ANNEX 7 Uncertainty

The annual U.S. Inventory presents the best effort to produce 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). This Annex provides an overview of the uncertainty analysis conducted to support the U.S. Inventory, describes the sources of uncertainty characterized throughout the Inventory associated with various source categories (including emissions and sinks), and describes the methods through which uncertainty information was collected, quantified, and presented. An Addendum to Annex 7 is provided separately which includes additional information related to the characteristics of input variables used in the development of the uncertainty estimates reported in the Inventory.

7.1. Overview

The primary purpose of the uncertainty analysis conducted in support of the U.S. Inventory is (1) to determine the quantitative uncertainty associated with the emission (and removal) estimates presented in the main body of this report based on the uncertainty associated with the input parameters used in the emission (and removal) estimation methodologies and (2) to evaluate the relative importance of the input parameters in contributing to uncertainty in the associated source or sink category inventory estimate and in the overall inventory estimate. Thus, the U.S. Inventory uncertainty analysis provides a strong foundation for developing future improvements to the inventory estimation process. For each source or sink category, the analysis highlights opportunities for changes to data measurement, data collection, and calculation methodologies. These are presented in the "Planned Improvements" sections of each source or sink category's discussion in the main body of the report.

For some of the current estimates, such as CO_2 emissions from energy-related combustion activities, the impact of uncertainties on overall emission estimates is believed to be 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). As noted, for all source categories, 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* (i.e., completeness of data, representativeness of data and models, sampling errors, measurement errors, etc.). 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), resulting in the use of incorrect or incomplete estimation methodologies, and (2) parameter uncertainty, which arises due to a lack of precise input data such as emission factors and activity data.

The model uncertainty can be partially analyzed by comparing the model results with those of other models developed to characterize the same emission (or removal) process, after taking into account the differences in their conceptual framework, capabilities, data, and assumptions. However, it would be very difficult—if not impossible—to quantify the model uncertainty associated with the emission estimates (primarily because, in most cases, only a single model has been developed to estimate emissions from any one source). 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, misreporting or misclassification, or missing data. Parameter uncertainty is, therefore, the principal type and source of uncertainty associated with the national Inventory emission estimates and is the main focus of the quantitative uncertainty analyses in this report. Parameter uncertainty has been quantified for all of the emission sources and sinks included in the U.S. Inventory totals, with the exception of one very small emission source category, CH_4 emissions from Incineration of Waste, given the very low emissions for CH_4 from Incineration of Waste, no uncertainty estimate was derived. Uncertainty associated with three other source categories (International Bunker Fuels, Energy Sources of Indirect Greenhouse Gas Emissions, and CO_2 emissions from Wood Biomass and Biofuel Consumption) whose emissions are not included in the Inventory totals is discussed qualitatively in their respective sections in the main body of the report.

7.2. Methodology and Results

The United States has developed 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 quality. Although the plan provides both general and specific guidelines for implementing 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 2017 Inventory, EPA has used the uncertainty management plan as well as the methodology presented in the *2006 IPCC Guidelines.*

The *2006 IPCC Guidelines* recommends two methods—Approach 1 and Approach 2—for developing quantitative estimates of uncertainty in the inventory estimate of individual source categories and the overall Inventory. Of these, the Approach 2 method is both more flexible and reliable than Approach 1; both approaches are described in the next section. The United States is in the process of implementing a multi-year strategy to develop quantitative estimates of uncertainty for all source categories using the 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 source categories.[136] 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 does provide an estimate of CO_2 emissions from Biomass and Biofuel Consumption provided 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 error propagation equation. This equation combines the uncertainty associated with the activity data and the uncertainty associated with the emission (or the other) factors. The Approach 1 method is applicable where emissions (or removals) are usually estimated as the product of an activity value and an emission factor or as the sum of individual sub-source or sink category values. Inherent in employing the Approach 1 method are the assumptions that, for each source and sink category, (i) both 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 (i) if the uncertainty associated with the input variables is significantly large, (ii) if the distributions underlying the input variables are not normal, (iii) if the estimates of uncertainty associated with the input variables are correlated, and/or (iv) if a sophisticated estimation methodology and/or several input variables are used to characterize the emission (or removal) process correctly. In practice, the Approach 2 is the preferred method of uncertainty analysis for all source 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, estimates of emissions (or removals) for a particular source or sink category are generated many times (equal to the number of simulations specified) using an uncertainty model, which is an emission (or removal) estimation equation that imitates or is the same as the inventory estimation model for a particular source or sink category. These estimates are generated using the respective, randomly-selected values for the constituent input variables using commercially available simulation software such as @RISK.

