# ANNEX 7 Uncertainty

The annual U.S. Inventory presents the best effort to produce emission estimates for greenhouse gas source and sink categories in the United States. These estimates were generated according to the UNFCCC reporting guidelines, following the recommendations set forth in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) and *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019). This Annex provides an overview of the overall uncertainty analysis conducted to support the U.S. Inventory, including the sources of uncertainty characterized throughout the Inventory associated with various source categories (including emissions and sinks), and the methods used to collect, quantify, and present this uncertainty information. An Addendum to Annex 7 is provided separately which includes additional information related to the uncertainty characteristics of input variables used in the development of the overall uncertainty estimates reported in Section 1.7 of the Inventory report.

## 7.1. Overview

The uncertainty analysis conducted in support of the Inventory (1) determines the quantitative uncertainty associated with the emission source and sink estimates presented in the main body of this report, (2) evaluates the relative contribution of the input parameters to the uncertainty associated with each source or sink category estimate and in the overall inventory and (3) estimates the uncertainty in the overall emissions for the latest year, the base year and in the emissions trend.  Note, overall uncertainty estimates in the Inventory capture quantifiable uncertainties in the input activity and emission factors data, but do not account for the potential of additional sources of uncertainty such as modeling uncertainties, measurement errors, and misreporting or misclassification. Thus, the U.S. Inventory uncertainty analysis helps inform and prioritize improvements for source and sink categories estimation process which are discussed in the "Planned Improvements" sections of each source or sink category's discussion within the main body of the report. For each source or sink category, the uncertainty analysis highlights opportunities for changes to data measurement, data collection, and calculation methodologies to reduce uncertainties.

For some category estimates, such as $CO_2$ emissions from energy-related combustion activities, the impact of uncertainties on overall emission estimates is relatively small. For some other limited categories of emissions, uncertainties could have a larger impact on the estimates presented (i.e., storage factors of non-energy uses of fossil fuels). In all source and sink category chapters, the inventory emission estimates include "Uncertainty and Time-Series Consistency" sections that consider both quantitative and qualitative assessments of uncertainty, considering factors consistent with good practices noted in Volume 1, Chapter 3 of the *2006 IPCC Guidelines* (e.g., completeness of data, representativeness of data and models, sampling errors, measurement errors). The two major types of uncertainty associated with these emission estimates are (1) model uncertainty, which arises when the emission and/or removal estimation models used in developing the Inventory estimates do not fully and accurately characterize the respective emission and/or removal processes (due to a lack of technical details or other resources), and (2) parameter uncertainty, which arises due to potential bias or a lack of accurate, complete, representative, or precise input data such as emission factors and activity data and inherent variability.

The uncertainty associated with emission (or removal) estimation models can be partially analyzed by comparing the model emission (or removal) results with those of other models developed to characterize the same emission (or removal) process, after taking into account differences in their conceptual framework, capabilities, data, and underlying assumptions. However, in many cases it would be very difficult—if not impossible—to use this approach to quantify the model uncertainty associated with the emission estimates in this report, primarily because most categories only have a single model that has been developed to estimate emissions. Therefore, model uncertainty was not quantified in this report. Nonetheless, it has been discussed qualitatively, where appropriate, along with the individual source or sink category description and inventory estimation methodology.

Parameter uncertainty encompasses several causes such as lack of completeness, lack of data or representative data, sampling error, random or systematic measurement error, or misreporting or misclassification. Uncertainties associated with input emission parameters have been quantified for all of the emission sources and sinks included in the U.S. Inventory totals. Given the very low emissions for these source categories, uncertainty estimates were not derived.

## 7.2. Methodology and Results

The United States has developed both a quality assurance and quality control (QA/QC) and uncertainty management plan (EPA 2002). Like the QA/QC plan, the uncertainty management plan is part of a continually evolving process. The uncertainty management plan provides for a quantitative assessment of the Inventory analysis itself, thereby contributing to continuing efforts to understand both what causes uncertainty and how to improve Inventory and accuracy. Although the plan provides both general and specific guidelines for implementing a quantitative uncertainty analysis, its components are intended to evolve over time, consistent with the inventory estimation process. The U.S. plan includes procedures and guidelines, and forms and templates, for developing quantitative assessments of uncertainty in the national Inventory estimates (EPA 2002). For the 1990 through 2020 Inventory*,* EPA has used the uncertainty management plan as well as the methodology presented in the *2006 IPCC Guidelines* and *2019 Refinement.*

The *2006 IPCC Guidelines* and *2019 Refinement* recommend two methods—Approach 1 and Approach 2—for developing quantitative estimates of uncertainty associated with individual categories and the overall Inventory estimates. The United States is continuing efforts to develop quantitative estimates of uncertainty for all source categories using Approach 2. In following the UNFCCC requirement under Article 4.1, emissions from International Bunker Fuels, Wood Biomass and Biofuel Consumption, and Indirect Greenhouse Gas Emissions are not included in the total emissions estimated for the U.S. Inventory; therefore, no quantitative uncertainty estimates have been developed for these categories.[1] $CO_2$ Emissions from Biomass and Biofuel Consumption are accounted for implicitly in the Land Use, Land-Use Change and Forestry (LULUCF) chapter through the calculation of changes in carbon stocks. The Energy sector provides an estimate of $CO_2$ emissions from Biomass and Biofuel Consumption as a memo item for informational purposes, consistent with the UNFCCC reporting requirements.

**Approach 1 and Approach 2 Methods**

The Approach 1 method for estimating uncertainty is based on the propagation of errors, as shown in Eq. 3.1 and Eq. 3.2 of the *2006 IPCC Guidelines* and *2019 Refinement*. These equations combine the random component of uncertainty associated with the activity data and the emission (or the other) factors. Inherent in employing the Approach 1 method are the assumptions that, for each source and sink category, (i) both the uncertainties in the activity data and the emission factor values are approximately normally distributed, (ii) the coefficient of variation (i.e., the ratio of the standard deviation to the mean) associated with each input variable is less than 30 percent, and (iii) the input variables within and across sub- source categories are not correlated (i.e., value of each variable is independent of the values of other variables).

