Findings from the U.S. Greenhouse Gas Inventory

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ABSTRACT

This paper presents a brief summary of the process used to develop the *U.S. Inventory of Greenhouse Gas Emissions and Sinks: 1990-1999*. As global attention is turning toward the credibility of national greenhouse gas inventories, the importance of developing reporting estimates that are fully transparent, well documented, and of irreproachable quality becomes paramount. In May 2000, the Intergovernmental Panel on Climate Change (IPCC) finalized the *Final Draft Report on Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. The development of the latest U.S. greenhouse gas inventory focused on review and implementation of these guidelines, including refining our emission estimation methodologies for a number of source categories, designing formal systems for quality assurance/quality control (QA/QC), and for quantifying uncertainties in emission estimates.

INTRODUCTION

In June of 1992, the United States signed the United Nations Framework Convention on Climate Change (FCCC). The objective of the FCCC is "to achieve…stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."[1]

Parties to the Convention, by signing, make commitments "to develop, periodically update, publish and make available…national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol, using comparable methodologies…"[2]

In 1988, preceding the creation of the FCCC, the Intergovernmental Panel on Climate Change (IPCC) was jointly established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP). Under the IPCC, nearly 140 scientists and national experts from more than thirty countries corroborated in the creation of the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* to ensure that the emission inventories submitted to the FCCC are consistent and comparable across sectors and between nations.

However, despite the existence of various *IPCC Guidelines*, developing a comprehensive, detailed, and scientifically authoritative national greenhouse gas inventory is still a creative and iterative process, rather than one of simply collecting data and performing calculations. It is also, though, an essential process in climate change policy development both domestically and internationally.

WHAT ARE GREENHOUSE GASES?

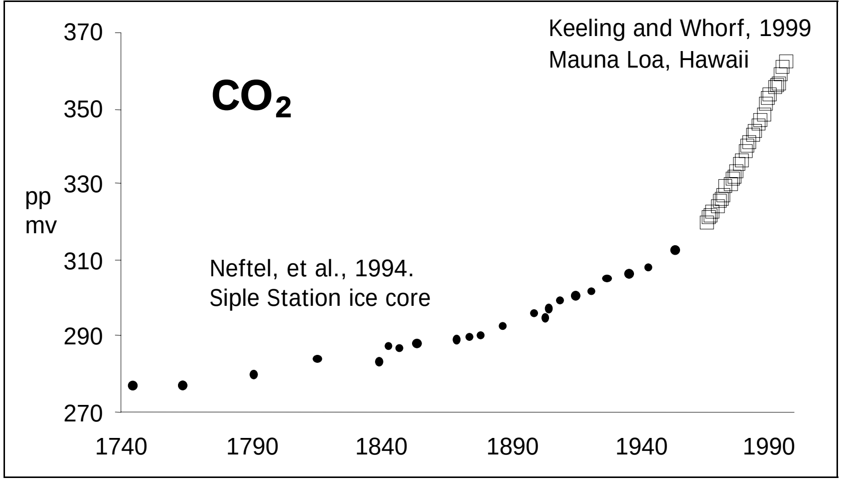
The Earth naturally absorbs and reflects incoming solar radiation and emits longer wavelength terrestrial (thermal) radiation back into space. On average, the absorbed solar radiation is balanced by the outgoing terrestrial radiation emitted to space. Gases in the atmosphere, though, absorb a portion of this terrestrial radiation. The energy from this absorbed terrestrial radiation warms the Earth's surface and atmosphere, creating what is known as the "natural greenhouse effect." Without the natural heat-trapping properties of these atmospheric gases, the average surface temperature of the Earth would be about 34°C lower.[3]

Although the Earth's atmosphere consists mainly of oxygen and nitrogen, neither plays a significant role in this greenhouse effect because both are essentially transparent to terrestrial radiation. The greenhouse effect is primarily a function of the concentration of water vapor, carbon dioxide, and other trace gases in the atmosphere that absorb the terrestrial radiation leaving the surface of the Earth. Changes in the atmospheric concentrations of these greenhouse gases can alter the balance of energy transfers between the atmosphere, space, land, and the oceans.

Under the FCCC, the definition of climate change is "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." Given that definition, in its 1995 assessment of the science of climate change, the IPCC concluded that:

> *Climate change can be driven by changes in the atmospheric concentrations of a number of radiatively active gases and aerosols. We have clear evidence that human activities have affected concentrations, distributions and life cycles of these gases* (see Figure 1).

Figure 1. Atmospheric and ice core global CO_2 concentration measurements.[4]



Atmospheric and ice core measurements of CH_4 and SF_6 concentrations have exhibited similar increases in atmospheric concentration that can be attributed to human activity.[5,6,7,8]

The three natural greenhouse gases included in the Kyoto Protocol are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Also included are another three—primarily man-made—greenhouse gas categories referred to as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). The IPCC has assigned each gas a Global Warming Potential (GWP) that accounts for the relative effectiveness of each gas at absorbing terrestrial radiation and its average lifetime in the atmosphere (see Table 1). These normalized emissions are generally measured in units of teragrams of carbon dioxide equivalents (Tg CO_2 Eq.).

Table 1. Global Warming Potentials and atmospheric lifetimes (years).