Characterization of Uncertainty in Input Variables

Both Approach 1 and Approach 2 uncertainty analyses require that all the input variables are well-characterized in terms of their Probability Density Functions (PDFs). In the absence of particularly convincing data measurements, sufficient 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, and beta distributions. The choice among these five PDFs depended largely on the observed or measured data and expert judgment.

Source and Sink Category Inventory Uncertainty Estimates

Discussion surrounding the input parameters and sources of uncertainty for each source and sink category appears in the body of this report. Table A-265 summarizes results based on assessments of source and sink category-level

[136] 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.

uncertainty. The table presents base year (1990 or 1995) and current year (2017) 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 deviation above and below the total 2017 emissions estimated for that source and category. Source or sink category trend uncertainty is described subsequently in this Appendix.

Table A-265: Summary Results of Source and Sink Category Uncertainty Analyses

Source or Sink Category	Base Year Emissions[a]	2017 Emissions[b]	2017 Uncertainty[b]	
	MMT CO_2 Eq.	MMT CO_2 Eq.	Low	High
CO_2	**5,121.2**	**5,270.7**	**-2%**	**4%**
Fossil Fuel Combustion	4,738.8	4,912.0	-2%	5%
Non-Energy Use of Fuels	119.6	123.2	-23%	37%
Iron and Steel Production & Metallurgical Coke Production	101.6	41.8	-18%	18%
Cement Production	33.5	40.3	-6%	6%
Petrochemical Production	21.2	28.2	-5%	5%
Natural Gas Systems	30.0	26.3	-16%	17%
Petroleum Systems	9.0	23.3	-30%	34%
Ammonia Production	13.0	13.2	-5%	5%
Lime Production	11.7	13.1	-2%	2%
Incineration of Waste	8.0	10.8	-11%	15%
Other Process Uses of Carbonates	6.3	10.1	-12%	15%
Urea Fertilization	2.4	5.1	-43%	3%
Urea Consumption for Non-Agricultural Purposes	3.8	5.0	-12%	12%
Carbon Dioxide Consumption	1.5	4.5	-5%	5%
Liming	4.7	3.2	-111%	89%
Ferroalloy Production	2.2	2.0	-12%	12%
Soda Ash Production	1.4	1.8	-9%	8%
Titanium Dioxide Production	1.2	1.7	-13%	13%
Glass Production	1.5	1.3	-4%	5%
Aluminum Production	6.8	1.2	-3%	3%
Phosphoric Acid Production	1.5	1.0	-19%	21%
Zinc Production	0.6	1.0	-16%	16%
Lead Production	0.5	0.5	-15%	15%
Silicon Carbide Production and Consumption	0.4	0.2	-9%	9%
Abandoned Oil and Gas Wells	+	+	-83%	215%
Magnesium Production and Processing	+	+	-8%	8%
Wood Biomass, Ethanol, and Biodiesel Consumption[c]	*219.4*	*116.6*	*NE*	*NE*
International Bunker Fuels[d]	*103.5*	*120.1*	*NE*	*NE*
CH_4	**779.8**	**656.3**	**-9%**	**14%**
Enteric Fermentation	164.2	175.4	-11%	18%
Natural Gas Systems	193.1	165.6	-16%	17%
Landfills	179.6	107.7	-11%	40%
Manure Management	37.1	61.7	-18%	20%
Coal Mining	96.5	55.7	-9%	19%
Petroleum Systems	42.1	37.7	-30%	34%
Wastewater Treatment	15.3	14.2	-28%	22%
Rice Cultivation	16.0	11.3	-25%	49%
Stationary Combustion	8.6	7.8	-33%	124%
Abandoned Oil and Gas Wells	6.6	6.9	-83%	215%
Abandoned Underground Coal Mines	7.2	6.4	-21%	19%
Mobile Combustion	12.9	3.2	-8%	27%
Composting	0.4	2.2	-50%	50%
Petrochemical Production	0.2	0.3	-57%	45%
Field Burning of Agricultural Residues	0.1	0.2	-51%	49%
Ferroalloy Production	+	+	-12%	12%
Silicon Carbide Production and Consumption	+	+	-8%	8%
Iron and Steel Production & Metallurgical Coke Production	+	+	-19%	19%
Incineration of Waste	+	+	NE	NE
International Bunker Fuels[d]	*0.2*	*0.1*	*NE*	*NE*

