greenhouse-gas-inventory-report-archive.

methodological and completeness notations, and associated explanations. The inventory coordinator and cross-cutting compilation staff import the U.S. category and subcategory background data into the online reporting platform to export CRTs, assuring consistency and completeness across all sectoral background tables. The summary reports for emissions and removals, methods, and emission factors used; the summary tables indicating completeness of estimates; the recalculation tables; and the emission and removal trends tables are automatically compiled by the online reporting software and reviewed by the inventory coordinator with support from the cross-cutting compilation staff. Internal automated quality checks within the software, as well as checks by the cross-cutting and category leads, are completed for the entire time series of tables.

Quality Assurance and Quality Control, and Uncertainty Analysis

Quality assurance (QA) during inventory preparation and compilation consists of a two-stage review process that includes an expert review and public review. During the first stage, a 30-day expert review, the first draft of updated sectoral chapters, including a guidance memo and charge questions is sent to technical experts who are not directly involved in preparing estimates. This stage is intended to provide an objective review of the methodological approaches and data sources used, especially for sources and sinks which have experienced any changes since the previous *inventory*. The expert review follows good practices from EPA's Peer Review handbook.[24] Expert reviewers include other federal agency staff, researchers, industry experts, and others who have technical knowledge of the data, industry, and methods. EPA reviews and updates expert participation and outreach on an annual basis prior to each expert review cycle. Experts are identified in various ways; for example, many reach out to EPA with technical feedback and are added to the expert reviewer list. Reviewers are also identified through direct outreach by inventory staff based on expertise. Currently, EPA's expert list includes nearly 300 experts across all sectors.

The second review stage following expert review is a public review that consists of a second draft of the document, including cross-cutting synthesis chapters, being released for review to the U.S. public through a notice in the U.S. *Federal Register*. The entire draft inventory is typically published on the EPA website and a federal eDocket. Public comments are submitted and tracked using this publicly accessible eDocket. Similar to expert review, some public comments received may require further discussion with commenters or other experts and/or additional research. Feedback from all QA/QC processes that contribute to improving inventory quality over time are described within each category's Planned Improvement section. See also the Improvement Planning section that follows in this chapter.

EPA also publishes responses to comments received during both expert and public reviews along with the publication of the final report on its website.[25] While all phases significantly contribute to improving inventory quality, the public review phase is also essential for promoting the openness of

[24] See https://www.epa.gov/osa/peer-review-handbook-4th-edition-2015.

[25] See https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022.

the inventory development process and the transparency of the inventory methods and underlying input data sources.

Quality control is implemented by staff preparing inventory estimates and —is applied at every stage of inventory development and document preparation. Further information about QA/QC practices and planning can be found in Section 1.7 and Annex 8. More information on uncertainty analysis is found in Section 1.8.

Publication

After the final revisions to incorporate any comments from the expert review and public review periods, EPA prepares the final *Inventory*, which includes this report, and the accompanying CRTs.

EPA publishes the final *Inventory* report on EPA's website.[26] On EPA's website, users can also visualize and download the current time-series estimates from the GHG Inventory Data Explorer Tool,[27] and users can also download more detailed data presented in tables within the report and report annex in CSV format. Concurrently, EPA makes the official U.S. inventory data available using commonly-used international tables.

Improvement Planning

Each year, several emission and sink estimates in the inventory are recalculated and revised using better methods and/or data, with the goal of improving inventory quality and reducing uncertainties and ensuring the transparency, accuracy, completeness, consistency, and overall usefulness of the report. In this effort, the United States follows the *2006 IPCC Guidelines* (IPCC 2006) and its *2019 Refinement* (IPCC 2019), which state,

> *"Both methodological changes and refinements over time are an essential part of improving inventory quality. It is good practice to change or refine methods when available data have changed; the previously used method is not consistent with the IPCC guidelines for that category; a category has become key; the previously used method is insufficient to reflect mitigation activities in a transparent manner; the capacity for inventory preparation has increased; improved inventory methods become available; and/or for correction of errors."*

The EPA's OAP coordinates improvement planning across all sectors as well as cross-cutting analyses. These plans are based on annual reviews and inputs from the technical teams leading the compilation of source-level estimates. Planned improvements are also identified through implementation of QC processes, the key category analysis, and the uncertainty analysis. The inventory coordinator, with input from EPA source and sink category leads, maintains a log of all planned improvements, by sector and cross-cutting, tracking the category significance, specific category improvement, prioritization, anticipated time frame for implementation of each proposed improvement, and implementation status. Improvements for significant or key categories are usually prioritized unless the effort or resources required to implement that improvement are disproportionate relative to improvements for other key categories.

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[26] See https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

[27] See https://cfpub.epa.gov/ghgdata/inventoryexplorer/.

1.5 Methodology and Data Sources

Emissions and removals of greenhouse gases from various source and sink categories have been estimated using methodologies that are consistent with the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) and its supplements and refinements. To a large extent, this report makes use of published official economic and physical statistics for activity data along with emission factors and other key parameters as inputs to the methods applied. Depending on the category, activity data can include fuel consumption or deliveries, vehicle-miles traveled, raw material processed, or commodity produced, etc. Emission factors are factors that relate quantities of emissions to an activity. For more information on data sources see Figure 1-1, Box 1-1 on use of GHGRP data, and categories' methodology sections for more information on other data sources. In addition to official statistics, the report utilizes findings from academic studies, trade association surveys and statistical reports, along with expert judgment, consistent with the *2006 IPCC Guidelines* (IPCC 2006).