The Approach 2 method is preferred if (i) the uncertainty associated with the input variables is large (i.e., >30 percent), (ii) the distributions of uncertainties in the underlying the input variables are not normal (e.g., non-gaussian), (iii) the estimates of uncertainty associated with the input variables are correlated, and/or if (iv) a complex estimation methodology and/or several input variables are used to characterize the emission (or removal) process. Due to the input parameters and estimation methodologies used in the Inventory, the uncertainties are assessed using the Approach 2 method for all categories where sufficient and reliable data are available to characterize the uncertainty of the input variables.

The Approach 2 method employs the Monte Carlo Stochastic Simulation technique (also referred to as the Monte Carlo method). Under this method, emission (or removal) estimates for a particular source (or sink) category are estimated by randomly selecting values of emission factors, activity data, and other estimation parameters according to their individual Probability Density Functions (PDFs). This process is repeated many times using computer software, in order to build up the probability density function, which is then used to estimate the final uncertainty values of the overall emission (or removal) estimates for that source (or sink). For most categories, the Monte Carlo approach is implemented using commercially available simulation software such as Palisade's @RISK Microsoft Excel add-in.

[1] However, because the input variables that determine the emissions from the Fossil Fuel Combustion and the International Bunker Fuels source categories are correlated, uncertainty associated with the activity variables in the International Bunker Fuels was taken into account in estimating the uncertainty associated with the Fossil Fuel Combustion.

## Characterization of Uncertainty in Input Variables

Both Approach 1 and Approach 2 uncertainty analyses require that all the input variables have defined PDFs. In the absence of sufficient data measurements, data samples, or expert judgments that determined otherwise, the PDFs incorporated in the current source or sink category uncertainty analyses were limited to normal, lognormal, uniform, triangular, pert, and beta distributions. The choice among these six PDFs depended largely on the observed or measured data and expert judgment. If no additional uncertainty information is available than the previous year's Inventory uncertainty data is used. Input variables with asymmetrical PDFs shift the overall output which can lead to asymmetrical bounds for a source (or sink) category and in turn, for the overall Inventory uncertainty analysis.

## Individual Source and Sink Category Inventory Uncertainty Estimates

The body of this report provides an overview of the input parameters and sources of uncertainty for each source and sink category. Table A-252 summarizes results based on assessments of source and sink category-level uncertainty. The table presents base year (1990) and current year (2020) emissions for each source and sink category. The combined uncertainty (at the 95 percent confidence interval) for each source and category is expressed as the percentage above and below the total 2020 emissions estimated for each source and sink category. Uncertainty in the trend of each source and sink category is described subsequently in this Appendix.

**Table A-252: Summary Results of Source and Sink Category Uncertainty Analyses**

| Source or Sink Category | Base Year Emissions[a] | 2020 Emissions[b] | 2020 Uncertainty[b] | |
|---|---|---|---|---|
| | | | Lower Bound | Upper Bound |
| | MMT $CO_2$ Eq. | MMT $CO_2$ Eq. | | |
| **$CO_2$** | **5,122.5** | **4,715.7** | **-3%** | **3%** |
| Fossil Fuel Combustion | 4,731.2 | 4,342.7 | -2% | 4% |
| Non-Energy Use of Fuels | 112.2 | 121.0 | -37% | 49% |
| Cement Production | 33.5 | 40.7 | -6% | 6% |
| Iron and Steel Production & Metallurgical Coke | *104.7* | *37.7* | *-17%* | 17% |
| Natural Gas Systems | *31.9* | *35.4* | -16% | 19% |
| Petroleum Systems | 9.6 | 30.2 | *-22%* | 26% |
| Petrochemical Production | 21.6 | 30.0 | -5% | 6% |
| Incineration of Waste | 12.9 | 13.1 | -17% | 17% |
| Ammonia Production | 13.0 | 12.7 | -10% | 11% |
| Lime Production | 11.7 | 11.3 | -2% | 2% |
| Other Process Uses of Carbonates | 6.2 | 9.8 | -19% | 29% |
| Urea Consumption for Non-Agricultural Purposes | 3.8 | 6.0 | -14% | 14% |
| Urea Fertilization | 2.4 | 5.3 | -43% | 3% |
| Carbon Dioxide Consumption | 1.5 | 5.0 | -5% | 5% |
| Liming | 4.7 | 2.4 | -111% | 98% |
| Coal Mining | 4.6 | 2.2 | -68% | 76% |
| Glass Production | 2.3 | 1.9 | -2% | 2% |
| Aluminum Production | 6.8 | 1.7 | -2% | 2% |
| Soda Ash Production | 1.4 | 1.5 | -9% | 8% |
| Ferroalloy Production | 2.2 | 1.4 | -13% | 13% |
| Titanium Dioxide Production | 1.2 | 1.3 | -13% | 13% |
| Zinc Production | 0.6 | 1.0 | -19% | 20% |
| Phosphoric Acid Production | 1.5 | 0.9 | -18% | 20% |
| Lead Production | 0.5 | 0.5 | -15% | 16% |
| Carbide Production and Consumption | 0.2 | 0.2 | -9% | 9% |
| Abandoned Oil and Gas Wells | + | + | -83% | 197% |
| Magnesium Production and Processing | 0.1 | + | -4% | 4% |
| *Wood Biomass, Ethanol, and Biodiesel Consumption[c]* | *219.4* | *291.6* | *NE* | *NE* |
| *International Bunker Fuels[d]* | *103.6* | *69.6* | *NE* | *NE* |
| **$CH_4$** | **780.8** | **650.4** | **-10%** | **10%** |
| Enteric Fermentation | 163.5 | 175.2 | -11% | 18% |
| Natural Gas Systems | 195.5 | 164.9 | -18% | 18% |
| Landfills | 176.6 | 109.3 | -23% | 22% |