N_2O	**370.3**	**360.5**	**-12%**	**21%**
Agricultural Soil Management	251.7	266.4	-17%	26%
Direct	*212.7*	*227.7*	*-17%*	*19%*
Indirect	*39.0*	*38.8*	*-59%*	*144%*
Stationary Combustion	25.1	28.6	-28%	52%
Manure Management	14.0	18.7	-16%	24%
Mobile Combustion	42.0	16.9	-8%	14%
Nitric Acid Production	12.1	9.3	-5%	5%
Adipic Acid Production	15.2	7.4	-5%	5%
Wastewater Treatment	3.4	5.0	-75%	108%
N_2O from Product Uses	4.2	4.2	-24%	24%
Composting	0.3	1.9	-50%	50%
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.7	1.4	-31%	32%
Incineration of Waste	0.5	0.3	-47%	301%
Semiconductor Manufacture	+	0.2	-12%	12%
Field Burning of Agricultural Residues	+	0.1	-47%	46%
Petroleum Systems	+	+	-30%	34%
Natural Gas Systems	+	+	-16%	17%
International Bunker Fuels[d]	*0.9*	*1.0*	*NE*	*NE*
HFCs, PFCs, SF_6 and NF_3	**130.8**	**169.1**	**-+%**	**11%**
Substitution of Ozone Depleting Substances	31.4	152.7	-+%	12%
HCFC-22 Production	46.1	5.2	-7%	10%
Semiconductor Manufacture[e]	3.6	4.7	-6%	6%
Electrical Transmission and Distribution	23.1	4.3	-14%	17%
Magnesium Production and Processing	5.2	1.2	-7%	7%
Aluminum Production	21.5	1.1	-9%	9%
Total Emissions[f]	**6,371.0**	**6,456.7**	**-2%**	**4%**
LULUCF Emissions[g]	**7.8**	**15.5**	**-17%**	**20%**
LULUCF Carbon Stock Change[h]	**(814.8)**	**(729.6)**	**50%**	**-33%**
LULUCF Sector Net Total[i]	**(807.0)**	**(714.1)**	**51%**	**-34%**
Net Emissions (Sources and Sinks)[f]	**5,564.0**	**5,742.6**	**-6%**	**7%**

+ Does not exceed 0.05 MMT CO_2 Eq. or 0.5 percent.
NE (Not Estimated)
[a] Base Year is 1990 for all sources except Substitution of Ozone Depleting Substances, for which the United States has chosen 1995.
[b] The uncertainty 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.
[c] Emissions from Wood Biomass and Biofuel Consumption are not included in summing energy sector totals.
[d] Emissions from International Bunker Fuels are not included in the totals.
[e] This source category's estimate for 2017 excludes 0.023 MMT CO_2 Eq. of HTF emissions, as uncertainties associated with those sources were not assessed. Hence, for this source category, the emissions reported in this table do not match the emission estimates presented in the Industrial Processes and Product Use chapter of the Inventory.
[f] Totals exclude emissions for which uncertainty was not quantified.
[g] 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*; and N_2O emissions from Forest Soils and Settlement Soils.
[h] 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.
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.

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. The uncertainty models of all the emission source categories could not be directly integrated to develop the overall uncertainty estimates due to software constraints in integrating multiple, large uncertainty models. Therefore, an alternative approach was adopted to develop the overall uncertainty estimates. The Monte Carlo simulation output data for each emission source or sink category uncertainty analysis were combined by type of gas and the probability distributions were fitted to the combined simulation output data, where such simulated output data were available. If such detailed output data were not available for particular emissions sources, individual probability distributions were assigned to those source or sink category emission estimates based on the most detailed data available from the quantitative uncertainty analysis performed.