The methodologies provided in the *2006 IPCC Guidelines* (IPCC 2006) represent foundational methodologies for a variety of source and sink categories, and many of these methodologies continue to be improved and refined as new research and data become available. This report uses those IPCC methodologies when applicable, and supplements them with refined guidance, other available country-specific methodologies and data where possible (e.g., EPA's GHGRP). For example, as noted earlier in this chapter, this report does apply recent supplements and refinements to *2006 IPCC Guidelines* (IPCC 2006) in estimating emissions and removals from coal mining, wastewater treatment and discharge, low voltage anode effects (LVAE) during aluminum production, drained organic soils, and management of wetlands, including flooded lands. Choices made regarding the methodologies and data sources used are provided in the Methodology and Time-Series Consistency discussion of each category within each sectoral chapter of the report, applying higher tiered methods when feasible, especially for key categories consistent with methodological decision trees. Where additional detail is helpful and necessary to explain methodologies and data sources used to estimate emissions, complete documentation is provided in the annexes as indicated in the methodology sections of those respective source categories (e.g., Annex 3.14 for forest land remaining forest land and land converted to forest land). Methods used for key categories are summarized in Annex 1.

Figure 1-1: Key Data Institutions and Data Sources by Sector

Energy	Agriculture and LULUCF	IPPU	Waste
U.S. Energy Information Administration	USDA U.S. Forest Service Forest Inventory and Analysis Program (FIA)	EPA Greenhouse Gas Reporting Program (GHGRP)	EPA Greenhouse Gas Reporting Program (GHGRP)
U.S. Department of Commerce – Bureau of the Census	USDA Natural Resource Conservation Service (NRCS)	U.S. Geological Survey (USGS) National Minerals Information Center	EPA Office of Land and Emergency Management (OLEM)
U.S. Department of Defense – Defense Logistics Agency	USDA National Agricultural Statistics Service (NASS) and Agricultural Research Service (ARS)	American Chemistry Council (ACC)	EPA Clean Watershed Needs Survey (CWNS)
U.S. Department of Homeland Security	EPA Office of Research and Development (ORD)	American Iron and Steel Institute (AISI)	American Housing Survey
U.S. Department of Transportation - Federal Highway Administration	U.S. Fish and Wildlife Service	U.S. International Trade Commission (USITC)	Data from research studies, trade publications, and industry associations
U.S. Department of Transportation - Federal Aviation Administration	U.S. Department of Agriculture (USDA) Animal and Plant Health Inspection Service (APHIS)	Air-Conditioning, Heating, and Refrigeration Institute	
U.S. Department of Transportation & Bureau of Transportation Statistics	Association of American Plant Food Control Officials (AAPFCO)	Data from other U.S. government agencies, research studies, trade publications, and industry association	
U.S. Department of Labor – Mine Safety and Health Administration	National Oceanic and Atmospheric Administration (NOAA)	UNEP Technology and Economic Assessment Panel (TEAP)	
U.S. Department of Energy and its National Laboratories	EPA Office of Land and Emergency Management (OLEM)		
EPA Acid Rain Program	USDA Farm Service Agency		
EPA MOVES Model	U.S. Geological Survey (USGS)		
EPA Greenhouse Gas Reporting Program (GHGRP)	U.S. Department of the Interior (DOI) - Bureau of Land Management (BLM)		
U.S. Department of Labor – Mine Safety and Health Administration	EPA Office of Land and Emergency Management (OLEM)		
American Association of Railroads	Alaska Department of Natural Resources		
American Public Transportation Association	U.S. Department of Commerce – Bureau of the Census		
U.S. Department of Interior - Bureau of Ocean Energy Management	Data from research studies, trade publications, and industry associations		
Federal Energy Regulatory Commission			
Data from research studies, trade publications, and industry associations			

Note: This table is not an exhaustive list of all data sources.

1.6 Key Categories

Key categories are "inventory categories which individually, or as a group of categories (for which a common method, emission factor and activity data are applied) are prioritized within the national inventory system because their estimates have a significant influence on a country's total inventory of greenhouse gases in terms of the absolute level, the trend, or the level of uncertainty in emissions or removals. The term *key category* includes both source and sink categories" (IPCC 2006; IPCC 2019). A key category analysis identifies source or sink categories for focusing efforts to improve overall inventory quality, including additional review when feasible.

The *2006 IPCC Guidelines* (IPCC 2006) and its *2019 Refinement* (IPCC 2019) define several approaches, both quantitative and qualitative, to conduct a key category analysis and identify key categories both in terms of absolute level and trend, along with consideration of uncertainty. This report employs all approaches to identify key categories for the United States.

1. **Approach 1**: Identifies significant or key categories without considering uncertainty in its calculations. The level assessment identifies all source and sink categories that cumulatively account for 95 percent of total level, i.e., total emissions (gross) in a given year when assessed in descending order of absolute magnitude. Trend analysis can identify categories with trends that significantly influence overall trends by identifying all source and sink categories that cumulatively account for 95 percent of the sum all the trend assessments (e.g., percent change relative to national trend) when sorted in descending order of absolute magnitude).
2. **Approach 2**: Incorporation of each category's uncertainty assessments in its calculations can be used to identify any additional key categories not already identified from the Approach 1 level and trend assessments by considering uncertainty. An Approach 2 level assessment identifies all sources and sink categories that cumulatively account for 90 percent of the sum of all level assessments when sorted in descending order of magnitude. Similarly, an Approach 2 trend analysis can identify categories whose trends contribute significantly to overall trends weighing the relative trend difference with the category's relative uncertainty assessment for 2023.

The level and trend analyses were performed twice, including, and excluding sources and sinks from the land use, land-use change, and forestry (LULUCF) sector categories. For 2023, based on the key category analysis, excluding the LULUCF sector , 33 categories accounted for 95 percent of emissions (Table 1-4). Four categories account for 54 percent of emissions: CO_2 from road transport-related fuel combustion, CO_2 from gas-fired electricity generation, CO_2 from coal fired electricity generation, and CO_2 from gas-fired industrial processes. When considering uncertainties, additional categories such as emissions from substitutes for ozone depleting substances in aerosols were also identified as a key category. In the trend analysis, 30 categories were identified as key categories, and when considering uncertainties, 6 additional categories were identified as key. The trend analysis shows that CO_2 emissions from coal-fired electricity generation, CO_2 from road transport related combustion, and HFC and PFC emissions from substitutes for ozone depleting substances in the refrigeration and air conditioning sector, and N_2O

from domestic wastewater treatment are also significant with respect to trends over the time series.