Gas	**Atmospheric Lifetime**	**GWP**[a]
Carbon dioxide (CO_2)	50-200	1
Methane (CH_4)[b]	12±3	21
Nitrous oxide (N_2O)	120	310
HFC-23	264	11,700
HFC-125	32.6	2,800
HFC-134a	14.6	1,300
HFC-143a	48.3	3,800
HFC-152a	1.5	140
HFC-227ea	36.5	2,900
HFC-236fa	209	6,300
HFC-4310mee	17.1	1,300
CF_4	50,000	6,500
C_2F_6	10,000	9,200
C_4F_{10}	2,600	7,000
C_6F_{14}	3,200	7,400
SF_6	3,200	23,900

Source: (IPCC 1996)

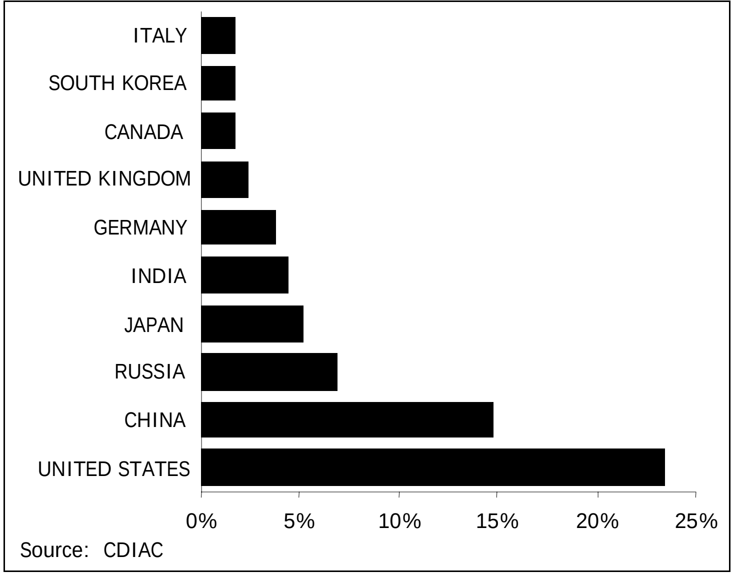
[a] 100 year time horizon

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

WHAT ARE U.S. GREENHOUSE GAS EMISSIONS?

The United States is currently the largest emitter of anthropogenic greenhouse gases in the world, accounting for approximately a quarter of global CO_2 emissions from fossil fuel combustion, cement production, and natural gas flaring (see Figure 2). The United States is also estimated to have the highest per capita emissions of any major industrialized country, equivalent to twice that of Japan and many European nations. The United States, however, sequesters carbon through the growth of its forests equivalent to roughly 15 percent of its total greenhouse gas emissions. Globally, though, deforestation is a net source of CO_2 to the atmosphere.

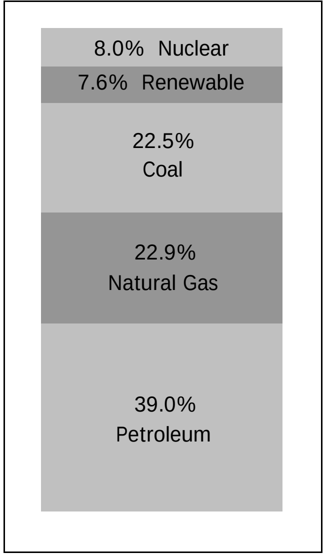
Figure 2. 1996 percent of global CO_2 emissions from fossil fuel combustion, cement manufacture, and natural gas flaring (top 10 countries).



Source: CDIAC

Like most nations, emissions in the United States are dominated by CO_2 produced from the combustion of fossil fuels for energy. Fossil fuels supplied a relatively constant 85 percent of the energy consumed in the United States in the 1990s (see Figure 3) and accounted for 81 percent of all anthropogenic greenhouse gas emissions in1999.

Figure 3. U.S. energy consumption in 1999.

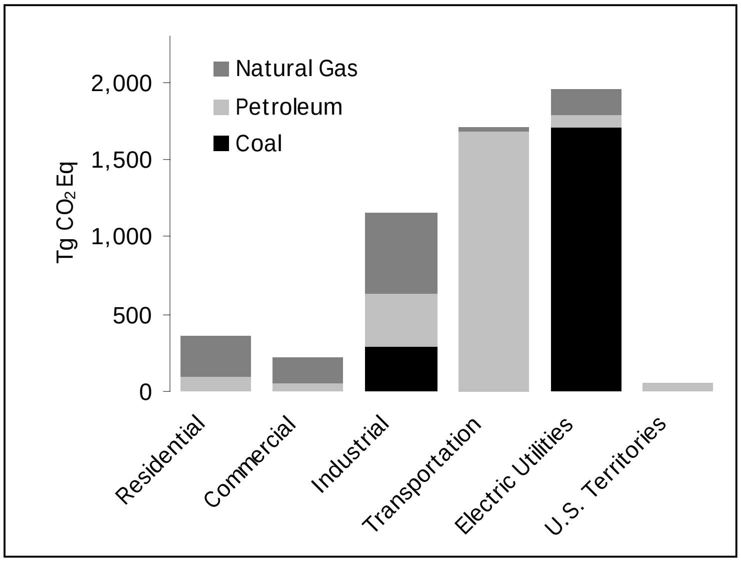


Source: EIA (2000)

The amount of carbon in fossil fuels varies significantly by fuel type. For example, coal contains the highest amount of carbon per unit of useful energy. Petroleum has roughly 75 percent of the carbon per unit of energy as coal, and natural gas has only about 55 percent. Therefore, by switching from coal, to say, natural gas, CO_2 emissions can be reduced without a reduction in energy consumption.