For Composting and parts of Agricultural Soil Management source categories, Approach 1 uncertainty results were used in the overall uncertainty analysis estimation. However, for all other emission sources (excluding international bunker fuels, CO_2 from biomass and biofuel combustion, and CH_4 from incineration of waste), Approach 2 uncertainty results were used in the overall uncertainty estimation.

The overall uncertainty model results indicate that the 2017 U.S. greenhouse gas emissions are estimated to be within the range of approximately 6,350.6 to 6,742.9 MMT CO_2 Eq., reflecting a relative 95 percent confidence interval uncertainty range of -2 percent to 4 percent with respect to the total U.S. greenhouse gas emission estimate of approximately 6,456.7 MMT CO_2 Eq. The uncertainty interval associated with total CO_2 emissions, which constitute about 82 percent of the total U.S. greenhouse gas emissions in 2017, 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 -9 percent to 14 percent, uncertainty associated with the total inventory N_2O emission estimate ranges from -12 percent to 21 percent, and uncertainty associated with fluorinated greenhouse gas (F-GHG) emissions ranges from -0.1 percent to 11 percent.

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

Table A-266: Quantitative Uncertainty Assessment of Overall National Inventory Emissions (MMT CO_2 Eq. and Percent)

Gas	2017 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	5,270.7	5,154.8	5,499.8	-2%	4%	5,326.0	88.7
CH_4[d]	656.3	596.0	747.6	-9%	14%	670.5	38.7
N_2O[d]	360.5	316.2	434.7	-12%	21%	368.7	30.4
PFC, HFC, SF_6, and NF_3[d]	169.1	168.9	188.2	-+%	11%	178.4	5.0
Total Emissions	**6,456.7**	**6,350.6**	**6,742.9**	**-2%**	**4%**	**6,543.6**	**101.0**
LULUCF Emissions[e]	**15.5**	**12.9**	**18.6**	**-17%**	**20%**	**15.7**	**1.5**
LULUCF Carbon Stock Change Flux[f]	**(729.6)**	**(1,094.4)**	**(488.5)**	**50%**	**-33%**	**(793.4)**	**154.0**
LULUCF Sector Net Total[g]	**(714.1)**	**(1,078.2)**	**(472.8)**	**51%**	**-34%**	**(777.7)**	**154.0**
Net Emissions (Sources and Sinks)	**5,742.6**	**5,408.2**	**6,130.0**	**-6%**	**7%**	**5,765.9**	**183.6**

+ Does not exceed 0.5 percent.

[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 2017.

[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*; 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*.

[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: 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.

Trend Uncertainty

In addition to the estimates of uncertainty associated with the current year's emission estimates, this Annex also presents the estimates of trend uncertainty. The *2006 IPCC Guidelines* defines trend as the difference in emissions between the base year (i.e., 1990) and the current year (i.e., 2017) 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, the trend uncertainty for a source and sink category is estimated using the sensitivity of the calculated difference between the base year and the current year (i.e., 2017) emissions to an incremental (i.e., 1 percent) increase in one or both of these values for that source and sink category. The two sensitivities are expressed as percentages: Type A sensitivity highlights the effect on the difference between the base and the current year emissions caused by a 1 percent change in both, while Type B sensitivity highlights the effect caused by a change to only the current year's emissions. Both sensitivities are simplifications introduced in order to analyze the correlation between the base and the current year estimates. Once calculated, the two sensitivities are combined using the error propagation equation to estimate the overall trend uncertainty.

Under the Approach 2 method, the trend uncertainty is estimated using the Monte Carlo Stochastic Simulation technique. The trend uncertainty analysis takes into account the fact that the base and the current year estimates often share input variables. For purposes of the current Inventory, 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., 2017) uncertainty output data. These were adjusted to account for differences in magnitude between the two years' inventory estimates. Then, for each source and sink category, a trend uncertainty estimate was developed using the Monte Carlo method. The overall inventory trend uncertainty estimate was developed by combining all source and sink category-specific trend uncertainty estimates. These trend uncertainty estimates present the range of likely change from base year to 2017 and are shown in Table A-267.