When considering the contribution of the LULUCF sector, 41 categories accounted for 95 percent of emissions and sinks, with the most significant category from LULUCF being net CO_2 emission from forest land remaining forest land, forest carbon pools excluding harvested wood products. In the trend analysis, 38 categories were identified as key, and when considering uncertainties, 4 additional categories were identified as key.

Finally, in addition to approaches described, a qualitative assessment of the source and sinks categories was also considered to capture any additional key categories that were not identified using the previously described quantitative approaches. For this *Inventory*, no additional categories were identified using qualitative criteria recommend by IPCC, but EPA continues to review its qualitative assessment on an annual basis. Find more information on the key category analysis, including the approach to disaggregation of inventory estimates, see Annex 1 to this report.

Table 1-4: Summary of Key Categories for the United States (1990 and 2023) by Sector

Source/Sink Category Code	Greenhouse Gas	Approach 1				Approach 2				2023 Emissions (MMT CO_2 Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	
Energy										
1.A.3.b Transportation: Road	CO_2	◉	•	◉	•	◉	•	◉	•	1,455.3
1.A.1 Stationary Combustion - Gas - Electricity Generation	CO_2	◉	•	◉	•	◉	•	◉	•	704.5
1.A.1 Stationary Combustion - Coal - Electricity Generation	CO_2	◉	•	◉	•	◉	•	◉	•	694.6
1.A.2 Stationary Combustion - Gas - Industrial	CO_2	◉	•	◉	•	◉	•	◉	•	514.8
1.A.4.b Stationary Combustion - Gas - Residential	CO_2	◉	•	◉	•	◉		◉		247.5
1.A.2 Stationary Combustion - Oil - Industrial	CO_2	◉	•	◉	•	◉	•	◉	•	241.3
1.A.4.a Stationary Combustion - Gas - Commercial	CO_2	◉	•	◉	•	◉	•	◉		182.8
1.A.3.a Transportation: Aviation	CO_2	◉		◉		◉		◉		179.7
1.A.5 Non-Energy Use of Fuels	CO_2	◉		◉		◉	•	◉	•	107.1
1.A.3.e Transportation: Other	CO_2	◉	•	◉	•		•			71.3
1.A.4.a Stationary Combustion - Oil - Commercial	CO_2	◉	•	◉	•					60.2
1.A.4.b Stationary Combustion - Oil - Residential	CO_2	◉	•	◉	•		•			59.6
1.B.2 Natural Gas Systems	CO_2	◉		◉		◉				37.7
1.A.2 Stationary Combustion - Coal - Industrial	CO_2	◉	•	◉	•	◉	•	○	•	36.5
1.A.3.d Transportation: Domestic Navigation	CO_2	◉		◉						34.6
1.A.3.c Transportation: Railways	CO_2	◉		◉						30.9
1.B.2 Petroleum Systems	CO_2	•	•	•	•	•	•		•	23.3
1.A.5 Stationary Combustion - Oil - U.S. Territories	CO_2	○		○						17.9
1.A.1 Stationary Combustion - Oil - Electricity Generation	CO_2	○	•	○	•	○	•		•	14.7
1.A.5.b Transportation: Military	CO_2		•		•					4.6

Source/Sink Category Code	Greenhouse Gas	Approach 1				Approach 2				2023 Emissions (MMT CO_2 Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	
1.A.4.a Stationary Combustion - Coal - Commercial	CO_2		•		•					1.1
1.A.4.b Stationary Combustion - Coal - Residential	CO_2						•			0.0
1.B.2 Natural Gas Systems	CH_4	◉	•	◉	•	◉	•	◉	•	162.4
1.B.1 Fugitive Emissions from Coal Mining	CH_4	◉	•	◉	•	◉	•	◉	•	45.4
1.B.2 Petroleum Systems	CH_4	◉	•	◉	•	◉	•	◉		38.0
1.B.2 Abandoned Oil and Gas Wells	CH_4					◉		◉		8.5
1.A.4.b Stationary Combustion - Residential	CH_4					◉	•	◉	•	4.5
1.A.1 Stationary Combustion - Coal - Electricity Generation	N_2O	○				◉	•			12.1
1.A.3.b Transportation: Road	N_2O	○	•	○	•	○	•		•	8.3
1.A.2 Stationary Combustion - Industrial	N_2O					○				1.9
Industrial Processes and Product use										
2.C.1 Iron and Steel Production & Metallurgical Coke Production	CO_2	◉	•	◉	•	◉	•	○	•	46.2
2.A.1 Cement Production	CO_2	◉		◉						40.6
2.B.8 Petrochemical Production	CO_2	◉	•	◉	•					30.5
2.B.3 Adipic Acid Production	N_2O		•		•					1.2
2.F.1 Emissions from Substitutes for Ozone Depleting Substances: Refrigeration and Air conditioning	HFCs, PFCs	•	•	•	•	•	•	•	•	154.7
2.F.4 Emissions from Substitutes for Ozone Depleting Substances: Aerosols	HFCs, PFCs		•		•	•	•	•	•	17.4
2.F.2 Emissions from Substitutes for Ozone Depleting Substances: Foam Blowing Agents	HFCs, PFCs		•		•					12.1
2.G Electrical Equipment	PFCs, SF_6	○	•	○	•		•		•	5.1
2.B.9 Fluorochemical Production	PFCs, HFCs, SF_6, NF_3	○	•	○	•	○	•	○	•	4.7
2.C.3 Aluminum Production	PFCs	○	•		•					0.5