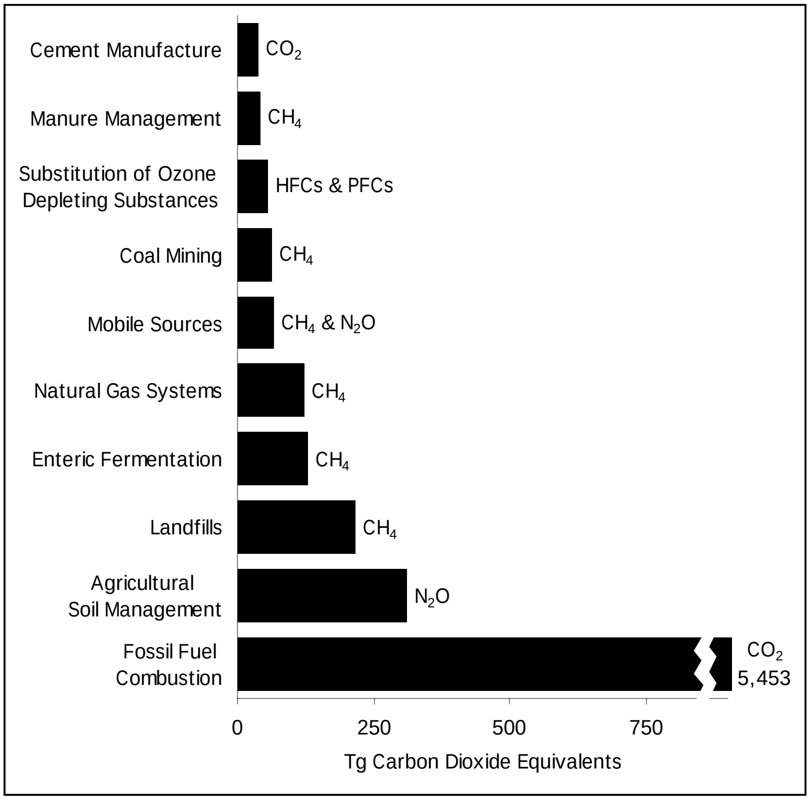
Of the energy consumed in the United States, a large portion is related to the production of electricity for consumption in the residential, commercial and industrial sectors. The majority of this electricity is produced through the combustion of coal by electric utilities. Natural gas consumption, on the other hand, occurs mainly in the residential and industrial sectors for heating homes and for process heat. The transportation sector is almost exclusively dependent on petroleum products such as motor gasoline and jet fuel (see Figure 4).

Figure 4. 1999 U.S. CO_2 emissions from fossil fuel combustion.



The other approximately 20 percent of greenhouse gas emissions in the United States result from a variety of sources that include CH_4 and N_2O emissions related to fossil fuel combustion, other energy production activities, industrial processes, agricultural activities, and waste systems. The primary sources of these emissions are shown in Figure 5, and emissions data for all sources are provided in Table 2.

Figure 5. 1999 U.S. greenhouse gas emission sources (top 10).



Referring to Figure 5, each source listed is defined below:

- Agricultural soil management refers to cropping and fertilizer use practices that are often intended to increase the nitrogen in agricultural soils, but also result in the generation of N_2O through biological nitrification and denitrification processes.
- Landfills emit CH_4 through the anaerobic decomposition of organic material, and are the largest source of methane in the United States.
- Enteric fermentation and manure management are related to the domestic livestock industry. Anaerobic conditions and the presence of methanogenic bacteria in livestock digestive systems and in manure lagoons lead to the generation of CH_4. Cattle and swine are the primary contributors to emissions from these two sources.
- Natural gas is composed primarily of CH_4 and is found in conjunction with both coal and petroleum deposits. The production and distribution of natural gas and the mining of coal are both fugitive sources of CH_4.
- Mobile sources include such things as highway passenger cars and trucks and non-highway boats, planes, and trains. The combustion of fuel in these vehicles emits both CH_4 and N_2O, primarily from automobiles and light-duty trucks.
- As CFCs and HCFCs are phased out under the *Montreal Protocol*, they are being replaced in many applications with non-ozone depleting chemicals such as HFCs and PFCs. Unfortunately, many HFCs and PFCs are potent greenhouse gases. Emissions of these substitute gases are growing rapidly, primarily from their use in air conditioning systems.
- The cement manufacturing process, in addition to being quite energy-intensive, also produces non-energy related by-product CO_2 emissions from calcium carbonate, which is heated to produce lime.

There are also many other smaller industrial and agricultural sources of greenhouse gas emissions in the United States, including but not limited to: PFCs from aluminum production, HFC-23 from HCFC-

22 production, SF_6 from electrical transmission and distribution systems, CH_4 and N_2O from wastewater treatment, CH_4 and N_2O from stationary fossil fuel combustion, N_2O from adipic and nitric acid production, and CH_4 from rice cultivation.

Table 2. U.S. greenhouse gas emissions and sinks (Tg CO_2 Eq.).