| | | | | |
|---|---|---|---|---|
| Manure Management | 34.8 | 59.6 | -18% | 20% |
| Coal Mining | 96.5 | 41.2 | -9% | 17% |
| Petroleum Systems | 47.8 | 40.2 | -28% | 32% |
| Wastewater Treatment | 20.3 | 18.3 | -35% | 23% |
| Rice Cultivation | 16.0 | 15.7 | -75% | 75% |
| Stationary Combustion | 8.6 | 7.9 | -34% | 125% |
| Abandoned Oil and Gas Wells | 6.5 | 6.9 | -83% | 197% |
| Abandoned Underground Coal Mines | 7.2 | 5.8 | -22% | 20% |
| Composting | 0.4 | 2.3 | -58% | 58% |
| Mobile Combustion | 6.5 | 2.2 | -8% | 24% |
| Field Burning of Agricultural Residues | 0.4 | 0.4 | -18% | 18% |
| Petrochemical Production | 0.2 | 0.3 | -57% | 46% |
| Anaerobic Digestion at Biogas Facilities | + | 0.2 | -54% | 54% |
| Carbide Production and Consumption | + | + | -9% | 9% |
| Ferroalloy Production | + | + | -12% | 13% |
| Iron and Steel Production & Metallurgical Coke | + | + | -21% | 23% |
| Anaerobic Digestion at Biogas Facilities | + | + | NE | NE |
| *International Bunker Fuels*[d] | *0.2* | *0.1* | *NE* | *NE* |
| **$N_2O$** | **450.5** | **426.1** | **-21%** | **27%** |
| Agricultural Soil Management | 316.0 | 316.2 | -27% | 26% |
| Stationary Combustion | 25.1 | 23.2 | -24% | 51% |
| Manure Management | 13.9 | 19.7 | -16% | 24% |
| Mobile Combustion | 44.6 | 17.4 | -8% | 19% |
| Wastewater Treatment | 16.6 | 23.5 | -35% | 194% |
| Nitric Acid Production | 12.1 | 9.3 | -5% | 5% |
| Adipic Acid Production | 15.2 | 8.3 | -5% | 5% |
| $N_2O$ from Product Uses | 4.2 | 4.2 | -24% | 24% |
| Composting | 0.3 | 2.0 | -58% | 58% |
| Caprolactam, Glyoxal, and Glyoxylic Acid Production | 1.7 | 1.2 | -31% | 32% |
| Incineration of Waste | 0.5 | 0.4 | -53% | 162% |
| Electronics Industry | + | 0.3 | -10% | 11% |
| Field Burning of Agricultural Residues | 0.2 | 0.2 | -17% | 17% |
| Petroleum Systems | + | + | -22% | 26% |
| Natural Gas Systems | + | + | -16% | 19% |
| *International Bunker Fuels*[d] | *0.9* | *0.6* | *NE* | *NE* |
| **HFCs, PFCs, $SF_6$ and $NF_3$** | **99.7** | **189.2** | **-8%** | **8%** |
| Substitution of Ozone Depleting Substances | 0.2 | 176.3 | -3% | 14% |
| Electronics Industry | 3.6 | 4.4 | -6% | 7% |
| Electrical Transmission and Distribution | 23.2 | 3.8 | -16% | 18% |
| HCFC-22 Production | 46.1 | 2.1 | -7% | 10% |
| Aluminum Production | 21.5 | 1.7 | -6% | 7% |
| Magnesium Production and Processing | 5.2 | 0.9 | -9% | 9% |
| **Total Gross Emissions**[e] | **6,453.5** | **5,981.4** | **-2%** | **5%** |
| LULUCF Emissions[f] | 31.4 | 53.2 | -17% | 18% |
| LULUCF Carbon Stock Change Flux[g] | (892.0) | (812.2) | 32% | -20% |
| **LULUCF Sector Net Total**[h] | **(860.6)** | **(758.9)** | **35%** | **-22%** |
| **Net Emissions (Sources and Sinks)**[e] | **5,592.8** | **5,222.4** | **-5%** | **6%** |

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

+ Does not exceed 0.05 MMT $CO_2$ Eq. or 0.5 percent.

NE (Not Estimated)

[a] Base Year is 1990 for all sources.

[b] The uncertainty estimates correspond to a 95 percent confidence interval, with the lower bound corresponding to 2.5$^{th}$ percentile and the upper bound corresponding to 97.5$^{th}$ percentile.

[c] Emissions from Wood Biomass and Biofuel Consumption are not included in the energy sector totals.

[d] Emissions from International Bunker Fuels are not included in the totals.

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

[f] LULUCF emissions include the $CH_4$ and $N_2O$ emissions reported for Peatlands Remaining Peatlands, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; $CH_4$ emissions from *Land Converted to Coastal Wetlands*, Land Converted to Flooded Land, and Flooded Land Remaining Flooded Land; and $N_2O$ emissions from Forest Soils and Settlement Soils.
[g] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Wetlands Remaining Wetlands, Land Converted to Wetlands, Settlements Remaining Settlements*, and *Land Converted to Settlements*. Since the resulting flux is negative the signs of the resulting lower and upper bounds are reversed.
[h] The LULUCF Sector Net Total is the net sum of all $CH_4$ and $N_2O$ emissions to the atmosphere plus net carbon stock changes.