Source/Sink Category Code	Greenhouse Gas	Approach 1				Approach 2				2023 Emissions (MMT CO_2 Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	
Agriculture										
3.A.1 Enteric Fermentation: Cattle	CH_4	◉		◉		◉		◉		180.4
3.B.1 Manure Management: Cattle	CH_4	•	•	•	•	•	•	•	•	37.6
3.B.2 Manure Management: Swine	CH_4	•		•						24.3
3.C Rice Cultivation	CH_4	◉				◉		◉		18.7
3.D.1 Direct Agricultural Soil Management	CH_4	◉		◉		◉		◉		266.8
3.D.2 Indirect Applied Nitrogen	N_2O	◉		◉		◉		◉		29.6
Waste										
5.A MSW Landfills	CH_4	◉	•	◉	•	◉	•	◉	•	100.6
5.A Industrial Landfills	CH_4	•				•	•			18.9
5.D Domestic Wastewater Treatment	CH_4					◉				14.0
5.D Domestic Wastewater Treatment	N_2O	•		•		◉	•	◉	•	20.3
Land Use, Land Use Change, and Forestry										
4.E.2 Net Land Converted to Settlements	CO_2			◉	•			◉	•	79.8
4.B.2 Net Land Converted to Cropland	CO_2			◉	•			◉	•	35.6
4.C.1 Net Grassland Remaining Grassland	CO_2			◉				◉	•	22.0
4.C.2 Net Land Converted to Grassland	CO_2			◉	•			◉	•	20.9
4.E.1 Net Settlements Remaining Settlements: LYTFS	CO_2			○	•			○	•	-11.7
4.B.1 Net Cropland Remaining Cropland	CO_2			•	•			•	•	-30.5
4.A.1 Net Forest Land Remaining Forest Land: HWP	CO_2			◉	•			◉	•	-90.9
4.A.2 Net Land Converted to Forest Land	CO_2			◉				◉		-103.8
4.E.1 Net Settlements Remaining Settlements: C Stocks in Trees and Soils	CO_2			◉	•			◉	•	-122.6
4.A.1 Net Forest Land Remaining Forest Land: Forest C Pools	CO_2			◉	•			◉	•	-789.1
4.D.1 Flooded Lands Remaining Flooded Lands	CH_4			◉						45.8

Source/Sink Category Code	Greenhouse Gas	Approach 1				Approach 2				2023 Emissions (MMT CO_2 Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	
Subtotal Without LULUCF										**6,025.4**
Total Emissions Without LULUCF										**6,197.3**
Percent of Total Without LULUCF										**97%**
Subtotal With LULUCF										**5,033.9**
Total Emissions With LULUCF										**5,257.4**
Percent of Total With LULUCF										**96%**

NO (Not Occurring)

[a] Symbols correspond to the year(s) in which a category is key: 1990 = ○; 2023 = •. When both years are key, the open dot and filled dot are combined, for example, 1990 and 2023 = ◉.

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

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

Note: Parentheses indicate negative values (or sequestration).

1.7 Quality Assurance and Quality Control

As part of efforts to achieve its stated goals for inventory quality, transparency, and credibility, the EPA has developed a quality assurance and quality control plan known as the *Quality Assurance/Quality Control and Uncertainty Management Plan for the U.S. Greenhouse Gas Inventory* (QA/QC plan). The QA/QC plan is designed to check, document, and improve the quality of the *Inventory* over time. It is also in alignment with good practice guidance laid out in the *2006 IPCC Guidelines*.

The implementation of QA/QC and uncertainty analysis are guided by the QA/QC and inventory coordinators, who help to maintain the QA/QC plan and the overall uncertainty analysis procedures. The QA/QC coordinator works closely with the inventory coordinator and the category leads to ensure consistent implementation of the QA/QC plan and uncertainty analysis across all inventory categories. The QA/QC activities are integrated throughout the process of preparing the *Inventory*. Quality control—in the form of both good practices (such as documentation procedures) and checks on whether good practices and procedures are being followed—is applied at every stage of inventory development and document preparation. Key elements of the EPA QA/QC plan are summarized in Figure 1-2.

The QA/QC plan guides the process of ensuring inventory quality by defining data quality objectives, describing data and methodology checks, developing processes governing peer review and public comments, and developing guidance on conducting an analysis of the uncertainty surrounding the emission and removal estimates. The QA/QC procedures also include feedback loops and provide for corrective actions that are designed to improve the inventory estimates over time. Specific improvements identified through QA/QC and uncertainty procedures are noted in the *Planned Improvements* sections of respective categories.

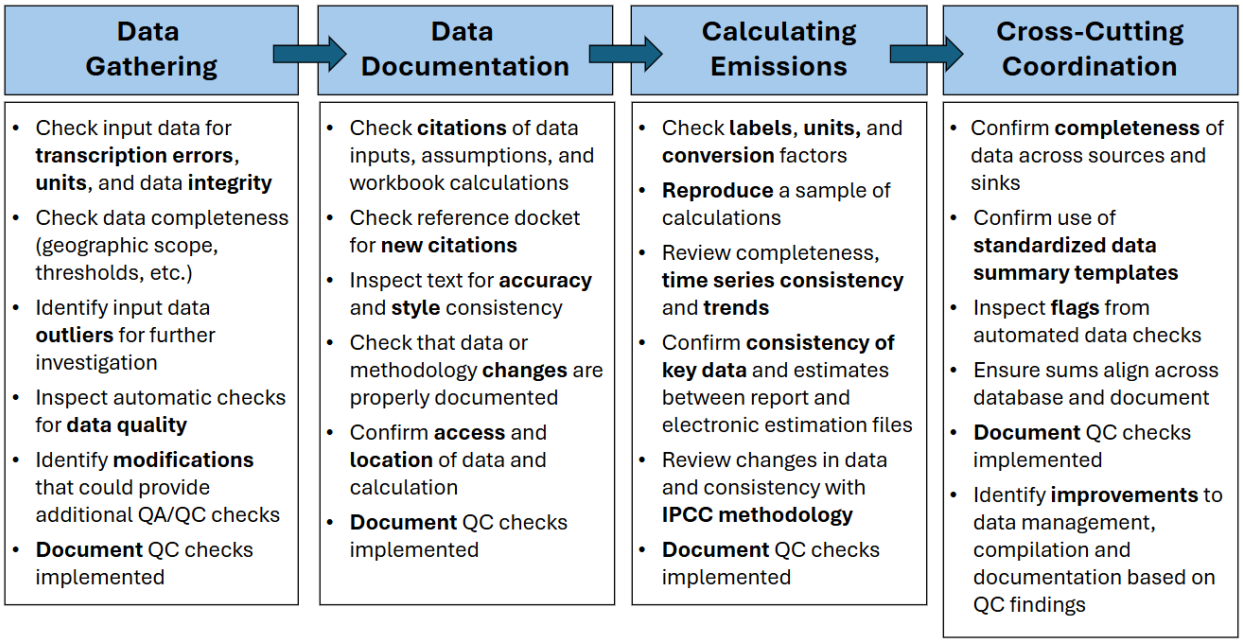
Key elements of the QA/QC plan include:

- Procedures, Templates and Forms which standardize the implementation, documentation and archival of QA/QC activities and related information throughout the whole *Inventory* development process. They also guide the implementation of additional QC for more significant sources. Uncertainty information templates facilitate compilation and review of uncertainty inputs and the inventory uncertainty analysis.
- Quality Assurance (QA) processes for implementing annual expert and public reviews of the *Inventory*. See Section 1.4 for more details on these QA processes.
- Quality Control (QC) procedures that apply General (Tier 1) and Category-specific (Tier 2)methodology or checks as recommended by *2006 IPCC Guidelines* (IPCC 2006) to be completed by staff compiling estimates. General checks are implemented on an annual basis for each greenhouse gas emissions source or sink category included in this *Inventory*. Where QC activities for a particular category go beyond the minimum general checks and include category-specific checks (Tier 2) or include verification, further explanation is provided within the respective source or sink category text.

- Communication of required and encouraged QA/QC practices, along with conveying findings from implementation within the EPA, across federal agencies and departments, research institutions, and organizations involved in supplying data or compiling estimates for the *Inventory*. These communications include periodic trainings reviewing procedures and lessons, or improvement areas from recent cycles.
- Record-keeping practices that ensure transparent documentation to track which procedures have been followed, the results of the QA/QC, uncertainty analysis, and feedback mechanisms for corrective action to improve the inventory estimates over time. Records also include tracking the application of more involved QA/QC procedures which may take more than one cycle to fully implement as part of improvement planning, especially for category-specific QC, prioritizing key categories (see Section 1.4).

These points and additional information about the QA/QC plan are further expanded upon in Annex 8.

Figure 1-2: Example QC Processes from Inventory QA/QC Plan



Box 1-3: Examples of Verification Activities

Consistent with IPCC guidance for national greenhouse gas inventories, verification activities include comparisons with emission or removal estimates prepared by other bodies and comparisons with estimates derived from fully independent assessments, e.g., atmospheric concentration measurements. Verification activities provide information to improve inventories and are part of the overall QA/QC system.

Use of Lower Tier Methods. Complete a "top-down" reference approach for estimating CO_2 emissions from fossil fuel combustion in addition to the “bottom-up” sectoral methodology for purposes of verification is an IPCC good practice. This estimation method uses alternative methodologies and different data sources than those contained in that section of the Energy chapter. The reference

approach estimates fossil fuel consumption by adjusting national aggregate fuel production data for imports, exports, and stock changes rather than relying on end-user consumption surveys (see Annex 4 of this report). The reference approach assumes that once carbon-based fuels are brought into a national economy, they are either saved in some way (e.g., stored in products, kept in fuel stocks, or left unoxidized in ash) or combusted, and therefore the carbon in them is oxidized and released into the atmosphere. Accounting for actual consumption of fuels at the sectoral or sub-national level is not required.

Use of Ambient Measurements Systems for Validation of Emission Inventories. Several recent studies have estimated emissions at the national or regional level with estimated results that sometimes differ from EPA's estimate of emissions. EPA has engaged with researchers on how remote sensing, ambient measurement, and inverse modeling techniques for estimating greenhouse gas emissions could assist in improving the understanding of inventory estimates. In working with the research community to improve national greenhouse gas inventories, EPA follows guidance from the IPCC on the use of measurements and modeling to validate emission inventories.[28] An area of particular interest in EPA's outreach efforts is how ambient measurement data can be used to assess estimates or potentially be incorporated into the *Inventory* in a manner consistent with this *Inventory* report's transparency of its calculation methodologies, and the ability of inverse modeling to attribute emissions and removals from remote sensing to anthropogenic sources, as defined by the IPCC for this report, versus natural sources and sinks.

The *2019 Refinement to the IPCC 2006 Guidelines for National Greenhouse Gas Inventories* (IPCC 2019) Volume 1 General Guidance and Reporting, Chapter 6: Quality Assurance, Quality Control and Verification notes that emission estimates derived from atmospheric concentration measurements can provide independent data sets as a basis for comparison with inventory estimates. The *2019 Refinement* provides guidance on conducting such comparisons (as summarized in Table 6.2 of IPCC [2019] Volume 1, Chapter 6) and provides guidance on using such comparisons to identify areas of improvement in national inventories (as summarized in Box 6.5 of IPCC [2019] Volume 1, Chapter 6). Further, it identified fluorinated gases as particularly suitable for such comparisons due their limited natural sources, their generally long atmospheric lifetimes, and well-understood loss mechanisms, which makes it relatively more straightforward to model their emission fluxes from observed mass quantities. Unlike emissions of CO_2, CH_4, and N_2O, emissions of fluorinated greenhouse gases are almost exclusively anthropogenic, meaning that the fluorinated greenhouse gas emission sources included in this *Inventory* account for the majority of the total U.S. emissions of these gases detectable in the atmosphere. This evaluation approach is also useful for gases and sources with larger uncertainties in available bottom-up inventory methods and data, such as emissions of CH_4, which are primarily from uncertain biological (e.g., enteric fermentation) and fugitive (e.g., natural gas production) activities.

In this *Inventory*, EPA includes the results from current and previous comparisons between fluorinated gas emissions inferred from atmospheric measurements and fluorinated gas emissions estimated based on bottom-up measurements and modeling. These comparisons, performed for HFCs and SF_6 respectively, are described under the QA/QC and Verification discussions in Chapter 4, Sections 4.25

[28] See http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1003_Uncertainty%20meeting_report.pdf.

Substitution of Ozone Depleting Substances and 4.26 Electrical Equipment in the IPPU chapter of this report.