Gas/Source	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**
CO_2	**4,913.0**	**5,219.8**	**5,403.2**	**5,478.7**	**5,489.7**	**5,558.1**
Fossil Fuel Combustion	4,835.7	5,121.3	5,303.0	5,374.9	5,386.8	5,453.1
Natural Gas Flaring	5.1	13.6	13.0	12.0	10.8	11.7
Cement Manufacture	33.3	36.8	37.1	38.3	39.2	39.9
Lime Manufacture	11.2	12.8	13.5	13.7	13.9	13.4
Limestone and Dolomite Use	5.1	7.0	7.3	8.3	8.1	8.3
Soda Ash Manufacture and Consumption	4.1	4.3	4.3	4.4	4.3	4.2
Carbon Dioxide Consumption	0.8	1.0	1.1	1.3	1.4	1.6
Waste Combustion	17.6	23.1	24.0	25.7	25.1	26.0
Land-Use Change and Forestry (Sink)[a]	(1,059.9)	(1,019.1)	(1,021.6)	(981.9)	(983.3)	(990.4)
International Bunker Fuels[b]	114.0	101.0	102.2	109.8	112.8	107.3
CH_4	**644.5**	**650.5**	**638.0**	**632.0**	**624.8**	**619.6**
Stationary Sources	8.5	8.9	9.0	8.1	7.6	8.1
Mobile Sources	5.0	4.9	4.8	4.7	4.6	4.5
Coal Mining	87.9	74.6	69.3	68.8	66.5	61.8
Natural Gas Systems	121.2	124.2	125.8	122.7	122.1	121.8
Petroleum Systems	27.2	24.5	24.0	24.0	23.3	21.9
Petrochemical Production	1.2	1.5	1.6	1.6	1.6	1.7
Silicon Carbide Production	+	+	+	+	+	+
Enteric Fermentation	129.5	136.3	132.2	129.6	127.5	127.2
Manure Management	26.4	31.0	30.7	32.6	35.2	34.4
Rice Cultivation	8.7	9.5	8.8	9.6	10.1	10.7
Agricultural Residue Burning	0.5	0.5	0.6	0.6	0.6	0.6
Landfills	217.3	222.9	219.1	217.8	213.6	214.6
Wastewater Treatment	11.2	11.8	11.9	12.0	12.1	12.2
International Bunker Fuels[b]	+	+	+	+	+	+
N_2O	**396.9**	**431.9**	**441.6**	**444.1**	**433.7**	**432.6**
Stationary Sources	13.6	14.3	14.9	15.0	15.1	15.7
Mobile Sources	54.3	66.8	65.3	65.2	64.2	63.4
Adipic Acid	18.3	20.3	20.8	17.1	7.3	9.0
Nitric Acid	17.8	19.9	20.7	21.2	20.9	20.2
Manure Management	16.0	16.4	16.8	17.1	17.2	17.2
Agricultural Soil Management	269.0	285.4	294.6	299.8	300.3	298.3
Agricultural Residue Burning	0.4	0.4	0.4	0.4	0.5	0.4
Human Sewage	7.1	8.2	7.8	7.9	8.1	8.2
Waste Combustion	0.3	0.3	0.3	0.3	0.2	0.2
International Bunker Fuels[b]	1.0	0.9	0.9	1.0	1.0	1.0
HFCs, PFCs, and SF_6	**83.9**	**99.0**	**115.1**	**123.3**	**138.6**	**135.7**
Substitution of Ozone Depleting Substances	0.9	24.0	34.0	42.1	49.6	56.7
Aluminum Production	19.3	11.2	11.6	10.8	10.1	10.0
HCFC-22 Production	34.8	27.1	31.2	30.1	40.0	30.4
Semiconductor Manufacture	2.9	5.5	7.0	7.0	6.8	6.8
Electrical Transmission and Distribution	20.5	25.7	25.7	25.7	25.7	25.7
Magnesium Production and Processing	5.5	5.5	5.6	7.5	6.3	6.1
Total Emissions	**6,038.2**	**6,401.3**	**6,597.8**	**6,678.1**	**6,686.8**	**6,746.1**
Net Emission (Sources and Sinks)	**4,978.3**	**5,382.3**	**5,576.2**	**5,696.2**	**5,703.5**	**5,755.7**

+ Does not exceed 0.05 Tg CO_2 Eq.

[a] Sinks are only included in net emissions total. Estimates of net carbon sequestration due to land-use change and forestry activities exclude non-forest soils, and are based partially upon projections of forest carbon stocks.

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

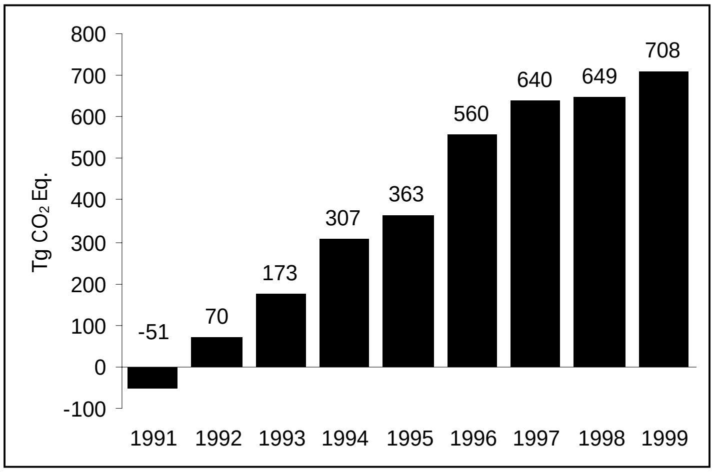
Note: Totals may not sum due to independent rounding. Parentheses indicate negative values (or sequestration).

WHAT ARE THE TRENDS IN U.S. EMISSIONS?

The dominant greenhouse gas emitted in the United States is CO_2, which accounted for 82 percent of 1999 emissions. The vast majority of CO_2 emissions resulted from fossil fuel combustion, and fossil fuel consumption is the primary determinant of U.S. emission trends. As of 1999, total U.S. greenhouse gas emissions had increased approximately 11.7 percent compared to 1990 levels (see Figure 6). This rise was primarily the result of increased consumption of fossil fuels for energy in all sectors at a time when the United States underwent robust economic growth, and when fuel efficiency improvements were relatively stagnant.

The annual increases in 1998 and 1999 were significantly affected by mild weather conditions (i.e., warm winters) and increased output from nuclear power plants. The annual increase in emissions in 1999 was 0.9 percent (see Figure 7).

Figure 6. Change in total U.S. greenhouse gas emissions since 1990.