### Overall (Aggregate) Inventory Level Uncertainty Estimates

The overall level uncertainty estimate for the U.S. Inventory was developed using the IPCC Approach 2 uncertainty estimation methodology for 1990 and 2020. The overall Inventory uncertainty estimates were estimated by combining the Monte Carlo simulation output data for each emission source or sink category (as described above) across all sources and categories as a function of gas. If such detailed output data were not available for a particular source or sink category, individual PDFs were assigned based on the most detailed data available from the category-specific quantitative uncertainty analysis. The overall Inventory uncertainty was then derived through the resulting PDF of the combined emissions data.

For select categories such as composting, several LULUCF source categories, and parts of Agricultural Soil Management source categories, Approach 1 uncertainty results were used in the overall uncertainty analysis. However, for all other emission sources, Approach 2 uncertainty results were used in the overall uncertainty estimation.

The overall uncertainty model results indicate that the 1990 U.S. greenhouse gas emissions are estimated to be within the range of approximately 6,330.2 to 6,761.5 MMT $CO_2$ Eq., reflecting a relative 95 percent confidence interval uncertainty range of -2 percent to 5 percent with respect to the total U.S. greenhouse gas emission estimate of approximately 6,453.5 MMT $CO_2$ Eq. The uncertainty interval associated with total $CO_2$ emissions, ranges from -2 percent to 5 percent of total $CO_2$ emissions estimated. The results indicate that the uncertainty associated with the inventory estimate of the total $CH_4$ emissions ranges from -8 percent to 12 percent, uncertainty associated with the total inventory $N_2O$ emission estimate ranges from -19 percent to 28 percent, and uncertainty associated with fluorinated greenhouse gas (F-GHG) emissions ranges from -9 percent to 13 percent. When the LULUCF sector is included in the analysis, the uncertainty is estimated to be -5 to 6 percent of Net Emissions (sources and sinks) in 1990. The uncertainties presented are quantifiable uncertainties in the input activity and emission factors data, not uncertainties in the models, data representativeness, measurement errors, or misreporting or misclassification of data.

**Table A-253: Quantitative Uncertainty Assessment of Overall National Inventory Emissions for 1990 (MMT $CO_2$ Eq. and Percent)**

| Gas | 1990 Emission Estimate (MMT $CO_2$ Eq.) | Uncertainty Range Relative to Emission Estimate[a] (MMT $CO_2$ Eq.) | | (%) | | Mean[b] (MMT $CO_2$ Eq.) | Standard Deviation[b] |
|---|---|---|---|---|---|---|---|
| | | Lower Bound[c] | Upper Bound[c] | Lower Bound | Upper Bound | | |
| $CO_2$ | 5,122.5 | 5,017.3 | 5,357.6 | -2% | 5% | 5,186.5 | 88.0 |
| $CH_4$[d] | 780.8 | 720.1 | 871.5 | -8% | 12% | 794.9 | 38.8 |
| $N_2O$[d] | 450.5 | 365.6 | 574.9 | -19% | 28% | 457.8 | 54.1 |
| PFCs, HFCs, $SF_6$, and $NF_3$[d] | 99.7 | 90.2 | 112.5 | -9% | 13% | 100.4 | 5.6 |
| **Total Gross Emissions** | **6,453.5** | **6,330.2** | **6,761.5** | **-2%** | **5%** | **6,539.5** | **110.6** |
| LULUCF Emissions[e] | 31.4 | 29.3 | 33.8 | -7% | 8% | 31.5 | 1.1 |
| LULUCF Carbon Stock Change Flux[f] | (892.0) | (1,183.9) | (709.3) | 33% | -20% | (944.1) | 119.3 |
| **LULUCF Sector Net Total[g]** | **(860.6)** | **(1,152.7)** | **(677.7)** | **34%** | **-21%** | **(912.6)** | **119.3** |
| **Net Emissions (Sources and Sinks)** | **5,592.8** | **5,306.8** | **5,953.6** | **-5%** | **6%** | **5,626.9** | **163.9** |

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

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

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

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

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

[e] LULUCF emissions include the $CH_4$ and $N_2O$ emissions reported for Peatlands Remaining Peatlands, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; $CH_4$ emissions from *Land Converted to Coastal Wetlands*, Land Converted to Flooded Land, and Flooded Land Remaining Flooded Land; and $N_2O$ emissions from Forest Soils and Settlement Soils.

[f] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Wetlands Remaining Wetlands, Land Converted to Wetlands, Settlements Remaining Settlements*, and *Land Converted to Settlements*. Since the resulting flux is negative the signs of the resulting lower and upper bounds are reversed.

[g] The LULUCF Sector Net Total is the net sum of all $CH_4$ and $N_2O$ emissions to the atmosphere plus net carbon stock changes.

The overall uncertainty model results indicate that the 2020 U.S. greenhouse gas emissions are estimated to be within the range of approximately 5,863.8 to 6,253.0 MMT $CO_2$ Eq., reflecting a relative 95 percent confidence interval uncertainty range of -2 percent to 5 percent with respect to the total gross U.S. greenhouse gas emission estimate of approximately 5,981.4 MMT $CO_2$ Eq. The uncertainty interval associated with total $CO_2$ emissions, which constitute about 79 percent of the total U.S. greenhouse gas emissions in 2020, ranges from -2 percent to 4 percent of total $CO_2$ emissions estimated. The results indicate that the uncertainty associated with the inventory estimate of the total $CH_4$ emissions ranges from -8 percent to 11 percent, uncertainty associated with the total inventory $N_2O$ emission estimate ranges from -20 percent to 29 percent, and uncertainty associated with fluorinated greenhouse gas (F-GHG) emissions ranges from -3 percent to 13 percent. When the LULUCF sector is included in the analysis, the uncertainty is estimated to be -5 to 6 percent of Net Emissions (sources and sinks) in 2020.

A summary of the overall quantitative uncertainty estimates is shown below.