Consistent with the *2019 Refinement* (IPCC 2019), a key element to facilitate such comparisons is a spatially-explicit (or gridded) emissions inventory as an input to inverse modeling. To improve the ability to compare methane emissions from the national-level greenhouse gas inventory with observation-based emission estimates, a team of researchers from U.S. EPA, SRON Netherlands Institute for Space Research, Harvard University, and Lawrence Berkely National Laboratory developed a time series of annual anthropogenic methane emissions maps with 0.1° x 0.1° (~10km x 10km) spatial resolution and monthly temporal resolution for the contiguous United States.[29] The gridded methane inventory is designed to be consistent with the *U.S. EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks* estimates, which presents national totals for different source types.[30] The development of this gridded inventory is consistent with the recommendations contained in two National Academies of Science reports examining greenhouse gas emissions data (National Research Council 2010; National Academies of Sciences, Engineering, and Medicine 2018).

Finally, in addition to use of atmospheric concentration measurement data for comparison with *Inventory* data, information from top-down studies is directly incorporated in the Natural Gas Systems calculations to quantify emissions from certain well blowout events.

1.8 Uncertainty Analysis

Emissions and removals calculated for the U.S. *Inventory* reflect best estimates for greenhouse gas source and sink categories in the United States and are continuously revised and improved as new information becomes available. Uncertainty assessment is an essential element of a complete and transparent emissions inventory because it helps inform and prioritize inventory improvements. For the U.S. *Inventory*, uncertainty analyses are conducted for each source and sink category as well as for the uncertainties associated with the overall emission (current and base year) and trends estimates. These analyses reflect the quantitative uncertainty in the emission (and removal) estimates associated with uncertainties in their input parameters (e.g., activity data and EFs) and serve to evaluate the relative contribution of individual input parameter uncertainties to the overall *Inventory*, its trends, and each source and sink category.

The overall level and trend uncertainty estimates for total U.S. greenhouse gas emissions and sinks was developed using the IPCC Approach 2 uncertainty estimation methodology (assuming a Normal distribution for Approach 1 estimates), which employs a Monte Carlo stochastic simulation technique. The IPCC provides good practice guidance on two approaches—Approach 1 and Approach 2—to estimating uncertainty for both individual and combined source categories. Approach 2 quantifies uncertainties based on a distribution of emissions (or removals), built-up

[29] See https://www.epa.gov/ghgemissions/us-gridded-methane-emissions.

[30] See https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

from repeated calculations of emission estimation models and the underlying input parameters, randomly selected according to their known distributions. Approach 2 methodology is applied to each individual source and sink category wherever data and resources are permitted and is also used to quantify the uncertainty in the overall *Inventory* and its Trends. Source and sink chapters in this report provide additional details on the uncertainty analysis conducted for each source and sink category. See Annex 7 of this report for further details on the U.S. process for estimating uncertainty associated with the overall emission (base and current year) and trends estimates. Consistent with IPCC (IPCC 2006), the United States has ongoing efforts to continue to improve the overall *Inventory* uncertainty estimates presented in this report.

The United States has also implemented many improvements over the last several years to reduce uncertainties across the source and sink categories and improve *Inventory* estimates. These improvements result from the development of uncertainty assessments for sources previously not estimated, new data sources that provide more accurate data and/or increased data coverage, as well as methodological improvements. Following IPCC good practice, additional efforts to reduce *Inventory* uncertainties can occur through efforts to incorporate excluded emission and sink categories (see Annex 5), improve estimation methods, and collect more detailed, measured, and representative data. Individual category chapters and Annex 7 both describe current ongoing and planned *Inventory* and uncertainty analysis improvements. Consistent with IPCC (2006), the EPA and collaborating organizations have ongoing efforts to continue to improve the category-specific uncertainty estimates presented in this report, largely prioritized by considering improvements to categories identified as significant by the Key Category Analysis.

Estimates of quantitative uncertainty for the total U.S. greenhouse gas emissions and sinks in 1990 (base year) and 2023 are shown in Table 1-5 and Table 1-6, respectively. The overall uncertainty surrounding the total net emissions is estimated to be -6 to +5 percent in 1990 and -5 to +6 percent in 2023. When the LULUCF sector is excluded from the analysis the uncertainty is estimated to be -2 to +4 percent in 1990 and -2 to +4 percent in 2023.

Table 1-5: Estimated Overall Inventory Quantitative Uncertainty for 1990 (MMT CO_2 Eq. and Percent)

Gas	1990 Emission Estimate	Uncertainty Range Relative to Greenhouse Gas Estimate[a]				Mean[b]	Standard Deviation[b]
		(MMT CO_2 Eq.)		(%)			
	(MMT CO_2 Eq.)	Lower Bound[c]	Upper Bound[c]	Lower Bound	Upper Bound	(MMT CO_2 Eq.)	
CO_2	5,131.8	5,024.0	5,365.2	-2%	5%	4,972.0	88.0
CH_4[d]	873.1	767.4	914.6	-12%	5%	680.0	37.5
N_2O[d]	407.8	348.7	509.8	-15%	25%	428.6	40.7
PFC, HFC, SF_6, and NF_3[d]	125.6	103.3	149.1	-18%	19%	220.7	12.2
Total Gross Emissions	**6,538.3**	**6,384.5**	**6,787.1**	**-2%**	**4%**	**6,301.2**	**104.8**
LULUCF Emissions[e]	59.1	55.9	63.3	-6%	7%	61.1	2.0
LULUCF Carbon Stock Change Flux[f]	(1,096.9)	(1,386.3)	(949.2)	26%	-13%	(1,061.5)	111.7
LULUCF Sector Net Total[g]	**(1,037.9)**	**(1,326.8)**	**(889.2)**	**28**	**-14%**	(1,000.4)	111.7
Net Emissions (Sources and Sinks)	**5,500.4**	**5,177.2**	**5,779.7**	**-6%**	**5%**	**(5,300.8)**	**154.6**

[a] The lower and upper bounds for emission estimates correspond to a 95 percent confidence interval, with the lower bound corresponding to 2.5th percentile and the upper bound corresponding to 97.5th percentile.