Table A-267: Quantitative Assessment of Trend Uncertainty (MMT CO_2 Eq. and Percent)

Gas/Source	Base Year Emissions[a]	2017 Emissions	Emissions Trend	Trend Range[b]	
	(MMT CO_2 Eq.)		(%)	(%)	
				Lower Bound	Upper Bound
CO_2	**5,121.2**	**5,270.7**	**3%**	**-2%**	**8%**
Fossil Fuel Combustion	4,738.8	4,912.0	4%	-1%	9%
Non-Energy Use of Fuels	119.6	123.2	3%	-34%	60%
Natural Gas Systems	30.0	26.3	-12%	-39%	25%
Cement Production	33.5	40.3	20%	10%	31%
Lime Production	11.7	13.1	12%	9%	16%
Other Process Uses of Carbonates	6.3	10.1	61%	33%	95%
Soda Ash Production	1.4	1.8	22%	8%	39%
Carbon Dioxide Consumption	1.5	4.5	204%	183%	226%
Incineration of Waste	8.0	10.8	36%	13%	62%
Titanium Dioxide Production	1.2	1.7	41%	17%	69%
Aluminum Production	6.8	1.2	-82%	-83%	-82%
Iron and Steel Production & Metallurgical Coke Production	101.6	41.8	-59%	-68%	-47%
Ferroalloy Production	2.2	2.0	-8%	-23%	9%
Glass Production	1.5	1.3	-14%	-20%	-9%
Ammonia Production	13.0	13.2	1%	-5%	8%
Urea Consumption for Non-Agricultural Purposes	3.8	5.0	31%	11%	54%
Phosphoric Acid Production	1.5	1.0	-33%	-50%	-10%
Petrochemical Production	21.2	28.2	33%	23%	44%
Silicon Carbide Production and Consumption	0.4	0.2	-50%	-56%	-43%
Lead Production	0.5	0.5	-12%	-29%	9%
Zinc Production	0.6	1.0	60%	27%	101%
Liming	4.7	3.2	-32%	-786%	763%
Urea Fertilization	2.4	5.1	109%	19%	263%
Petroleum Systems	9.0	23.3	161%	26%	436%
Abandoned Oil and Gas Wells	+	+	12%	-1,368%	1,554%
Magnesium Production and Processing	+	+	123%	98%	152%
Wood Biomass and Biofuel Consumption[c]	*219.4*	*116.6*	*-47%*	*NE*	*NE*
International Bunker Fuelc[d]	*103.5*	*120.1*	*16%*	*NE*	*NE*
CH_4	**779.8**	**656.3**	**-16%**	**-29%**	**(+)%**
Stationary Combustion	8.6	7.8	-9%	-64%	126%
Mobile Combustion	12.9	3.2	-75%	-80%	-69%
Coal Mining	96.5	55.7	-42%	-57%	-23%
Abandoned Underground Coal Mines	7.2	6.4	-11%	-45%	47%
Natural Gas Systems	193.1	165.6	-14%	-40%	22%
Petroleum Systems	42.1	37.7	-10%	-57%	87%
Abandoned Oil and Gas Wells	6.6	6.9	6%	-1,361%	1,356%