**Table A-254: Quantitative Uncertainty Assessment of Overall National Inventory Emissions for 2020 (MMT $CO_2$ Eq. and Percent)**

| Gas | 2020 Emission Estimate (MMT $CO_2$ Eq.) | Uncertainty Range Relative to Emission Estimate[a] (MMT $CO_2$ Eq.) | | (%) | | Mean[b] (MMT $CO_2$ Eq.) | Standard Deviation[b] (MMT $CO_2$ Eq.) |
|---|---|---|---|---|---|---|---|
| | | Lower Bound[c] | Upper Bound[c] | Lower Bound | Upper Bound | | |
| $CO_2$ | 4,715.7 | 4,610.6 | 4,908.0 | -2% | 4% | 4,759.8 | 76.4 |
| $CH_4$[d] | 650.4 | 595.9 | 723.6 | -8% | 11% | 659.7 | 32.6 |
| $N_2O$[d] | 426.1 | 342.4 | 551.1 | -20% | 29% | 436.1 | 53.3 |
| PFC, HFC, $SF_6$, and $NF_3$[d] | 189.2 | 182.6 | 213.7 | -3% | 13% | 198.2 | 7.9 |
| **Total Gross Emissions** | **5,981.4** | **5,863.8** | **6,253.0** | **-2%** | **5%** | **6,053.7** | **98.2** |
| LULUCF Emissions[e] | 53.2 | 44.4 | 62.9 | -17% | 18% | 53.5 | 4.9 |
| LULUCF Carbon Stock Change Flux[f] | (812.2) | (1,075.7) | (647.8) | 32% | -20% | (860.2) | 109.4 |
| **LULUCF Sector Net Total[g]** | **(758.9)** | **(1,023.2)** | **(594.5)** | **35%** | **-22%** | **(806.7)** | **109.6** |
| **Net Emissions (Sources and Sinks)** | **5,222.4** | **4,956.9** | **5,540.9** | **-5%** | **6%** | **5,247.0** | **148.1** |

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

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

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

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

[d] The overall uncertainty estimates did not take into account the uncertainty in the GWP values for $CH_4$, $N_2O$, and high GWP gases used in the inventory emission calculations for 2020.

[e] LULUCF emissions include the $CH_4$ and $N_2O$ emissions reported for Peatlands Remaining Peatlands, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; $CH_4$ emissions from *Land Converted to Coastal Wetlands*, Land Converted to Flooded Land, and Flooded Land Remaining Flooded Land; and $N_2O$ emissions from Forest Soils and Settlement Soils.

[f] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Wetlands Remaining Wetlands, Land Converted to Wetlands, Settlements Remaining Settlements*, and *Land Converted to Settlements*. Since the resulting flux is negative the signs of the resulting lower and upper bounds are reversed.

[g] The LULUCF Sector Net Total is the net sum of all $CH_4$ and $N_2O$ emissions to the atmosphere plus net carbon stock changes.

**Trend Uncertainty**

In addition to the estimates of uncertainty associated with the current and base year emission estimates, this Annex also presents the estimates of trend uncertainty. The *2006 IPCC Guidelines* define trend as the difference in emissions between the base year (i.e., 1990) and the current year (i.e., 2020) Inventory estimates. However, for purposes of understanding the concept of trend uncertainty, the emission trend is defined in this Inventory as the percentage change in the emissions (or removal) estimated for the current year, relative to the emission (or removal) estimated for the base year. The uncertainty associated with this emission trend is referred to as trend uncertainty.

Under the Approach 1 method, there are two types of uncertainty to consider when estimating the trend uncertainty in an individual source or sink category. As described in the *2006 IPCC Guidelines*, correlated (Type A) uncertainties are estimated by comparing the change in emissions trend given a 1 percent change in both base (i.e., 1990) and current emissions (i.e., 2020), while uncorrelated or random errors in the emissions trend (Type B) are estimated by comparing the change in emissions trend given a 1 percent change in only the current year emissions. When combined, both types of uncertainty capture the sensitivity in trend emission estimates to sources of uncertainty that are correlated between the base and current year (Type A), as well as the random component of uncertainty in the emission estimates (Type B).

Under the Approach 2 method, the trend uncertainty is estimated using the Monte Carlo Stochastic Simulation technique. As described in the *2006 IPCC Guidelines*, this Approach follows four steps. First, the PDFs for emission factors, activity data, and other input estimation parameters are determined for both the current and base year. For purposes of this Inventory, due to data limitations, for some categories where uncertainty assessments for 1990 are undergoing updates for future reports but were not ready to incorporate for this submission, a simple approach has been adopted, under which the base year source or sink category emissions are assumed to exhibit the same uncertainty characteristics as the current year emissions (or removals). Source and sink category-specific PDFs for base year estimates were developed using current year (i.e., 2020) uncertainty output data. These were adjusted to account for differences in magnitude between the two years' inventory estimates. The second and third steps follow the Monte Carlo approach described previously to calculate repeated emission estimates for each source and sink category in the base and current years according to the input data PDFs. The overall Inventory trend uncertainty estimate was developed by combining all source and sink category-specific trend uncertainty estimates. These trend uncertainty estimates represent the 95 percent confidence interval of the estimated percent change in emissions between 1990 and 2020 and are shown in Table A-255.