Source: U.S. EPA

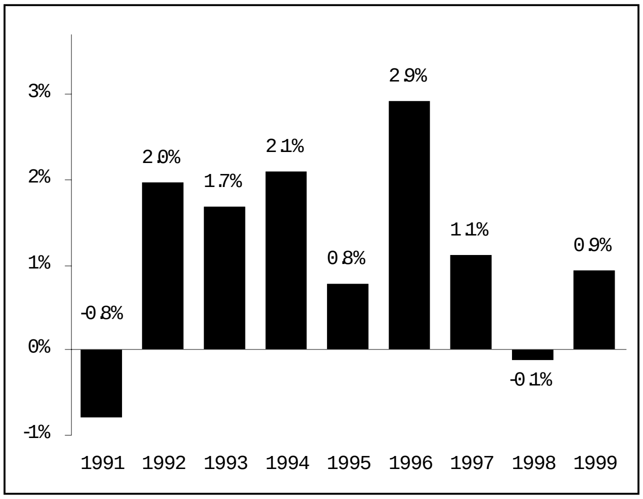
Methane emissions decreased by 4 percent from 1990 to 1999, mainly as a result of reduced emissions from coal mining as coal production shifted from underground to surface mines.

Emissions of N_2O rose by 9 percent during this period, primarily as a result of higher emissions from highway vehicles and agricultural soil management.

HFC, PFC, and SF_6 emissions, although they constituted a small portion of total U.S. emissions, grew rapidly over the ten-year period. Weighted emissions of these gases in 1999 were 62 percent above 1990 levels or 37 percent above emissions in 1995. Again, these increases were dominated by the substitution of ozone depleting substances, but were partly offset by reduction in emissions from primary aluminum and HCFC-22 production.

Under the commitments laid out in the Kyoto Protocol, the United States would have to reduce emissions to 7 percent below its 1990 baseline levels. The portion of this reduction that could come from measures other than domestic emission reductions (e.g., international emissions trades, joint implementation, or land-use and forestry sink credits) has yet to be resolved by the Parties to the FCCC.

Figure 7. Annual percent change in total U.S. greenhouse gas emissions.



Source: U.S. EPA

PREPARATION OF THE U.S. INVENTORY EMISSION ESTIMATES

To calculate the national emissions inventory, the U.S. employs methods, data sources, and analytical approaches that are consistent with guidelines for preparing national greenhouse gas emission inventories developed by the Intergovernmental Panel on Climate Change (IPCC). The IPCC, working in cooperation with scientists, national experts, and inventory specialists from around the world (including significant participation by the United States), has developed methodological guidelines to ensure that the national inventories submitted to the UNFCC are consistent and comparable across sectors and nations. The most recent version of these guidelines, the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, OECD, and IEA 1997), is the basis for national inventories prepared worldwide.

The IPCC *Guidelines* provide technical information for estimating anthropogenically-induced emissions of greenhouse gases. The *Guidelines* cover six broad categories of sources of emissions or removals (energy, industrial processes, solvent use, agriculture, land-use change and forestry, and waste), each with multiple sub-source categories. Because greenhouse gas emissions at the national level are generally calculated, rather than directly measured, the process of estimating emissions focuses on summing the products of activity data (i.e., measures of the occurrence of activities that produce greenhouse gas emissions in a given source category) and emission factors (i.e., the quantity of emissions per unit of the activity). Removals by sinks are calculated in analogous ways.

The *Guidelines* are designed to be followed by diverse nations, each with unique national circumstances, differences in key sources and sinks, and varying access to both the data and the resources required to estimate a greenhouse gas inventory. Consequently, the *Guidelines* permit alternative approaches to calculating the inventory, including relatively simple methods that use national activity data and default average emission factor data (referred to as Tier 1 or Reference Approach) for use by countries where country-specific data on key variables may be unavailable or difficult to obtain. The *Guidelines* also provide technical information and guidance for more detailed inventory methods (referred to as Tier 2 or 3). These methods may require a country to develop and use emission factors and other data specific to the country.

For some emission sources, the United States uses IPCC default methodologies and factors. However, for source categories that contribute significant emissions, the United States applies a more detailed analysis. In accordance with the *Guidelines,* whenever the U.S. approach involves a more rigorous calculation or method than the *Guidelines* provide, the *Inventory* reports and explains the approach in a clear and transparent manner. For comparison purposes, the *Inventory* also includes estimates prepared using the IPCC Reference approach.

To the extent possible, the emission estimates rely on published activity data and emission factors. Much of the data underlying the emission estimates comes from government statistics, including published or unpublished data supplied by agencies and departments such as the Energy Information Administration (EIA) of the U.S. Department of Energy and the U.S. Forest Service of the U.S. Department of Agriculture. State agencies and trade associations also supply important data. Some emissions estimates, such as those for NO_x (nitrogen oxides), CO (carbon monoxide), and NMVOCs (non-methane volatile organic compounds) are taken directly from U.S. Environmental Protection Agency estimates of emissions of ozone precursors, which are prepared to determine progress under the Clean Air Act in meeting national standards for air pollution.

THE U.S. INVENTORY DEVELOPMENT PROCESS

In practice, the development of an annual national inventory requires the institutionalization of a variety of procedures to ensure that the final document is of high quality. Each year, data and text describing each source are updated from the previous year. Source experts are identified and are provided with the opportunity to update and improve the data and analysis. This year, considerable attention was devoted to ensuring that the 1990-1999 *Inventory* was consistent with the *IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (*Good Practice Guidance*), which was developed by the IPCC to augment the 1996 *Guidelines*. The process designed for use in the United States relies on the coordination of numerous individuals and institutions. To ensure that the *Inventory* development proceeds smoothly and is completed each year by April 15, the following procedures have been put into place.