[b] Mean value indicates the arithmetic average of the simulated emission estimates; standard deviation indicates the extent of deviation of the simulated values from the mean.

[c] The lower and upper bound emission estimates for the sub-source categories do not sum to total emissions because the low and high estimates for total emissions were calculated separately through simulations.

[d] The overall uncertainty estimates did not take into account the uncertainty in the GWP values for CH_4, N_2O and high GWP gases used in the *Inventory* emission calculations for 1990.

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

[f] LULUCF carbon stock change is the net C stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements. Since the resulting flux is negative the signs of the resulting lower and upper bounds are reversed.

[g] The LULUCF sector net total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Total emissions (excluding emissions for which uncertainty was not quantified) are presented without LULUCF. Net emissions are presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 1-6: Estimated Overall Inventory Quantitative Uncertainty for 2023 (MMT CO_2 Eq. and Percent)

Gas	2023 Emission Estimate	Uncertainty Range Relative to Greenhouse Gas Estimate[a]				Mean[b]	Standard Deviation[b]
		(MMT CO_2 Eq.)		(%)			
	(MMT CO_2 Eq.)	Lower Bound[c]	Upper Bound[c]	Lower Bound	Upper Bound	(MMT CO_2 Eq.)	
CO_2	4,918.4	4,818.4	5,128.7	-2%	4%	4,969.4	80.5
CH_4[d]	686.7	638.6	762.4	-7%	11%	700.4	31.8
N_2O[d]	387.0	328.8	493.6	-15%	28%	404.2	42.3
PFC, HFC, SF_6, and NF_3[d]	205.3	183.0	217.6	-11%	6%	199.7	8.9
Total Gross Emissions	**6,197.3**	**6,088.8**	**6,466.6**	**-2%**	**4%**	**6,273.6**	**96.7**
LULUCF Emissions[e]	60.6	57.5	65.0	-5%	7%	61.1	2.0
LULUCF Carbon Stock Change Flux[f]	(1,000.5)	(1,257.8)	(862.8)	26%	-14%	(1,061.9)	101.6
LULUCF Sector Net Total[g]	(939.9)	(1,196.5)	(801.5)	27%	-15%	(1,000.8)	101.6
Net Emissions (Sources and Sinks)	**5,257.4**	**5,002.9**	**5,549.1**	**-5%**	**6%**	**5,272.9**	**140.5**

[a] The lower and upper bounds for emission estimates correspond to a 95 percent confidence interval, with the lower bound corresponding to 2.5th percentile and the upper bound corresponding to 97.5th percentile.

[b] Mean value indicates the arithmetic average of the simulated emission estimates; standard deviation indicates the extent of deviation of the simulated values from the mean.

[c] The lower and upper bound emission estimates for the sub-source categories do not sum to total emissions because the low and high estimates for total emissions were calculated separately through simulations.

[d] The overall uncertainty estimates did not take into account the uncertainty in the GWP values for CH_4, N_2O and high GWP gases used in the *Inventory* emission calculations for 2023.

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

[f] LULUCF carbon stock change is the net C stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements. Since the resulting flux is negative the signs of the resulting lower and upper bounds are reversed.

[g] The LULUCF sector net total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Total emissions (excluding emissions for which uncertainty was not quantified) are presented without LULUCF. Net emissions are presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

The uncertainty for 2023 is similar to the uncertainty for 1990, though slightly lower. There have been some improvements in significant categories which do not necessarily reduce uncertainties. For example, use of higher tier methods may reveal a "more realistic acknowledgement of the limitations of existing knowledge" of uncertainty, including reflecting additional complexity of a system compared to a lower tier method (IPCC 2006). Methodological and data quality improvements were also made for HFCs, PFCs, SF_6 and NF_3 this year but the uncertainties for these sources also slightly increased. Use of extrapolation techniques to ensure time series consistency, such as for direct N_2O emissions from agricultural soil management, may also result in higher uncertainties in the current year relative to the base year of the time series. Note, the methods and data for fossil fuel combustion categories, the most significant source, has not changed significantly and neither have uncertainties. It is also worth noting that some of the improvements

to shift to use of GHGRP have reduced uncertainties (e.g., CH_4 from landfills) but several have been in less significant categories within the inventory (e.g., CO_2 from ammonia production). So, the overall uncertainty for latest year reflects these offsetting effects and trends within the uncertainty assessment.

In addition to the estimates of uncertainty associated with the current and base year estimates, Table 1-7 presents the estimates of inventory trend uncertainty. The *2006 IPCC Guidelines* (IPCC 2006) defines trend as the difference in emissions between the base year (i.e., 1990) and the current year (i.e., 2023) *Inventory* estimates. However, for purposes of understanding the concept of trend uncertainty, the trend is defined in this *Inventory* as the percentage change in the gross emissions (or net emissions) estimated for the current year, relative to the gross emission (or net emissions) estimated for the base year. The uncertainty associated with this trend is referred to as trend uncertainty and is reported as between -11 and 5 percent at the 95 percent confidence level between 1990 and 2023. This indicates a range of approximately -11 percent below and 5 percent above the trend estimate of -4 percent. See Annex 7 for trend uncertainty estimates for individual source and sink categories by gas.

Table 1-7: Quantitative Assessment of Trend Uncertainty (MMT CO_2 Eq. and Percent)

Gas	(MMT CO_2 Eq.)		Emissions Trend (%)	Trend Range[b] (%)	
	Base Year Emissions[a]	2023 Emissions		Lower Bound	Upper Bound
CO_2	5,131.8	4,918.4	-4%	-8%	0%
CH_4	873.1	686.7	-21%	-28%	-9%
N_2O	407.8	387.0	-5%	-31%	49%
HFCs, PFCs, SF_6, and NF_3	125.6	205.3	64%	43%	119%
Total Gross Emissions[c]	**6,538.3**	**6,197.3**	**-5%**	**-9%**	**0%**
LULUCF Emissions[d]	59.1	60.6	3%	-6%	13%
LULUCF Carbon Stock Change Flux[e]	(1,096.9)	(1,000.5)	-9%	-30%	19%
LULUCF Sector Net Total[f]	**(1,037.9)**	**(939.9)**	**-9%**	**-32%**	**20%**
Net Emissions (Sources and Sinks)[c]	**5,500.4**	**5,257.4**	**-4%**	**-11%**	**5%**

[a] Base Year is 1990 for all sources.