**Table A-255: Quantitative Assessment of Trend Uncertainty (MMT $CO_2$ Eq. and Percent)**

| Gas/Source | Base Year Emissions[a] | 2020 Emissions | Emissions Trend | Trend Range[b] | |
|---|---|---|---|---|---|
| | (MMT $CO_2$ Eq).) | | (%) | (%) | |
| | | | | Lower Bound | Upper Bound |
| **$CO_2$** | **5,122.5** | **4,715.7** | **-8%** | **-12%** | **-4%** |
| Fossil Fuel Combustion | 4,731.2 | 4,342.7 | -8% | -13% | -4% |
| Non-Energy Use of Fuels | 112.2 | 121.0 | 8% | -39% | 80% |
| Cement Production | 33.5 | 40.7 | 22% | 7% | 40% |
| Iron and Steel Production & Metallurgical Coke Production | 104.7 | 37.7 | -64% | -72% | -55% |
| Natural Gas Systems | 31.9 | 35.4 | 11% | -14% | 42% |
| Petroleum Systems | 9.6 | 30.2 | 214% | 115% | 357% |
| Petrochemical Production | 21.6 | 30.0 | 39% | 28% | 51% |
| Incineration of Waste | 12.9 | 13.1 | 2% | -20% | 30% |
| Ammonia Production | 13.0 | 12.7 | -3% | -18% | 19% |
| Lime Production | 11.7 | 11.3 | -3% | -6% | -1% |
| Other Process Uses of Carbonates | 6.2 | 9.8 | 57% | 24% | 113% |
| Urea Consumption for Non-Agricultural Purposes | 3.8 | 6.0 | 58% | 27% | 97% |
| Urea Fertilization | 2.4 | 5.3 | 118% | 23% | 281% |
| Carbon Dioxide Consumption | 1.5 | 5.0 | 238% | 196% | 288% |
| Liming | 4.7 | 2.4 | -49% | -601% | 523% |
| Coal Mining | 4.6 | 2.2 | -53% | -87% | 68% |
| Glass Production | 2.3 | 1.9 | -19% | -22% | -16% |
| Aluminum Production | 6.8 | 1.7 | -74% | -75% | -73% |
| Soda Ash Production | 1.4 | 1.5 | 2% | -10% | 16% |
| Ferroalloy Production | 2.2 | 1.4 | -36% | -46% | -24% |
| Titanium Dioxide Production | 1.2 | 1.3 | 12% | -7% | 34% |
| Zinc Production | 0.6 | 1.0 | 60% | 22% | 109% |
| Phosphoric Acid Production | 1.5 | 0.9 | -39% | -55% | -17% |
| Lead Production | 0.5 | 0.5 | -4% | -22% | 18% |
| Carbide Production and Consumption | 0.2 | 0.2 | -37% | -48% | -21% |
| Abandoned Oil and Gas Wells | 0.0 | + | 9% | -1494% | 1331% |
| Magnesium Production and Processing | 0.1 | + | -99% | -99% | -99% |
| *Wood Biomass and Biofuel Consumption[c]* | *219.4* | *291.6* | *33%* | *NE* | *NE* |
| *International Bunker Fuels[d]* | *103.6* | *69.6* | *-33%* | *NE* | *NE* |
| **$CH_4$** | **780.8** | **650.4** | **-17%** | **-28%** | **-5%** |
| Enteric Fermentation | 163.5 | 175.2 | 7% | -21% | 45% |
| Natural Gas Systems | 195.5 | 164.9 | -16% | -35% | 9% |
| Landfills | 176.6 | 109.3 | -38% | -56% | -12% |
| Manure Management | 34.8 | 59.6 | 71% | 9% | 168% |
| Coal Mining | 96.5 | 41.2 | -57% | -64% | -49% |
| Petroleum Systems | 47.8 | 40.2 | -16% | -46% | 33% |
| Wastewater Treatment | 20.3 | 18.3 | -10% | -46% | 30% |
| Rice Cultivation | 16.0 | 15.7 | -2% | -528% | 905% |
| Stationary Combustion | 8.6 | 7.9 | -8% | -66% | 156% |
| Abandoned Oil and Gas Wells | 6.5 | 6.9 | 6% | -87% | 752% |
| Abandoned Underground Coal Mines | 7.2 | 5.8 | -20% | -43% | 13% |
| Composting | 0.4 | 2.3 | 498% | 161% | 1255% |
| Mobile Combustion | 6.5 | 2.2 | -66% | -70% | -58% |
| Field Burning of Agricultural Residues | 0.4 | 0.4 | 14% | -22% | 66% |
| Petrochemical Production | 0.2 | 0.3 | 43% | -43% | 251% |
| Anaerobic Digestion at Biogas Facilities | + | 0.2 | 952% | 349% | 2386% |
| Carbide Production and Consumption | + | + | -46% | -57% | -30% |

| | | | | | |
|---|---|---|---|---|---|
| Ferroalloy Production | + | + | -43% | -52% | -33% |
| Iron and Steel Production & Metallurgical Coke Production | + | + | -69% | -77% | -59% |
| Incineration of Waste | + | + | -13% | *NE* | *NE* |
| *International Bunker Fuels*[d] | *0.2* | *0.1* | *-54%* | *NE* | *NE* |
| **$N_2O$** | **450.5** | **426.1** | **-5%** | **-31%** | **32%** |
| Agricultural Soil Management | 316.0 | 316.2 | 0% | -36% | 58% |
| Stationary Combustion | 25.1 | 23.2 | -7% | -48% | 71% |
| Manure Management | 13.9 | 19.7 | 41% | -7% | 115% |
| Mobile Combustion | 44.6 | 17.4 | -61% | -70% | -43% |
| Wastewater Treatment | 16.6 | 23.5 | 42% | -55% | 268% |
| Nitric Acid Production | 12.1 | 9.3 | -23% | -29% | -18% |
| Adipic Acid Production | 15.2 | 8.3 | -45% | -48% | -42% |
| $N_2O$ from Product Uses | 4.2 | 4.2 | 0% | -25% | 28% |
| Composting | 0.3 | 2.0 | 498% | 167% | 1249% |
| Caprolactam, Glyoxal, and Glyoxylic Acid Production | 1.7 | 1.2 | -28% | -54% | 15% |
| Incineration of Waste | 0.5 | 0.4 | -13% | -76% | 203% |
| Electronics Industry | + | 0.3 | 730% | 454% | 1518% |
| Field Burning of Agricultural Residues | 0.2 | 0.2 | 15% | -20% | 65% |
| Petroleum Systems | + | + | 153% | 50% | 329% |
| Natural Gas Systems | + | + | 105% | 40% | 197% |
| *International Bunker Fuels*[d] | *0.9* | *0.6* | *-30%* | *NE* | *NE* |
| **HFCs, PFCs, $SF_6$, and $NF_3$** | **99.7** | **189.2** | **90%** | **73%** | **125%** |
| Substitution of Ozone Depleting Substances | 0.2 | 176.3 | 77486% | 29230% | 797019% |
| Electronics Industry | 3.6 | 4.4 | 25% | 10% | 42% |
| Electrical Transmission and Distribution | 23.2 | 3.8 | -84% | -89% | -75% |
| HCFC-22 Production | 46.1 | 2.1 | -95% | -96% | -95% |
| Aluminum Production | 21.5 | 1.7 | -92% | -93% | -92% |
| Magnesium Production and Processing | 5.2 | 0.9 | -82% | -85% | -78% |
| **Total Gross Emissions**[e] | **6,453.5** | **5,981.4** | **-7%** | **-12%** | **-3%** |
| LULUCF Emissions[f] | 31.4 | 53.2 | 70% | 39% | 103% |
| LULUCF Carbon Stock Change Flux[g] | (892.0) | (812.2) | -9% | -37% | 30% |
| **LULUCF Sector Net Total**[h] | **(860.6)** | **(758.9)** | **-12%** | **-40%** | **28%** |
| **Net Emissions (Sources and Sinks)**[e] | **5,592.8** | **5,222.4** | **-7%** | **-14%** | **1%** |