Petrochemical Production	0.2	0.3	14%	-54%	174%
Silicon Carbide Production and Consumption	+	+	-67%	-70%	-63%
Iron and Steel Production & Metallurgical Coke Production	+	+	-66%	-74%	-54%
Ferroalloy Production	+	+	-18%	-31%	-3%
Enteric Fermentation	164.2	175.4	7%	-21%	44%
Manure Management	37.1	61.7	66%	6%	159%
Rice Cultivation	16.0	11.3	-29%	-68%	58%
Field Burning of Agricultural Residues	0.1	0.2	82%	-53%	656%
Landfills	179.6	107.7	-40%	-64%	1%
Wastewater Treatment	15.3	14.2	-7%	-36%	33%
Composting	0.4	2.2	464%	149%	1,216%
Incineration of Waste	+	+	*-32%*	*NE*	*NE*
International Bunker Fuels[d]	*0.2*	*0.1*	*-44%*	*NE*	*NE*
N_2O	**370.3**	**360.5**	**-3%**	**-20%**	**22%**
Stationary Combustion	25.1	28.6	14%	-35%	101%
Mobile Combustion	42.0	16.9	-60%	-65%	-53%
Natural Gas Systems	+	+	438%	327%	578%
Petroleum Systems	+	+	77%	11%	178%
Adipic Acid Production	15.2	7.4	-51%	-55%	-48%
Nitric Acid Production	12.1	9.3	-23%	-28%	-18%
Manure Management	14.0	18.7	34%	-12%	105%
Agricultural Soil Management	251.7	266.4	6%	-21%	44%
Field Burning of Agricultural Residues	+	0.1	72%	-50%	488%
Wastewater Treatment	3.4	5.0	46%	-68%	556%
N_2O from Product Uses	4.2	4.2	+%	-30%	42%
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.7	1.4	-16%	-47%	34%
Incineration of Waste	0.5	0.3	-32%	-84%	192%
Settlement Soils	1.4	2.5	72%	-10%	222%
Composting	0.3	1.9	464%	152%	1,149%
Semiconductor Manufacture	+	0.2	597%	490%	722%
International Bunker Fuels[d]	*0.9*	*1.0*	*19%*	*NE*	*NE*
HFCs, PFCs, SF_6, and NF_3	**130.8**	**169.1**	**29%**	**24%**	**45%**
Substitution of Ozone Depleting Substances	31.4	152.7	386%	347%	429%
HCFC-22 Production	46.1	5.2	-89%	-91%	-87%
Semiconductor Manufacture[e]	3.6	4.7	31%	21%	42%
Aluminum Production	21.5	1.1	-95%	-95%	-94%
Electrical Transmission and Distribution	23.1	4.3	-81%	-85%	-77%
Magnesium Production and Processing	5.2	1.2	-78%	-82%	-77%
Total Emissions[f]	**6,402.1**	**6,456.7**	**1%**	**-3%**	**5%**
LULUCF Emissions[g]	**7.8**	**15.5**	**99%**	**60%**	**169%**
LULUCF Carbon Stock Change[h]	**(814.8)**	**(729.6)**	**-10%**	**-50%**	**62%**
LULUCF Sector Net Total[i]	**(807.0)**	**(714.1)**	**-12%**	**-51%**	**62%**
Net Emissions (Sources and Sinks)[f]	**5,595.1**	**5,742.6**	**3%**	**-7%**	**13%**

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

NE (Not Estimated)

[a] Base Year is 1990 for all sources except Substitution of Ozone Depleting Substances, for which the United States has chosen 1995.

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

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

[e] This source category's estimate for 2017 excludes 0.023 MMT CO_2 Eq. of HTF emissions, as uncertainties associated with those sources were not assessed. Hence, for this source category, the emissions reported in this table do not match the emission estimates presented in the Industrial Processes and Product Use chapter of the Inventory.

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

[g] 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*; and N_2O emissions from Forest Soils and Settlement Soils.

[h] 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.

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.

7.3. Reducing Uncertainty

There have been many improvements in reducing uncertainties across source and sink categories over the last several years. These improvements are result of new data sources that provide more accurate data or more coverage, as well as methodological improvements. Several source categories now use the U.S. EPA's GHGRP reported data, which is an improvement over prior methods using default emission factors and provides more country-specific data for Inventory calculations. EPA's GHGRP relies on facility-level data which undergoes a multi-step verification process, including automated data checks to ensure consistency, comparison against expected ranges for similar facilities and industries, and statistical analysis.

For example, the use of EPA's GHGRP reported data to estimate CH_4 emissions from Coal Mining resulted in the uncertainty bounds of -9 to 19 percent in the 1990 to 2017 Inventory, which was an improvement over the uncertainty bounds in the 1990 to 2011 Inventory of -15 to 18 percent. Prior to 2012, Coal Mining emissions were estimated using an array of emission factor estimations with higher assumed uncertainty. Estimates of CH_4 emissions from MSW landfills were also revised with the availability of GHGRP reported data resulting in methodological and data quality improvements that reduced uncertainty. Previously, MSW landfill emissions estimates were calculated using a model and default factors with higher assumed uncertainty.

Due to the availability of GHGRP reported data, Semiconductor Manufacturing emissions methodology as well as the uncertainty model was revised for the 1990 to 2012 Inventory. The revised model to estimate uncertainty relies on analysis conducted during the development of the EPA's GHGRP Subpart I rulemaking to estimate uncertainty associated with facility-reported emissions. These results were applied to the GHGRP-reported data as well as to the non-reported emissions. An improved methodology to estimate non-reported emissions along with improved methodology to estimate uncertainty of these non-reported emissions led to a reduced overall uncertainty of -6 to 6 percent in the 1990 to 2017 Inventory compared against a range of -8 to 9 percent in the 1990 to 2011 Inventory for the emissions of F-GHGs from the Semiconductor Manufacturing source category.