Once sector experts complete the initial emission estimates and write-up for each end-use sector, a single person (the inventory coordinator) collects them. The data are then compiled into a system of linking spreadsheets, and a single summary file is created that gathers and summarizes all of the information for each year, thus allowing comparisons to be made and trends to be analyzed. Due to the large number of individuals involved in creating the *Inventory*, one integral facet of the U.S. development process is that the inventory coordinator maintains control of all data and text after they have been submitted. Once the inventory coordinator compiles the document, any further changes must be authorized and performed on the master document. This ensures that all changes are correctly incorporated and helps maintain quality control. After the *Inventory* has been assembled, both the inventory estimates and the inventory document undergo a rigorous review process, including an expert review and a general public review.

The expert review is conducted in two stages: a review of the initial set of draft emission estimates and, subsequently, a review of the estimates and text of the inventory document. In addition, experts are consulted and involved throughout the development of the inventory estimates, providing further review and opportunities for evaluation and assessment of the inventory methodologies and data. The ultimate goal of these expert reviews is to provide an objective review of the *Inventory*, in order to ensure that the final inventory estimates and inventory document reflect sound technical information and analysis.

The expert and public reviews each present opportunities to uncover technical issues related to the application of methodologies, selection of activity data, or the development and choice of emission factors. The expert review process can also facilitate developing solutions to pending issues in the preliminary work. The subsequent public review of the draft document offers a broader range of researchers and practitioners in industry and academia, as well as the general public, the opportunity to contribute to the final document. The comments received during these processes are reviewed and, as needed, incorporated into the inventory document or reflected in the inventory estimates.

QA/QC AND UNCERTAINTY

The IPCC *Good Practice Guidance* report devotes considerable attention both to quality assurance/quality control procedures and practices, and to quantifying and managing uncertainty in emission estimates. Informal quality control and quality assurance practices and uncertainty estimation and management have been integral components of the U.S. greenhouse gas inventory program since its inception. Concurrent with the recent round of the inventory estimation process, the U.S. initiated a long-term effort to develop a more formal program of quality checks and uncertainty management that would be consistent with the recommendations in the *Good Practice Guidance*. As part of this effort, the U.S. plans to perform a thorough quality check of the inventory estimates and to develop detailed uncertainty estimates, over a period of three years.

In the area of quality assurance and quality control (QA/QC), a comparison of historical practices in developing the U.S. greenhouse gas inventory with IPCC recommendations indicated that, while important elements of QA/QC and uncertainty analysis were already in place, more formal processes and procedures were needed. In particular, the review found the following:

- A well-developed process for quality assurance—i.e., annual expert review of the inventory estimates—existed and adequately met the IPCC standards of independent and critical review.
- Quality control procedures include procedures to improve, control, or check the quality of the emission estimates and the underlying data, such as providing appropriate and complete documentation for the estimate, checking the methodology, assumptions, or data inputs used, or checking the accuracy of calculations. The application of these procedures to the inventory tends to be informal rather than systematic and rigorously documented, although many of the IPCC-recommended QC activities are frequently and in some cases routinely performed by the inventory analysts and the inventory coordinator.
- Uncertainty analysis is a stand-alone effort to understand the accuracy of inventory estimates, and also contributes to the quality of the estimates and minimizes the uncertainty over time, by improving data and inventory methods. The U.S. program has always evaluated the uncertainty of the source-category estimates and ranked them as low, medium, or high through qualitative analysis. Although formal modeling and detailed analysis of uncertainty have been undertaken in the past for selected inventory source categories (such as methane and nitrous oxide emission sources), the inventory process does not routinely involve formal modeling or detailed analyses of uncertainty, which the IPCC recommends for ascertaining the accuracy of the inventory estimates.

The U.S. is in the midst of developing more detailed QC procedures and formalizing the QA process that is already in place, as well as designing an uncertainty model and developing detailed uncertainty estimates for as many sources as are practicable. These processes are integrated among one another, as well as with the inventory program and the development of the inventory estimates. In addition to this integration, key features of the overall program (referred to as the “QA/QC plan”) include:

- QA/QC and uncertainty processes should run in parallel—particularly investigations of secondary data quality and uncertainty analysis, which must be closely coordinated;
- Protocols and templates could serve to standardize the documenting and archiving of information and guide the implementation of QA/QC and uncertainty analysis;
- The plan includes provisions for corrective action and follow-up, depending on the results of the QA/QC/uncertainty activities;
- Resources for implementing both QC and uncertainty analysis are allocated across source categories based on key source analysis.

Each stage of development in the plan will be subject to extensive internal review and testing. The plan is expected to be an evolving document and set of processes—to be revised depending on developments in inventory methods, programmatic priorities, and the experiences of analysts over time in implementing the plan.

More specifically, the QA portion of the plan includes formal procedures and templates for the expert peer and public review processes. The QC portion of the plan includes practices for minimizing problems with quality and accuracy in the inventory, as well as procedures for checking calculations, documentation, and assumptions in order to ensure that quality is as high as practicable. The uncertainty analysis includes procedures for gathering necessary data inputs and estimating uncertainty using a Monte Carlo model developed using @Risk© software.

The overall plan provides for roughly a three-year full implementation horizon—i.e., three years for a full check of the inventory and a full uncertainty estimation, with followed up iterations as needed. Initially, the focus is on drafting the QA/QC plan and on the design of information collection and management protocols and templates, including expert elicitation. The next stage will focus on developing uncertainty analysis tools and running and testing the model, concluding with a complete Monte Carlo simulation model with placeholder input values. Concurrent with model development and testing, the draft templates and protocols for QA/QC/uncertainty will be tested on select key sources. After rigorous internal review and testing, the final plan will be implemented and a complete check of the inventory and an uncertainty analysis completed.