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

+ Does not exceed 0.05 MMT $CO_2$ Eq. or 0.5 percent.

NE (Not Estimated)

[a] Base Year is 1990 for all sources.

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

[c] Emissions from Wood Biomass and Biofuel Consumption are not included specifically in the energy sector totals.

[d] Emissions from International Bunker Fuels are not included in the totals.

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

[f] LULUCF emissions include the $CH_4$ and $N_2O$ emissions reported for Peatlands Remaining Peatlands, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; $CH_4$ emissions from *Land Converted to Coastal Wetlands*, Land Converted to Flooded Land, and Flooded Land Remaining Flooded Land; and $N_2O$ emissions from Forest Soils and Settlement Soils.

[g] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Wetlands Remaining Wetlands, Land Converted to Wetlands, Settlements Remaining Settlements,* and *Land Converted to Settlements.*

[i] The LULUCF Sector Net Total is the net sum of all $CH_4$ and $N_2O$ emissions to the atmosphere plus net carbon stock changes.

## 7.3. Information on Uncertainty Analyses by Source and Sink Category

The quantitative uncertainty estimates associated with each emission and removal category are reported within sectoral chapters of this Inventory following the discussions of inventory estimates and their estimation methodology. To better understand the uncertainty analysis details, refer to the respective chapters and Uncertainty and Time-Series Consistency sections in the body of this report. EPA provides additional documentation on uncertainty information consistent with the guidance presented in Table 3.3 in Vol. 1, Chapter 3 of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) in an Uncertainty Addendum. Due to the number of detailed tables, it is not published with the Inventory but is available upon request. EPA plans to publish this in a more easily accessible format with future reports (e.g., the 2023 or 2024 Inventory reports). All uncertainty estimates are reported relative to the current Inventory estimates for the 95 percent confidence interval, unless otherwise specified.

## 7.4. Reducing Uncertainty and Planned Improvements

The U.S. has implemented many improvements over the last several years that have reduced uncertainties across the source and sink categories. These improvements largely result from new data sources that provide more accurate data and/or increased data coverage, as well as methodological improvements, as described below.

**Box A-4: Reducing Uncertainty**

The *2006 IPCC Guidelines* provides the following guidance for ways to reduce Inventory uncertainty and improve the quality of an Inventory and its uncertainty estimates.

- *Improving conceptualization*. Improving the inclusiveness of the structural assumptions chosen can reduce uncertainties. An example is better treatment of seasonality effects that leads to more accurate annual estimates of emissions or removals for the Agriculture, Land Use, Land Use Change and Forestry sector.

- *Improving models.* Improving the model structure and parameterization can lead to better understanding and characterization of the systematic and random errors, as well as reductions in these causes of uncertainty.

- *Improving representativeness.* This may involve stratification or other sampling strategies. For example, continuous emissions monitoring systems (CEMS) can be used to reduce uncertainty for some sources and gases as long as the representativeness is guaranteed. CEMS produces representative data at the facilities where it is used, but in order to be representative of an entire source category, CEMS data must be available for a random sample or an entire set of individual facilities that comprise the category. When using CEMS both concentration and flow will vary, requiring simultaneous sampling of both attributes.

- *Incorporating excluded emission sources.* Quantitative estimates for some of the sources and sinks of greenhouse gas emissions, such as from some land-use activities, industrial processes, and parts of mobile sources, could not be developed at this time either because data are incomplete or because methodologies do not exist for estimating emissions from these source categories. See Annex 5 of this report for a discussion of the sources of greenhouse gas emissions and sinks excluded from this report. Consistent with IPCC good practice principles, EPA continues efforts to estimate emissions and sinks from excluded emission and removal sources occurring in U.S. and developing uncertainty estimates for all source and sink categories for which emissions and removals are estimated.

- *Collecting more measured data.* Uncertainty associated with bias and random sampling error can be reducing by increasing the sample size and filling in data gaps. This applies to both measurements and surveys.

- *Using more precise measurement methods.* Measurement error can be reduced by using more precise measurement methods, avoiding simplifying assumption, and ensuring that measurement technologies are appropriately used and calibrated.

- *Eliminating known risk of bias.* This is achieved by ensuring instrumentation is properly positioned and calibrated, models or other estimation procedures are appropriate and representative, and by applying expert judgements in a systematic way.