[b] The trend range represents a 95 percent confidence interval for the emission trend, with the lower bound corresponding to 2.5th percentile value and the upper bound corresponding to 97.5th percentile value.

[c] Totals exclude emissions for which uncertainty was not quantified.

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

[e] LULUCF carbon stock change is the net C stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, land converted to wetlands, settlements remaining settlements, and land converted to settlements.

[f] The LULUCF sector net total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration. Total emissions (excluding emissions for which uncertainty was not quantified) are presented without LULUCF. Net emissions are presented with LULUCF.

1.9 Completeness

This report, along with its accompanying tables, serves as a thorough assessment of the anthropogenic sources and sinks of greenhouse gas emissions for the United States for the time series 1990 through 2023. This report 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 *Inventory* are excluded because they are not occurring in the United States, its territories, and tribal lands, or because data are unavailable to develop an estimate and/or the categories were determined to be insignificant in terms of overall national emissions.

The EPA is continually working to improve upon the understanding of such sources and sinks currently not included and identify the data required to estimate any emissions and removals currently excluded, focusing on categories that are anticipated to be significant. See Chapter 9 on Improvements and Recalculations for more information on completeness and improvements implemented this cycle. For a list of sources and sink categories not included and more information on the significance of these categories, see Annex 5 and the respective category sections in each sectoral chapter of this report.

Box 1-4: Organization of Report

The Inventory is organized according to the chapters listed below in Table 1-8, consistent with the structure used by other countries.

Table 1-8: Inventory Sector Descriptions

Chapter (Inventory Sector)	Activities Included
Energy	Emissions of all greenhouse gases resulting from stationary and mobile energy activities including fuel combustion and fugitive fuel emissions, and non-energy use of fossil fuels.
Industrial Processes and Product Use	Emissions resulting from industrial processes and product use of greenhouse gases.
Agriculture	Emissions from agricultural activities except fuel combustion, which is addressed under Energy.
Land Use, Land-Use Change, and Forestry	Emissions and removals of CO_2, and emissions of CH_4, and N_2O from land use, land-use change, and forestry.
Waste	Emissions from waste management activities.

Within each chapter, emissions are identified by the anthropogenic activity that is the source or sink of the greenhouse gas emissions being estimated (e.g., coal mining). Overall, the following organizational structure is consistently applied throughout this report:

Chapter/Reporting Sector: Overview of emissions and trends for each inventory reporting sector.

Source or Sink Category: Description of category pathway and emission/removal trends based on IPCC methodologies.

Methodology and Time-Series Consistency: Description of analytical methods (e.g., from *2006 IPCC Guidelines,* or country-specific methods) employed to produce emission estimates and identification of

data references, primarily for activity data and emission factors, and a discussion of time-series consistency.

Uncertainty: A discussion and quantification of the uncertainty in emission estimates.

QA/QC and Verification: A discussion on steps taken to QA/QC and verify the emission estimates, consistent with the U.S. QA/QC plan, and any key QC findings.

Recalculations Discussion: A discussion of any data or methodological changes that necessitate a recalculation of previous years' emission estimates, and the impact of the recalculation on the emission estimates, if applicable.

Planned Improvements: A discussion on any category-specific planned improvements, if applicable.

Special attention is given to CO_2 from fossil fuel combustion relative to other sources because of its share of emissions and its dominant influence on emission trends. For example, each energy consuming end-use sector (i.e., residential, commercial, industrial, and transportation), as well as the electricity generation sector, is described individually. Additional information for certain source categories and other topics is also provided in several methodological Annexes listed in Table 1-9.

Table 1-9: List of Annexes

ANNEX 1 Key Category Analysis	
ANNEX 2 Methodology and Data for Estimating CO_2 Emissions from Fossil Fuel Combustion	
2.1.	Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion
2.2.	Methodology for Estimating the Carbon Content of Fossil Fuels
2.3.	Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels
ANNEX 3 Methodological Descriptions for Additional Source or Sink Categories	
3.1.	Methodology for Estimating Emissions of CH_4, N_2O, and Indirect Greenhouse Gases from Stationary Combustion
3.2.	Methodology for Estimating Emissions of CH_4, N_2O, and Indirect Greenhouse Gases from Mobile Combustion and Methodology for and Supplemental Information on Transportation-Related Greenhouse Gas Emissions
3.3.	Methodology for Estimating Emissions from Commercial Aircraft Jet Fuel Consumption
3.4.	Methodology for Estimating CH_4 Emissions from Coal Mining
3.5.	Methodology for Estimating CH_4 and CO_2 Emissions from Petroleum Systems
3.6.	Methodology for Estimating CH_4 Emissions from Natural Gas Systems
3.7.	Methodology for Estimating CO_2 and N_2O Emissions from Incineration of Waste
3.8.	Methodology for Estimating Emissions from International Bunker Fuels used by the U.S. Military
3.9.	Methodology for Estimating Emissions from Other Fluorochemical Production
3.10.	Methodology for Estimating HFC and PFC Emissions from Substitution of Ozone Depleting Substances
3.11.	Methodology for Estimating CH_4 Emissions from Enteric Fermentation
3.12.	Methodology for Estimating CH_4 and N_2O Emissions from Manure Management
3.13.	Methodology for Estimating N_2O Emissions, CH_4 Emissions and Soil Organic C Stock Changes from Agricultural Lands (Cropland and Grassland)
3.14.	Methodology for Estimating Net Carbon Stock Changes in Forest Land Remaining Forest Land and Land Converted to Forest Land
3.15.	Methodology for Estimating CH_4 Emissions from Landfills
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