7.4. Planned Improvements

Identifying the sources of uncertainty in the emission and removal estimates of the Inventory and quantifying the magnitude of the associated uncertainty is the crucial first step towards improving those estimates. Quantitative assessment of the parameter uncertainty may also provide information about the relative importance of input parameters (such as activity data and emission factors), based on their relative contribution to the uncertainty within the source or sink category estimates. Such information can be used to prioritize resources with a goal of reducing uncertainty over time within or among inventory source categories and their input parameters. In the current Inventory, potential sources of model uncertainty have been identified for some emission source categories, and uncertainty estimates based on their parameters' uncertainty have been developed for all the emission source categories, with the exception of CH_4 from Incineration of Waste, and the International Bunker Fuels, CO_2 from Wood Biomass and Biofuel Consumption, and Indirect Greenhouse Gas Emissions source categories, which are not included in the energy sector totals. CO_2 Emissions from Wood Biofuel and Ethanol Consumption, however, 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 does include an estimate of CO_2 emissions from Wood Biomass and Biofuel Consumption in total emissions estimates, but rather it is provided as a memo item for informational purposes.

Specific areas that require further research to reduce uncertainties and improve the quality of uncertainty estimates include:

- *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, Forestry and Other Land Use (AFOLU) Sector.
- *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. In the future, consistent with IPCC good practice principles, efforts will focus on estimating emissions from excluded emission sources and developing uncertainty estimates for all source categories for which emissions are estimated.
- *Improving the accuracy of emission factors.* Further research is needed in some cases to improve the accuracy of emission factors used to calculate emissions from a variety of sources. For example, the accuracy of current

emission factors applied to CH_4 and N_2O emissions from stationary and mobile combustion are highly uncertain, and research is underway to improve these emission factors.

- *Collecting detailed activity data.* Although methodologies exist for estimating emissions for some sources, problems arise in obtaining activity data at a level of detail in which aggregate emission factors can be applied.
- *Improving models.* Improving 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.
- *Collecting more measured data and using more precise measurement methods.* Uncertainty associated with bias and random sampling error can be reducing by increasing the sample size and filling in data gaps. Measurement error can be reduced by using more precise measurement methods, avoiding simplifying assumption, and ensuring that measurement technologies are appropriately used and calibrated.
- *Refine source and sink category and overall uncertainty estimates.* For many individual source categories, further research is needed to more accurately characterize PDFs that surround emissions modeling input variables. This might involve using measured or published statistics or implementing rigorous elicitation protocol to elicit expert judgments, if published or measured data are not available. For example, activity data provided by EPA's GHGRP are used to develop estimates for several source categories—including but not limited to Magnesium Production and Processing, Semiconductor Manufacturing, and Electrical Transmission and Distribution—and could potentially be implemented for additional source categories to improve uncertainty results, where appropriate.
- *Improve characterization of trend uncertainty associated with base year Inventory estimates.* The characterization of base year uncertainty estimates could be improved, by developing explicit uncertainty models for the base year. This would then improve the analysis of trend uncertainty. However, not all of the simplifying assumptions described in the "Trend Uncertainty" section above may be eliminated through this process due to a lack of availability of more appropriate data.
- *Improving state of knowledge and eliminating known risk of bias.* Use expert judgment to improve the understanding of categories and processes leading to emissions and removals. Ensure methodologies, models, and estimation procedures are used appropriately and as advised by *2006 IPCC Guidelines*.

7.5. Summary 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, as needed. 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. All uncertainty estimates are reported relative to the current Inventory estimates for the 95 percent confidence interval, unless otherwise specified.

References

EPA (2002) *Quality Assurance/Quality Control and Uncertainty Management Plan for the U.S. Greenhouse Gas Inventory: Procedures Manual for Quality Assurance/Quality Control and Uncertainty Analysis*, U.S. Greenhouse Gas Inventory Program, U.S. Environmental Protection Agency, Office of Atmospheric Programs, EPA 430-R-02-007B, June 2002.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.