- *Improving state of knowledge.* Improve the understanding of categories and processes leading to emissions and removals, which can help to discover and correct for problems in incompleteness. It is *Good Practice* to continuously improve emissions and removal estimates based on new knowledge.

The following sections describe the ongoing and planned Inventory and Uncertainty analysis improvements in the context of these specific areas.

**Recent and Ongoing Improvements**

To *collect more measured data*, *improve representativeness,* and *use more precise measurement methods,* several source categories in the Inventory now use the U.S. EPA's Greenhouse Gas Reporting Program (GHGRP) data, which improves Inventory emission (or sink) estimation methods by allowing the incorporation of country-specific data rather than using default IPCC estimates. EPA's GHGRP relies on facility-level data reported from large facilities emitting over 25,000 metric tons of $CO_2$ equivalent each year. The reported GHGRP data undergo a multi-step verification process, including automated data checks to ensure consistency, comparison against expected ranged for similar facilities and industries, and statistical analysis. See Annex 9 for more information on use of GHGRP data in the Inventory.

In addition to improving Inventory input data and methodologies, the use of EPA's GHGRP data also reduces uncertainty in select Inventory emission categories. For example, replacing highly uncertain emission factor estimates with GHGRP data for the Coal Mining category reduced the 95 percent uncertainty bounds for methane emissions from this category from -15 percent to 18 percent in the 1990 to 2011 inventory down to -9 percent to 17 percent in the current (1990 to 2020) Inventory. Methane emission estimates from MSW landfills were also revised with GHGRP data, which resulted in methodological and data quality improvements that also reduced the 95 percent uncertainty bounds for this category compared to the prior use of default emission factors with larger assumed uncertainties.

Additional ongoing improvements to the U.S. Inventory uncertainty analyses for select categories will help to *eliminate known risk of bias, improve models,* and advance *the state of knowledge,* which may lead to further Inventory and uncertainty analysis improvements in other areas including *improved conceptualization* and *data representativeness*. Finally, ongoing improvements include review of documentation of source-specific input data and references, PDF distributions, and Monte Carlo analysis results through the implementation of standardized source-specific uncertainty reporting and documentation templates. Ongoing improvements to the overall *Inventory* Uncertainty Analysis documentation will additionally ensure consistency with IPCC *Good Practice* and increase the transparency of the overall analysis.

**Planned Improvements**

EPA continuously seeks new knowledge to improve the Inventory emissions and removal estimates. With available resources, planned future improvements to the Inventory and Uncertainty Analysis are prioritized by focusing improvements on categories identified in the Key Category Analysis (Chapter 1.5), or by quantitatively comparing the relative contributions of uncertainties from various input parameters (e.g., activity data and emission factors) to the total uncertainty levels within a source or sink category. Quantifying the sensitivity of the overall Inventory uncertainty bounds to the uncertainty within each source or sink category can also prioritize future Inventory updates.

As described in Chapter 1.5, Key Categories in the current (1990 to 2020) Inventory include (but are not limited to) categories that fall under Fossil Fuel Combustion (Chapter 3.1), Petroleum and Natural Gas Systems (Chapter 3.6 and 3.7), Industrial Processes and Product Use (Chapter 3), and Agriculture (Chapter 4). Planned improvements for these key categories largely include the incorporation of more accurate and/or representative input parameters. For example, as described in Chapter 3.1, planned inventory improvements for emissions from fossil fuel combustion categories include efforts to assess the incorporation of more measured input activity data (e.g., GHGRP data, domestic marine activity) and other input parameters (e.g., updated carbon factors for petroleum fuels, emission factors for non-road equipment, etc.). Similarly, Chapters 3.6 and 3.7 discuss plans to continue stakeholder engagement to assess the potential for incorporating new input data (e.g., from peer-reviewed publications, industry studies, etc.), updating methods for select sources (e.g., Offshore Production, unassigned high-emitters), or including new sources (e.g., anomalous leak events) within the Petroleum and Natural Gas System categories. Categories within the IPPU sector (Chapter 4) also discuss plans to assess the future incorporation of additional facility-level GHGRP data, improve emission models (e.g., for ozone depleting substance substitutes) and the methodological descriptions in the Inventory report. Similar to other categories, planned improvements to Agricultural emissions from Manure Management and Enteric Fermentation include the incorporation of new, more accurate and representative data, updates to emission models and conceptualization (including moving to Tier 2 methods for all sources), as well as revised uncertainty estimates to the account for recent updates. Details describing the planned improvements for these and nearly all other individual source and sink categories are included in the category-specific Chapters of this report.

Implementation of these planned improvements will occur on an ongoing basis as new information becomes available. Improvements are prioritized to make best use of available resources, including efforts to improve the accuracy of emission factors, collect more detailed and representative activity data, as well as provide better estimates of input parameter uncertainty. For example, further research is needed in some cases to improve the accuracy of emission factors, including those currently applied to $CH_4$ and $N_2O$ emissions from manure management. Lastly, for many individual source categories, further research is also needed to characterize the PDFs of their input parameters more accurately (e.g., emission factors and activity data). This might involve using measured or published statistics or implementing a rigorous protocol to elicit expert judgment, if published or measured data are not available. Continued efforts in these areas will reduce Inventory uncertainty and increase the completeness, accuracy, and transparency of the category-specific and overall Inventory estimates.

Additional planned improvements for the overall Inventory uncertainty analysis include improving the presentation of uncertainties in a format consistent with suggested tables in Volume 1, Chapter 3 of the *2006 IPCC Guidelines*. As resources permit, in particular for key categories, improvements include reviewing and updating the existing uncertainty models for the base year. This process would improve the base year and trend uncertainty analyses but may not eliminate every simplifying assumptions described above due to limited data availability in the base year.

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