IMPROVEMENTS TO THIS YEAR’S INVENTORY

Improvements to the inventory process are made each year, not only in the data and methodologies for specific sectors, but also by the addition of new topics to ensure completeness. In addition to the many changes that have been implemented due to the *Good Practice Guidance*, estimates of CO_2 from fossil fuel combustion have been expanded to focus on the topics discussed in the following sections.

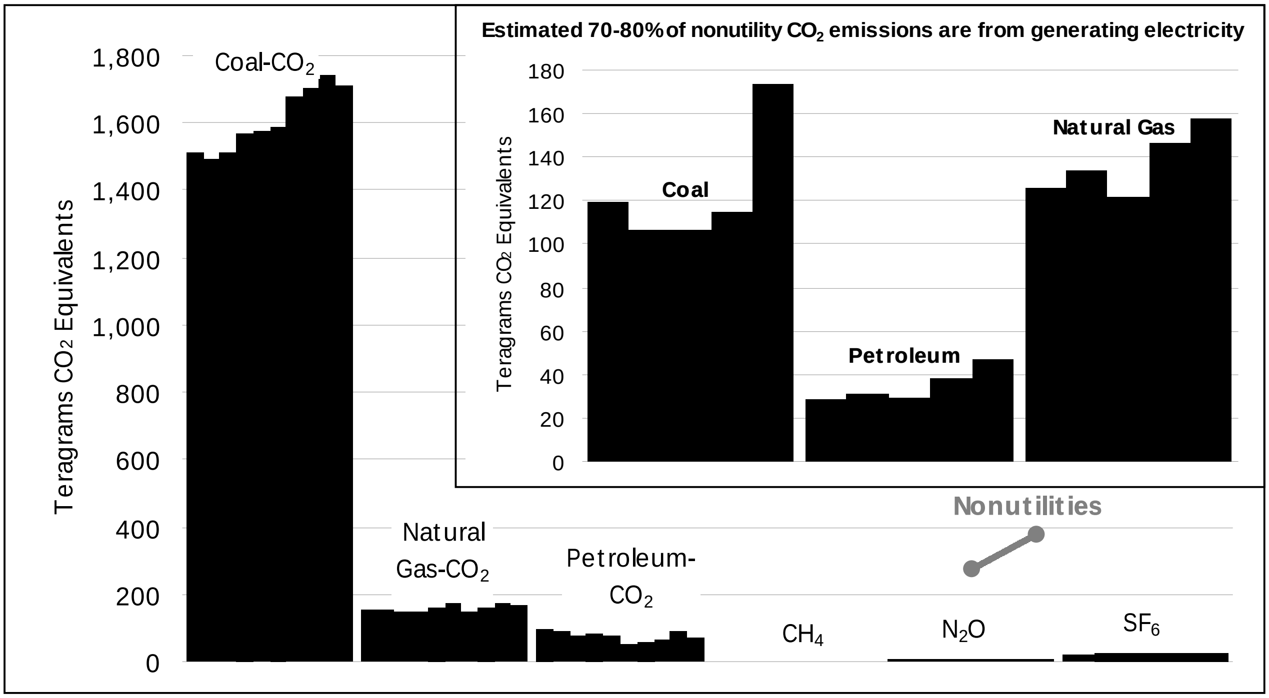
The Electric Power Industry

Activities related to the generation of electricity have historically been responsible for the largest fraction of total greenhouse gas emissions in the United States. Carbon dioxide is the primary greenhouse gas emitted by the electric power industry; however, the industry also emits combustion-related CH_4 and N_2O, as well as SF_6 from gas insulated switchgear and circuit breakers. Electric utilities still dominate emissions from the industry; however, nonutilities are accounting for a growing fraction of total emissions as deregulation opens the market for generation to competition.

Figure 8 presents greenhouse gas emission estimates from electric utility and nonutility activities. Overall, emissions from electric utilities were dominated by CO_2 emissions from coal combustion, while nonutilities relied much more heavily on natural gas. The drop in coal emissions from utilities in 1999 was countered with an increase from nonutilities, and can be accounted for by the sell-off of utility assets to new independent power producers.

Overall, emissions from the electric power industry accounted for approximately 41 percent of U.S. CO_2 emissions in 1999. However, when all greenhouse gases are included, the industry’s fraction drops to 34 percent (see Figure 9). The increase in this fraction over the last several years can be attributed to the increased demand for electricity relative to other fuels by other sectors of the economy.

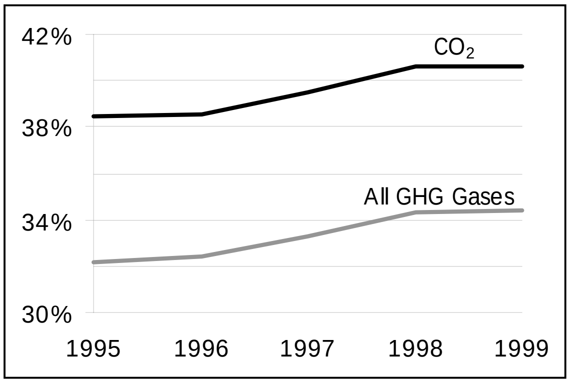
Figure 8. Greenhouse gas emissions from electric utilities (1990-1999) and nonutilities (1990-1995).



Source: U.S. EPA

Note: Nonutility data includes emission from fuel input for both process heat production and electricity generation.

Figure 9. Fraction of U.S. CO_2 and total greenhouse gas emissions from the electric power industry.



Source: U.S. EPA

Note: Includes only fuel input for the generation of electricity.

Carbon Storage in Non-energy End-uses

In addition to being combusted for energy, some of the fossil fuel consumption in the industrial and transportation sectors is consumed for non-energy end-uses. These non-energy fuel uses are diverse, and include application as solvents, reduction agents in metals production, lubricants, and waxes, or as raw materials in the manufacture of plastics, rubber, synthetic fibers, and fertilizers.

To estimate carbon dioxide emissions from fossil fuel combustion, the amount of carbon stored by non-energy end-uses must be subtracted from the total carbon in the fuels consumed. To estimate this storage, factors are multiplied by the appropriate fuel consumption in the industrial and transportation sectors. In previous inventories, these factors were taken directly from the literature.[9] For this year's *Inventory*, the factors for several fuel types (asphalt and road oil, petroleum feedstocks, liquefied petroleum gas, pentanes plus, natural gas, and lubricants) were revised using data on U.S. carbon flows. A lifecycle approach was used, accounting for carbon losses during the production process—from raw material acquisition through manufacturing and processing—and during use. The storage factors were then calculated by comparing the carbon residing in each fuel's products to the total carbon originally found in the parent fuel.

The storage factors for the six fuel types addressed in this year's *Inventory* were chosen for revision based on the availability of data regarding their products, the amount of carbon associated with the non-energy end-uses, and the relative uncertainty of storage factors presented in the literature. Storage factors were revised for fuels comprising approximately 80 percent of the fossil fuel carbon consumed for non-energy end-uses. The effect of the revisions in methodology were to increase the estimate of the amount of carbon stored, for 1990 through 1998, by an average annual of 26.9 Tg CO_2 Eq., or about 10 percent. This change is a significant one, exceeding the total emissions estimated for 27 of the individual source categories listed in Table 2. Over the next year, we expect to further improve the methodology for carbon storage in non-fuel uses.

CONCLUSION

Much has been learned in the preparation of seven U.S. greenhouse gas inventories. Although there still exist sources of anthropogenic greenhouse gas emissions that have not been fully quantified, the number and magnitude of these sources is believed to be small.

Overall, as common sense would suggest, the level of uncertainty, detail, and precision desired of the estimates in a national inventory of anthropogenic greenhouse gas emissions and sinks depends upon the application of the estimates themselves. There can be several uses for a national inventory, such as: (1) for compliance with international treaties and commitments, (2) for accounting in an international emissions trading system, (3) for identification of mitigation opportunities, (4) for tracking progress of national mitigation efforts, (5) as feedback to data collection agencies to improve emissions relevant statistics, and (6) as a step in the iterative improvement of estimating methodologies. Further efforts to improve the U.S. inventory will in part depend upon the outcome of ongoing policy debates regarding its purpose or purposes.

FOR MORE INFORMATION

- U.S. EPA Global Warming website: <http://www.epa.gov/globalwarming/publications/emissions>
- Carbon Dioxide Information Analysis Center (CDIAC), Oak Ridge National Laboratory, P. O. Box 2008 MS 6335, Oak Ridge, TN 37831-6335, Internet: <http://cdiac.esd.ornl.gov>
- Intergovernmental Panel on Climate Change (IPCC), World Meteorological Organization Building, 41 Av. Giuseppe-Motta, Case postale No. 2300, 1211 Geneva 2, Switzerland, Internet: <http://www.ipcc.ch>
- United Nations Framework Convention on Climate Change (UNFCCC), P.O. Box 260124, D-53153 Bonn, Germany, Internet: <http://www.unfccc.de>

REFERENCES

1. Article 2 of the Framework Convention on Climate Change published by the UNEP/WMO Information Unit on Climate Change.
2. Article 4 of the Framework Convention on Climate Change published by the UNEP/WMO Information Unit on Climate Change (also identified in Article 12).
3. IPCC. *Climate Change 1995: The Science of Climate Change*; Intergovernmental Panel on Climate Change; Houghton, J.T.; Meira Filho, L.G.; Callander, B.A.; Harris, N.; Kattenberg, A.; Maskell, K.; Eds.; Cambridge University Press; Cambridge, UK, 1996.
4. Keeling, C.D. and Whorf, T.P.; "Atmospheric CO_2 records from sites in the SIO air sampling network", *Trends: A Compendium of Data on Global Change*; Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN, 1998.

5. Neftel, A.; Friedli, H.; Moor, E.; Lötscher, H.; Oeschger, H.; Siegenthaler, U.; Stauffer, B.; "Historical CO_2 record from the Siple Station ice core", *Trends '93: A Compendium of Data on Global Change*; Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN, 1994.
6. Khalia, M.A.K.; Rasmussen, R.A.; "Global CH_4 record derived from six globally distributed locations", *Trends '93: A Compendium of Data on Global Climate Change*; Boden, T.A.; Kaiser, D.P; Sepanski, R.J.; Stoss, F.W. Eds.; Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN, 1994, pp 268-272.
7. Etheridge, D.M.; Pearman, G.I.; Fraser, P.J.; "Historical CH_4 record from the 'DE08' ice core at Law Dome", *Trends '93: A Compendium of Data on Global Climate Change*; Boden, T.A.; Kaiser, D.P; Sepanski, R.J.; Stoss, F.W. Eds.; Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN, 1994, Pp. 256-260
8. Sturges, W.T.; Wallington, T.J.; Hurley, M.D.; Shine, K.P.; Sihra, K.; Engel, A.; Oram, D.E.; Penkett, S.A.; Mulvaney, R.; Brenninkmeijer, C.A.M.; "Trifluoromethyl Sulfur Pentafluoride (SF_5CF^3) and Sulfur Hexafluoride (SF_6) from Dome Concordia", *Trends: A Compendium of Data on Global Change*; Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, TN, 2000.
9. Marland, G. and Rotty, R.M. "Carbon dioxide emissions from fossil fuels: a procedure for estimation and results for 1950-1982", *Tellus.* 1984, 36B, 4, 232-261.

Key Words: greenhouse gas, emissions, climate change, inventory, United States